PAPER • **OPEN ACCESS**

3rd International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters

To cite this article: S O Semerikov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 011001

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 011001 doi:10.1088/1755-1315/1049/1/011001

3rd International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters

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Abstract. This paper represents a preface to the Proceedings of the 3rd International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters (ICSF 2022) held at the Kryvyi Rih, Ukraine, 24–27 May 2022. Background information and the organizational structure of the meeting, program committee, and acknowledgments of the contributions of the many people who made the conference a success are presented.

1. Background

The **International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters** (**ICSF**) is a peer-reviewed international conference, which is the premier interdisciplinary forum for life scientists, social scientists, engineers, and practitioners to present their latest research results, ideas, developments, and applications (figure 1).

Since 2020, ICSF occupies contributions in all aspects of sustainable development, focused on the intersection of sustainability, environment and technology, and their more significant

Figure 1. ICSF 2022 logo.

implications for a corporation, government, education institutions, regions, and society both at present and in the future [1–3].

ICSF 2022 has two presentation levels, Pre-conference Workshops and Main Conference.

1.1. Sustainable Development of Mining Science and Industry (SusDevMiningScI'2022)

Sustainable development of Mining Science and Industry workshop (SusDevMiningScI'2022) is a peer-reviewed international workshop devoted to the latest scientific and technological achievements in mine safety, geological study, and safeguarding of mineral resources.

SusDevMiningScI'2022 Program Committee chair is Dr. Serhii Chukharev (figure 2).

1.2. Geography for Sustainable Development (GSD-2022)

Geography for Sustainable Development (GSD-2022) is a peer-reviewed international workshop. During the GSD-2022, the researchers who are committed to the problems of geography for sustainable development can present their latest research findings, ideas, developments and programs.

GSD-2022 main topics of interest are:

- Geographical bases of sustainable future: methodological bases
- Problems and prospects for the development of physical and socio-economic geography in the context of sustainable future
- Regional problems of sustainable future and local lore research of territories
- Cartographic research and geoinformatics: theory and practice
- Noosphere nature management is the key to a sustainable future
- The theory of sustainable future in geographical education

GSD-2022 Program Committee chair is Dr. Olga Bondarenko (figure 3).

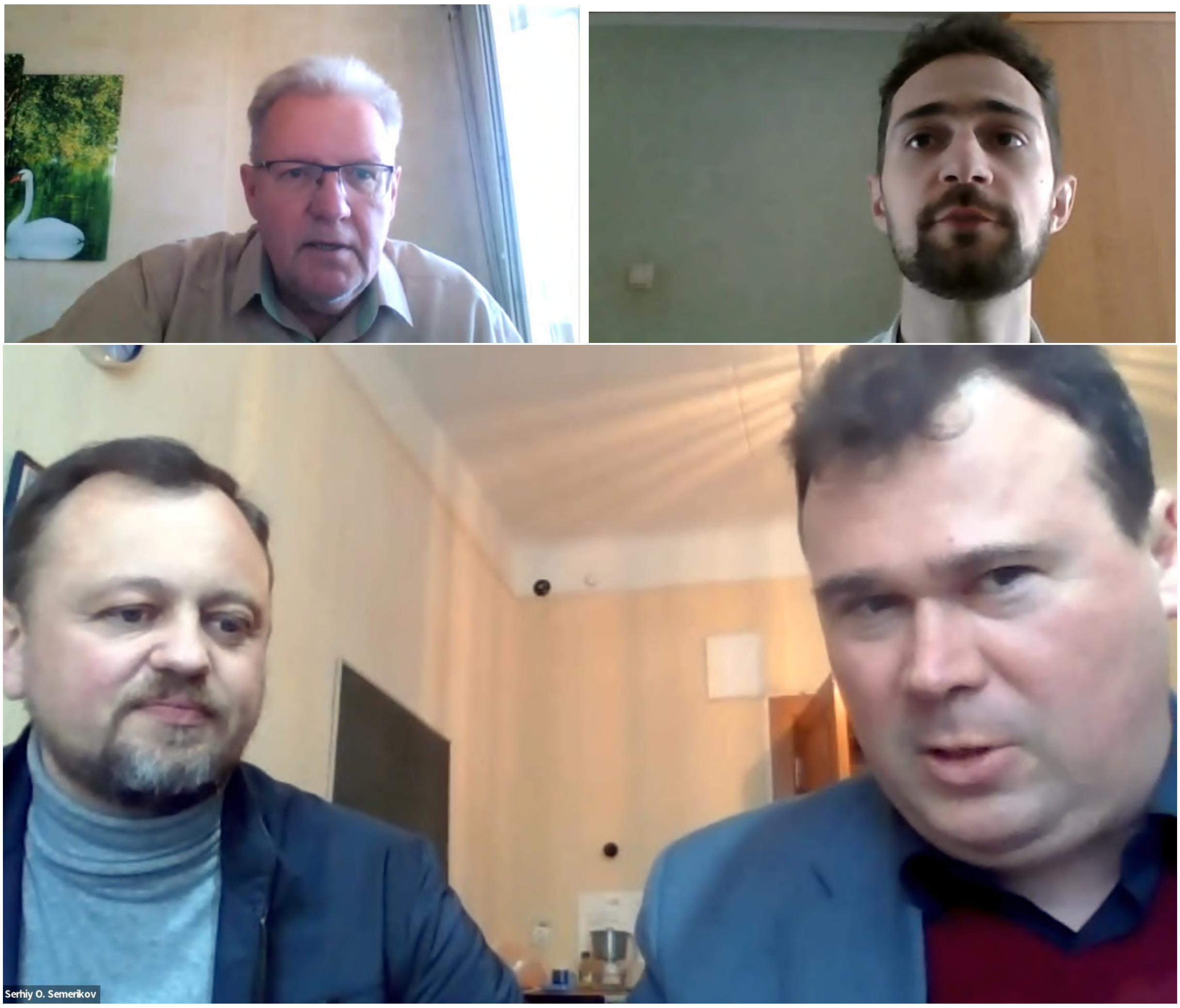

Figure 2. SusDevMiningScI'2022 session chairs: Serhii Chukharev, Yulian Hryhoriev, Andrii Striuk, and Serhiy Semerikov.

1.3. Biodiversity and Ecosystems Sustainability (BiodES-2022)

Biodiversity and Ecosystems Sustainability (BiodES) is a peer-reviewed international workshop focusing on solving problems of biodiversity conservation and ecosystem sustainability from the point of view of applied science and education, which is the important basis for solving global problems of the mankind and sustainable futures.

BiodES-2022 contributes to all aspects of solving problems of biodiversity conservation and ecosystem sustainability by reflecting the environmental, technological, physiological and biochemical aspects of the problem; methods of application of modern information and communication technologies and mathematical approaches for their solution; discussion of modern educational concepts aimed at solving the problems of ecosystem sustainability with the purpose of sustainable development of the future.

BiodES-2022 main topics of interest are:

- Biodiversity in animals and plants as the indicator of ecosystem sustainability
- Ecological monitoring in preservation of biodiversity and ecosystem sustainability
- Physiological, biochemical and technological aspects of biodiversity and ecosystem

Figure 3. Olga Bondarenko at the GSD-2022.

sustainability
- Sustainable development in the context of global climate change
- Biodiversity and ecosystem functioning
- Risks to human well-being from the degradation of ecosystems and species

BiodES-2022 Program Committee chair is Dr. Viacheslav Osadchyi (figure 4).

Figure 4. BiodES-2022 session chairs: Viacheslav Osadchyi, and Vladyslav Kruhlyk.

1.4. Water Management and Environmental Engineering (WaterManEnvE-2022)
Water Management and Environmental Engineering (WaterManEnvE-2022) is a peer-reviewed international workshop occupies contributions in all aspects of water management and environmental engineering, environmental education and modern educational technologies.

WaterManEnvE-2022 main topics of interest are:

- Water management and water resources use
- Monitoring of water resources
- Irrigation and drainage
- Water treatment and water supply
- Hydraulic engineering & hydraulics
- Hydropower, etc.

WaterManEnvE-2022 Program Committee chairs is Dr. Serhii Klimov (figure 5).

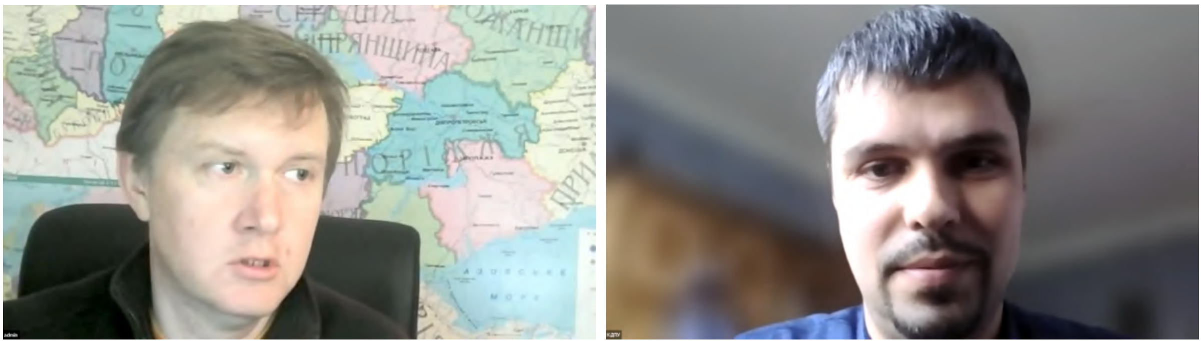

Figure 5. WaterManEnvE-2022 session chairs: Serhii Klimov, and Pavlo Nechypurenko.

1.5. Innovative Approaches for Solving Environmental Issues (IASEI-2022)

Innovative Approaches for Solving Environmental Issues (IASEI-2022) is a peer-reviewed international workshop focusing on advanced research in environmental science.

IASEI-2022 main topics of interest are:

- Environmental protection
- Nuclear and radiation safety
- Complex, economic and technological solutions
- Problems of training and advanced training of specialists in the field of energy and ecology

IASEI-2022 Program Committee chair is Dr. Andrii Iatsyshyn (figure 6).

1.6. Main Conference

Workshops and conference presentations are grouped into 7 tracks (figure 7):

- Sustainable Development of Mining Science and Industry [4–15]
- Innovative Approaches for Solving Environmental Issues [16–27]
- Geotechnical and Geoenvironmental Engineering. Sustainable Mining [28–39]
- Sustainable Environment and Environmental Management [40–50]
- Sustainable Energy, Building and Architecture, Materials and Technologies [51–58]
- Biodiversity and Ecosystems Sustainability [59–77]
- Sustainable Cities and Society. Governance, Legislation and Policy for Sustainability [78–87]

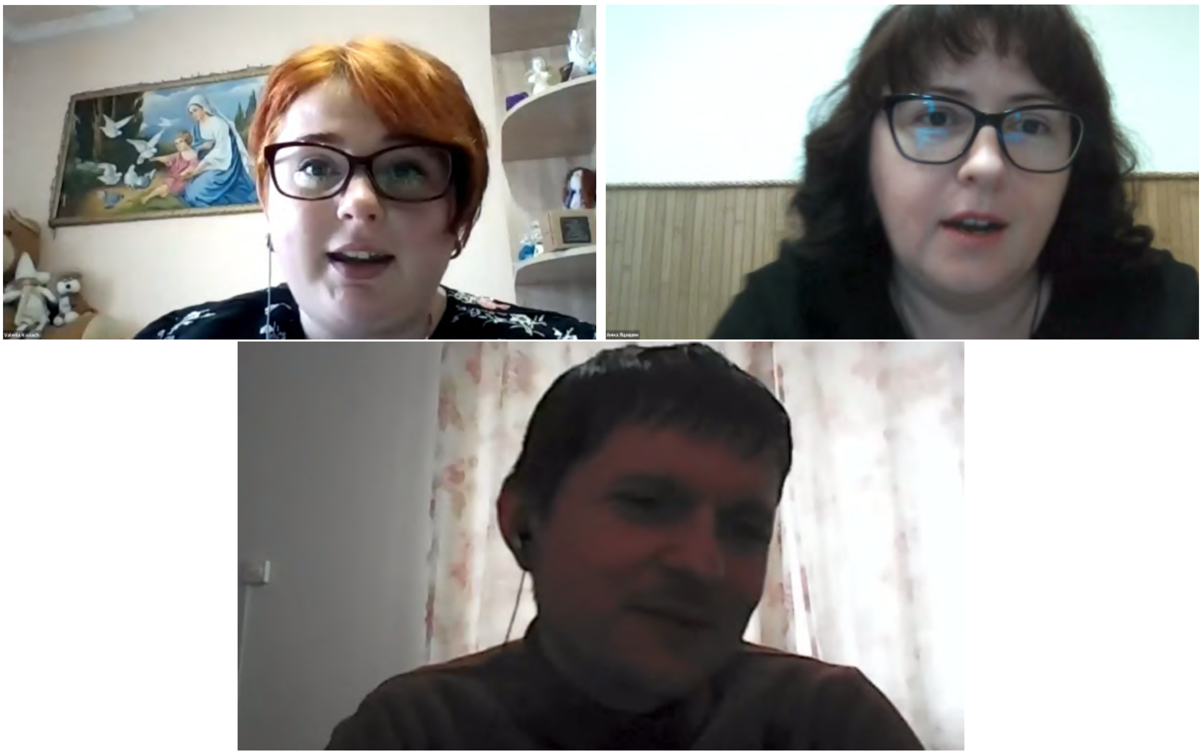

Figure 6. IASEI-2022 session chairs: Valeriia Kovach, Anna Iatsyshyn, and Andrii Iatsyshyn.

This volume contains the papers presented at ICSF 2022: 3rd International Conference on Sustainable Futures: Environmental, Technological, Social, and Economic Matters held on May 24-27, 2022 in Kryvyi Rih, Ukraine.

On the first stage, authors were invited to submit abstracts (`https://www.morressier.com/call-for-abstracts/ICSF-2022`). There were 169 submissions. Each abstract was reviewed by 2 program committee members. The committee decided to accept 152 abstracts [88].

On the second stage, authors of accepted abstracts were invited to submit full research papers including surveys, tutorials, perspective/colloquia articles in conference topics of interest (`https://www.morressier.com/call-for-papers/6127d6ec0bfa8e001283d3a2`). There were 125 submissions received. Each submission was reviewed by at least 3 program committee members. The committee decided to accept 84 papers.

The spread of the coronavirus that causes COVID-19 and the ongoing Russian invasion of Ukraine has changed the conference organization (figure 8). Therefore, the 3rd International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters (ICSF 2022) took place on 24–27 May 2022 at the Kryvyi Rih National University, Ukraine, both in-person and online.

More than 130 attendees from 14 countries are joined to ICSF 2022 using Zoom. The presentation slots were defined as follows:

- invites talks (30 min): 20 min presentation, 10 min question answering and discussion,
- other talks (15 min): 10 min presentation and 5 minutes question answering and discussion.

The full program is available at the `https://icsf.ccjournals.eu/2022/` where details of the sessions, usually headed by one or more invited presentations. Video records of talks are available at the *Not So Easy Science* YouTube channel (`https://www.youtube.com/channel/UCH3gego79m-ofCiNEgEzMuA`).

Figure 7. Main Conference session chairs: Serhiy Sakhno, Tetiana Vakaliuk, and Hanna Danylchuk.

2. ICSF 2022 program committee

- Dr. *Rovshan Abbasov*, Head of the Department of Geography and Environment at Khazar University and the Representative of the Pure Earth International Organization in Azerbaijan, Azerbaijan
- Assoc. Prof. *Leon A. Abdillah*, Associate Professor of Computer Science and Information Systems, Department of Information Systems, Universitas Bina Darma, Palembang, Indonesia
- Dr. *Khairulla Aben*, Underground Mine Planning Manager, Mining Department, Eurasian Resources Group, Nur-Sultan, Kazakhstan
- Dr. *George Abuselidze*, Professor of Economics and Business, Department of Finance, Banking and Insurance, Batumi Shota Rustaveli State University, Batumi, Georgia
- *R. S. Ajin*, Hazard Analyst (Geology) with the Kerala State Disaster Management Authority (KSDMA), Thiruvananthapuram, India, and Research Fellow with the Resilience Development Initiative (RDI), Bandung, Indonesia
- PhD *Tetiana Alokhina*, Senior Researcher, Leading researcher of section of geology and

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TCH > War

The occupiers hit Kryvyi Rih with three missiles: the enterprise was destroyed

18:02, 25.05.22 1 min

Share:

Photo: TCH.ua

The Russian troops fired missiles at Kryvyi Rih and also fired from "Uragan" multiple launch rocket system two communities in the Kryvorizkyi district.

FEED

The Russians have intensified bombers to search for positions of the Ukrainian air defense - the Ministry of Defense
18:15, 25.05.22

"Poland is seriously preparing": the Ukrainian ambassador said that Russia could fire on this country
17:49, 25.05.22

"You will have to send your own troops into battle": Yermak called the only way to prevent a world war
17:48, 25.05.22

"The longer this war lasts, the greater the price will be": Zelenskyy urged the partners to send weapons to Ukraine
17:22, 25.05.22

"Russian invaders want to destroy everything there": Zelenskyy described the situation in the Donbas as "very difficult"
14:58, 25.05.22

Russian propaganda connects the origin of monkeypox to fictional Ukrainian "biological laboratories"
14:47, 25.05.22

"Sievierodonetsk is barely alive": Haidai said that the situation in the Ukrainian Luhansk region is getting worse every hour
14:29, 25.05.22

Shmyhal Explained How Ukraine Will Help Europe to Survive Without Russian Coal and Reduce Consumption of Russian Gas

Figure 8. Conference in Kryvyi Rih during the War (`https://tinyurl.com/ynkyucf5`).

environmental problems of ore deposits State Scientific Institution "Center for problems of marine geology, geoecology and sedimentary ore formation of the National Academy of Science of Ukraine", Kryvyi Rih, Ukraine

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3. Conclusion

The vision of the ICSF 2022 is to create a leading interdisciplinary platform for researchers, practitioners and educators, to present and discuss the most recent innovations, trends, and concerns as well as practical challenges encountered and solutions adopted in the fields of sustainability.

3rd installment of ICSF was organized by the Academy of Cognitive and Natural Sciences (`https://acnsci.org`) in in cooperation with Kryvyi Rih National University, Kryvyi Rih State Pedagogical University, National University of Water and Environmental Engineering, Bogdan Khmelnitsky Melitopol State Pedagogical University and State Institution "The Institute of Environmental Geochemistry of National Academy of Sciences of Ukraine".

We are thankful to all the authors who submitted papers and the delegates for their participation and their interest in ICSF as a platform to share their ideas and innovation. Also, we are also thankful to all the program committee members for providing continuous guidance and efforts taken by peer reviewers contributed to improving the quality of papers provided constructive critical comments, improvements, and corrections to the authors are gratefully appreciated for their contribution to the success of the conference. Moreover, we would like to thank the developers of Morressier, who made it possible for us to use the resources of this excellent and comprehensive conference management system, from the call of papers and inviting reviewers, to handling paper submissions and creating the volume of the conference proceedings. Special thanks to session chairs for their work on the conference and its program, excellent and gratefully appreciated conference support.

We are looking forward to excellent presentations and fruitful discussions, which will broaden our professional horizons. We hope all participants enjoy this conference and meet again in a more friendly, hilarious, and peaceful further ICSF 2023. The next meeting in the series is the 4th International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters, 2023, Kryvyi Rih, Ukraine (`https://icsf.ccjournals.eu/2023/`).

Acknowledgments

The authors thank the Armed Forces of Ukraine for providing security for this work. This work was carried out despite the ongoing aggression of the Russian Federation, which poses a threat to global academic community.

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Peer Review Statement

To cite this article: 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 011002

Peer Review Statement

All papers published in this volume have been reviewed through processes administered by the Editors. Reviews were conducted by expert referees to the professional and scientific standards expected of a proceedings journal published by IOP Publishing.

- **Type of peer review:** Double Anonymous
- **Conference submission management system:** Morressier
- **Number of submissions received:** 125
- **Number of submissions sent for review:** 112
- **Number of submissions accepted:** 84
- **Acceptance Rate (Submissions Accepted / Submissions Received × 100):** 67.2
- **Average number of reviews per paper:** 0
- **Total number of reviewers involved:** 76
- **Contact person for queries:**
  Name: Serhiy Semerikov
  Email: semerikov@gmail.com
  Affiliation: Kryvyi Rih State Pedagogical University

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Changes in hydrogeological conditions at the territories adjacent to tailings storage facilities in Kryvyi Rih iron ore basin

To cite this article: O Hrytsai *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012001

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012001 doi:10.1088/1755-1315/1049/1/012001

Changes in hydrogeological conditions at the territories adjacent to tailings storage facilities in Kryvyi Rih iron ore basin

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Abstract. Tailings of mining and processing plants of Kryvbas are new areas of groundwater supply which have led to significant changes in the hydrodynamic and hydrogeochemical regimes of aquifers. The purpose of the research was to assess the degree of damage to the areas adjacent to the tailings of mining enterprises by dangerous The purpose of the research was to assess the degree of damage to the areas adjacent to the tailings of mining enterprises by dangerous hydrogeological processes, flooding and inundation. The quantitative regime of groundwater is in a stable state and corresponds to the modern conditions of operation of industrial facilities. During the research, chemical pollution in groundwater of all aquifers was recorded. At the time of research, there was an increased content of such microcomponents as: carcinogenic cadmium and nickel (up to 1.9-34 MPC; and 2.6-8.4 MPC, respectively); non-carcinogenic lead (up to 1.7-7 MPC); manganese (up to 2-320 MPC); bromine (up to 14-94 MPC) in the groundwater of all aquifers in the north. In the center, there was the accumulation of abnormally high concentrations of elements such as iron, manganese (up to 36-1420 MPC rate of 0.3 mg / dm^3 and 1.3-66 MPC rate of 0.1 mg / dm^3, respectively, and a significant increase in the value of dry residue and the content of major macrocomponents in all aquifers. In the south for the modern period there is pollution of groundwater of the Quaternary and Neogene systems with such elements as total iron (15-2800 MPC), manganese (1.9-132 MPC), sometimes vanadium, cadmium. The geochemical essence of the formation of the chemical composition of polluted waters lies in the intensity of changes in the hydrogeochemical system and in the change in the migratory properties of chemical elements. The newest techniques and scientific developments on localization and the prevention of migration of heavy metals with the subsequent pollution of waters are required.

1. Introduction

The Kryvbas iron ore deposits have been developed for more than 140 years. Over the years of operation, tens of billions of tons of overburden and concentration tailings have been accumulated. Tailings storage facilities are an integral part of the ore treatment process.

At present, six tailings storage facilities belonging to Mining and Beneficiation Works are operated within the area of Kryvyi Rih.

Tailings storage facilities are sets of structures required for impounding and storage of tailings, including a tailings pond, a tailings dam(s), a settling pond, pipelines, etc. The Kryvbas tailings storage facilities were made in natural gullies more than 60 years ago and did not have any anti-leakage pad liners. All of them use a washed-in way of filling. 5,700 hectares of fertile land

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012001 doi:10.1088/1755-1315/1049/1/012001

were alienated for them. The embankments of the tailings impoundments have been raised to the absolute elevations from 120 m to 170 m. Tailings storage facilities are subject to potential environmental risk [1, 2]. In accordance with existing regulations, the companies conduct a system of monitoring the conditions of dams, groundwater, surface water, and soil in order to prevent emergencies.

The tailings storage facilities of the Kryvbas Mining and Beneficiation Works are new sources of groundwater supply, they were formed after the 1960s and have led to significant changes in the hydrodynamic and hydrogeochemical regimes of aquifers. The main aquifers in the areas adjacent to these hydraulic structures are confined to the Quaternary and Neogene sediments. Water-bearing rocks include loams starting from light loess soil to medium silt loams, sands and limestones of the Neogene age.

Prior to the creation of tailings storage facilities, aquifers of the Cenozoic sediments were widely exploited by wells, single holes, used for economic purposes by the local population, and represented the only source of water supply.

According to existing data Natarov, D.V. for the period from 1950 to 1955 groundwater in almost all research areas was of satisfactory quality. No flooding was observed; the depth of groundwater levels was 5-10 m [3].

Subsequently, the hydrotechnical and hydrochemical regimes of these aquifers have undergone significant changes. For the period from 1963 to 1974, the increase in levels reached 10-15 m and 18-30 m respectively in some areas. The intensive rise of groundwater levels occurred in the period from 1970 to 1980, when water levels in tailings storage facilities reached +84.7 - +98.0 m. During a year the rate of level rise reached 0.6-1.2 m for the first aquifers from the surface and 0, 62 -2.52 m for the Neogene sediments horizon.

At the beginning of the 1990s, the total area of flooding around tailings storage facilities ranged from 30 km^2 to 500 km^2. Since 1976, there has been flooding of some settlements, especially within the area of influence of the southern group tailings impoundments.

At present, in general, all Mining and Beneficiation Works have efficient drainage facilities, which mainly intercept filtration seepage and provide safe groundwater depth. Some local flooding areas are concentrated on the industrial sites of GOKs, in surface depressions areas of natural and man-made origin. To date, the problem of chemical pollution of groundwater aquifers has come out on top.

Today, almost all water sources in the world are polluted. [4, 5] Water contains more than 13,000 toxic elements. Depending on the “technophilicity” of each element there is a change in the composition of water with the accumulation of the most popular ones. For the first time, professor - hydrochemist M. Hlazovska drew attention to this fact, she noticed that increase in iron content is typical for cultural landscapes [6]. Her research was based on her own studies conducted in Russia and Kazakhstan, and the generalization of data of scientists from almost all countries.

The studies have confirmed the increased level of iron content in the urban area and have expanded the list of pollutants.

2. Aim and methodology

The aim of the research was to assess the degree of damage to the territories adjacent to the tailings storage facilities of mining enterprises by dangerous hydrogeological processes, flooding and inundation with further development of measures to localize the environmental consequences of mining and reduction of impact on the ecosystem.

To solve the tasks

- - analysis, systematization, generalization, comparative analysis of the results of monitoring observations of groundwater condition over a long period of time, both at the facility and regional levels;

- - reconnaissance survey of areas to identify flooding and other dangerous geological processes;
- - office studies of materials have been performed.

3. Results

Groundwater monitoring in Ukraine is carried out in accordance with the Water Code of Ukraine, the Regulation №391 "On the State Environmental Monitoring System", approved by the Cabinet of Ministers of March 30, 1998 and with "Procedure for State Water Monitoring" №815, approved by the Cabinet of Ministers of July 30, 1996.

The obligation to conduct on-site monitoring by enterprises, institutions and organizations whose activities affect adversely the state of groundwater, especially those that operate industrial wastewater or waste storage, is defined by Article 105 of the Water Code of Ukraine.

Organizing and arranging a special network of observation wells for systematic monitoring industrial sites of enterprises, areas adjacent to the tailings storage facilities, dumps began in 1977 and were followed by its subsequent expansion over the entire area of the potential impact of enterprises facilities on groundwater and surface water.

During the construction of tailings storage facilities, natural outcrops of rocks in the bottoms of the gullies were not isolated. When filling the tailings storage facilities to the mark of the earth's surface and above (1970-1980), filtration seepage resulted in the process of groundwater backing-up, and in the formation of new man-made horizons in previously arid areas.

Dozens of research and production organizations, institutes of various profiles and areas of activity (VIOGEM, VSETINGEO, VODGEO, "Ukrvodokanalproekt" and others) have been involved in solving the problems of groundwater formation, quantitative assessment of groundwater balance components, forecasting changes in the hydrological and engineering-geological situation for many years. According to the researchers, the areas where large structures are located (tailings storage facilities, gathering pond for mine waters, etc.) are areas of high risk of emergencies. The reason is that these technical facilities are located in natural gullies, which in themselves are the products of certain tectonic disturbances, associated primarily with cracks in the earth's crust.

When creating large mass technical facilities in the gullies, areas of increased water permeability may occur due to additional excessive load on the blocks and fracture zones, which can significantly disrupt the natural hydrogeological regime of the whole region, and reduce seismic resistance.

During 2019-2021, the work was performed at the request of the Kryvbas Mining and Beneficiation Works to assess the effectiveness of the existing network of observation wells; control testing of wells, reconnaissance survey of drainage structures, territories, detection of flooding and other hazardous geological processes, studies of archival materials and those of the enterprises concerning hydrogeochemical and quantitative regime of groundwater have been conducted ("The development of design solutions to protect against flooding, directing them to prevent the development of unsafe geological processes, or reduce to an acceptable level of negative influx of the territory and objects of PRJSC "InGZK" (PRJSC "PIVNGZK", PJSC "CGZK"). Carrying out field hydrogeological studies, laboratory and cameral work."). The works were performed on the basis of the City Program for Solving Environmental Problems of the Kryvbas and Improving the State of the Environment for the years 2016-2025.

To assess the degree of damage to the research area by flooding, groundwater pollution, archival materials of geological organizations, research institutes, materials on existing hydraulic and drainage structures provided by enterprises, the results of monitoring investigations of groundwater conditions, field hydrogeological surveys of drainage structures and adjacent areas have been studied in the process of research work. The available materials on changes in the quality of groundwater composition in the areas of Kryvbas tailings storage facilities have been analyzed, a comparative analysis of current data with retro data from previous studies of the facilities and regional levels have been fulfilled. These kinds of works have been carried out for the facilities of PJSC "Northern GOK", PJSC "Central GOK" and PJSC "Ingulets GOK".

The geological structure, namely the bottoms of the gullies, are composed mainly of sand, loam, limestone, or a layer of weathered crystalline rocks, water-resistant deposits are thin, in some areas they are missing. In the northern and central parts of Kryvbas, in the tailings facilities locations, sands lie directly on the weathering crust of granites and migmatites, which creates conditions for the hydraulic interconnection of aquifers. In the south, the Neogene limestones of various cavernosity, fissility and water-filtration properties are widespread in the bottom of the gullies. They represent an individual sustained aquifer.

Geophysical studies have confirmed that all gullies are "alive" and their tectonic activity affects the state of the rock massif of the territory as a whole. They serve as "conductors" for contaminated water to the aquifers and further to the rivers due to the high natural fissility of rocks.

The qualitative composition of groundwater in the entire study area is undergoing significant changes moving towards increasing contamination by chemical elements.

Today there is a threat of spreading of heavy metals inherent in ore treatment processes throughout the area and to the depth. The presence of man-made zones of high water permeability of rocks, man-made fissility in the sedimentary cover, the absence of water-resistant rocks in some areas facilitates their penetration into aquifers.

Generalization and systematization of the available factual material concerning changes in the hydrogeological, hydrogeochemical, geological and ecological situation in the study area, allow us to draw the following conclusions.

All drainage structures in the tailings storage facilities and adjacent areas were designed and built in the days of the Soviet Union, mainly before 1990, taking into account the hydrogeological and hydrodynamic conditions at that time.

The purpose of creating a system of protective measures was to intercept filtration losses, to reduce groundwater levels and maintain them at safe depths. According to previous studies, the intensive rise of groundwater levels, the formation of man-made aquifers in previously anhydrous strata occurred in 1970-1980. The set of special engineering measures allowed to minimize the impact of tailings impoundments filtration losses on the environment. In recent years, significant fluctuations in groundwater levels have not been observed. The hydrodynamic regime of groundwater within the study areas is in a very stable state and meets modern operating conditions for tailings storage facilities and drainage systems. At their change, or in emergency situations deterioration of a quantitative condition of underground waters massif is possible.

There occur such processes as flooding, contamination of groundwaters and surface waters on the research territory.

Today, the hydrodynamic situation in the area of the potential impact of the enterprise's facilities is stably tense, but there is a deterioration in the quality of groundwater composition of all aquifers.

Characteristics of changes in groundwaters and surface waters chemical composition of the study areas are given below from north to south.

In the northern part of the Kryvbas, today the most difficult in hydrogeological terms is the situation between the tailings storage facilities and the Saksagan floodplain, taking into account geochemical processes and phenomena occurring within the influence of production activities of PJSC "Northern GOK". The floodplain and the Saksagan River itself serve as a reservoir for both filtration water and surface runoff. Groundwater pollution of the Neogene-Paleogene aquifer and fractured crystalline rocks below the drainage depths is occurring (before 60 m).

Existing drainage structures today have largely minimized the impact of filtration losses from the tailings storage facilities on the environment. In recent years, significant fluctuations in groundwater levels have not been observed.

Ground geophysical surveys were conducted to identify the impact of filtration waters from the tailings on the aquifers of the Saksagan floodplain. Zones of the stress of moistened rocks, with a high degree of their man-made fissility, have been found along the southern boundary of the tailings dam. Geophysical studies have confirmed modern neotectonic disturbances at the bottom of the Petrikov gully and the upper reach of the Bezimenna gully. The gullies themselves are alive and, due to the high natural fissibility of rocks, serve as "conductors" of contaminated water to aquifers and further to the Saksagan River.

According to the available data, there is an increased content of such microcomponents as carcinogenic cadmium and nickel (up to 1.9-34 MAC and 2.6-8.4 MAC, respectively), non-carcinogenic lead (up to 1.7-7 MAC), manganese (up to 2-320 MAC), bromine (up to 14-94 MAC) and others in the groundwaters of all aquifers (figure 1).

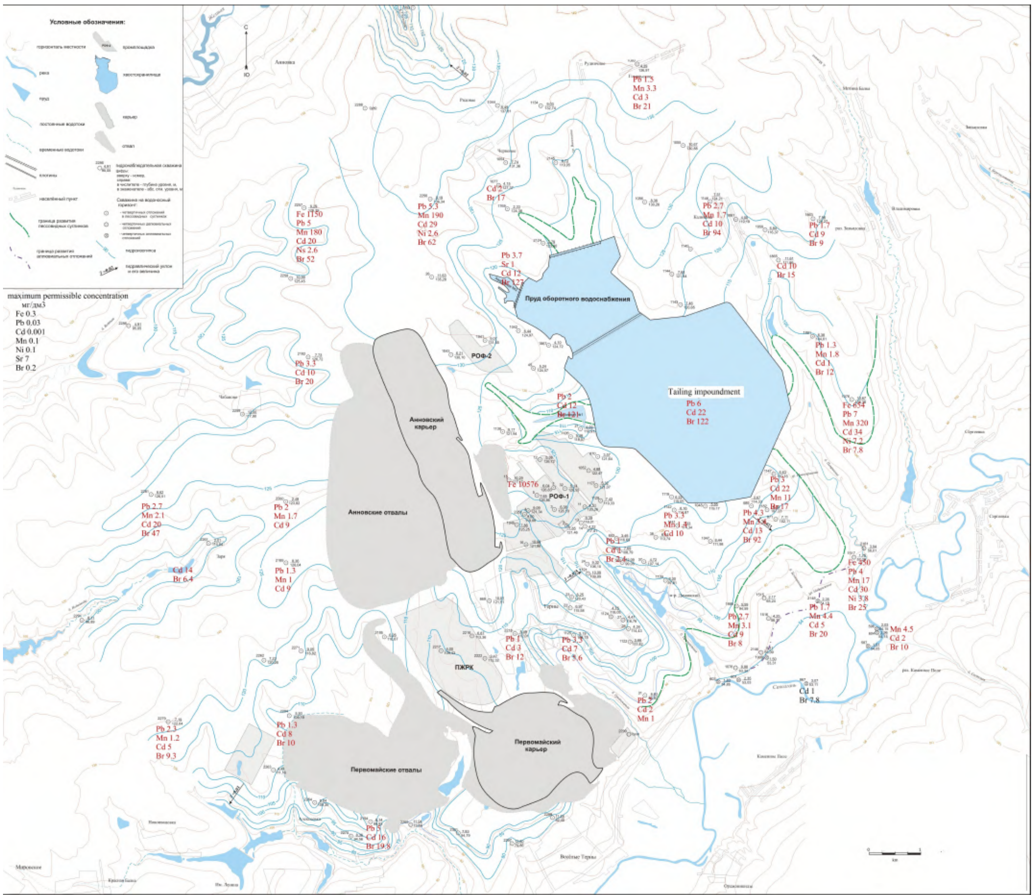

Figure 1. Schematic map of groundwater contamination by heavy metals around the tailings storage facility of the Northern GOK for 2019 (iron, lead, cadmium, manganese, nickel, strontium, bromine). The values are shown in units of exceeding the maximum allowable concentrations (MAC) based on the isogypsum map of the aquifer of the Quaternary sediments as of October 2017 Northern GOK. SE "Ukrchermetgeologiia".

Significant accumulation of iron total (up to 68-10576 MAC) was also found at the industrial site of the enterprise, near the dumps of overburden. As already noted, an abnormally high value of the content of heavy metals is observed at different depths and over the entire area of research at distances up to 5.0 km to the north, up to 2.7 km to the east, up to 7.5 km north-west, up to 3 km of the Saksagan floodplain.

In the waters of the tailings impoundment, return water supply pond an anomalous content of cadmium has also been recorded – it exceeds 22 and 12 MAC respectively, that of lead is 6.3 and 7 MAC, that of bromine is 122 and 127 MAC.

In addition, in some observation wells, there is a significant increase in the content of macrocomponents, and, accordingly, the growth of dry residue, total hardness, and others. The active reaction of water (pH) in the area varies from acidic (3.8-6.5) to alkaline (7.8-10.3) one.

The sands of the Neogene-Paleogene age, a planar weathering crust of crystalline rocks, the presence of neotectonic movement in both the sedimentary cover and the crystalline massif of rocks are probably the routes of pollutants migration.

For the central part of the Kryvbas, the analysis of observations of changes in groundwater chemical composition in the research area of PJSC "Central GOK", their comparing with the regional background, indicates the unstable nature of its formation. During the year, there are sharp fluctuations of individual macrocomponents (sulfates, calcium, magnesium), ammonium, iron total, nitrates, total hardness, and others in some areas. There is a fluctuation of the active pH response from acidic (4.4-5.7) to alkaline (7.2-9.74) one. Changes in the quality of groundwaters can occur under the influence of both natural factors (precipitation, air temperature) and man-made (changes in the water level in the Ingulets River during dilution and washing of the riverbed with water from the Dnipro River, filtration losses from the tailings storage facilities, water-bearing communications of various purposes, use of mineral fertilizers on agricultural land, etc.).

The "tailings" strata are permeable. The penetration of polluted waters into aquifers is facilitated by geological and tectonic structure, geomorphological features.

The quality of groundwaters is subject to significant fluctuations, both in the direction of deteriorating quality and abrupt desalination of water, which differs from the natural state of groundwaters in areas remote from the facilities.

The tests of the groundwaters of all aquifers (10-70 m) have shown in some areas abnormally high iron content (up to 36-23660 MAC, at a norm of 0.3 mg / dm^3), high manganese content (1.3-66 MAC at a norm of 0.1 mg / dm^3), other elements (lead, cadmium, nickel) are not in evidence (figure 2). Changes in the quality of groundwaters are possible under the influence of both natural and man-made factors.

The direction of groundwater movement is to the west and southwest towards the river Ingulets. At the time of research, the direct impact of PJSC "CGOK" on the Inhulets River was not established, but, given the location of anomalies of various origins close to the river, there is a possibility of a further inflow of pollutants into river waters.

For the southern part of the Kryvbas, the generalized results of monitoring observations of PJSC "InGOK" for the period 2013-2020, their comparative analysis with hydrogeological studies of previous years 1950-1955, 2003-2008 indicate the stabilization of the groundwaters level in almost the entire study area. Existing drainage structures mainly intercept filtration seepage and provide a safe depth of groundwaters. Activation of flooding processes in previously identified local areas of flooding is not observed. Thus, the set of special engineering measures allowed to minimize the influence of filtration losses from the tailings storage facilities of PJSC "InGOK" on the environment. In recent years, significant fluctuations in groundwater levels have not been observed. But today, according to the results of long-term observations of groundwaters, there is another problem, which is the intensive change of the hydrogeochemical system.

According to monitoring observations, abnormally high content of elements such as iron total, manganese, sometimes cadmium and strontium has been found in the groundwater of Quaternary and Sarmatian deposits (10-90 m). Local water pollution is observed in alluvial sands near Andriivka, where the content of iron total is 832-1000 mg / dm^3 at a maximum

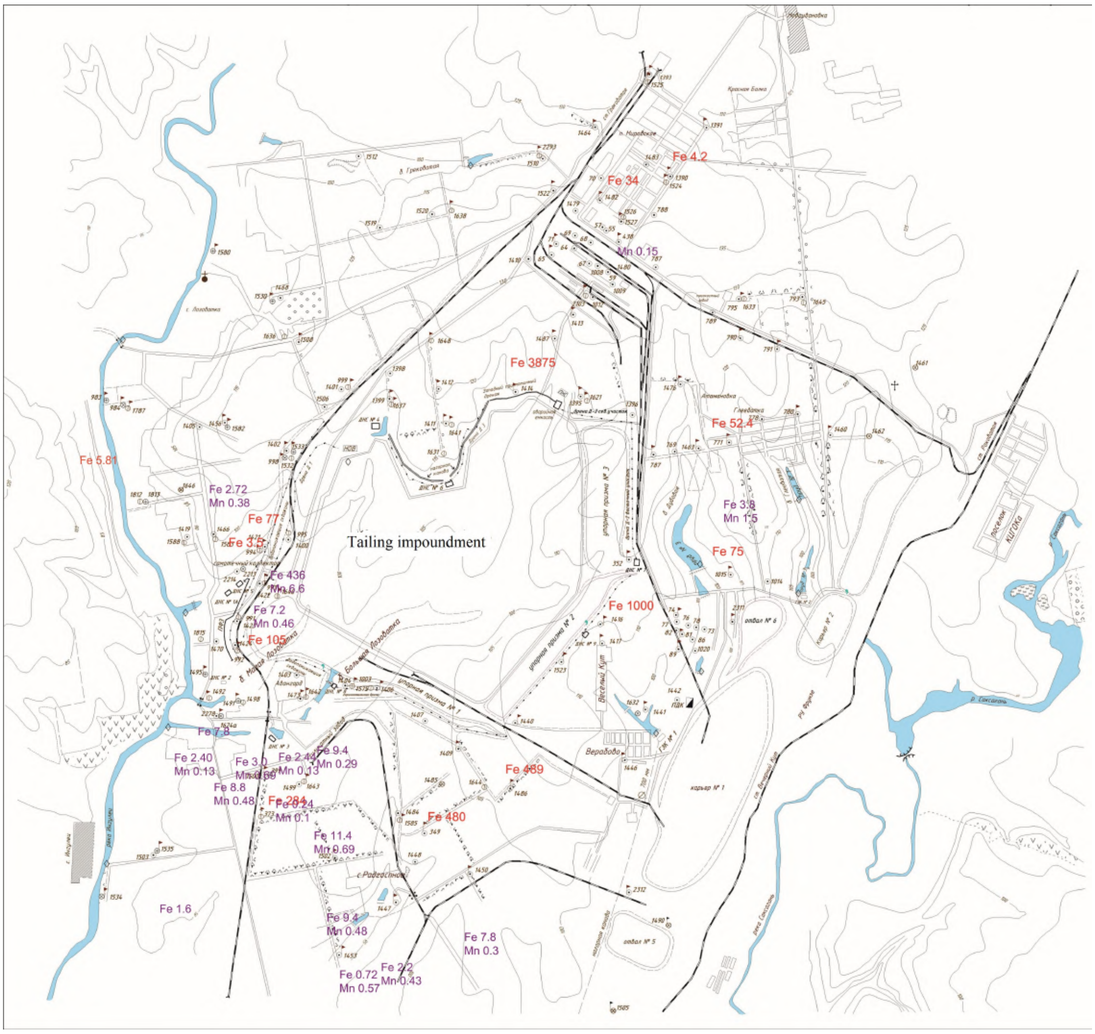

Figure 2. Schematic map of accumulation of iron total and manganese (mg / dm^3) in groundwaters around the tailings storage facilities of the Central GOK for 2019-2020 based on the location of wells of the monitoring observation network of PJSC "CGOK".

concentration limit of 0.3 mg / dm^3, that of manganese is 40.5 mg / dm^3 at a maximum concentration limit of 0.1 mg / dm^3 (figure 3).

To the south of the tailings in individual wells equipped for groundwater, the iron total content reaches 753-6355 mg / dm^3, which exceeds the MAC in 2510-21183 times, the dry residue is 14.3 - 20.4 g / dm^3. In some wells that have opened up limestones of the Sarmatian region of the Neogene age, the content of iron total varies between 1.12 and 162 mg / dm^3 at depths of 50.4 m and 27.5 m, respectively.

The chemical composition of groundwater of the Neogene sediments differs in anionic and cationic composition - mainly the mixed type prevails, which is three-component in terms of anions, their mineralization varies from 1.1 to 6.2 g / dm^3. The active reaction of water (pH) in the study area varies from acidic (3.2-5.86) to alkaline (7.9-9.79). The chemical elements might migrate through permeable loess loams strata, the horizon of karst limestones of the Sarmatian Regional Stage, the roof of which can be traced at depths of 5.7-18.0 m, and their outcrop can be observed in the Inhulets river valley.

The qualitative composition of groundwaters in the entire research area has undergone

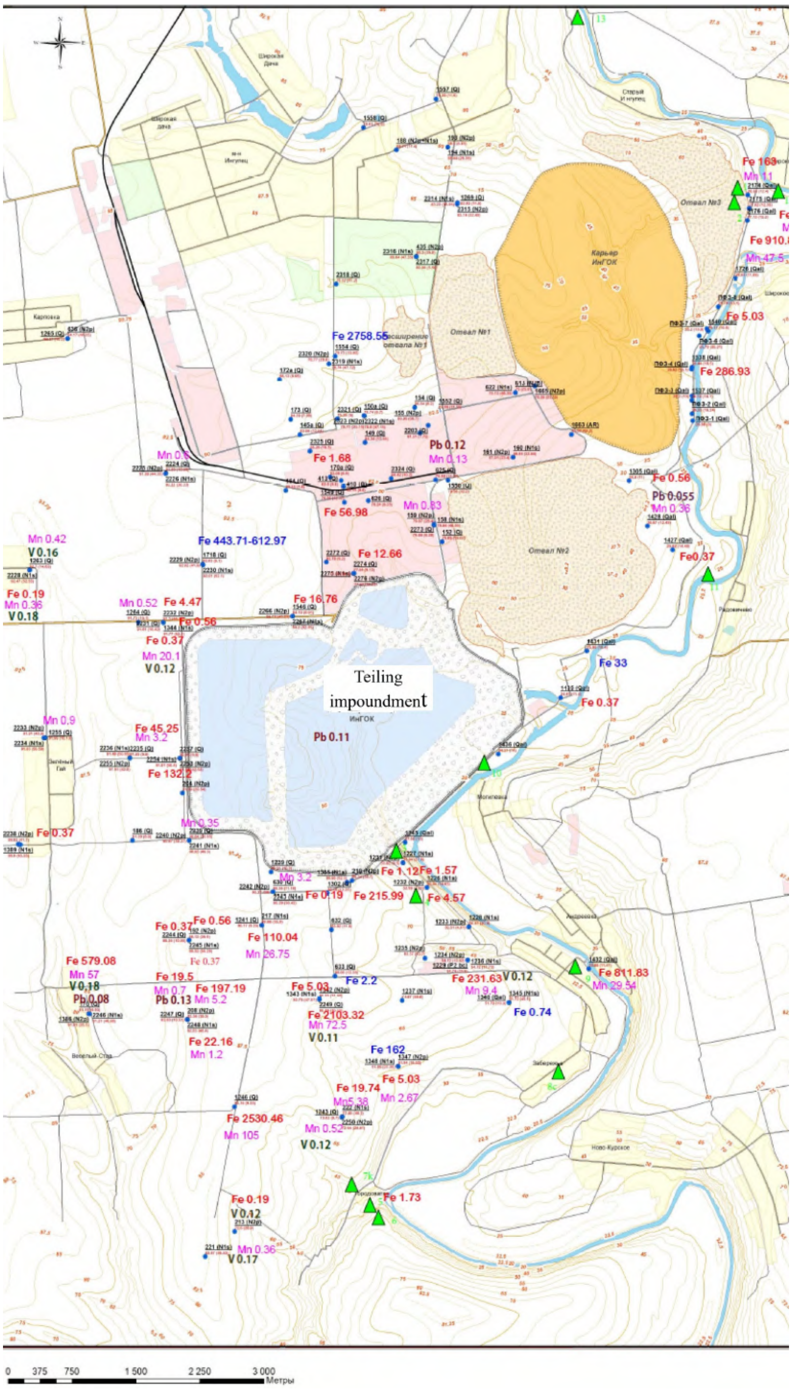

Figure 3. Schematic map of the distribution of heavy metals (mg / dm^3) in groundwaters around the tailings storage facilities of Inhulets GOK based on the location of wells of the monitoring observation network of PJSC "InGOK". Red marks show the content in 2018-2019, other colors in 2020.

significant changes and mainly in the direction of deterioration - contamination with chemical elements, the solid residue increase, hardness. Deterioration of the hydrogeochemical regime occurred in the aquifers of the Quaternary and Neogene systems.

According to laboratory studies, the groundwaters of the Quaternary sediments have, for the current period, abnormally high iron total content from 1.68 mg / dm^3 to 2530.46 mg / dm^3, which exceeds the maximum allowable concentrations by 5.9 and 8435 times. There is also an increased content of manganese, which is up to 267-1050 MAC.

The groundwaters of the first aquifer from the surface are characterized mainly by sodium chloride and sodium chloride-sulfate types, their mineralization varies widely from 3.3 to 6.07 g / dm^3 to 10.02-21.26 g / dm^3.

According to the given data for the current period, there exists contamination of underground waters of the Quaternary and Neogene systems with such elements as iron total, manganese, in some places it is with vanadium, cadmium. The highest content of iron total is observed in the west, south and southwest from the tailings storage facilities.

It is impossible to establish the sources of these microelements penetration in groundwaters, the factors influencing their content, changes over time, at this stage of research. The waters in tailings impoundments do not contain these elements.

The inflow of polluted waters into aquifers occurs through permeable loess loams, areas of carbonate rocks leaching, eroded limestones at the bottoms of gullies. As already noted, the research area is characterized by complex geological-tectonic and geomorphological conditions such as extensive development of gully network, the presence of karst limestones, which already had high porosity and cavernosity in natural conditions. The pond-accumulator of mine waters of Svistunov gully located above the facilities of PJSC “InGOK” also contributes to the pollution of groundwaters of the Neogene deposits and the Inhulets River.

Geological and ecological research in the period from 1997 to 2008 and special research works conducted in 2016 showed an abnormally high value of microcomponents such as iron (15-2800 MAC), manganese (1.9-132 MAC), strontium (1.2-4.79 MAC), lithium (1.2-6.3 MAC) in the groundwaters of the Neogene sediments located within the influence of the pond. During the hydrogeological survey of the territory of sheet L-36-IV (Kryvyi Rih) from the hydrogeological map of Ukraine in some exploration and production wells exploiting the groundwaters of the Sarmatian deposits within the Kherson region, increased iron content of up to 1.0-3.8 MAC has been found, other trace elements of II-IV class of danger have not been detected.

The occurrence of hydrogeochemical halos of pollution is facilitated by the infiltration of precipitation and surface runoff through overburden dumps, tailings dams composed of ferruginous quartzites and concentration wastes. Deterioration of the quality of groundwaters can also occur under the influence of agricultural production (mineral fertilizers), corrosion of metal casing in wells.

Due to the established fact of distribution of iron, manganese, other chemical elements and compounds in groundwaters along the area and to the depth, there is a possibility that they will be found in the Saksahan River, Inhulets River and Karachuny Reservoir. According to geological and ecological studies conducted in the periods from 1989 till 1997, from 2000 till 2012 abnormal concentrations of zinc, lead, phosphorus, manganese, cadmium, iron, etc. were found in the bottom sediments of the Inhulets River at the area of water discharge of the Karachuny Reservoir and further downstream.

It should be noted that in natural conditions, before the creation of the Mining and Beneficiation Works, a high content of heavy metals in groundwaters was not detected. At that time, almost on the entire territory of the Kryvyi Rih basin, there was an increased content of bromine and boron in groundwaters.

The movement of significant masses of rocks when extracting iron ore, the use of vibration and blasting technologies, the creation of dumps, hydraulic structures with their embankment dams, filtration seepage lead to the restoration of natural fissility, intensification of karst processes and, consequently, the emergence of man-made zones of high water permeability. All this contributes to filtration seepages into aquifers and their spread to the depth and throughout the area.

4. Conclusions

Tailings storage facilities are complex, potentially dangerous hydraulic structures that affect the hydrosphere of the location area. At present, quite effective drainage systems have been created that intercept filtration seepages and maintain the quantitative regime of groundwaters in a stable state.

Today there is a threat of spreading of heavy metals inherent in ore-treatment processes around the area and to the depth. The presence of man-made zones of high water permeability of rocks, man-made cracks in the sedimentary cover, the absence of water-resistant rocks in some areas facilitates their penetration into aquifers.

Accumulation of pollutants (mainly iron and manganese), growth of solid residue and main macrocomponents have been detected in all aquifers. At the same time, iron and manganese are not contained in tailings impoundment waters, and other indicators largely meet the requirements for technical water.

In general, contamination spreads over time and covers a large area around industrial facilities. Monitoring observations show the diversity of the chemical composition of polluted waters. It is clearly associated with the formation of redox (Eh) and the active response (pH) of aqueous media. Almost everywhere there is a significant temporal and spatial heterogeneity in the distribution of macro-components of the salt composition of water, which is due to the dynamics of man-made contaminated water and surface runoff.

The content of contaminating microcomponents increases over the years. Sharp fluctuations in the content of individual wells from abnormal to normal and vice versa during the year cannot be attributed to currently known factors. It is impossible to determine factors influencing their content, change over the course of time at this stage of the research.

Addressing the issue of accumulation and migration of pollutants requires special hydrogeochemical studies [7]. The geochemical essence of the formation of polluted waters chemical composition depends on the state and intensity of changes in the hydrogeochemical system and changes in the migratory properties of chemical elements. [8,9] It is recommended to expand the observation network in the directions from outermost wells with signs of pollution, which are tested by enterprises, to a relatively clean area.

The involvement of heavy metals in the geochemical cycle can reduce the productivity of agricultural land, reduce the value of landscapes and species diversity of plants, may lead to diseases of domestic animals and humans, and to pollution of water bodies.

Man-made geochemical phenomena and processes that are being detected today are subject to a detailed comprehensive study. Today it is necessary to review the system of groundwaters protection from contamination taking into account the geochemical processes and phenomena that occur within the area of impact of enterprises production activities where research was conducted. According to world practice, the study of groundwater pollution processes, movement of heavy metals is a special field of research where computer modeling is extensively used. The latest methods and scientific developments are needed to localize and prevent the migration of heavy metals with subsequent pollution of groundwaters and surface waters.

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PAPER • OPEN ACCESS

Ways to reduce technogenic landscape disturbances in mining production

To cite this article: V Antonik *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012002

Ways to reduce technogenic landscape disturbances in mining production

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Abstract. Iron ore mining is followed by significant disturbances of the earth's surface caused by both iron ore mining facilities (underground mines and open pits) and disposal of mining and concentration wastes on the surface (waste and substandard ore dumps at underground mines, overburden and oxidized rock dumps at open pits, tailings storage facilities at mining and beneficiation plants). In addition, operation of mining enterprises leads to creating hundreds of kilometers of above-ground pipelines, technological roads and railroads; drilling and blasting operations at underground mines and open pits lead to seismic phenomena and geotectonic disturbances of the surface in the form of sinkholes and craters in places of underground workings. The presented scientific work aims to generalize the practice of measures to optimize landscape disturbances caused by mining and develop individual issues of arrangement and technology of reclamation of disturbed surface areas in conditions of Kryvyi Rih iron ore basin. Technogenic surface disturbances accumulated during the period of economic exploitation of the region require a comprehensive solution in two directions. The first one consists in reducing the rate of new destructive impacts on the state of the relief by switching from extensive methods of deposit exploitation to all-round intensification of production (introduction of low-waste technologies, concentration waste re-treatment, oxidized ores processing, transition to technologies of internal dumping). The second one involves optimization of already formed landscape disturbances through reclamation. It is recommended to implement a number of methods of improving individual technogenic landscape formations by engineering and biological methods.

1. Introduction

Kryvyi Rih iron ore basin includes 15 iron ore deposits located on a relatively small area of 43.1 thousand ha. Both underground and open pit mining methods are used here. As of 2022, there are 8 iron ore underground mines specializing in rich iron ore mining (47-67% Fe content) and 5 mining and beneficiation plants (GZKs) engaged in open pit mining of lean (under 46% Fe content) iron ores which are to be concentrated. Most iron ore inderground mines are located within the city of Kryvyi Rih, while GZKs surround the city in a semicircle, their names corresponding to their location – the Pivnichnyi GZK, the Tsentralnyi (western) GZK, the Pivdennyi GZK, the Novokryvorizkyi GZK of the PJSC "ArcelorMittal Kryvyi Rih" and the Inhulets GZK (located in the southern part of the city).

The most destructive action on the region's landscape is produced by GZKs' facilities, i.e. open pits (the area of nine main open pits makes up over 6 thousand ha), beneficiation complexes and gigantic waste accumulation areas (overburden and substandard oxidized ore dumps, tailings storage facilities (TSFs)). There are eight TSFs that are complex hydro-engineering structures in the form of reservoirs created by dams of dried tailings and overburden and filled with pulp (a mixture of ground iron ore raw material wastes and water). The total area of a modern tailings storage facility can reaches 700-800 ha, and being a multilevel structure it can rise 150-180 m above the surface (e.g. "Obiednane" that includes Karta I and Karta IV of the Pivdennyi and the Novokryvorizkyi GZKs repectively) [1].

Reduction of adverse effects of long-term mining operations (disturbed urban and farming lands, ruined natural landscapes and deteriorated hydrogeological conditions) is one of the essential tasks of environmental protection and stabilization in Kryvyi Rih iron ore basin. According to the data provided by the institute "Hipromashzbahachennia", one thousand tonnes of the rock mass mined accounts for only about 200 t of marketable iron ore products, the remaining 800 t consists of mining and concentration wastes. At that, about 2.5 t of fine-dispersed dust and 1.8 t of poisoning gases are emitted into the air, 40 m^3 of land is allotted, 50 m^3 is flooded and 110 m^3 of highly mineralized water is made [2].

At present, in Kryvyi Rih, waste dumps and TSFs contain over 4 bn m^3 of iron ore mining and concentration wastes; their total area exceeds 12 thousand ha (dumps – up to 5 thousand ha, TSFs – over 7 thousand ha). Displacement and caving (crater formation) zones caused by underground mining occupy over 5 thousand ha of urban lands. In general, there is over 34 thousand ha of urban and suburban areas, which are technogenically disturbed and need restoration. The total area of Kryvyi Rih makes 431 km^2, its mining and industrial landscapes comprise about 48.8% of this area, and they tend to increase. To this, 20 thousand ha should be added as these mostly farming lands are adjacent to the GZKs and are being degraded under the action of dust and highly mineralized water filtrates from TSFs and waste dumps. Soils within a 15-20 km circle from Kryvyi Rih industrial objects are contaminated with heavy metals and often salinized or swamped [1]. In the city's central part alone, there is over 600 ha requiring immediate reclamation. Yet, in spite of the current legal requirements and the increased level of public involvement, Kryvyi Rih enterprises' owners are very reluctant to finance environmental measures and rates of disturbed land restoration remain extremely low – up to 1.5% of the areas annually - and they greatly lag behind mining rates with a yearly 2.1% increment [2].

Under current conditions, tens of thousands of residents of areas with open pits and underground mines as well as dwellers of villages located close to the city have to live in close proximity to technogenic structures. Sanitary protection zones make just several hundreds of meters (1000 m for open pits, 150 – 500 m for dumps and TSFs). At that, some residential areas are practically surrounded by mining landscapes and not only contact with the disturbed landforms but also are exposed to their harmful emissions, primarily dust. Parts of residential areas of the Pivnichnyi GZK, settlements of Verabove, Rakhmanivka, Stepove, Myroliubivka, villages of Novolativka rural territorial community and others are examples of such territories. The mentioned facts indicate that the current environmental situation in the city of Kryvyi Rih with over 600 thousand residents is critical and requires a comprehensive approach to its solution.

There are many works aimed at intensifying mining production and preventing or reducing significantly the rate of new mining landscape formation. Since the 1980-s, the issues of disposing overburden from open pits in internal dumps have been actively discussed in Kryvbas [3–5]. Yet, the developed technologies are hardly implemented practically and all pits of Kryvyi Rih GZKs continue the long-standing practice of land consuming external dumping.

Over the recent years, significant landscape disturbances have been caused by oxidized ore dumps of the Southern group of mining and beneficiation plants. For example, at the

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012002 doi:10.1088/1755-1315/1049/1/012002

Novokryvorizskyi GZK, the Mining Department of the PJSC "ArcelorMittal Kryvyi Rih" is now creating a dump of oxidized ores on the eastern wall of open pit No. 3 with a design elevation +180 m and oxidized ore disposal areas at dumps No. 2-3 and "Stepovyi-2". As of 2020, the enterprise disposed over 200 Mt of oxidized quartzites (about 3 Mt annually) [6]. To concentrate weak-magnetic oxidized ores, in the 1980s, a mining and beneficiation plant of oxidized ores (KGZKOR) was being built with the participation of Ukraine, Bulgaria, East Germany, Romania and Czechoslovakia in Dolynska, Kirovohrad region. The design capacity of the plant was 26.4 Mt of ore annually. Despite over 1.7 bn USD invested in the construction, due to self-liquidation of the CMEA and subsequent prolonged stagnation of the Ukrainian economy, the project is not yet completed. The owners of the current mining and beneficiation plants of Kryvyi Rih are still reluctant to implement technologies for concentrating oxidized ores [7] and this potentially useful resource is intensively being stored in dumps.

Another equal problem consists in availability of substandard ore mass fractions (SOMFs) of underground mines that contain less than 46% of iron and are disposed in temporary dumps. Since SOMFs are a useful resource to be further concentrated, such dumps with millions of tonnes of the rock mass are not reclaimed in a traditional way and remain intensive sources of dusting near residential areas. There exist many methods of concentrating lean ores [6–9], but in fact, SOMF dumps have been raising around Kryvyi Rih underground mines for years.

TSFs of GZKs are another factor of significant environmental and landscape problems for Kryvyi Rih. The amount of tailings can be reduced by decreasing volumes of their production through their re-treatment and more complete recovery of iron, up to 20 -24% of which currently remains in wastes. For example, since the beginning of operation of the Novokryvorizkyi GZK (the PJSC "ArcelorMittal Kryvyi Rih"), its TSFs have accumulated over 310 Mm^3 of tailings and over 6 Mm^3 of new tailings are added every year. Implementation of the technology for this resource re-treatment could enable production of a fifth of annual volumes of agglomerate from re-treating the tailings and accordingly reduce production of raw ore by nearly 8-10 Mm^3/year [6, 7, 10, 11]. The proposal to dewater tailings and use them for backfilling mine workings and worked-out open pits is also of interest [12].

At present, there exists a method of obtaining iron-containing concentrate and fluxed broken stone directly from tailings without disposing them in TSFs. One installation of this kind can process up to 2.6 Mm^3 of slime annualy, produce up to 45 kt of iron ore concentrate and up to 9 kt of broken stone. At the same time, the calculated reduced final amount of concentration waste makes it possible to eliminate up to 20 ha of land from use annually. Unfortunately, despite obvious effectiveness of the described technology, the owners of the mining enterprises do not implement it widely.

Issues of optimization and reclamation of surfaces of worked-out and finally formed mining landscapes are treated in a large number of works by national and foreign authors. Great experience in designing and conducting reclamation works in the coal, ore mining and construction industries is accumulated in Russia [13, 14]. In Ukraine, problems of restoration of disturbed lands in mining production are covered by scientists of Dnipro State University [15], Dnieper Institute for Nature Management Problems and Ecology of National Academy of Sciences of Ukraine [16, 17], Donetsk and Kryvyi Rih Botanical Garden [18, 19], as well as Kryvyi Rih Research Iron Ore Mining Institute [20].

A new trend in solving problems of optimizing technogenic landscapes is implementation of eco-oriented technologies aimed at activating the biosphere revitalization potential. Deposition of production wastes containing organic matter on the surface of disturbed lands is one of them. It helps both reduce dusting and accelerate formation of a fertile layer favorable for plant settlement [17].

The presented scientific work aims to generalize national and foreign experience in optimizing landscape disturbances caused by activities of mining enterprises and develop individual organizational issues and technology of restoring disturbed lithosphere areas in Kryvyi Rih iron ore basin.

2. Methods

The conducted brief analysis of known developments on the problem of optimizing mining landscapes enables stating that nowadays there is no single universally recognized approach to solving this problem. At the same time, there is a clear tendency to search for solutions in two directions: by engineering and biological methods.

Engineering-technological methods of optimizing landscape disturbances in ore mining are designed to help reduce the rate of technogenic development of new territories by limiting underground mine and open pit facilities and allocation of new areas for disposal of ore mining and concentration wastes.

To reduce the volume of substandard ore mass fractions (SOMFs) of Kryvbas underground mines, the method of processing the oversize products of crushing and sorting plants (CSPs) with an average iron content of about 37 wt.%. Laboratory tests on crushing oversize products of CSPs show that the degree of crushing of poor quartzites is two times lower than that of rich minerals. After preconcentration of the initial product by selective crushing in a centrifugal crusher, the material in the 1-0 mm grain size class is the final product by its qualitative characteristics, and the material in the 10+1 mm grain size class should be subjected to further concentration. It is substantiated that for a more complete processing of the underground mine ore, screened out materials of DSF should be subjected to regrinding to a grain size of less than 1 mm. In this case, maximum release of ore non-metallic particles is achieved in ground products. Wet gravity concentration of ground raw materials using wet tables, cone and screw separators is used for final recovery of ore components. Application of the proposed method to concentrating samples of the screened out materials of all Kryvbas underground mines' CSPs and low-grade (iron content 46-52 wt.%) rich hematite ores of open pits "Pivnichnyi" and "Pivdennyi" (Ilyich Iron and Steel Works of Mariupol) and run-of-mine hematite quartzites (iron content about 37 wt.%) from Kryvbas deposits enables obtaining marketable iron ore concentrate with iron content of minimum 65 wt.%.

To reduce the level of landscape disturbances, various methods of optimizing the technogenic relief are applied. According to the established practice, restoration of technogenically disturbed lands usually includes two reclamation stages: mining-engineering (preparatory) and biological.

Mining-engineering reclamation works depend primarily on the type and degree of a landscape disturbance. In Kryvbas, there are two types of such disturbances: the first one includes consequences of deepening below the daylight surface; the second one is associated with works that lead to piling up rock masses on the surface. As for the degree of surface disturbances, they can be significant or relatively small. Pits, caving zones, sinkholes and cracks within the land allotments of underground mines are examples of significant disturbances of the first type. The second type of landscape disturbance is associated with creation of dumps for underground mines' waste rocks and substandard ore materials, and multilevel overburden and substandard ore dumps and TSFs on the surface of open pit mining areas.

In most cases, operations of the mining-engineering stage in zones of caving, sinkholes and worked-out small pits are reduced to backfilling voids with rocks, followed by leveling horizontal areas and covering them with a layer of fertile or conditionally fertile soil.

In open-pit mining areas, besides worked-out open pits, reclamation is required for waste dumps, TSFs, and settling ponds. In Kryvyi Rih basin, dumps are very rarely used to backfill mined out areas of open pits and usually remain man-made landscape formations in the form of huge hills, mounds and slagheaps. Small single-level dumps can reach 15-40 m, while large multilevel ones - up to 180 m or over. Areas occupied by dumps can also vary widely: from 2-5 ha to 800 ha or over. Operations of the mining-engineering stage of dump reclamation are reduced to dismantling temporary facilities (railway tracks for dumpcars, power lines, substations, technological roads, etc.), followed by bulldozer leveling of horizontal and slightly inclined (up to 18^o) areas of upper sites and all accessible berms and finally total earthing of the rock surface with a soil layer of 0.2-0.5 m to 1.0 m and over (depending on the type of subsequent biological reclamation). For 5 - and more year-old dumps, the surface layer of which contains over 7% of fine fractions (particle diameter $\leq$ 1 mm) local earthing can be conducted if there is lack of soft rocks.

Application of the fertile substrate to 35-40^o slopes is one of complicated problems of engineering preparation of waste dumps and multilevel TSFs for subsequent reclamation. Attempts to earth their surface with soil from the upper berms prove ineffective, as soft rocks are easily washed away by precipitation.

Operations of the mining-engineering stage of reclamation at TSF are complicated by the fact that in the course of their implementation, it is necessary to not only solve problems of leveling and earthing the surface, but also eliminate hydrological problems, dismantle pulp lines, decant towers and pumping stations.

During the final stage of reclamation of waste dumps, TSFs and other areas of disturbed lands of open pits and underground mines, biological reclamation of the sanitary-hygienic character is usually conducted to consolidate the surface dusting layer of the soil by planting vegetation. Directions and methods of biological reclamation should primarily be selected on the basis of agrochemical suitability of the substrate for planting vegetation. Observations over natural overgrowing of technogenic objects' surfaces allow distinguishing three groups of suitability of rocks: suitable (fertile and conditionally fertile), marginally suitable and unsuitable. The first group (chernozem, loam, loess) is usually used for earthing to create the upper fertile layer. The second group is the major part of the weathered rock mass of dumps and it contains few nutrients for plants because of its poor mechanical composition, yet it is conditionally suitable for planting. The third group includes hard rocks unsuitable for planting without creating local areas of the nutrient substrate. Absolutely unsuitable soils include coarse hard rocks (under 3% of fine fraction), as to their chemical properties – they are strongly acidic, strongly alkaline or salinized.

Waste dumps of underground mines commonly have the following mineralogical composition: granites (2%), martite jaspilites (21%), hematite-martite hornstones (42%), quartz-sericite-chlorite schists, hematite talcose schists (33.5%) and loam (up to 1.5%). As for the granulometric composition, fractions of coarse lumps, gravel and broken stone (21-30%) prevail, while sand and dust make 12% and 8% repectively. Mine dumps of substandard ores have a similar mineralogical composition, but unlike waste rocks, they contain up to 40-46% of lean ores (martite-silicate quartzites, martite jaspilites, disperse-hematite or martite quartzites). As for their chemical composition, waste rocks comprise considerable amounts of silica, soluble iron and metal oxides. These elements are mostly deprived of phyto-toxic properties and are even sources of microelements necessary for plants. The degree of water absorption is medium and high, pH is close to neutral. Thus, waste rocks from underground mine dumps are potentially an acceptable substrate for herbaceous plants, tree crops and shrubs.

The open pit overburden at dumps is usually represented by lumps of 10-150 mm with prevailing fractions of 20-70 mm and a small quantity (up to 7%) of up to 10 mm fraction as well as the 151 mm fraction (up to15%). The mineralogical composition of open pit overburden is noted for a mixture of loam, limestone and sand (2-3%), amphibolites (10%), quartz-chlorite, quartz-biotite and quartz-amphibole-chlorite schists (54%), low metallic (Fe¡ 10%) quartzites (31%), oxidized ores and brown ironstones (2-3%). According to their agrochemical composition, hard overburden rocks as well as waste rocks of underground mines are conditionally suitable for vegetation as they have optimal soil pH (4.5-7.5); they contain very little if any organic substances, though [3, 5].

Wastes of concentrating plants stored at TSFs are crushed or ground ore materials produced after extracting the major part of iron ore. The mineral composition of tailings is characterized by availability of chlorides, biotites, feldspars, calcites, magnetites and clay minerals. Oxides of silicon (62%), iron (up to 24.6%), magnesium, calcium and aluminium (4-5%) prevail among chemical elements. Admixtures of various elements including those of heavy metals make the remaining 8-9%. Tailings storage is accompanied by gravitative differentiation of ground materials due to which the mineral and chemical composition of mature tailings can vary considerably in certain places. Vegetation growing on the TSF surface without earthing is complicated because of high salinization and strong consolidation of the surface after drying.

Selection of plants is one of the key issues of successful biological reclamation. In useful mineral mining, there occurs displacement of geological strata, and thus the plants settled on these rocks face changed edaphic conditions. Successful artificial planting during biological reclamation requires selection of plants that are most able to survive in specific conditions, i.e. which naturally settle and grow in natural biotopes adjacent to the reclamation zone, as well as use of plants able to adapt to poor soils. Plants should be oligonitrophilic and drought-resistant.

Biological reclamation of highly steep slopes of waste dumps and multilevel tailings facilities of GZKs is of great significance for Kryvyi Rih iron ore basin. Vast areas of bare slopes of these structures are powerful sources of wind-caused dusting.

This problem is especially evident at dumps and TSFs of the southern GZKs where there are three waste dumps and three multilevel TSFs on a rather small area. They not only occupy large areas of hundreds of hectares, but also are 150-180 m high. The dust formed at the slopes of these structures spreads for 7-8 km along wind plumes covering residential areas and farming lands.

The qualitative composition and density of the resulting green massifs primarily depend on the age of the dump, the degree of weathering of the upper rock layer, the proportion of fine fraction particles and the mineralogical composition of piled rocks. Thickness of the newly formed conditionally fertile layer also depends on the slope angle: the larger the angle is, the more likely the fertile layer will be washed away by water flows and the less vegetation covers the slopes. Poor vegetation is observed at 5-6-year-old dumps and in large-fraction zones. Indirectly, self-seeding depends on the wind rose, precipitation quantity and quality, temperatures and even slope orientation (at the eastern, western and southern slopes, vegetation rates are 1.8-2.3 times greater than those at the northern slopes). Biological reclamation is considered to reach its final stage if vegetation density at the slope makes minimum 65% of the surface. It should be noted that self-seeded plants on slopes are the most resistant to complicated agrochemical conditions and do not require additional care.

Based on scientifically and practically proven suitability of wastes of iron ore underground mines and overburden of open pits to function as a substrate for vegetation, it is expedient to stimulate natural planting of steep slopes of waste dumps by artificial application of seeds of plants capable of self-overgrowing to these slopes starting with ruderal vegetation (for newly built dumps) and ending with tree and shrub crops. Seeds of plant species should be selected for each dump individually considering data on its age, the degree of surface rock weathering (% of fine fraction) and agrochemical parameters of the rock environment.

To implement the idea of stimulating natural overgrowth of slopes of waste dumps, the method of hydroseeding is proposed. Hydroseeders are currently available on the market in a wide range and they allow creating a hydraulic mixture jet up to 30 m. For application to waste dump slopes, we have successfully tested and proposed for implementation hydro-mixtures consisting of a nutrient substrate, fertilizers, a mixture of seeds of legume grasses, trees and shrubs adapted to biotopes of dumps.. Once applied to bare rocks, the mixture accumulates in gaps between rocks and creates spots for germination of seeds, primarily those of herbaceous plants and over time - tree crops as well. The degree of seed germination and subsequent plant establishment is significantly larger after repeated one- or twofold application of the pulp with the nutrient substrate, as well as after watering plantations in hot dry weather. The process flows developed by us make it possible to perform hydroseeding in both bottom-up and top-down directions.

Methods of applying a mixture of fertile substrates and binders (e.g. latex brands SKP-65PG, SKS-60PG, SPK-40PP, etc.) with added seeds of herbaceous plants should also be used to temporary fix and plant the surface with vegetation, especially that of slopes of dumps of substandard ores (underground mines) and oxidized ores (open pits).

Application of hydroseeders and hydroseeding technology for biological reclamation of the surface of TSFs which is practically unsuitable for plants is also promising. To do this, it is first recommended to make multiple (up to 5-7 layers) hydro-applications of the initial fertile substrate (e.g. organic-mineral material composed of the city sewage system sludge and nitrogen-phosphorus-potassium fertilizers). After that, 1-2 layers of hydro-mixture of the fertile substrate, mineral fertilizers, binders and seeds of herbaceous plants - saltworts and steppe grasses are applied. After 2-3 years of this kind of reclamation, a nutrient mixture with seeds of steppe perennial leguminous-grass plants and seeds of drought-resistant shrubs can be applied to the surface of TSFs. Sprouts should be watered during dry and hot summer months, especially in the first year of vegetation, (1-2 times a month) at the rate of 2-3 liters of water per 1 m2 by hydroseeders.

In Kryvyi Rih, there are disturbed landscape areas with complicated hydrogeological conditions. Restoration of such areas requires unconventional technological solutions and methods of reclamation. Worked-out open pit No. 1 of the Novokryvorizkyi GZK (the PJSC "ArcelorMittal Kryvyi Rih") is an example of such areas. The first shell of the open pit was worked out in 1976 and during 1979 - 1985 its cavity of 20 Mm^3 was backfilled with overburden rocks by internal dumping. After that, the resulted surface was reclaimed with soft rocks, including a layer of fertile soil. Subsequently, this area of about 8 ha was transferred to a dacha cooperative, which is a rare example of complete restoration of disturbed lands.

The second shell of the open pit of over 49 ha was worked out in 1987 at the depth of -300 m. After stopping all operations, the cavity of the pit was filled with water to the level of -200 m. Since 1995, water-flooded pit No.1 dent has been used for storing (up to 60%, 8-10 Mm^3 annualy) overburden of pit No.2-bis applying the technology of internal dumping by backfilling from the outer walls with bulldozers and excavators. Lack of national and foreign experience in backfilling deep pits water-flooded to over 1/3 of the wall height has caused the problem of instability of slopes of the internal dump, thus complicating movement of mining equipment on the work front to the pit centre and considerably reducing safety of operations. As of 2020, dumping is only performed in places with the highest wall stability using the excavator with a 100 m boom EK -11/100. However, this cannot solve the problem of complete backfilling of the mentioned pit - the diameter of the unfilled part exceeds 800 m, and the remaining cavity volume makes up to 75 Mm^3. Various methods to continue operations are proposed, including use of stackers with a cantilever arm of up to 190 m; construction of a circular ropeway with car unloading in the center of the pit; use of self-propelled vibratory stackers and remotely controlled equipment (for example, a Cat bulldozer with an integrated MineStar control system). Thus, formation of an internal dump in high-flooded pit No. 1 (the PJSC "ArcelorMittal Kryvyi Rih") can be considered an original, innovative and, to a certain extent, experimental work in the field of pit reclamation.

3. Results and discussion

Implementation of the above engineering and biological methods to solve the problem of optimizing mining landscapes of Kryvbas (provided sufficient funding and activities of the owners of the mining enterprises) can yield positive results.

Thus, production tests of methods for additional recovery of iron from CSP screened out materials confirm the above laboratory data. In compliance with the proposed technology, three experimental concentrating plants were built and have been successfully operating for several years. Large-scale implementation of the proposed technological solutions will reduce the amount of wastes in dumps, enable re-treatment of substandard hematite ores in current dumps and storage areas and, consequently, enhance economic performance of iron ore enterprises, intensify use of ore materials, decrease dump area growth rates, reduce landscape erosion and ease the burden on the environment of residential areas. Industrial implementation of the proposed methods of concentrating substandard ores of CSP wastes will allow underground mines not to create SOMF storage areas and, thus make it possible to save dozens of hectares of urban lands.

An uncontrolled increase of oxidized ore dumps that are actually storage areas for raw materials for subsequent re-treatment is a significant problem for Kryvyi Rih environment and landscape. Due to this, application of traditional methods of earthing and planting to these objects is not expedient. It is more feasible and economically sound to use special methods of fixing the surface to prevent dusting by applying special long-term binders such as latex or bitumen wastes. The second way proposed by us consists in planting vegetation (perennial herbaceous plants) by applying a hydro-mixture of the nutrient substrate, mineral fertilizers and seeds of appropriate grasses to their surface using modern hydroseeders.

However, in any case, conservation of surface rock storage areas contributes little to optimization of the landscape structure of the region. Thus, a more radical way is to demand that oxidized ores should be stored in internal dumps of mined areas of pits or, in general, prohibit mining such ores without their further concentration. In this connection, it is necessary to develop appropriate legislative norms obliging the owners of mining enterprises to invest in implementation of oxidized ore concentrating machinery and technologies known since the 90s of the last century.

As mentioned above, storage of overburden in the mined out area of open pits remains an actual and practically unsolved problem for Kryvyi Rih GZKs. For example, in the center of the city there are two almost worked-out open pits "Pivnichnyi" and "Pivdennyi" which are shared by several owners. The company "Rudomain" is currently cleaning up iron ore deposits in the "Pivdennyi" open pit, and disposing overburden in the external dump. At that, a responsible approach implies internal dumping for which there are a sufficient number of mined out areas in the pit. A similar situation takes place in the pits of the Mining Department of the PJSC "ArcelorMittal Kryvyi Rih", where, for example, up to 60% of the overburden of pit No.2-bis is used to backfill the worked-out pit No.1, and the remainder (up to 1 Mm^3 annually) is transported to external dumps No.2-3. External overburden dumps are intensively formed at the other mining and beneficiation plants of Kryvyi Rih without any search for alternative ways to solve this problem. These facts indicate that without strict legislation, the economic entities of Kryvyi Rih mining enterprises prefer obsolete land-intensive technologies of disposing mining wastes in external dumps.

A similar situation occurs with respect to TSFs. The well-known positive experience of Metivest mining and smelting company in re-treating tailings of the Pivnichnyi GZK is still the only example of implementing innovative technologies in Kryvbas. At the other GZKs, lack of large-scale implementation of technologies for re-treating tailings leads to a progressive increase in areas of their storage. A recent example of this is the increase of the area of the TSF "Obiednane. IV Karta" (the PJSC "ArcelorMittal Kryvyi Rih") by 400 hectares at the expense of farming lands of Novolativka rural territorial community of Shyroke district.

In addition to re-treatment of concentration tailings, transition of GZKs to backfilling worked-out areas of open pits with tailings is a significant reserve for reducing the current rate of their area increase.

Among other ways, previously created TSFs, especially multilevel ones, should be optimized by engineering and biological reclamation to plant the surface with vegetation by the above-described hydraulic method.

Long-term (over 140 years) exploitation of Kryvyi Rih ore deposits has resulted in landscape disturbances that cannot be removed but they should be transformed into plant biogeocenoses. This activity should involve engineering and biological methods with final planting of trees and shrubs, stimulation of self-restoration of vegetation in hard-to-reach areas of technogenic landscape formations.

Biological reclamation of areas disturbed by mining operations is prevalently of a sanitary-hygienic character with the main task of planting vegetation on a technogenic object in the shortest time possible in order to reduce the negative impact of dusting on the environment or increase the aesthetic level of the landscape. Our practice indicates that in the climatic conditions of Kryvbas at areas of biological reclaimation with not thinner than 0.3 m potentially fertile soil layers (loam, loam and quartzite), the following species can be most successfully planted: the black locust (Robinia pseudoacacia L.), the sharp-leaved maple (Acer platanoides L.), the Asian sumach (Ailanthu saltissima). The Chinese elm or the English elm (Ulmus parvifolia), Lombardy poplar (Populus nigra pyramidális) and the black poplar (Populus nigra) take root less successfully. Among shrubs, the false indigo (Amorpha fruticosa), the common smoke tree (Cotinus coggýgria), the viburnifolious spirea (Physocarpus opulifolius) and the blueash (Syrínga vulgáris) show best establishment and growth. In these conditions, the vegetation technology should envisage adding minimum 5-6 kg of a nutrient substrate (e.g. chernozem with organic-mineral materials of the city sewage system sludge or peat) and 30-40 g of mixed nitric-phosphoric-potassium nonorganic fertilizers. Watering plants during their planting as well as minimum 3-4-times watering - in the dry summer season in the first year after planting is essential.

The similar technology of planting seedlings can be recommended for biological reclamation of old waste dumps without earthing but containing over 7% of the fraction diameter $\leq$ 1 mm. In this case, planting holes for seedlings can be made directly in the rocks, but they should be filled with minimum 8 kg of the nutrient substrate with of 50 - 60 g of mineral nitrogen - phosphorous - potassium fertilizers.

The most reliable and least expensive way of solving the issues of technogenic landscape reclamation is to stimulate processes of self-overgrowth. Observations show that plants grown from seeds even in complicated agrochemical conditions are highly viable and hardy, and most importantly – they reliably vegetate without additional care. One of the ways to stimulate self-overgrowing is targeted dispersal of plant seeds over the surface of the object under reclamation. The best way to solve this problem is hydroseeding applying typical hydroseeders that allow using complex hydro-mixtures, including nutrient substrates, mineral fertilizers and plant seeds. Technical characteristics of modern hydroseeders allow remote application of seeding mixtures to the most hard-to-reach areas of reclamation, including steep slopes of waste dumps. An important advantage of this method is that there is no need for any costly and dangerous mining-engineering operations on preliminary preparation of slopes of dumps and other complex landscape formations for reclamation. The same hydraulic method can be used to remotely conduct initial reclamation works by repeated application of the nutrient (fertile) substrate to the most unsuitable for plant growth surfaces, e.g. TSF slopes or stone surfaces, etc.

Selection of the seed composition is the key to hydroseeding. Based on our experience, mixtures should be composed of mainly three groups of plants (herbaceous, shrubs and deciduous plants) for vegetation to cover all possible levels. In some cases, when temporary planting is required (e.g. on substandard ore storage areas), seeds of perennial herbaceous plants suffice. The species composition of plants in each case is selected depending on the age of the dump or other landscape formations, the agrochemical state and the fractional composition of rocks of the surface. The best way to consider these three factors is to study in advance the species composition of plants that have already settled on the object or on neighbouring areas with similar conditions by the time of the planned reclamation. For example, in 2020 we developed a project for reclamation of a waste dump (operated in 2012-15) of one of the underground mines in the center of Kryvyi Rih. The total area of the dump was 8.8 ha, of which the area of bare slopes with a slope angle of 35 - 40^o was 3.9 ha. The technology was chosen to stimulate natural planting of steep slopes by hydroseeding grass, shrub and tree seeds. To justify the species composition of the seeds for hydroseeding, there was made inventory of the species composition of plants self-established during 2000-2012 on the surface of the adjacent dump of the same mine. The studies showed that the degree of self-growth as of 2020 averaged 65% (on the slopes) to 95% (on the upper platform). The slopes of the dump mostly consisted of medium-sized rock lumps (5 to 20 cm in diameter). At the time of the study, the rocks were sufficiently weathered, the fine fraction made 20 - 30%, the humus layer of 0.7-2.1 cm was formed on 40 - 70% of the area. The plants of the formed layer included grasses (the longleaf, the tumbleweed, the Swiss ryegrass, the knotgrass, etc.), shrubs (the wild rose, the fustic, the red dogwood, the false indigo,) and trees (the robinia, the black poplar, the Chinese elm, the ash-leaved maple, etc.). At the time of the survey, the condition of mature trees was satisfactory, crowns looked normally formed, there was intensive young root-shoot of maples, ash-trees and acacia trees. Thus, the identified plant species made up the main list of seed species for hydroseeding slopes of the waste dump to be reclaimed.

4. Conclusions

The long-term activities of mining enterprises in Kryvyi Rih iron ore basin have adversely impacted the landscape structure of the region. Optimization of technogenic surface disturbances accumulated during the period of economic exploitation of the region requires a comprehensive solution in two directions. The first one consists in reducing the rate of new destructive impacts on the state of the relief by switching from extensive methods of deposit mining to intensification of production. The second one involves restoration of the landscape through reducing technogenic relief disturbances by engineering and biological methods. To do this, it is necessary to:

– increase financial responsibility of economic entities for violation of the Ukrainian environmental legislation and recommendations of international environmental programs concerning the rational use of minerals and land resources, disposal and recycling of industrial wastes;;
– introduce a requirement in the National Building Code of Ukraine on mandatory development of the landscape planning section in all projects on construction and reconstruction of mining enterprises;;
– oblige all developers of projects for mining enterprises to include allocations for reclamation and optimization of disturbed landscapes in the estimate;
– include in Comprehensive environmental programs of the region and the city specific works on gradual elimination of previously accumulated landscape disturbances (currently under abeyance) with annual allocation of minimum 15% of the city's environmental fund and funds of enterprises for these purposes;
– raise tax rates for increased volumes of accumulated wastes and introduce environmental fines for mismanagement of leased land plots;
– significantly increase enterprises' investment in development of measures to intensify iron ore production, namely in technologies of tailings re-treatment, oxidized and substandard ore processing, reduction of external dump areas through tax benefits and subsidies from the state, regional and city environmental budgets:
– introduce innovative technologies for restoration of natural ecosystems on mining landscape areas by stimulating the process of disturbed lands self-overgrowth using the hydromethod

of remote application of nutrient substrates and seeds of herbaceous plants, trees and shrubs to the surface of complex landscape formations.

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To cite this article: V Antonik *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012003

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012003 doi:10.1088/1755-1315/1049/1/012003

New technology of reclamation of slopes of waste and excavated rocks of mines and quarries

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Abstract. The urgent environmental problem of industrial Kryvbas is the reduction of dust formation from wind erosion of bare surfaces, especially slopes, dumps of iron ore mines and quarries. The best way to reduce the dusting of dumps is to afforest their surface with trees and bushes, but naturally this process can take up to 15-20 years, and the well-known scientific developments to solve this problem are ineffective or too time-consuming. The objective of our work is to create the innovative technology for active stimulation of self-organized vegetation of hard-to-reach steep slopes of dumps. To implement the idea, it is proposed to use standard hydroseeders for a new purpose, in particular, HM-0-HARV Turbo Turf hydroseeder, which is able to create hydroflow at a distance of 30-50 m. The article describes in detail the essence of the developed technology, method of organizing and conducting hydraulic sowing from both the lower and upper edge of the dumps. It is recommended to include seeds of herbaceous grass and legumes, deciduous trees and shrubs, mineral fertilizers and nutrient substrate (sewage sludge) in the seeding hydraulic mixture. The proportion of seeds of various plant species, fertilizers and nutrient substrate in the hydraulic mixture for sowing on the slopes of Kryvyi Rih dumps, which have a neutral soil acidity and contain at least 3% of the fine fraction of rocks in the surface structure, is substantiated. According to the results of testing the proposed technology, it is concluded that applying a mixture of seeds of herbaceous plants, trees and shrubs in combination with mineral fertilizers and nutrient substrate to the surface of dump slopes by hydroflow accelerates their self-organized vegetation by about 3-4 times. It is shown that crop care measures in the first year of plant vegetation (periodic watering and, if necessary, fertilizing using hydroseeder) can save up to 60-75% of seedlings and help stabilize newly created biogeocenosis in subsequent years.

1. Introduction

The most difficult issue in the reclamation of mineral composition of iron gangue and overburden dumps of open pits of mining and processing plants (GOK) is to carry out biological reclamation of hard-to-reach slopes, which usually have a natural angle of slope of free-deposited loose rocks (30^o or more). The surface of the slopes of newly formed dumps (up to 3-5 years old) is mostly covered with large pieces of rock, contains almost no humic substances, therefore both agrochemical and mechanical properties are not suitable as a substrate for plant habitat. Over the years, lump fractions of shale rocks of the surface layer of dumps gradually evaporate and as a result of oxidation and precipitation water action are crushed, crumble and then the slopes become more suitable for plant habitation, including spontaneous overgrowth from seeds of shrubs, trees and herbaceous plants that accidentally brought by wind, birds or animals. It is known that self-overgrowth of technogenic-disturbed areas begins in the second or third year after the cessation of their formation in areas containing more than 3-6% of the fine fraction. At first, representatives of ruderal vegetation appear, and later the species composition gradually increases. Observations show that up to 35 plant species take part in early self-overgrowing processes on Kryvbas dumps, of which coenomorphs include 54%, steppe weed species to 12%, and meadow weeds up to 16% [1]. Subsequent stages of demutation gradually lead to the emergence of long-rhizome plants, including trees and shrubs. Under favorable conditions, the vegetation can cover up to 60 - 70% of the surface of waste dumps in 15-20 years by self-overgrowing, which some authors consider one of the cheapest and most reliable methods of biological reclamation of man-made landscape formations [2].

Since self-overgrowing in general is, a natural, and haphazard process, the quality of the natural landscaping of the surfaces of the dumps looks quite diverse and, especially on the slopes, often there are significant bare areas that become sources of air pollution and require mandatory measures for dust suppression, including through artificial planting.

In the practice of purposeful work on biological reclamation of slight (angle up to 18^o) slopes of man-made objects of mining enterprises, there is a positive experience of applying conditionally fertile soils (low-fertile chernozem, loam) layer of 40-50 cm followed by planting trees and shrubs. But if the angle of the slopes exceeds 18^o, then grounding the surface of the slopes with soft rocks becomes ineffective. This is because the fertile substrate is almost not kept on steep slopes, subsequently subject to significant water erosion during precipitation and slides down. Attempts to preliminarily prepare the slopes for the application of a layer of soft soil by cutting the cross terraces with an excavator - dragline every $10 - 11$ m of the slope height, also failed in practice due to significant technical complexity and cost of implementation. The same disadvantage has a patented method of forming waste heaps with slopes up to 30^o, followed by biological reclamation, in which waste masses are placed in the heap by layer-by-layer dumping with simultaneous compaction and earthing of the surface and creating a vegetative cover. At the same time, horizontal enclosed terraces are formed in the slopes with a 30 m interval [3].

Various methods of direct planting on the slopes of a heap by making holes 10-20 cm deep for planting directly in rocky soil, followed by the introduction of a nutrient substrate, fertilizers, and water into such holes were also studied. It is proposed to protect such pits from backfilling and erosion from the side of the slope with special racks [4]. However, the process of creating holes in the rock substrate on the slopes by humans is a dangerous and time-consuming process that requires work using special protective cables, which is extremely unprofitable and unreasonably expensive.

Noteworthy is the method of hydro washing of plant seeds with a soil mixture on the slopes of dumps with an angle of 35-40^o. However, this method has not been implemented in the absence of the equipment proposed by the authors for the implementation of such a hydro washing system [5].

At present, the technology of hydroseeding of perennial herbaceous plants is widely used in international practice in the reclamation of disturbed lands, including backfilled slopes. Unlike conventional sowing, hydroseeding is carried out by a water flow, to which, together with grass seeds, a nutritious substrate (mulch) and various fixing emulsions can be added [6]. Straw, hay, chopped tree leaves, pine needles, soybean stalks, etc. can be used as mulch. Fertilizers and bacterial preparations that promote the accumulation of organic matter can also be added to the composition of the hydro mixture. In world practice, for example, the drug Biobert, developed in France based on peat and Agrobiol, developed in Germany and widely used in Austria and Spain [7].

The use of reclamation technologies with the application of various ameliorants, which promote the accelerated formation of a nutrient substrate, in particular on the surface of rocks, is promising. In Poland, for example, in the reclamation of man-made disturbed lands of mines, components of sewage sludge are successfully used as ameliorants [8].

Thus, despite the availability of some scientific and practical experience in the biological reclamation of mining wastes and enrichment of iron ore, the search for modern technologies for landscaping hard-to-reach slopes of gangue and overburden rocks of mines and quarries remains an urgent issue of landscape ecology in regions with the developed mining industry.

The work aims to develop and test the method and technology of active stimulation of self-organized vegetation of hard-to-reach slopes of dumps of gangue and overburdened rocks of iron ore mines and quarries.

2. Methods

The developed technology is proposed for use in solving problems of biological reclamation (landscaping) of hard-to-reach slopes of gangue of iron ore mines and overburden of quarries of mining and processing plants, regardless of the age of dumps, degree of stability of incline layer, and mineralogical and fractional composition of the surface layer. The task is accomplished by seeding the slopes of the heaps by watering a mixture of seeds of perennial grasses, trees, and shrubs using a typical hydroseeder.

In the developed technology of hydroseeding, it is offered to use the HM-0-HARV Turbo Turf hydroseeder as the most productive and acceptable for simultaneous drawing on a surface of slopes which do not have vegetative soil, not only seeds of plants but also water mix of nutrients that will promote initial enrichment of the substrate in the locations of plant seeds. The HM-0-HARV Turbo Turf hydroseeder is freely available on the market of the corresponding goods and, according to the instruction, is characterized by the following main technical parameters: l / minute, the range of spraying the hydraulic mixture using a stationary ejector up to 35 m, and using a nipper hose - up to 60 m. In practice, any other similar water seeding technique can be used.

The main stage of work on biological reclamation of slopes of heaps by hydroseeding is the preparation of the mixture. According to the developed technology, the mixture includes water, seeds of perennial grasses, trees and shrubs, and mineral fertilizers. As mulch and primary nutrient substrate, it is recommended to add sewage sludge to the mixture, which is an organo-mineral mixture produced from municipal sewage and its agrochemical parameters meet the requirements of the state standard of Ukraine [9]. According to the Ministry of Agrarian Policy and Food of Ukraine, the sludge is a high-quality concentrate of humic substances with elements of antioxidant plant protection system (tripeptides), has sorption properties, and contains several microorganisms capable of decomposing soil toxins. The use of the mixture optimizes the structural condition of soils, increases the content of available plant nutrients. The sludge contains significant concentrations of phosphorus, nitrogen, and potassium, that's why this mixture can act as a mineral fertilizer, the estimated application rate of which is 20 - 35 t/ha, depending on the derived state of agrochemical parameters of specific soils. At present, the sludge of treatment plants has passed a toxicological, radiological, and microbiological examination and received a positive assessment for all parameters [9].

The process of hydroseeding consists in the fact that the mixture with all additives hydroflow, created by the equipment of the seed drill, is applied in a certain layer on the slopes of the dumps within a radius of 30-50 m from the location of the seed drill. After applying the mixture on the slope surface, the sludge solution of sewage treatment plants and mineral fertilizers create a favorable temperature and temperature regime for germination and plant development in the places of the runoff between lumps of rocks.

The composition of the mixture is recommended to include seeds of perennial cereals - legumes, which should be sown in spring and early summer. The addition of tree and shrub seeds into the mixture creates a real probability that under the cover of grassy vegetation these seeds will eventually germinate and give a stable growth that will not require additional care.

It is known that the waste rock dumps are chemically characterized by the presence of a significant amount of silica, soluble iron, metal oxides, and low sodium content. The reaction of aqueous extraction of waste rocks and quarry rocks is close to neutral. Rocks have medium and high absorption capacity, contain potassium and phosphorus therefore these rocks are considered potentially favorable places for plant growth. In order to ensure the highest probability of formation of a stable biocenosis, it is recommended to use plant seeds of three biological groups on the slopes of mining dumps:

- cereal with a loose bush and rhizome cereals, which quickly create a good turf and give it greater tensile strength in the horizontal direction (for example, red fire, annual ryegrass, stokolos, etc.;
- legumes (taproot), which form long roots, securely fasten turf with the soil of the slope, and subsequently contribute to the enrichment of the substrate with nitrogen (eg, sainfoin, clover, alfalfa, and other species);
- seeds of deciduous trees and shrubs (it is recommended, first of all, to use certified seeds of white acacia, elm, and amorphous shrubs).

In addition to seeds, mineral fertilizers and sewage sludge should be added to the mixture for hydroseeding, the amount of which is determined by table 1:

Table 1. The recommended proportion of fertilizers and sewage sludge per 1000 liters of water.

№	Name of components	Unit	Quantity per 1000 liters of water
1	Nitroammophos (nitrogen-phosphorus)	kg	90
2	Potassium (potassium salts)	kg	15
3	Treatment plant sludge	kg	250

As part of the mixture, sludge from sewage treatment plants is used as a starting soil, enriched with the necessary minerals, which also serves as mulch. The recommended proportion of sewage sludge to water is 250 kg/1000 l.

The proposed HM-0-HARV Turbo Turf hydroseeder has a 2.8 m^3 tank, is equipped with an independent 27 hp petrol engine, a hydraulic pump, and a mechanical (paddle) hydro mixture mixer.

It is recommended to move the hydroseeder to the reclamation area with the help of a tanker trailer device, which will also provide a water supply for the preparation of the mixture. After delivery of the hydroseeder to the site, the tank capacity is loaded with water to a volume of approximately 1 m^3 (1000 l), then the sludge of treatment plants, fertilizers, and seeds are loaded, and, finally, the tank is filled with water to full capacity. After tightly closing the hatch of the tank, turn on the engine to thoroughly mix the loaded mixture for 10 - 15 minutes. The approximate composition of the seeding mixture for one filling of the tank of hydroseeder is given in table 2. According to the results of testing, such composition of the hydraulic mixture is recommended for landscaping the dump slopes, which have near-neutral pH of rocks and contain at least 3% of the fine fraction ($\leq$ 1 mm) in the structure of slope surface.

During the operation of the hydroseeder, the hydraulic mixture is constantly maintained in the state of suspension by constant mechanical stirring by the blade mechanism of the tank. The resulting mixture is pumped under pressure into the spray and then sent by the operator to the treated area.

Table 2. Composition of components for preparation of disposable mixture.

Name of components	Unit	The required quantity of components
Water	L	up to 2090
Sewage sludge (DSTU 7369: 2013 [9])	kg	500
Mineral fertilizers including:	kg	210
nitroamophos	kg	180
potassium	kg	30
Seeds of grasses, trees and shrubs including	kg	39
-meadow fescue (Lolium pratense)	kg	4
-Italian ryegrass (Lolium multiflorum	kg	3
-leyss (Bromus arvenis L.)	kg	4
-yellow melilot (Melilotus officinalis)	kg	15
-sainfoins (Onobrichis sativa lam)	kg	3
-alfalfa (Medicágo satíva)	kg	3
-black locust (Robínia pseudoacácia)	kg	3
-lacebark elm (Úlmus Ulmaceae)	kg	2
-bastard indigobush (Amorpha fruticosa)	kg	2

The HM-0-HARV Turbo Turf hydroseeder according to the technical possibilities allows to carry out seeding in two ways:

- directly from the work site above the tank of the hydroseeder using a special stationary ejector, attached to the body of the hydroseeder and connected to the pressure pump by a short hose. This option is convenient and safe for the operator, but can be used only in conditions of close access to the sowing area, for example, to the bottom edge of the slope, and allows to sow from one point only a sector with a radius of 30 m;
- sowing with the use of a pressure hose up to 30 m long with a manual ejector. This method allows the operator to move more freely within the operating point and get as close as possible to the sowing area, even in the presence of certain landscape obstacles.

The working point for placing the hydroseeder can be both at the bottom of the slope (hydroseeding is carried out along the slope from bottom to top, by direct flow) and at the level of the upper edge of the slope (hydroseeding is carried out from top to bottom, by spraying).

When carrying out hydroseeding from the lower point of the slope, the operator, standing on the upper working platform of the hydroseeder, can rotate the stationary ejector in the horizontal plane by 80 - 100^o, and in the vertical plane - can tilt it up or down within 40^o from the horizontal, providing thus the output of hydroflow and hydroseeding direct current over the entire plane of the slope in a radius of 30-35m. The task of the operator is not only to move the ejector nozzle but also to control the jet velocity by adjusting the revs of the pump, the need for which arises, for example, when changing the distance from the hydroseeder to the seed surface. It is important to constantly ensure the formation of a hydroflow of such intensity that the mixture is evenly laid on the surface, there are no unsown gaps, and that the mixture does not flow in significant flows from the slope. The approximate rate of consumption of the hydro mixture is 1-0.9 l/m^2. For visual determination of the treated area by the operator, a dye (green, blue, etc.) can be added to the mixture.

When carrying out top-down water seeding works, the hydroseeder should be installed as close as possible to the border of the upper slope edge or the inner edge of the embankment slope, and hydroseeding should be carried out not by direct flow, but by mounted spraying with the ejector position from horizontal to the lowest possible position. The distance of the sowing zone and the uniformity of hydroseeding in this case is regulated by the current force of the hydro mixture.

In areas where there are complications with hydroseeding with a stationary ejector (for example, due to the impossibility of installing a hydroseeder at the required point, with an insufficient range of the seeding mixture flow, and so on, it is necessary to use a pressure hose up to 30 m with a manual ejector. In this case, an operator, holding an ejector sprayer, can sow along the entire length of the slope to a width of 50-60 m. It is important to note that sowing with a hose requires at least two workers: the first one (the operator) controls the ejector and directly conducts hydroseeding and the second worker supports the hose at a distance of 4-5 m from the operator and helps to carry the hose when the operator moves along the slope.

To reduce the risk of runoff of the seeding hydro mixture on the sloping surface in both types of its application, it is recommended to sow in two phases. During the first phase, approximately half of the planned volume of the mixture is distributed over the sowing area, and the rest is distributed during the second phase. At the same time, cover the missed places with a mix and achieve a more uniform distribution of the mixture over the entire sowing area.

Care of hydroseeding should consist of the following:

- in case of prolonged dry weather during June-September in the first year after hydroseeding it is recommended to carry out watering of plantings (not less than 1-2 times a month, up to 4-6 times a season, including using a hydroseeder). The best time for watering is in the evening, after 7 pm;
- if there are signs of deviations in the development of grass cover (plants during the growing season become pale green or yellow), then it is recommended to use a hydroseeder to fertilize plants (up to 50% of the area) in June - July with a solution of mineral fertilizers water. The recommended working mix should include (per filling hydroseeder): nitro amorphous (nitrogen-phosphorus) fertilizers - 110-120 kg, potassium fertilizers - 30 kg, water - 2500 l;
- under the optimal conditions, the plants after germination should be evenly distributed on the sloping surface, without gaps and clusters at the bottom. If these conditions are not met or mechanical damage (erosion) of slopes has occurred, it is recommended to reseed poorly landscaped areas (up to 30% of the area) in autumn or spring of the next year.

3. Results and discussion

It is known that the level of the air pollution with dust in Kryvyi Rih is at least 2 times higher than sanitary standards. Dozens of bare dumps of mines and quarries located within the city play a significant role in creating this environmental problem. Therefore, the innovative technology of biological reclamation of the dumps of mines and quarries developed and described above is extremely important and relevant for industrial Kryvbas. The article proposes an innovative way to stimulate and accelerate 3-4 times the self-organized vegetation of the most complex parts of dumps – their steep slopes – by hydroseeding with a mixture of grass seeds, trees and shrubs in combination with mineral fertilizers and nutrient substrate. The tests have shown that the proposed hydroseeding technology can also be successfully used for rapid (in 3-5 years) landscaping the landforms of any man-made nature, including horizontal sections, slopes of multi-layer tailings dumps, slopes of craters in places of geotectonic shift and pits in areas of completed underground works, etc.

The advantage of the proposed technology is that, unlike traditional methods of landscaping the man-made areas, the use of hydroseeding technology completely eliminates the need for expensive and dangerous work on preliminary technical preparation of surfaces, including the slopes of dumps of any steepness and age, before conducting biological reclamation.

The recommendations described in the article regarding the composition of the seeding hydraulic mixture (see Table 2) are adapted for use in landscaping the slopes of gangue dumps of mines, which have near-neutral pH of soil and contain at least 3-5% of the fine fraction with a diameter not exceeding 1 mm in the rocks of slope surface. At the same time, the simple technology of preparing a mixture from various components using modern hydroseeders, in particular HM-0-HARV Turbo Turf hydroseeder, allows easy combining various types of seeds of herbaceous and woody plants and related components in the hydraulic mixture depending on the agrotechnical condition or hydraulic regime of the territory or on the agrochemical composition of the derived substrate of the surface of reclamation objects.

Special attention should be paid to the possibility of using the developed method of hydroseeding for temporary landscaping and removing the dust from the surface of warehouses of substandard fractions of ore materials in iron ore mines and dumps of oxidized ores in quarries. Since these man-made objects are actually warehouses of potentially useful iron ore raw materials that can gradually be selected for further concentration, the biological reclamation of their surface by afforestation becomes impractical, but landscaping by hydroseeding their surface with a layer of herbaceous plants is an extremely rational measure from ecological and economic point of view.

The death of plants due to drought is always the main cause of failures while attempting to biologically reclaim the slopes of dumps in many known ways. The experience shows that the developed technology of using hydroseeder allows caring for plantings and crops on steep slopes and in other difficult landscape conditions, for example, watering and fertilizing plants in the hot summer months, especially in the first years of vegetation. This significantly increases the efficiency of work on landscaping the slopes and with correct application of the crop care regime recommended in the article, it is possible to maintain up to 60-75% of seedlings in the most critical first year of vegetation. In the next 2-3 years, as usual, the mechanism of self-renewal of perennials with gradual stabilization of the newly created biogeocenosis is launched, and then the need for care disappears.

4. Conclusions

Based on the materials of the article, the following conclusions can be made:

(i) Control of dust formation from wind erosion of bare surfaces of gangue dumps and substandard ores in mines and quarries of mining enterprises is an important and urgent environmental task of industrial Kryvbas.

(ii) The greatest difficulty in reducing the dusting of dumps is their slopes with an angle of inclination of 30 degrees or more, and the most reliable solution to this problem is self-organized vegetation of their surface by trees and shrubs, which can naturally take 15-20 years or more.

(iii) The latest technology of stimulating and accelerating the self-organized vegetation of dump slopes by 3-4 times by applying a mixture of seeds of herbaceous plants, trees and shrubs in combination with mineral fertilizers and nutrient substrate to their surface by hydroflow has been developed and tested.

(iv) As equipment for remote sowing of dump slopes, it is recommended to use standard hydroseeders for a new purpose, in particular, HM-0-HARV Turbo Turf hydroseeder, which is able to create hydroflow at a distance of 30-50 m.

(v) It is recommended to include seeds of four groups of plants in the composition of the hydraulic mixture for landscaping the slopes of dumps: herbaceous grasses, herbaceous legumes, deciduous trees and shrubs, which will quickly create a green “cover” of grass and humus, and in 2-3 years ensures the development of three layers of landscaping.

(vi) Inclusion of a reasonable amount of components of mineral fertilizers and sewage sludge to the composition of the hydraulic mixture is intended to create a primary nutrient substrate for germination of seeds applied to the slope surface.

(vii) The mixture and proportion of seeds together with other components, which are substantiated in the article, are recommended for sowing on the slopes of most gangue dumps of mines and quarries in Kryvyi Rih, which have near-neutral pH of soil and contain at least 3% of the fine fraction ($\leq$ 1 mm) of rocks in the surface structure. Under other agrotechnical conditions, the composition of the hydraulic mixture can change arbitrarily.

(viii) In the hot months (June-September) of the first year after sowing the slopes, it is recommended to water them, and, if necessary, nourish the soil with solution of mineral fertilizers or sewage sludge using hydroseeder. Care measures allow saving up to 60-75% of seedlings in the most critical first year of vegetation.

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IOP Conference Series: Earth and Environmental Science

Investigation into near-contour stresses in stoping with backfilling by the polarization-optical method

To cite this article: V P Shchokin *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012004

Investigation into near-contour stresses in stoping with backfilling by the polarization-optical method

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Abstract. When mining deposits with room-and-pillar methods with backfilling, available hanging wall rocks and ores of medium or low stability can cause hanging wall rock collapses into stoping areas, thus causing escalation of ore dilution with waste rocks. The research work is aimed at determining areas of maximum stresses and their quantitative characteristics which can cause collapses of hanging wall rocks in the mined-out stope area and developing technological solutions to reduce concentration of stresses. Options of mining stopes located on the hanging wall of the deposit are investigated on polarization-optical models. According to the results of studying polarization-optical models with different designs of stope chains, there are obtained stress fields for each model in the zone of stope influence. The research reveals that when using a stoping method with partial processing of hanging wall rocks in the contact plane with the country rocks, the maximum stresses are much higher than in case of the arched form of the stoping area. On the basis of the obtained research results, it is recommended to carry out chambers with the formation of a vaulted shape of the roof from the hanging side in order to reduce the clogging of the ore.

1. Introduction

When performing stoping operations, there is a tendency of increasing the robbed-out space in rooms resulting in changes in the volumetric stress state of the rock massif adjacent to the stoping area [1–3]. This consequently initiates geomechanical processes that cause strains of the rock massif and the stope contour collapse. The nature of geomechanical processes occurring in the rock massif adjacent to the robbed-out space is determined by mining and geological conditions [4]. With increased mining depths, rock pressure naturally increases and so do stresses in the near-contour massif [5–7] in room-and-pillar mining. In conditions of mining deep levels of Pivdenno-Bilozirskyi deposit, poor stability and low strength of the hanging wall rocks are the main and determining factors causing disturbances of stoping area contours [8] in mining operations [4]. Low and extremely low stability of ores and country rocks contributes to lost stability of stoping area contours.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012004 doi:10.1088/1755-1315/1049/1/012004

2. Purpose

The research aims to develop recommendations on parameters, forms and procedures for stoping, including search for possible partial changes in the shape of stopes, and procedures of their mining under increased stresses in the near-contour massif when conducting stoping operations by the room-and-pillar method with backfilling.

3. Methodology

To research into stresses in the near-contour massif when stoping, a polarization-optical method with transparent models made of optically sensitive materials (photoelasticity) [9, 10] is used to obtain data on distribution and values of stresses in the rock massif with mine workings of various purposes and sizes.

The polarization-optical method of studying stresses is based on properties of most transparent isotropic materials to acquire the ability of double radiation under the influence of stresses (or strains). The value of double refraction associated with that of stresses can be measured optically when the model is transilluminated with polarized light. Polarization and double refraction are optical phenomena underlying the polarization-optical method. When conducting research by the polarization-optical method for obtaining flat-polarized light, so-called polarizers are used that permit light oscillations only in one plane – in the plane of oscillations.

As is known from the theory of elasticity, the stress-strain state of the solid's point is characterized by six components of stresses: $\sigma_x, \sigma_y, \sigma_z, \tau_{xy} = \tau_{yx}, \tau_{xz} = \tau_{zx}, \tau_{yz} = \tau_{zy}$ or six components of strains: $\epsilon_x, \epsilon_y, \epsilon_z, \gamma_{xy} = \gamma_{yx}, \gamma_{yz} = \gamma_{zy}, \gamma_{zx} = \gamma_{xz}$ [11].

The method of photoelasticity is based on laws of the elasticity theory which sate that the relationship between stresses and strains is subject to the Hooke law and for triaxial stress is expressed in the form of:

$$\left.\begin{aligned}
\varepsilon_x &= \frac{1}{E}[\sigma_x - \mu(\sigma_y + \sigma_z]\\
\varepsilon_y &= \frac{1}{E}[\sigma_y - \mu(\sigma_x + \sigma_z]\\
\varepsilon_z &= \frac{1}{E}[\sigma_z - \mu(\sigma_x + \sigma_y.]\\
\gamma_{xy} &= \frac{1}{2G}\tau_{xy}; \gamma_{yz} = \frac{1}{2G}\tau_{yz}\\
\gamma_{zx} &= \frac{1}{2G}\tau_{zx}; G = \frac{E}{2(1+\mu)}
\end{aligned}\right\} \tag{1}$$

where $\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}$ are stress components,
$\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ are strain components,
μ is the Poisson ratio,
E is the elasticity modus,
G is a the shear modus.

Many problems of the elasticity theory can be reduced to solving a flat problem eliminating significant difficulties of manufacturing a model and, especially, of mathematical processing of test results. Then, the Hooke law is written in the form of:

$$\left.\begin{aligned} \varepsilon_x &= \frac{1}{E}[\sigma_x - \mu\sigma_y] \\ \varepsilon_y &= \frac{1}{E}[\sigma_y - \mu\sigma_x] \\ \gamma_{xy} &= \frac{1}{2G}\tau_{xy} \end{aligned}\right\} \quad (2)$$

To match the modelled processes and the prototype ones when manufacturing a model, it is necessary to follow a number of similarity criteria [12].

To bring the geometrical parameters of the model in line with the prototype ones, the geometric scale of modelling is taken:

$$\alpha = \frac{l_n}{l_m} = const \quad (3)$$

where l_n ,l_m are the length of any similar segments in the prototype and the model respectively. For concentrated loads, the force scale is accepted:

$$\beta = \frac{P_n}{P_m} = const \quad (4)$$

where P_n ,P_m are the forces applied to similar points of the prototype and the model.

Then the similarity scale of uniformly distributed loads or stresses δ will be associated with the force scale β through the geometric scale α:

$$\delta = \frac{\sigma_n}{\sigma_m} = \frac{\beta}{\alpha^2} = const \quad (5)$$

where σ_n, σ_m are the stresses applied to similar points of the prototype and the model.

Poisson ratios of materials of the prototype μ_n and the model μ_m as dimensionless quantities should be equal

$$\mu_n = \mu_m \quad (6)$$

Fulfillment of similarity conditions (3)-(6) is sufficient for the studied stresses, shears and strains in the model to meet the same prototype parameters.

The polarization-optical method of studying stresses on transparent models of optically sensitive materials makes it possible to obtain distribution and values of stresses in the rock massif with different geometric parameters of the stope. To do this, the model gradually reproduces stoping stages and at each stage isochromatic (lines of the same colour, characterizing stress differences) and isoclinic (lines with the same angle of main stresses) images are taken. An isostatic image is built based on the isoclinic image. According to the obtained isochromatic, isoclinic and isostatic images, the values of stresses along straight lines parallel to the coordinate axes (x and y) are calculated.

To study the stress state of the rock massif on polarization-optical models, the latter are made of low-modulus materials that operate under their own weight. The optically sensitive material – igdantine – is used for manufacturing polarization-optical models.

4. Research results

To manufacture the models, the optically sensitive material – igdantine – of the following composition is adopted: gelatin - 25%, glycerin - 30%, water - 45%, as it is the most suitable for modelling the desired processes providing sufficient information about the stress state of the rock massif in the proximity of the robbed-out stoping area of various geometry.

The igdantine model is made according to the generally accepted methods [10] as follows. According to parameters of a cassette for manufacturing the model, the required amount of igdantine is prepared. To do this, the required amount of water is poured into the calculated portion of gelatin stirring slowly. The mixture swells for 5-8 hours and is mixed thoroughly with glycerin added. The resulting mixture is aged for 20-24 hours, after which it is thoroughly mixed again and heated for 5 hours to the temperature of 80-90°C in a water bath. When heating, the mixture is slowly stirred three-four times to remove the foam layer. The molten mixture is aged at this temperature for 1.0-2.0 hours. The resulting solution is filtered and poured into the specially prepared split mould (cassette) with transparent walls. The cassette with the filled molten mixture is placed into the bath with water heated to 70-80°C in order to slowly cool and remove bubbles. 10-15 hours after cooling the model to the ambient temperature (18-20°C), the mould (cassette) is split in a horizontal position and the model is carefully separated from the walls of the cassette. The surface of the model is coated with oil (castor oil) to reduce friction against the walls of the cassette.

When manufacturing, building and testing the model, it is necessary to ensure compliance with determining criteria of similarity, observe geometric similarities of the model and the prototype as well as boundary conditions.

Based on the model dimensions determined by the size of the mould (cassette) and considering boundary conditions and trying to achieve the maximum possible size of the studied objects (robbed-out areas of stopes and the adjacent rock massif) the geometric scale α = 1:1000 is used when modelling.

At the first stage of testing in the rock massif, the models form the position of stoping operations prior to testing the studied objects, i.e. mining and backfilling are modelled in the upper levels.

Thus, the model is ready for modelling stoping operations in the research area.

Next, stoping is modelled according to the scheme in figure 1, i.e. for stoping conditions of partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall as shown in figure 2 – for breaking stope reserves so that in the place of the robbed-out stoping area exit in contact with the hanging wall rocks, an arched form of the robbed-out area is formed.

After cutting the model in the massif according to the scale of the stoping area, the model is placed in a polarizer for testing through transilluminating by polarized rays. During the tests, isoclinic images and isochromatic images are photographed at different angles of the polarizer. The performed researches of the manufactured and tested models made of optically sensitive material during transillumination by polarized rays allow obtaining data on distribution and values of stresses in the rock massif adjacent to the mined-out stope. The research is performed in accordance with generally accepted classical methods [9, 10]. The testing results of models are processed after testing each model.

The procedure for processing and obtaining the testing results of each of the models is performed in the following sequence: first, isoclines at different angles of the polarizer are built.

When building isoclinic lines, the following properties of isoclines should be observed:

1. Only one isocline of a certain parameter passes through each stress point of the model. Exceptions are isotropic points.

2. Isoclines of all parameters run through isotropic points. The position of isotropic points is determined by the isochromatic image in which isotropic points are represented by dark zones.

3. Isoclines of all parameters converge at the point of load application in the same way as at the isotropic point. This phenomenon should be observed in a completely acute incision. In fact, the incision has a curvature of a small radius. Therefore, isoclines of different parameters will cross the curved zone of the incision. With a small radius of the curvature, it seems that in sharp incisions, isoclines converge at one point. Isotropic points at which the isocline parameter (determined by synchronous rotation of the polarizer and the analyzer corresponding to the inclination angle of one of the main stresses) increases counterclockwise by traversing, are called positive isotropic points. If the isocline parameter increases when traversed clockwise, the isotropic point is called negative.

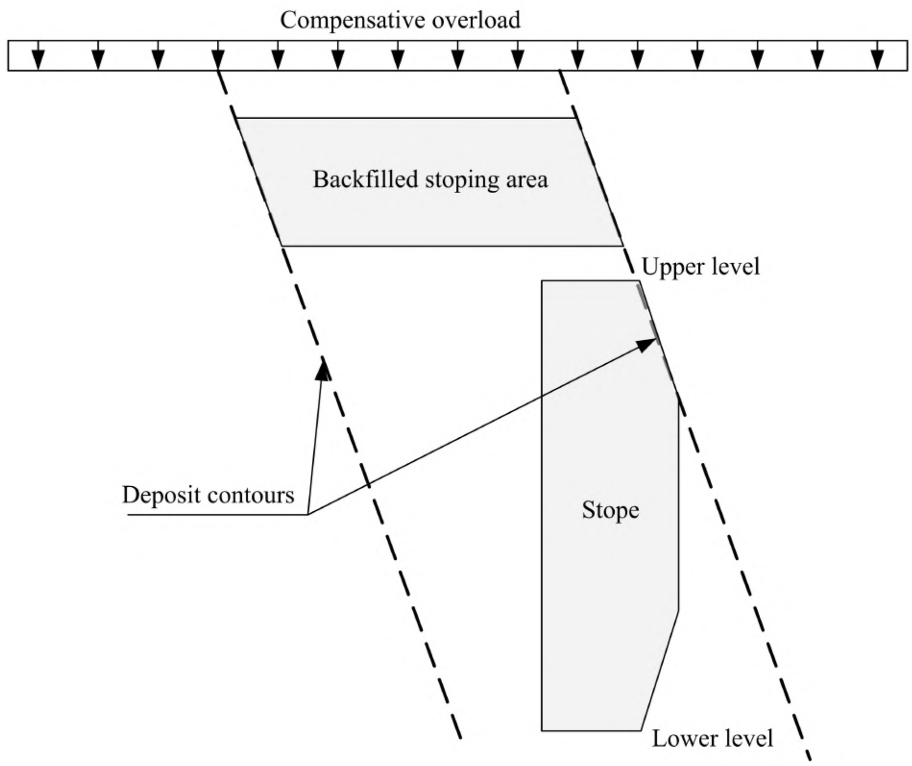

Figure 1. Modelling of stoping with partial undermining of the hanging wall rocks in the plane of contact with the country rocks of the hanging wall.

4. The parameter of the isocline that goes to the free contour is determined by the direction of the tangent at this point of the contour. Since there is only one main stress on the free contour directed tangentially to the contour, the sections of the rectilinear contour are isoclines of constant parameters.

5. The isocline field determines the direction of the main stresses at all points of the model and is used to build trajectories of main stresses (isostatic lines).

According to the described method, isoclines are built by rotating the polarizer and the analyzer every 10°: i.e. isoclines 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70° and 80° for each model. According to the general isoclinic image, the isostatic line image for each model is graphically built. Isostatic lines, or trajectories of main stresses, are lines tangents to which coincide with the direction of one of the main normal stresses at each point. Since main stresses at each point are mutually perpendicular, trajectories of the main stresses form a system of orthogonal curves.

After building isoclines by auxiliary polarization quarter-wave plates, an isochromatic image is photographed. According to the isochromatic image, in accordance with the results of calibration

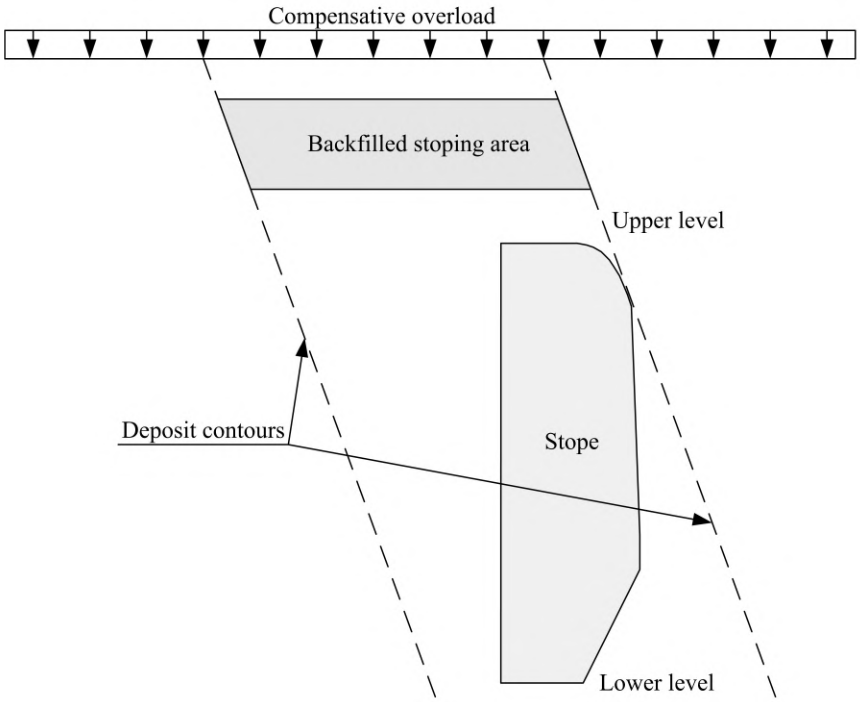

Figure 2. Modelling stoping with breaking reserves so that at the stoping area exit in contact with the hanging wall rocks an arched stoping area is formed.

of the models, images of stress differences for each model are built.

According to the combined image of isoclines and stress differences and the isostatic image, the differences of the main stresses σ_1 - σ_2 and the angles of inclination of the maximum main stresses θ are determined.

Components and are determined by equations according to the methods [9, 10]:

$$\sigma_x = \sigma_{x_0} - \int_{x_0}^{x} \frac{\Delta\tau_{xy}}{\Delta y} dx \tag{7}$$

$$\sigma_y = \sigma_{y_0} - \int_{y_0}^{y} \frac{\Delta\tau_{xy}}{\Delta x} dy + \int_{y_0}^{y} \gamma dy \tag{8}$$

These equations are solved approximately by graph-analytical integration by the trapezoidal method [9, 10]:

$$\sigma_{x_n} = \sigma_{x_0} - \sum_{i=1}^{n} (\Delta\tau_{xy})_{cpi} \frac{\Delta x}{\Delta y} \tag{9}$$

$$\sigma_{y_{kk}} = \sigma_{y_0} - \sum_{i=1}^{k} (\Delta\tau_{xy})_{cpi} \frac{\Delta y}{\Delta x} + \gamma \sum_{i=1}^{k} \Delta y_i \tag{10}$$

where σ_{x_0}, σ_{y_0} are known values of σ_x, σ_y in the initial point (usually within the unmined massif).

$$\Delta\tau_{xy} = \tau_{xy_3} - \tau_{xy_1}, \tag{11}$$

1 is the auxiliary line number with algebraically smaller ordinate;

3 is the auxiliary line number with algebraically greater ordinate.

$$(\Delta\tau_{xy})_{cp} = \frac{\Delta\tau_{xyi} + \Delta\tau_{xyi+1}}{2} \tag{12}$$

If $\sigma_1 > 0$ and $\sigma_2 > 0$, $\sigma_1 = \sigma_{max}$, while $\sigma_2 = \sigma_{min}$. If $\sigma_1 < 0$ and $\sigma_2 < 0$, $\sigma_1 = \sigma_{min}$, while $\sigma_2 = \sigma_{max}$. If the stress has different symbols and $|\sigma_1| > |\sigma_2|$, $\sigma_1 = \sigma_{max}$, $\sigma_2 = \sigma_{min}$ and vice versa. If calculations are conducted along the axis x , after calculating σ_{xi} by [9] , σ_{yi} is calculated by the formula [10] :

$$\sigma_{yi} = \sigma_{xi} - (\sigma_1 - \sigma_2)cos2\theta, if|\theta| < 45^0 \tag{13}$$

$$\sigma_{yi} = \sigma_{xi} + (\sigma_1 - \sigma_2)cos2\theta, if|\theta| > 45^0 \tag{14}$$

If calculations are performed along the axis Y, after calculating σ_{yi} by (9), σ_{xi} is calculated by the formula [11] :

$$\sigma_{xi} = \sigma_{yi} + (\sigma_1 - \sigma_2)cos2\theta, if|\theta| < 45^0 \tag{15}$$

$$\sigma_{xi} = \sigma_{yi} - (\sigma_1 - \sigma_2)cos2\theta, if|\theta| > 45^0 \tag{16}$$

The value of tangential stress is determined by the formula:

$$\tau_{xy} = \frac{\sigma_1 - \sigma_2}{2} sin2\theta \tag{17}$$

where θ is the angle between the positive direction of the axis x and the direction σ_1;

$\sigma_1 - \sigma_2$ is algebraically greater and algebraically less main normal stresses

Then, σ_1 and σ_2 are calculated as follows [9]:

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \tau_{max}, \tag{18}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \tau_{max}, \tag{19}$$

where $\tau_{max} = \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2}$

Based on the calculation results, there are curves of stress concentration factors built for each model in the area of stope influence as they move away from the contours of the robbed-out stoping area towards the hanging and footwalls (figure 2,3).

The results of the tests and researches show that when conducting stoping operations with partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall, maximum stress concentration factors are observed in the upper parts of the hanging walls and footwalls of the stope in the place of their transition into the crown and reach 9γH (figure 3). In the point of transition of the inclined exposure of the hanging wall rocks to the vertical wall of the stope from the side of the hanging wall, the stress concentration factor is 1.8γN (figure 3). When conducting stoping operations with breaking stope reserves so that at the stoping area exit in contact with the hanging wall rocks the arched form of the robbed-out space is formed, the maximum stress concentration is observed in the upper part of the stope wall from the hanging wall side where it is transformed into the crown and reaches 1.6γH (figure 4), while in the upper part of the stope from the hanging wall side in the middle of the arched crown, the stress concentration factor is 1.1γH (figure 4).

In the mid-height of the vertical stope wall from the hanging wall side near the stoping area contour, the stress concentration factor reaches 1.2γH in both models (figure 3,4).

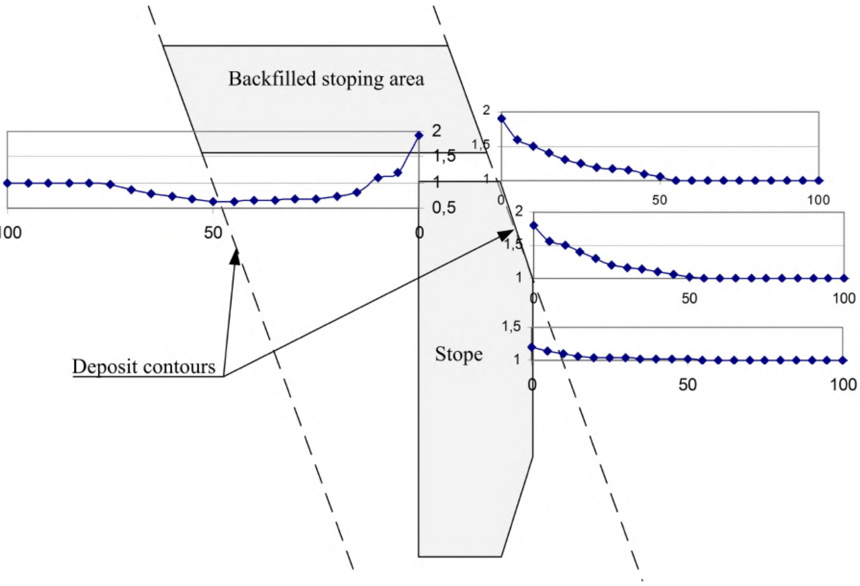

Figure 3. Curves of coefficients of maximum stress concentrations in the rock massif after stoping in the hanging wall of the deposit with partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall.

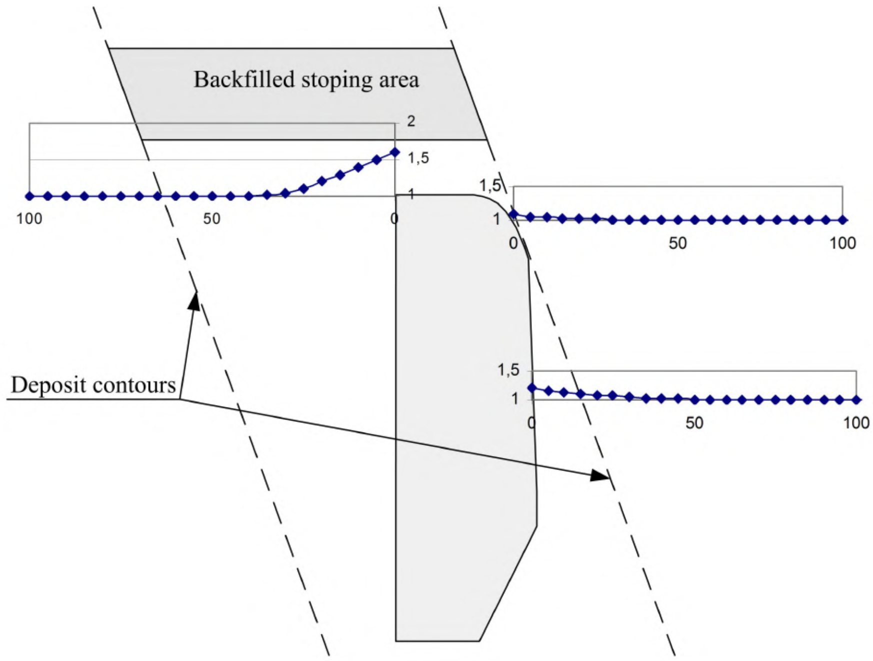

Figure 4. Curves of coefficients of maximum stress concentrations in the rock massif after stoping in the hanging wall of the deposit so that at the stoping area exit in contact with the rocks of the hanging wall an arched stoping area is formed.

5. Conclusion

The research indicates that when stoping in the hanging wall of the deposit with partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall, stresses reach from $1.8\gamma N$ at the transition point of the inclined exposure of the hanging wall rocks into the vertical stope wall from the hanging wall side to 1.9γH at the transition of the inclined plane of the exposed country rocks of the hanging wall in the stope crown. With an arched form of the robbed-out stoping area in contact with the hanging wall rocks in the middle of the arched crown, stresses reach 1,1γH which is much less than at partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall with stresses reaching from 1,8γH to 1,9γH.

Thus, the results of the research enable stating that with hanging wall rocks of medium and low stability, it is expedient to form an arched stope in contact with the exposure of hanging wall rock in order to prevent collapses of the hanging wall rocks into the robbed-out stoping area which can cause greater ore dilution.

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Assessment of safe exploitability of undermined objects of the Underground Ore Mining Department of the Mine Management of the PJSC “ArcelorMittal Kryvyi Rih”

To cite this article: Y Babets *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012005

Assessment of safe exploitability of undermined objects of the Underground Ore Mining Department of the Mine Management of the PJSC "ArcelorMittal Kryvyi Rih"

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Abstract. The article is devoted to monitoring surface displacement and the condition of monitored objects. The object of research is the process of displacement of the earth's surface and the state of protected objects of the "United" deposit of the mine department for underground mining of ores of PJSC "ArcelorMittal Kryvyi Rih". The displacement process is monitored based on long-lasting instrumental observations to determine surface deformations and assess the safety of exploitation of the monitored objects within the mining allotment. The study findings enable ascertaining that in the southern and central parts of the minefield, the displacement process has stopped, but in the northern part, it is still developing, and mining will have no impact on the technological objects of the Mine Management in the next two years. Over the recent two years, actual subsidence rates in the railway area have not exceeded 2.7 mm/month, and they are significantly lower than the permissible values (100 mm/month). The road sections shifting and the base for the removal of the road continue to develop. Mining operations at the deposit "Obiednanyi" have no hazardous impact on the "Schistose Rocks" natural geological reserve, the settlement of Karnavatka and the cemetery "Zakhidne". Displacement on road and road base sections is in progress. In the vicinity of the settlement of Zhukivka, the maximum relative deformations (3.2 mm/m) are still much lower than the permissible one (6 mm/m), and they will not reach their maximum permissible values in the nearest two three years. In the last year, deformation rates decreased and reached the 2018 figure. Therefore, all the monitored objects within the mining allotment can be safely exploited.

1. Introduction

Ensuring environmental and technical safety in the mining of iron ore by the underground method is secured, among other things, by monitoring the displacement process of the earth's surface and the state of protected objects within the mining allotment. The monitored objects are adversely affected by surface displacement, resulting in crater formation. The research object is the deposit "Obiednanyi" of the Underground Ore Mining Department of the Mine Management of the PJSC "ArcelorMittal Kryvyi Rih".

The Underground Mine Management (as an underground mine) of the PJSC "ArcelorMittal Kryvyi Rih" (from now on referred to as the Mine Management) is engaged in mining the rich iron deposit "Obiednanyi" by ore and country rock caving. Iron ore is extracted in a blind area of the ore deposit within survey axes 159-231 in the 1045m-1065m sublevel.

The dip of the hanging wall rocks varies from 30° in the upper part of the section to 65° in its lower part. Likewise, the dip of the footwall rocks varies from 30° in the upper section to 55° in its lower part.

In the northern part of the ore field (northwards of survey axis 55) from the mark -360 m, a blind area of the deposit occurs. Barren inclusions between it and the main layer reaching 150 m along the strike disappear at a depth of 600 m. In the northwest, this deposit section inclines to the mark - 800 m and joins the deposit "Osnovnyi 95" of the underground mine to form a shared ore body.

The deposit depth "Obiednanyi" increases from -950 m in the south to -1250 m in the north.

Heavily watered dolomites occur in the deep hanging wall with karst caverns filled with water.

Currently, mining operations are conducted within axes 159-231 in the sublevel 1045-1065 m. Due to deposit thinning, mining operations have been stopped to the south of axis 55.

The displacement process caused by mining operations on the surface has acquired a classic landslide trough with a crater, caving, crack zones and areas of hazardous and general impacts. Currently, the width of the displacement trough across the strike reaches 2.8 km.

The monitored objects on the surface in the footwall of the deposit are:

- The frame bridge PK73 km+200; PK73 km+250;
- The railway track (section 71.74 km) and the access line Kirov station - Shmakove station;
- The railway depot facilities of the PJSC "KZRK";
- Buildings and facilities of the industrial site of "Pivnichna" mine (the PJSC "Central GZK");
- Facilities of the Crushing-Sorting Plant (CSP) and the industrial site of the Mine Management;
- Buildings in Kovlska Street;
- The "Schistose Rocks" natural geological reserve of local importance;

The monitored objects on the surface in the hanging wall of the deposit are:

- The settlement of Karnavatka;
- The municipal cemetery "Zakhidne";
- The section of the motor road "Tekhbaza – Cemetery "Zakhidne";
- The road base for the motor road section "Tekhbaza – Cemetery "Zakhidne";
- The settlement of Zhukivka.

The research aims to study the earth's surface deformations and assess the safety of exploitation of the monitored objects within the mining allotment.

2. Methods

As a result of instrumental measurements in reference points tied to benchmarks of profile lines on the monitored area, the parameters of surface deformations are determined based on analysis, systematization and generalization of the observation data of the current and previous years. According to the results of measurements, graphs of deformations of the earth's surface are built, which allows you to determine the trend line and predict values for two years in advance.

The measurement results are used for statistical analysis of various mathematical models to forecast deformations' values for two years ahead.

According to the requirements of the regulatory documents [1–5], mines are to monitor displacement process development. Therefore, since 2016, in the mining allotment of the Mine

Management, the Research Ore Mining Institute of Kryvyi Rih National University has been conducting special observations.

The observations are conducted along profile lines located nearby and on the monitored objects in the displacement area in the hanging wall of the deposit.

There are ten profile lines in the footwall of the deposit: "Railway", "Axis 159", "Axis 127"," Axis 55", "Depot", "Axis 11", "Axis 6", "Axis 3", "Axis 220, frame bridge", "Arch bridge".

Over the last five years, two sets of instrumental observations (in spring and autumn) have been conducted along profile lines of the footwall.

The research methods are as follows:

- determining elevations and horizontal distances between ground and wall benchmarks;
- levelling wall benchmarks on buildings of the industrial site, the railway depot of the PJSC "KZRK", the frame and the arch bridges;
- levelling rail joints on the section 71km - 74 km of the railway track;
- measuring chords and butt gaps on the section 71km - 74 km of the railway track;
- laying connecting passages between profile lines - geometric levelling of IV class;
- office analysis of observation results.

There are nine profile lines in the hanging wall: "Settlement of Zhukivka", "Road", "Cemetery", "Sklonenie", "Axis 105", "Axis 25", "Axis 6", "Axis 54", "Road base".

The following observations are conducted at the observation station of the hanging wall of the deposit "Obiednanyi":

- along the profile lines "Axis 54", "Axis 6", "Axis 25", "Cemetery" – one set;
- along the profile lines "Road Basis" "Road" - two sets (in spring and autumn)
- along the profile lines "Axis 105", "Sklonenie", and "Settlement of Zhukivka" - four sets of observations.

The work includes the following stages:

- determining elevations and horizontal distances between ground and wall benchmarks;
- laying connecting passages between profile lines - geometric levelling of IV class;
- office analysis of observation results.

After office analysis, the observation results are summarized in the sheet of vertical displacements (subsidence), vertical displacement rates, vertical deformations of intervals between benchmarks, horizontal deformations of intervals between benchmarks, horizontal displacements of benchmarks.

3. Results and discussion

3.1. Study of the displacement process in the footwall of the deposit "Obiednanyi"

According to the nature of the displacement process development in the footwall of the deposit "Obiednanyi", the mine field can be conditionally divided into three sections: I section - southern (southwards of axis 80), II - central (axes 80-55) and III - northern (northwards of axis 55).

In the southern section of the mine field, measurements were made along the profile lines "Arch bridge" and "Axis 220". Mining operations in this section were suspended in 1990. At present time, the vertical and relative horizontal deformations rates are within the measurement accuracy.

Observations of the behaviour of the arch bridge abutments above the former channel of the Saksagan River (profile line "Arch Bridge") show that over 29 years, total subsidence of wall benchmarks has made 9mm to 32mm, i.e. the average annual rate of subsidence makes 0.3-1.1 mm/year (0.03-0.09 mm/month). However, last year subsidence does not exceed 1 mm/year.

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On the profile line “Axis 220” benchmarks, total subsidence for the 56-year observation period ranges from 33 mm to 399 mm, and the average annual subsidence rate is 0.6-7.1 mm/year. Last year subsidence rates do not exceed 5 mm/year.

In the central section of the mine field (survey axis 80 - survey axis 55), mining operations were finished in 1997 due to deposit thinning. Instrumental observations are conducted along the profile lines “Axis 3”, “Axis 6”, “Axis 11”, and “Depot”.

Total subsidence by ground benchmarks of the profile line “Axis 3” for the 58-year observation period ranges from 9 mm to 480 mm. These benchmarks’ average annual subsidence rate is 0.2 - 8.3 mm/year.

Total subsidence by ground and wall benchmarks of the profile line “Axis 6” for the 56 years of observations ranges from 376 mm to 537 mm, i.e. 6.7 - 9.6 mm/year.

Average monthly subsidence rates for the last three-year period along the “Axis 3” and “Axis 6” profile lines do not exceed 1 mm/month.

Total subsidence by benchmarks of the profile line “Axis 11” for the 44 years of observations ranges from 272 mm to 557 mm, i.e. 6.2 - 12.7 mm/year.

Average monthly subsidence rates for the last three-year period do not exceed 1.5 mm/month.

Total subsidence by the profile line “Depot” benchmarks for the 28 years of observations ranges from 228 mm to 273 mm, i.e., 8.1-9.8 mm/year. Last year subsidence rate is 0.25-0.33 mm/month.

As is seen in figure 1, annual subsidence along all the profile lines of the southern and central parts of the footwall for the last year does not exceed 10 mm.

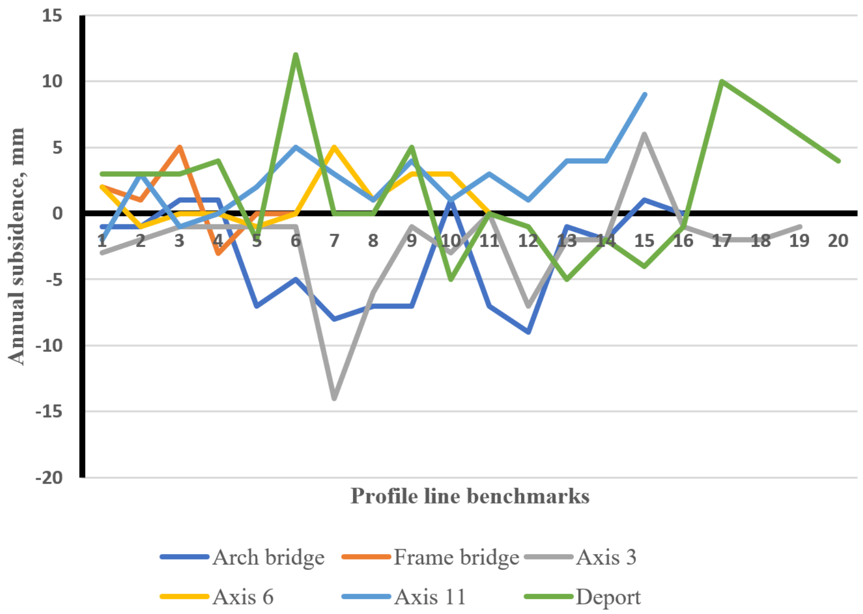

Figure 1. Annual subsidence along the profile lines of the footwall (southern and central parts) in 2021.

It can be concluded that, according to paragraph 2.22. of [1], the displacement process in the southern and central parts of the footwall is finished.

In the northern section of the footwall of the mine field (survey axis 55 - survey axis 263), instrumental observations are conducted along the profile lines “Axis 55”, “Axis 127”, and “Axis 159”.

Vertical subsidence along these profile lines increases towards the hanging wall. Depending on a year of observation, the maximum subsidence is approximated by linear dependences with a sufficiently high degree of approximation reliability (R^2 value):

- along the profile line "Axis 55 " $y = 23.9 \cdot x + 534.3$, approximation reliability (R^2 value) is 0.9976,
- along the profile line "Axis 127 " $y = 52.2 \cdot x + 393.5$, approximation reliability (R^2 value) is 0.9272,
- along the profile line "Axis 159 " $y = 23.9 \cdot x + 534.3$, approximation reliability (R^2 value) is 0.9298.

Forecast values of subsidence rates in the northern section of the footwall for 2022-2023 make 13.5 mm/year (1.1 mm/month) to 52.2 mm/year (4.4 mm/month) over the entire displacement area.

Annual subsidence along all profile lines of the northern part of the footwall for the last year exceeds 10 mm (figure 2).

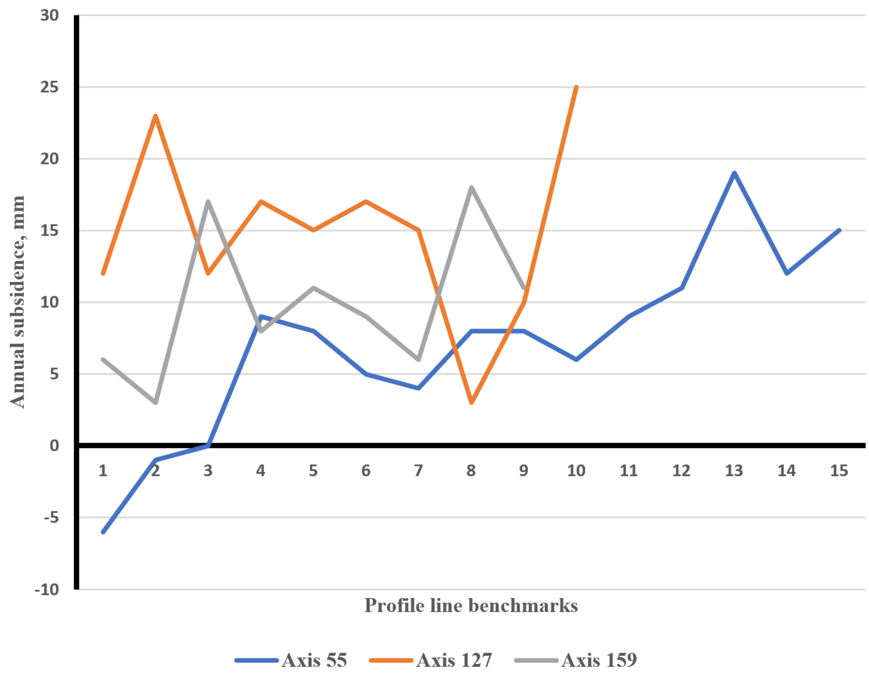

Figure 2. Annual subsidence along the profile lines of the footwall (northern part) in 2021.

It can be concluded that, according to paragraph 2.22 of [1], the process of displacement in the northern section of the footwall is still developing.

Also, in the footwall, observations are made along the profile line "Railway", which crosses the southern, central, and northern footwall.

Subsidence along the "Railway" profile line increases from south to north in the section PK73800 - PK71800 and decreases from south to north in the PK71800 - PK 71250.

Average monthly subsidence rates by benchmarks of the profile line "Railway" for the last two-year period do not exceed 2.7 mm/month, clearly seen in figure 3.

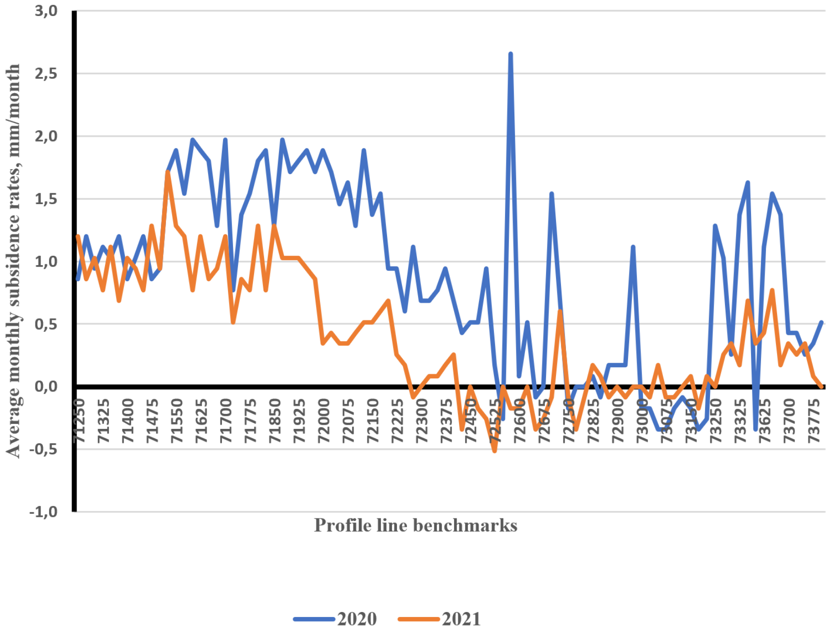

Figure 3. Average monthly subsidence rates by benchmarks along the profile line "Railway" in 2020-2021.

3.2. Study of the displacement process in the hanging wall of the deposit "Obiednany"

The trough of the hanging wall rock displacement can be conditionally divided into three sections considering the mine field from south to north: southern, central and northern.

In the southern section of the hanging wall, mining finished in 1990. Observations are conducted along the profile line "Axis 54". In 2021, surface subsidence ranged from 1 mm to 7 mm. Total subsidence of the last three-year period does not exceed 15 mm.

In the central section of the hanging wall (survey axis 80 - survey axis 55), mining operations stopped in 1997. Observations are conducted along the profile lines "Axis 6" and "Axis 25".

In 2021, surface subsidence along the "Axis 6" profile line made 2 mm to 7 mm. Total subsidence of the last three-year period does not exceed 26 mm.

Along the profile line "Axis 25", the largest subsidence for the last three-year period was recorded in 2020 (from 29 mm to 40 mm). However, over the last year, subsidence has significantly reduced in size. In general, over the last three years, the total subsidence along the profile line "axis 25" has not exceeded 50 mm.

Graphs (figure 4) shows annual subsidence along the profile lines of the southern and central sections of the hanging wall in 2021.

According to paragraph 2.22 of [1], the displacement process is considered finished for the hanging wall if surface subsidence during a year does not exceed 50 mm. In 2021 subsidence, the southern and central sections were well below 50 mm/year (figure 4).

Thus, it can be concluded that the displacement process is finished in the southern and central parts of the hanging wall.

In the northern section (northwards of axis 55.), observations were made along six profile lines of ground benchmarks: "Axis 105", "Sklonenie", "Cemetery", "Road", "Road base" and "Settlement of Zhukivka".

Analysis of the observation data in this section reveals that displacement continues to develop, its activity in different trough sections varies. The decrease in displacement activity is caused

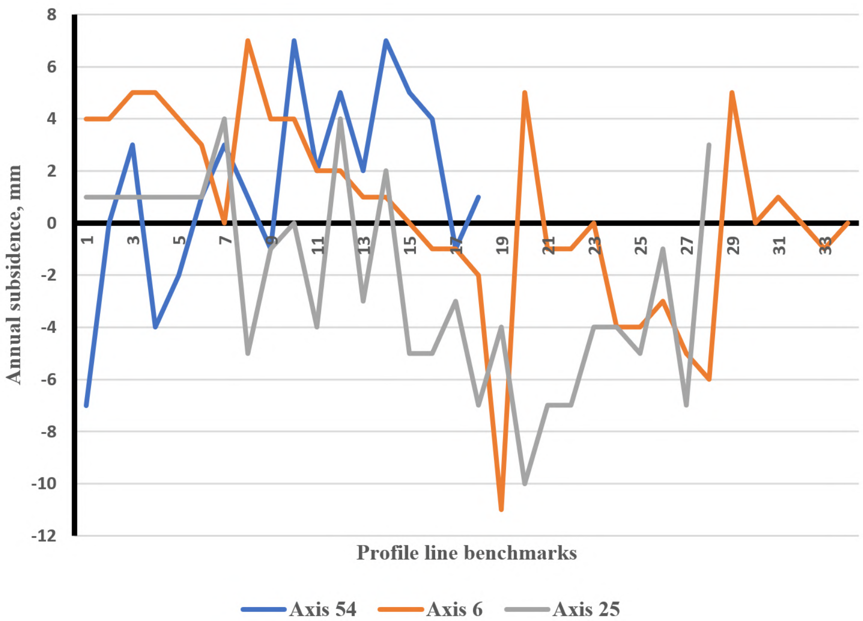

Figure 4. Annual subsidence along the profile lines of the footwall (southern and central part) in 2021.

by the development of the northern blind area of the deposit.

Subsidence by benchmarks on the profile line “Axis105” is growing every year towards the crater formed in 1985, and it equals 71 - 16900 mm (as of 07 November 2021). Surface subsidence tends to grow gradually every year. Depending on a year of observation, the maximum subsidence is approximated by the relationship $y = 67.717 \cdot x + 16251$, approximation reliability (R^2 value) is 0.9592. Over the last year (15 November 2020 - 07 November 2021), surface subsidence on the profile line “Axis105” was recorded 14 mm (Rp58) to 72 mm/year (Rp18), i.e. 1.2 - 6.0 mm/month. It should be noted that while in 2020, annual subsidence by the benchmarks of the profile line “Axis 105” increased by a factor of 1.5 - 2 on average as compared to 2019, in 2021, annual subsidence decreased by almost all benchmarks as compared to 2020 and almost reached the figures of 2019. This is demonstrated in figure 5.

The profile line “Axis105” crosses the crater formed in 1985. Directly around the crater, a caving zone was formed with terraces of over two meters and cracks of dozens of centimetres. In 2012, the crater turned out again, and another crater of 76 m in diameter was formed in the west within axes 151-159. Total subsidence over the 37 years (1984-2021) along the profile line “Sklonenie” ranges from 970 mm (Rp35) to 7706 mm (Rp12). Depending on a year of observation, the maximum subsidence is approximated by the relationship $y = 107.8 \cdot x + 7175.8$, the approximation reliability (R^2 value) is 0.989. Over the last year, surface subsidence by the benchmarks of the profile line “Sklonenie” has decreased compared to that in 2019-2020 (figure 6).

In 2021, annual subsidence on the profile line “Cemetery” also decreased compared to 2019-2020 (figure 7).

Currently, the main part of the cemetery area falls into the displacement trough, and the southern part (axes 103–159) - into the displacement area. The boundary of the crack zone goes at a distance of 50 m in the south and 190 m in the north from the cemetery area. No visible cracks are found in the cemetery area.

Along the profile line “Road”, the subsidence of the last year period is 9 - 88 mm/year

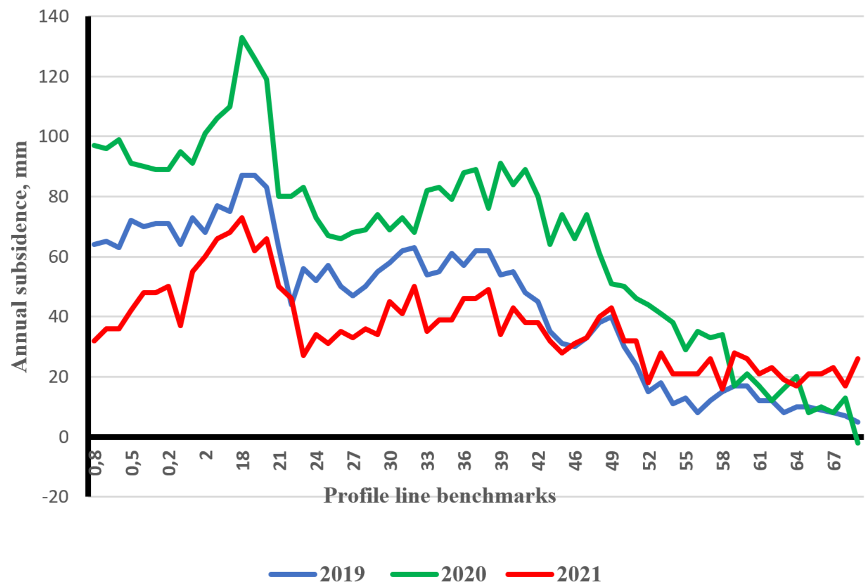

Figure 5. Annual subsidence by the profile line "Axis 105" benchmarks in 2019-2021.

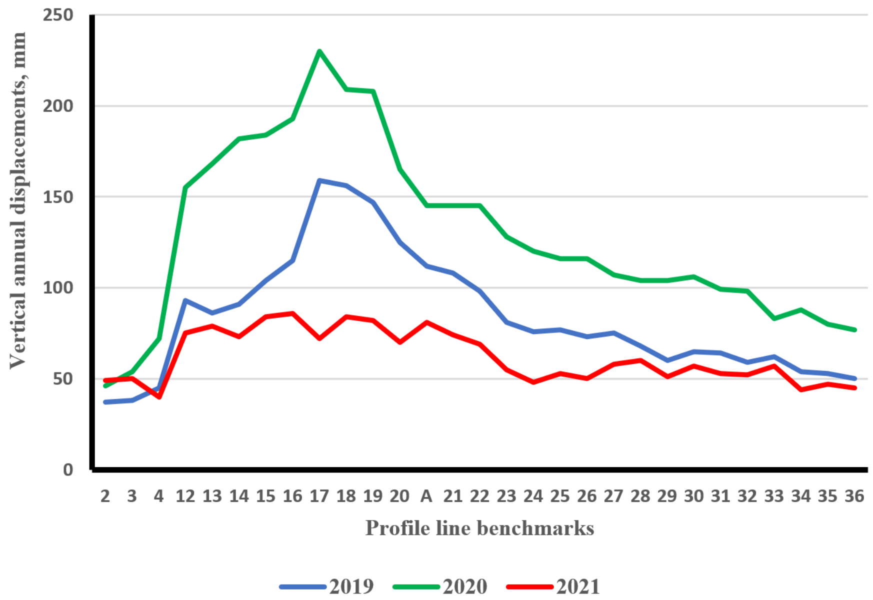

Figure 6. Annual subsidences by benchmarks along with the "Sklonenie" profile in 2019-2021.

(0.8-7.3 mm/month). Annual subsidence along this profile line and all the other profile lines of the northern part of the hanging wall tend to decrease. Thus, in 2021 annual subsidence of the surface decreased by all the benchmarks (except for one benchmark) of the profile line as compared to 2020 (figure 8).

The profile line "Road base" is located within axes 15-87 and LSP+450 - LSP+1350 above the depleted area of the deposit in the "old" zone of terraces and the zone of craters. Along this line, annual subsidence in 2021 by a significant number of benchmarks exceeds 50 mm/year, but it also tends to decrease compared to 2020 (figure 9).

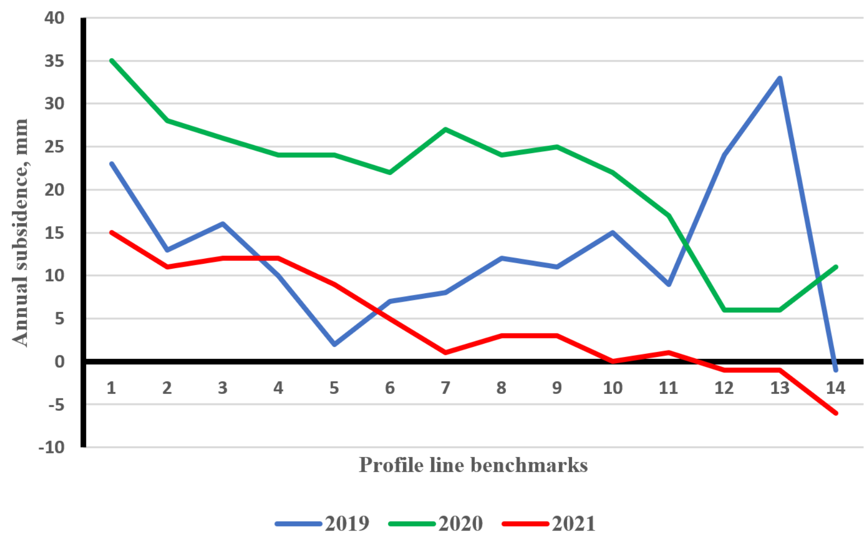

Figure 7. Annual subsidence along the profile line "Cemetery" in 2019-2021.

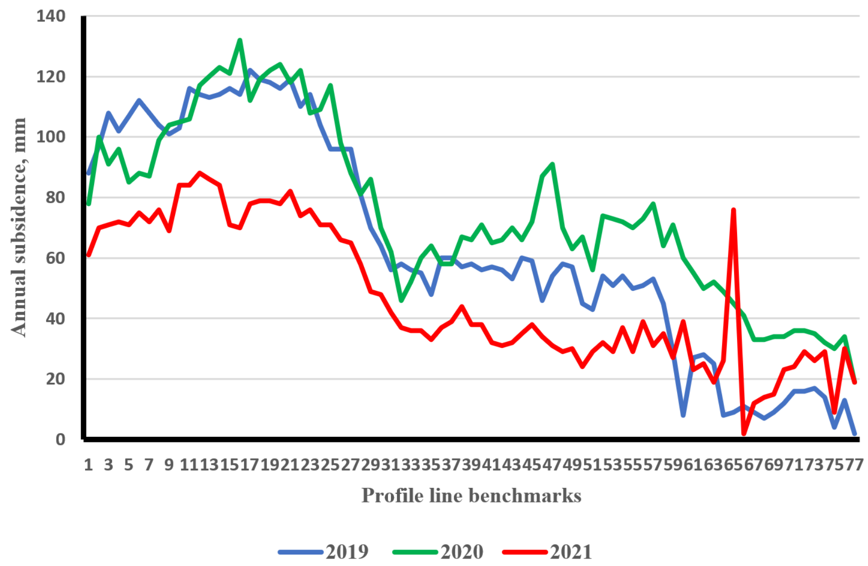

Figure 8. Annual subsidence along the profile line "Road" in 2019-2021.

Along the profile line "Settlement of Zhukivka", the last year subsidence rates in the residential area make 9 - 25 mm/year (0.8 – 2.1 mm/month). In 2021, the residential area annual subsidence decreased slightly by each benchmark of the profile line "Settlement of Zhukivka" compared to 2019 - 2020 and almost reached the figures of 2018 (figure 10).

For the conditions of residential buildings of Zhukivka, according to the methodology presented in [6] (Section 4), the permissible deformation values were calculated. Deformations of the earth's surface are considered permissible if they can damage the facilities to the extent that the facilities require normal maintenance and repair works and can be exploited by their intended purpose. According to the calculations, permissible horizontal deformations for buildings of Zhukivka equal $[\varepsilon]p = 6.0 \cdot 10^{-3}$. Comparison of the calculated values of permissible

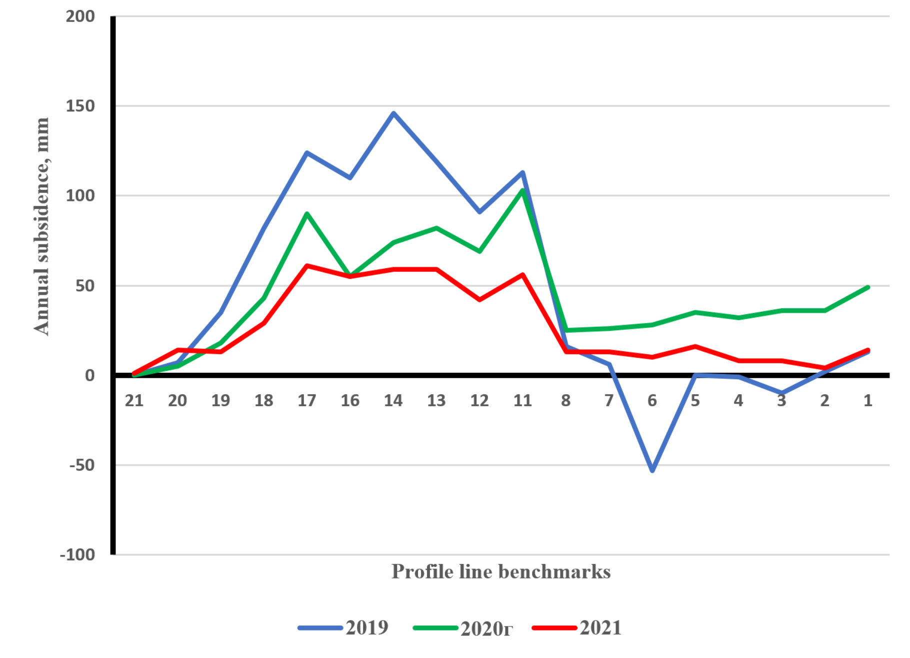

Figure 9. Annual subsidence along the “Road base” profile line in 2019-2021.

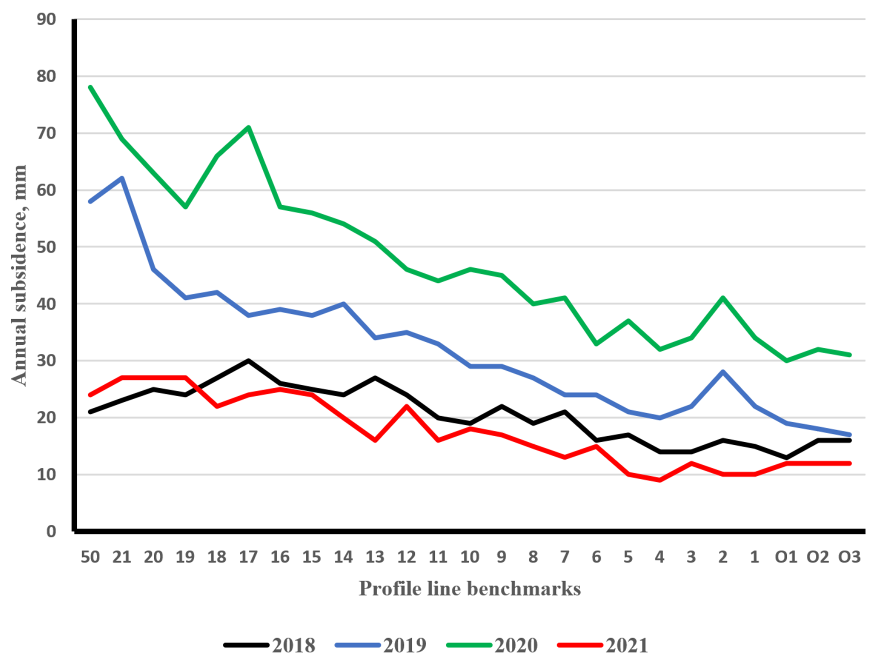

Figure 10. Annual subsidence along the profile line “Settlement of Zhukivka” in 2018-2021.

relative horizontal deformations for buildings of Zhukivka $[\,\varepsilon\,]\,p\ = 6.0 \cdot 10^{-3}$ with actual maximum relative horizontal deformations along the profile line “Settlement of Zhukivka” in 2021 $[\varepsilon]_{\max} = 3.2 \cdot 10^{-3}$ enables the conclusion that the latter is two times less than the permissible ones. On figure 11 plots the maximum relative horizontal deformations along the profile line “Settlement of Zhukivka” with a forecast for two years.

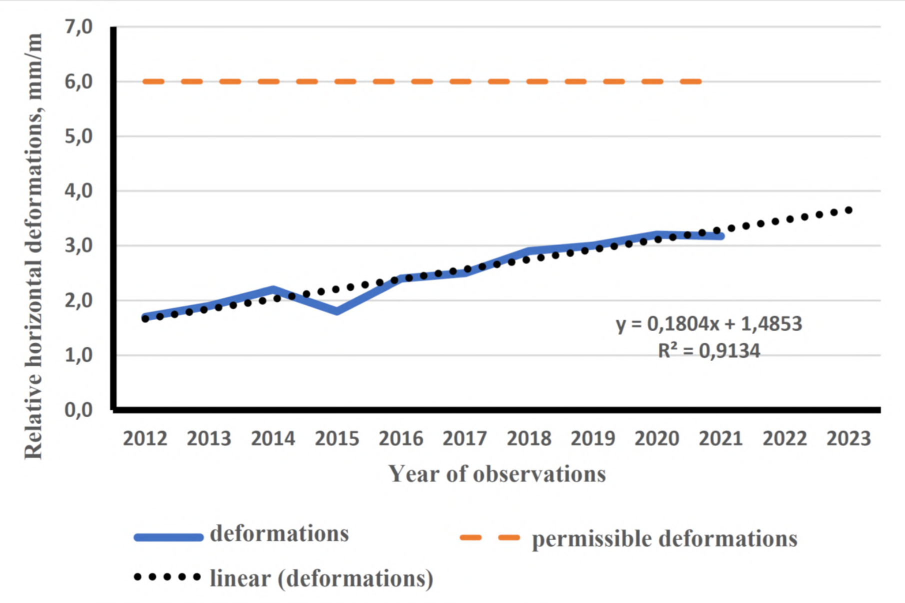

Figure 11. Maximum relative horizontal deformations along the profile line "Settlement of Zhukivka" in 2012-2021 with a forecast for two years.

Analysis of the graph in figure 11 enables the conclusion that in 2022 the forecast values of the maximum relative horizontal deformations along the profile line "Settlement of Zhukivka" will reach 3.5 mm/m and 3.7 mm/m - in 2023. These will not exceed values of permissible relative horizontal deformations for buildings of the settlement $[\ \varepsilon\ ]\ p\ = 6.0 \cdot 10^{-3}$ either.

4. Conclusions

The frame bridge is 73km+200m.73km+250m of Ukrzaliznytsia is located within survey axes 112.122 in the southern section of the mine field, where mining operations were ceased in 1990, and the displacement process finished. Over the entire observation period, the average annual rates of wall benchmarks subsidence have not exceeded 7.1 mm/year. Subsidence rates of the last year (06 September 2020 - 25 September 2021) are less than 5 mm/year (0.5 mm/month). Therefore, mining operations do not and will not have adverse impacts on the earth's surface in the area of the frame bridge.

The Piatykhatky - Kryvyi Rih line of Ukrzaliznytsia (PK71 - PK74km) and the Kirov station's connecting (access) line - Shmakove station are in the trough and the footwall rocks displacement zone. These sections of the railway track are located at a distance of 200 - 300 m from the deposit in crop and over 300 m from the zone of possible crater formation. Since 1981, the railway tracks have passed through the displacement zone (in the 1980s and 1990s within axes 104-135). At present, the actual boundary of the crack zone passes near the railway track within axes 87-135. The displacement zone crosses the railway tracks within axes 63-143. According to paragraph 4.8 of [1], main and access tracks can be located in the displacement and crack zones with a subsidence rate of no more than 100 mm/month. The actual annual rates of surface subsidence in the area of the Ukrzaliznytsia track and the access track have not exceeded 2.7 mm/month over the last two years, which is significantly lower than the permissible values (100 mm/month). Analysis of the field observations shows that the displacement process in the deposit's footwall has no adverse impact on the railway track of Ukrzaliznytsya and the access track. Therefore, there is no need for special protection measures for these facilities.

The railway depot of the PJSC KZRK was affected by surface subsidence during mining operations in the central section of the mine field (up to 1997). Analysis of the instrumental observations data along the profile lines “Axis 11” (ground benchmarks) and “Depot” (wall benchmarks on the depot and warehouse buildings) shows that the last year maximum annual rates of subsidence are from 9 mm (Rp6 profile line “Axis11”) to 13 mm (Rp38 on the warehouse building on the profile line “Depot”). Current underground mining operations to the north of survey axis 55 do not affect the depot facilities.

The shaft and the machine room of the mine “Pivnichna” (the PJSC Central GZK) fall into the zone of displacement caused by current mining operations. The maximum average annual subsidence rates are 7-15 mm/year (0.6-1.2 mm/month). The average annual increase in relative horizontal tensile strains is $\Delta\varepsilon = +(0.1 - 0.2) \cdot 10^{-3}$. Total subsidence $\eta = (272 - 485)$ mm. In 2021 - 2022, rates of subsidence and horizontal deformations will remain at the current level and have no adverse impact on the “Pivnichna” mine facilities.

The Crushing-Sorting Plant is located on the industrial site of the Mine Management within survey axes 96 - 44, LSP +0.0m and includes some facilities. The CSP area falls into the southern and central (south) sections of the mine field, where the boundaries of the displacement zones have remained unchanged since 1991. Development of the blind area of the deposit (northwards of axis 55) will have no adverse impact on the facilities of the CSP complex. The subsidence rates of the wall benchmarks on the Mine Management industrial site buildings are within the measurement accuracy. Current mining operations have no impact on the industrial site.

The condition of buildings in Kovalska Street has been unchanged for the recent 15 years. Therefore, in this area, the displacement process has finished.

The “Schistose Rocks” geological natural reserve of local importance is located on the right bank of the river Saksagan within axes 79 - 103 and does not fall into the displacement zone. In addition, according to [1] (paragraph 4.19), “The arable lands, urban forest parks, forest plantations, and similar natural objects that fall into the earth’s surface displacement zone may be used for their intended purpose, except for areas in a crater, sinkhole and terrace zones”. Therefore, the “Schistose Rocks” natural geological reserve of local importance can be safely exploited.

In 2022 - 2023, one should not expect the displacement zone boundaries to move; the crack zone boundary within axes 159-223 will move 50-80 m westwards of the current crack zone boundary; current mining operations at the deposit “Obiednanyi” will have no adverse impact on the area and residential buildings of the settlement of Karnavatka.

The municipal cemetery “Zakhidne” area is located within axes 103 - 207, LSP+2200m. LSP+2800 m. It started in 1993. According to paragraph 4.2. of [1], the cemetery belongs to the III category of protected objects, for which the earth’s surface deformations can result in underflooding and groundwater contamination. In 2022 - 2023, the crack zone boundary within axes 159-223 will move 50-80 m westwards of the current crack zone boundary, but it will not reach the cemetery boundary. Mining of the deposit up to the 1065 m level will have no impact on the area of the cemetery “Zakhidne”.

According to paragraph 4.2 of [1], the motor road belongs to the III category of protected objects, on which deformations of the earth’s surface in the crack zone have hazardous impacts. According to paragraph 4.8. of [1], motor roads are permitted in the displacement and crack zones with a subsidence rate of no more than 100 mm/month. Analysis of the observation data along the profile line “Road” demonstrates that the landslide process has resulted in a smooth deflection of the surface without cracks and loss of integrity. The main type of horizontal deformation is compression. As the analysis of observations shows, compressional deformations are often precursors of craters, sinkholes, or a zone of severe deformations. Further mining of the reserves on the northern flank of the mine field will lead to the activation of a landslide process in the motor road area.

According to [7], a crater should be expected after complete mining of level 1045 m of the deposit "Obiednanyi" by the Mine Management and level 1240 m by "Rodina" underground mine within axes 223-295, LSP+850 - LSP+1350 (justification by the Mine Management). Mine Management is currently mining iron ore in the blind area within axes 159-239 in the sub-level 1045-1065 m. "Rodina" mine performs mining operations on a level of 1390 m northwards of axis 152. The forecast for a crater formation at deepening and mining along the strike remains valid. In 2014, a section of the road with a possible crater was blocked off near Rp12 - 43; the traffic was stopped, thereby taking appropriate protective measures.

The profile line "Road base" is located above the depleted section of the deposit in the "old" terrace zone and the crater zone and falls into the displacement zone and the crack zone caused by underground mining. The displacement process on the profile line "Road base" section is still developing. According to paragraph 1.6 of [1] and paragraph 4 of [8], construction facilities are not allowed on the surface above depleted mineral deposits until the end of the displacement process.

The settlement of Zhukivka falls into the mining allotment of the Mine Management (axes 267-307, LSP+1700m - LSP +1950m) and the mining allotment of "Rodina" mine (axes 180-200, LSP +1750m - LSP +2000m). Thus, it is located at the joint of mining operations of the Mine Management and "Rodina" mine on the hanging wall of the depleted shared deposit and falls in the displacement zone caused by operations of these mines. Therefore, paragraph 4.2 of [1] states that the settlement belongs to the III category of protected objects. At present, mining of the deposit up to level 1065 m does not cause surface deformations above the permissible values for residential facilities of the settlement. Therefore, the measures to protect the settlement involve maintenance until the actual relative horizontal deformations do not exceed the calculated permissible value for residential buildings $[\varepsilon]p = 6.0 \cdot 10^{-3}$.

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Peculiarities of the raw material base of the Lykhmanivka iron ore region in Kryvyi Rih basin

To cite this article: O Yu Hrytsai *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012006

Peculiarities of the raw material base of the Lykhmanivka iron ore region in Kryvyi Rih basin

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Abstract. Lykhmanivka (Inhulets) iron ore district takes the southernmost position in the Kryvyi Rih iron ore basin. In the north, it is bordered by a series of sublatitudinal faults with the Southern Iron Ore District of Kryvbas. The productive strata of the area are Lykhmanivka iron ore pay streak, in the southern part of which the Inhulets deposit of magnetite quartzites is located in the zone of closing of Lykhmanivka syncline. However, in addition to them in the area, there are more than 20 types of other minerals, which are mined by-products and can be successfully used in the national economy. Syngenetic (sedimentation, diagenesis, dynamothermal metamorphism) and epigenetic processes (tectogenesis, metasomatism, hydrothermal processes, hypergenesis), which occurred during the formation of iron ore and host strata area have contributed to the formation of several minerals and rocks, which can be considered as associated complex useful minerals. The relevance of the work is due to the need for detailed research of the localization, formation conditions, directions of use of metallic and nonmetallic minerals of the area, the geological justification for their priority varieties. As a result of these studies, systematization of minerals of the area has been developed, their priority varieties have been identified. Their involvement in mining and processing significantly expands the spectrum of alternative ways of use of minerals and rocks of iron-banded formation, which will contribute to a significant addition to the mineral resource base as in Kryvyi Rih iron ore basin, and in Ukraine as a whole.

1. Introduction

The Kryvyi Rih basin (Dnepropetrovsk region, Ukraine) is a world-famous iron ore basin of high-quality iron ores, located in the central part of the Ukrainian shield, where the Kryvyi Rih structure in the form of a narrow strip more than 100 km long and 0.5 to 18 km wide stretches in a submeridional direction along the border of two heterochronous megablocks of the Ukrainian shield. They are the Inhul megablock (Kirovohrad), composed of the Paleoproterozoic granitoids with inclusions of the Archean, Paleoproterozoic metabasites, metaclastoliths, and the Middle Dnipro megablock, in the structure of which the Mesoarchean plagiogranitoids predominate, metabasites and metaclastolites of the Archean and Paleoproterozoic occur in a subordinate quantity [1, 2].

Iron ores have been the main mineral wealth of the Kryvyi Rih basin for more than 140 years of exploitation of its deposits. However, in addition to iron ores, more than 50 types of metal and non-metal minerals occur within the deposits of the Kryvyi Rih basin and the Right-Bank magnetic anomalies located nearby, which are simultaneously mined at iron ore deposits and can be successfully used in the national economy. The integrated use of the mineral mass extracted from the depths has become one of the main tasks on the way to increasing the supply of the national economy of Ukraine with mineral raw materials.

The Kryvyi Rih basin is divided into four iron ore regions: Northern (Hannivka), Central (Saksahan), Southern and Lykhmanivka (Inhulets)(figure 1).

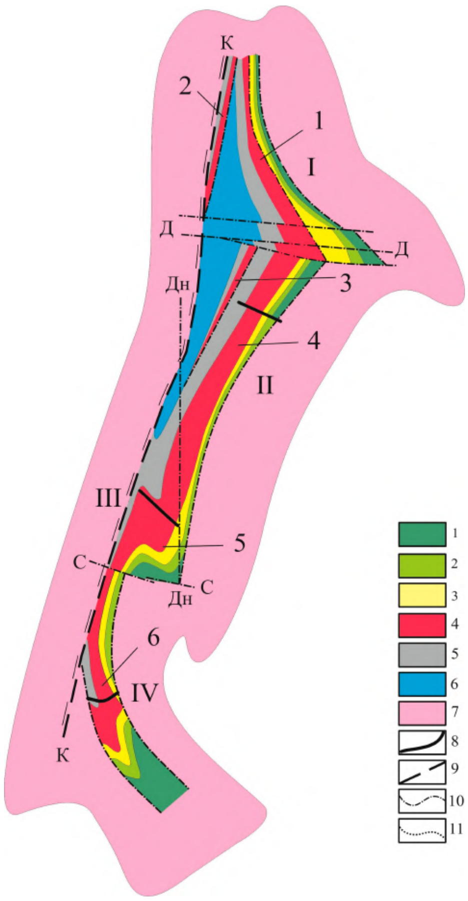


Figure 1. Schematic geological map of the Kryvyi Rih structure. *Metamorphic formations. The Upper Archean: 1 – Konka series. The Lower Proterozoic: 2-5 - Kryvyi Rih series: 2 - Novokrivorizka suite; 3 – Skeliuvatka suite; 4 – Saksahan suite; 5 – Hdantsevka suite. The Middle Proterozoic: (6) Hleiuvatka suite. Igneous formations: (7) granitoids of the Dnipropetrovsk Complex of the Middle Archean; (8) the Upper Proterozoic diabase dikes. Other symbols: 9 - mantle faults; 10 - mantle-crustal and crustal faults; 11 – lines of stratigraphic contacts. Iron ore regions: I - Northern (Hannivka) region; II - Central (Saksahan) region; III - South region; IV - Inhulets (Lykhmanivka) region. Iron ore packs: 1 - Eastern- Hannivka pack; 2 - Western- Hannivka pack; 3 - Distant Western packs; 4 - Saksahan pack; 5 - section of the Kryvyi Rih synclinorium closing; 6 – Lykhmanivka pack. Faults: K-K – Kryvyi Rih-Kremenchuk fault; D-D - Devladovo fault; Dn-Dn - Diagonal fault; S-S - Skeliuvatka fault zone.*

The Lykhmanivka iron ore region is part of the Kryvyi Rih iron ore basin, it occupies the southernmost part of the Kryvyi Rih basin. The productive stratum of the region is the Lykhmanivka iron ore pay streak, in the southern part of which, in the closing zone of the Lykhmanivka syncline, the Inhulets deposit of magnetite quartzites is located. To the north

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012006 doi:10.1088/1755-1315/1049/1/012006

of it, there is a chain of relatively small deposits of high-grade and low-grade hematite and magnetite ores along the entire strike of the Lykhmanivka pay streak. Most of its high-grade ores deposits have been worked out by open pits and underground mines of the former Inhulets and Rakhmanivka mining operations. At present, low-grade magnetite ores (magnetite quartzites), the feedstock for producing iron ore concentrate at the Inhulets Mining and Beneficiation Works, are the main mineral resources of the Lykhmanivka region.

Syngenetic (sedimentation, diagenesis, dynamothermal metamorphism) and epigenetic processes (tectogenesis, metasomatism, hydrothermal processes, hypergenesis) that occurred during the formation of the iron ore and enclosing strata of the region contributed to the formation of a number of minerals and rocks that can be considered as accompanying complex minerals.

2. Methodology

The authors have carried out detailed geological and mineralogical studies of the Kryvyi Rih series and underlying amphibolites and granitoids within the Lykhmanivka iron ore region. As a result of the research, minerals and rocks that can be mined as minerals have been identified. Their resources and technological possibilities of their extraction have been defined.

3. Results

Based on the results of geological, mineralogical and technological studies, the authors have concluded that there are occurrences of gold, platinoids, manganese, bauxites, garnet, muscovite, chlorite, talc, mineral pigments, facing stone, rock for the producing breakstone in the iron ore and host strata of the region. Their formation is associated with manifestations of syngenetic (sedimentation, diagenesis, dynamothermal metamorphism) and epigenetic (tectogenesis, metasomatism, hydrothermal processes, hypergenesis) processes that occurred during the formation of the Lykhmanivka region. A classification of associated minerals has been developed, and their priority types have been identified. According to their mineral and chemical composition, they can be divided into iron ores and metal and non-metal minerals (table 1).

Table 1. Main and associated minerals of Lykhmanivka iron ore region.

Metal	Non-metal
Iron	Talc
High-grade iron ores	Garnet
Low-grade iron ores	Muscovite-biotite schist
	Granite
Gold	Muscovite quartzite and quartz-muscovite schist
Platinum and platinoids	Ocher
Manganese	Reddle
Bauxites	Limestone
	Clay
	Loam soil
	Bentonite clay
	Gemological and collectable raw materials
	Waste of beneficiation plants

3.1. Iron ores

Low-grade hematite ores (hematite quartzites) are a product of post-Paleoproterozoic weathering of magnetite quartzites. Hematite quartzites compose the weathering crust of the ferruginous horizons of the Saksahan suite [3]. Its thickness is variable, within the boundaries of the Inhulets deposit it makes up from 50 to 100 m in the southern part and increases up to more than 450-500 m in the north. The horizontal thickness of the deposit (from east to west) varies within 400-600 m, the strike is 900-1000 m in the north-south direction. The main indicators of hematite quartzites (total iron content, structure, texture of ores) are close to the corresponding indicators of magnetite quartzites. These circumstances, as well as the growing volumes of hematite quartzites extraction from the Earth's interior, necessitate the search for ways of using them as additional iron ore raw materials. The composition of hematite quartzites is heterogeneous (figure 2).

a

b

c

d

Figure 2. Hematite quartzites of the Lykhmanivka iron ore region. a - micaceous hematite -martite quartzite; b - thinly-mediumly-coarsely laminated martite quartzite; c - goethitized dispersed hematite-martite quartzite; d - breccia, cavernous texture of martite-dispersed hematite-dispersed goethite quartzite.

The main reason for it is the manifestation of vertical and horizontal mineralogical zonality. In the vertical section, from top to bottom, the following mineralogical and geochemical zones are distinguished: goethite-martite → martite → magnetite-martite → martite-magnetite → unaltered magnetite quartzites. The horizontal mineralogical zonality of hematite quartzites deposits is due to the fact that the weathering crust succeeds their authigenic mineralogical zonality.

According to the results of preliminary laboratory mineralogical and technological studies, it is possible to obtain iron ore concentrate from hematite quartzites with an iron content of 66.5 to 68.5 mass percent. During the experiments, gravity, magnetic and combined schemes such as magnetic-gravity, magnetic-flotation flowsheets were used.

The high-grade iron ore deposits of the region are considered to be the so-called "lost" ones [1, 2]. During the mining activity of the mines of the former Inhulets mining operations, they were left in situ due to their small size, remoteness from the main deposit. At present, due to the advancement of the faces of the Inhulets open pit to the north, their approach to the leasehold of closed mines, the "lost" deposits have been opened up in the central part of the deposits of hematite quartzites of the fifth and sixth ferruginous horizons. Every year, together with hematite quartzites, high-grade hematite ores of the "lost" deposits of the Inhulets mining operations and the Inhulets open pit are extracted. Due to subsidence and mine workings sloughing, these ores are mixed with host hematite quartzites. Deposits of the Cenozoic martite-brown hematite ores have a total iron content of 50 mass pct. Lenticular and sheet-like ore bodies occur in the basal part of the Cenozoic sedimentary cover.

3.2. ***Metal minerals***

Gold. There are 4 generations of gold within the Lykhmanivka iron ore region [4]. The clastogenic gold of the Paleoproterozoic clastic rocks – metaconglomerates, quartzites, metasandstones, schists of different compositions of the Saksahan, Skeliuvatka and Hdantsevka suites is the most ancient. The size of the segregations is from less than 0.001 to 0.1 mm. The metal content does not exceed 0.2 g/t.

The sedimentation phase is associated with the accumulation of gold in the rocks of the ferruginous horizons of the Saksahan suite. It is the most dispersed, the size of the segregations does not exceed 0.01 mm.

The second generation of gold is associated with metamorphogenic gold of Alpine veins of hematite-quartz, carbonate-biotite-cummingtonite-quartz, pyrite-quartz composition. The size of gold segregations of this generation is more than 0.5 mm, the content is from 0.01 to 0.5 g/t.

The third generation is associated with the processes of post-metamorphic sodium metasomatism. The gold content in metasomatites is 0.01 - 0.3 g/t, at some points it is up to 1 g/t, the size of the segregations is up to 0.5 mm.

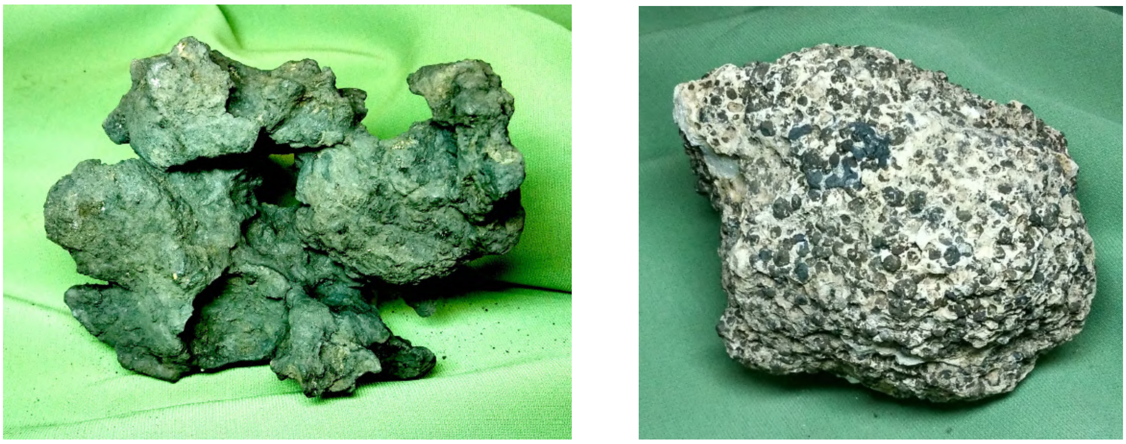
The gold of the fourth generation is associated with zones of hydrothermal-metasomatic transformations of rocks of the Kryvyi Rih series and host granitoids. The gold content at some points reaches 6-7 g/t.

Platinum and platinoids are present in the metaultrabasites of the upper subsuite (carbonate-talc horizon) of the Skeliuvatka suite [5]. Platinum, palladium, osmium with a total content of 1 g/t have been identified by atomic absorption analysis in titanium-chromium-vanadium concentrate from talc-bearing schists of the Inhulets deposit.

Manganese. The deposit of manganese ores with a thickness of 0 to 50 cm occurs in the basal part of the sedimentary cover. It is a continuation of the deposits of manganese ores of the Nikopol basin to the west [6] (figure 3).

The content of manganese ranges from 10 to 35 mass pct., the average content is 20 mass pct. According to preliminary data, the resources make up about 20 million tons.

According to the results of mineralogical studies, three typical varieties of the ores of the Nikopol basin are distinguished in the composition of ores. They are oxide ores (manganite-pyrolusite with psilomelane); carbonate-oxide ones (pyrolusite-oligonite with psilomelane) and carbonate ones (oligonite with an admixture of pyrolusite and psilomelane). The content of manganese depends on the mineral composition and ranges from 10 to 35 mass pct., the average one is close to 20 mass pct. According to the results of preliminary laboratory mineralogical and technological studies, it is possible to obtain a concentrate of about 30-32 mass pct. by



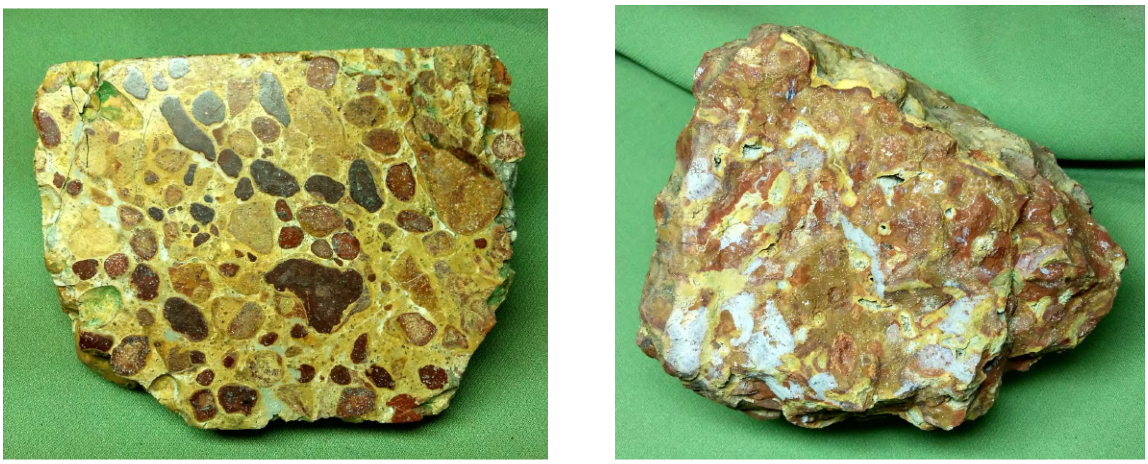
a b

Figure 3. Massive pory (a) and impregnated oolitic (b) oxide manganese ore.

crushing, washing and screening. A concentrate of this quality does not meet the requirements of the world market. The presence of the oligonite component in the ores interferes with upgrading of the concentrate and improvement of the quality of manganese in its composition.

The resources of manganese ores, according to preliminary data, are about 20 million tons.

Bauxites. Bauxite deposits occur on weathered crystalline rocks of the ferruginous-siliceous and host formations. The thickness of the layers and lenses is up to 5 m, the strata of the sedimentary Cenozoic cover overlies them. Preliminary and detailed exploration of several bauxite ore deposits of the Shesternya deposit in the Shyroke district has been carried out. The resources are about 50 million tons. The aluminum content is from 20 to 45 mass pct., the average one is 30 mass pct.(figure 4).



a b

Figure 4. The impregnated oolitic (a) and massive porous (b) bauxite.

3.3. *Non-metal minerals*
The upper subsuite of the Skeliuvatka suite is composed of **talc-bearing schists**. Most researchers consider it to be a product of dynamothermal metamorphism of effusives and tuffs of ultrabasic and basic composition [1]. Talc is the main rock-forming mineral of breunnerite-actinolite-chlorite-talc schists, the content of talc in schists is from 20 to 85 mass pst., on average, it is about 60 mass pct.(figure 5).

Figure 5. Actinolite-chlorite-talc schist.

The thickness of the stratum varies from 5 to 80 m. The main reason for significant fluctuations in the thickness is the high degree of rock plasticity. The mineral composition depends on the degree of their dynamothermal metamorphism. The content of schist, chlorite, and carbonate decreases in schists, and the content of amphibole increases with the transition from the thermodynamic conditions of the greenschist to the conditions of the epidote-amphibolite facies. This is accompanied by a deterioration in the chemical composition, physical and technical properties of schists.

Approved reserves of talc-containing schists are about 75 million tons, the resources make up 200 million tons.

The main properties of talc, determining the way of its use, are low hardness, eminent cleavage, high heat resistance (melting takes place at a temperature of 1800ºC).

Based on the results of preliminary technological studies, it was established that these schists can be used as raw materials for the manufacture of dry and oil paints, the production of sitall, ceramic bricks, fillers for pesticides and fertilizers, coating of welding electrodes, facing tiles, magnesia cements.

Garnet is a rock-forming mineral of the first and second schistose horizons of the Saksahan suite; it is also present in the rocks of the thin third, fourth, and sixth schistose horizons. The garnet formation was caused by dynamothermal metamorphism of primary alumina-iron-siliceous sediments under conditions of epidote-amphibolite facies [7, 8]. Garnet-quartz-biotite, cummingtonite-garnet-quartz-biotite, biotite-garnet-quartz-cummingtonite schists are most common within the region. The average content of garnet in schists ranges from less than 5 to more than 20 mass pct. According to preliminary data, the resources of garnet-bearing schists with an average content of 15-20 pct. are estimated at 300 million tons within the boundaries of the Inhulets deposit.

The chemical composition of the mineral corresponds to almandine, which is a variety of garnet with the highest hardness. In this regard, it serves the raw material for the manufacturing abrasives. Associated minerals are biotite, quartz, to a lesser extent, they are chlorite, cummingtonite.

Garnet forms round-shaped crystals of a tetragon-trioctahedral, rhombohedral habitus. Their size is from 0.5 to 5.0 mm, the predominant size is about 2 mm.

It is possible to produce a high-quality concentrate with a garnet content of about 98 mass pct. from the garnet-bearing rocks of the first and second schistose horizons (figure 6), which meets the requirements of the world market.

a

b

Figure 6. Garnet-bearing schist (a) and garnet concentrate obtained from it (b).

Preliminary studies of the garnet concentrate received from schists showed that it can be used in the manufacture of soft abrasives, water filters, abrasives for hydraulic cutting, etc.

Muscovite. Muscovite quartzites and quartz-muscovite schists make up the lower and middle subsuites of the Skeliuvatka suite and are the product of dynamothermal metamorphism of high-alumina clastogenic sedimentary formations [1]. As a result of metamorphism, clay minerals were replaced by muscovite forming thin (0.1 - 2 mm) parallel layers (figure 7).

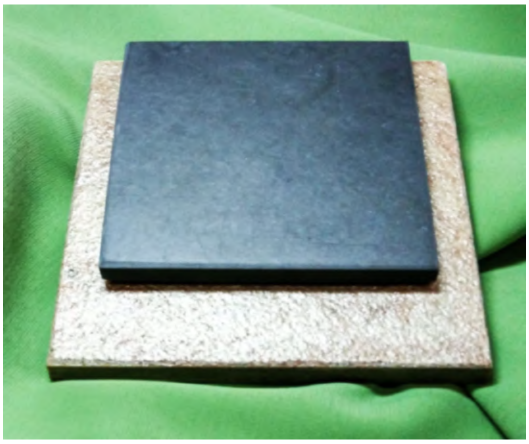
Figure 7. Quartz-muscovite schist.

The total thickness of their layers in the eastern wing of the Lykhmanivka syncline varies from 30 to 120 m. The inferred resources of muscovite quartzites and quartz-muscovite schists are more than 0.5 billion tons.

It is possible to produce fine-grain muscovite (muscovite scrap) by crushing quartz-muscovite schist to a particle size of 1-0 mm, followed by air separation of crushed products. According to preliminary data, it can be used in the manufacture of electrical insulating, building materials, mineral paints, rubber, plastics, etc

Muscovite quartzites can also be used to obtain high-quality facing tiles and paving flagstones (figure 8).

a



b

Figure 8. Unframed (a) and framed (b) facing tiles made of muscovite quartzite (white), two-mica schist (gray), aspide schist (black) and riebeckite-magnetite quartzite (blue).

There has been a practice of the extraction and production of facing tiles and paving flagstones from muscovite quartzite from the Hannivka deposit of the Northern GOK in the Kryvyi Rih basin. The range of facing tiles can be expanded by the use of certain types of barren, low-ore ferruginous quartzites and schists of various composition as the starting material.

Limestone within the boundaries of the Lykhmanivka iron ore region forms a layered deposit with a thickness of 5 to 30 m as part of the Cenozoic sedimentary cover. Its formation is chemogenic-organogenic, the main mineral component is calcite, dolomite is present in an insignificant amount.(figure 9).

a

b

Figure 9. High-quality shell limestone (a) and shell limestone with opal-clay cement (b).

Limestone resources make up about 500 million tons. According to preliminary data, its quality indicators meet the requirements for a metallurgical one (as one of the charge components).

Mineral pigments. There are about 10 minerals and rocks that can be used as mineral pigments of industrial and artistic quality within the boundaries of the Lykhmanivka iron ore region [9].

Industrial pigments include the following ones:

Reddle is a product of weathering of schists and silicate, magnetite-silicate quartzites of various compositions. The main mineral for reddle is dispersed hematite, which is a weathering product of iron-bearing silicates. Kaolinite is the main impurity. The color saturation of reddle depends on their quantitative ratio.

Ocher is a genetic analogue of reddle, the difference is that the main mineral of ocher is dispersed goethite. Its color varies from light yellow to dark brown, depending on the quantitative ratio of dispersed goethite and kaolinite.

Martite is a weathering product of magnetite, the main rock-forming mineral of the weathering crust of ferruginous quartzites, finely ground martite powder has a rich dark red (cherry) color.

Magnetite is the main rock-forming mineral of unweathered ferruginous quartzites; when crushed, it has a rich black color.(figure 10).

a

b

c

d

Figure 10. Engineering grade mineral pigments: a - ocher; b - magnetite; c - martite, d - reddle.

Riebeckite, celadonite, and goethite from the Lykhmanivka iron ore region (figure 11) can

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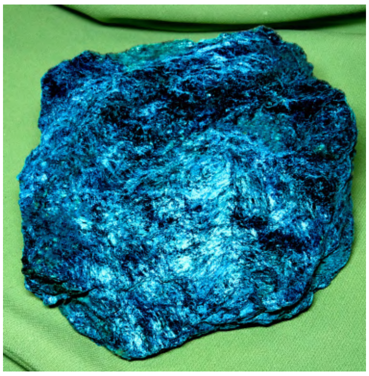
be considered as mineral pigments of artistic quality.



a

b

c

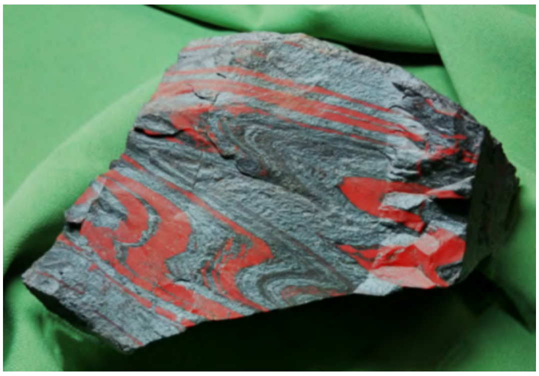
Figure 11. Mineral pigments of artistic quality: a - riebeckite metasomatite; b - quartz-celadonite diaphthorite; c - sintered aggregate of goethite (dark brown) and dispersed goethite (yellowish brown).

Ceramic clays and loam soils form interbeds from 3 to 40 m thick in the Cenozoic cover [1]. The mineral and chemical composition of clays and loam soils has not been studied enough; according to preliminary data, they can be used for the production of ceramic bricks, tiles, etc. The inferred resources within the boundaries of the mining license area of the Inhulets deposit are 0.5 billion tons.

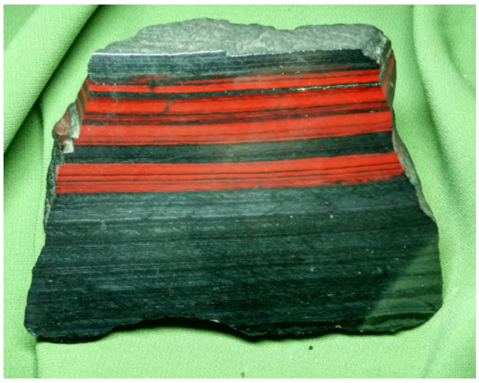
Gemological and collectable minerals. There are more than 20 minerals and rocks that can be used as gemological and collectable minerals in the productive and enclosing strata of the Lykhmanivka iron ore region [7, 10, 11]. The main types include: chalcedony, red-layered ferruginous quartzite, dispersed hematite-quartz-chalcedonic and dispersed goethite-quartz-chalcedonic jasperoids, crystals and druses, druses of quartz of different shades (rock crystal, milky, blue, yellow quartz, etc.), crystals and aggregates of calcite crystals, aragonite, gypsum, aegirine, riebeckite, goethite, hematite, celadonite, palygorskite, martite and other minerals.

Red-layered and yellow-layered ferruginous quartzites (figure 12) are the most common types of ornamental stone. They are used for manufacturing both large forms (balls, writing instruments, other gift items) and small artistic items (inserts in rings, brooches, gems, intaglio, etc.).

Hydrothermal and hypergene veins contain sinter aggregates, druses of quartz, pyrite, chalcedony, celadonite, calcite, aragonite, and other minerals (figure 13).



a



b

c

Figure 12. Red- (a, b) and yellow-layered (c) ferruginous quartzites of the Lykhmanivka iron ore region.

Many of them are brightly colored and have shapes characteristic of individuals and aggregates of these minerals. Crystals, druses, and other aggregates are the material for the creation of mineralogical, regional, and art collections.

Granites and migmatites are the most ancient formations, their age is 3.2-2.8 billion years, they are framing the rocks of the Kryvyi Rih series of the Lykhmanivka iron ore region from the east and from the west. Two massifs of granites differ in mineral composition, structure, texture. The granitoid massif of the western part is dominated by migmatites, granitoids with relict schistosity.(figure 14).

It is possible to manufacture block stone, road and sidewalk paving stones, high-quality crushed stone with a low flakiness index from granites of the eastern massif.

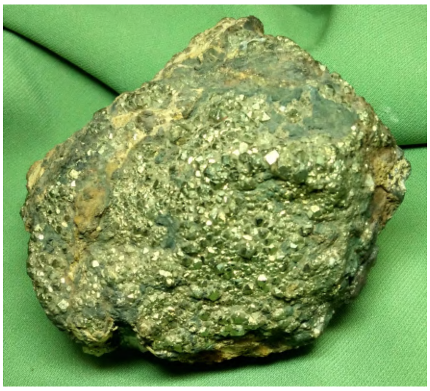
Due to its relict schistosity and gneissic nature, granite of the western massif can be used for the production of lower quality, flaky rubble.

Man-made deposits of natural minerals include mining and processing waste from the Inhulets Mining and Beneficiation Works, the former Inhulets operations, stored in dumps, tailings, emergency and other containers .

Tailings [12] in the amount of about 500 million tons are stored in the tailings storage facilities of the Works. The particle size ranges from 0.01 to 3 mm. Due to gravitational differentiation, there is a concentration of open ore particles and the most coarse-grained tailings material in the dam parts of the tailings storage facilities maps. The content of magnetite increases from 1-2 to 7-9 mass pct., the hematite one is up to 6-8pct. Based on the results of preliminary

a

b



c

d

Figure 13. Samples for creating mineralogical, regional, art collections.

Figure 14. Microcline-plagioclase granite of the eastern massif.

mineralogical and technological studies, it is possible to produce a complex hematite-magnetite concentrate with an iron content of 65-67 mass pct. and a yield of 6-8 pct. from dam deposits of mature tailings.

The technogenic types of iron ore raw materials also include the tailings of the flotation upgrading of the rough concentrate of the beneficiation plant No. 2 of the Inhulets Mining and Beneficiation Works. However, today their quality indicators, the possibilities of extraction and processing have not been studied enough.

Overburden rocks of different mineral, chemical composition and origin are stored in the dumps of the Works, they are sedimentary rocks of the Cenozoic cover, schists of different composition, monomineral silicate, substandard magnetite-silicate quartzites, products of supergene transformations of schists and ferruginous quartzites. The stripping rocks are stored in a non-selective way. Mineralogical, petrographic, and technological studies of the accumulated material have not been systematically carried out so far. In this regard, it is impossible to determine the potential of the dump material as a mineral raw material.

4. Conclusions

The deposits of the Lykhmanivka iron ore region are complex ones. According to the results of the studies, among about 20 types of associated minerals, several priority ones can be distinguished in terms of prevalence, degree of geologic certainty, existing methods of use, positive technical, economic, social, and environmental consequences of their utilization: high-grade and low-grade hematite ores (hematite quartzites), talc-containing schists, muscovite quartzites.

Low-grade hematite ores make up the weathering crust of the ferruginous horizons. The deposits of high-grade ores represent the "lost" ore bodies of the mines of the former Inhulets mining operations. Ores of both varieties can be used as feedstock for the production of iron ore concentrate.

Other metal minerals include gold, platinum and platinoids, manganese, and bauxite. Their manifestations are insignificant in size, the quality of ores has not been studied enough.

Non-metal minerals in the Lykhmanivka iron ore region are represented by talc-, garnet-, muscovite-bearing schists, granites and migmatites, reddle, ocher, ceramic clay, gemological and collectable raw materials, mature tailings and overburden rocks from dumps. The talc-bearing schists have been studied most deeply. Other minerals require detailed study.

The studied metal and non-metal minerals form industrial deposits that can be developed simultaneously with the extraction of iron ores. Involving them in mining and processing significantly expands the range of alternative directions for using the mined mineral mass.

The integrated use of metallic and non-metallic minerals of the Lykhmanivka iron ore region significantly expands the range of alternative directions for the use of minerals and rocks of the banded iron formation, their involvement in mining and processing will contribute to a significant addition to the mineral resource base of both the Kryvyi Rih basin and Ukraine as a whole.

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Implementation of microseismic monitoring for iron ore mines

To cite this article: A V Bakai 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012007

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012007 doi:10.1088/1755-1315/1049/1/012007

Implementation of microseismic monitoring for iron ore mines

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Abstract. The seismic station of the Subbot Institute of Geophysics of the NAS of Ukraine (IGP), in Kriviy Rih (Ukraine) ten earthquakes were registered from 2007 to 2013. Such activity is not typical for this region. One of the reasons is mining of mineral resources in this area, leading to irreversible changes in the stress-strain state of the massif, which activate dangerous natural and man-made processes (landslides, flooding, earthquakes, mountain strikes, etc.) The collapse of the mountain massif and the exit of the funnels occurs when the limit value of the loading in the massif is reached. Limit value warning of the stress-strain state of the massif is a condition for the danger of the zone. The task of control is to prevent the stress-strain state of the massif. Any unloading of the massif is accompanied by the formation of a crack, which is characterized by a burst of amplitude and a certain frequency of oscillations. For the geographic information system of mines, it is important to highlight significant phenomena by types of energy, affiliation to the mining allotment of the mine (distance to the hypocenter) and the nature of the primary source - technical or natural. The goal of research is to define a significant phenomena for identifying the stress-strain state of the massif using the microseismic monitoring. To increase noise immunity, it is advisable to use both physical filtration methods and software selection of significant phenomena against the background of man-made noise. To form conclusions, it is necessary to form a sample, so for reliable identification of the stress - strain state of the massif it is necessary to perform statistical processing of the measurement results. The usage of microseismic control at mining enterprises will reduce the possibility of mining shocks, landslides, which will reduce material damage. This will increase the safety of mining operations and ability to prevent man-made earthquakes of magnitude more than five.

1. Introduction

The certain part of Ukrainian territory is situated on a seismic active zone. To the most dangerous zones can be considered such regions as: Transcarpathian, Ivano-Frankivska, Chernihivska, Odeska and Crimea. The earthquakes in these areas have natural origin. Seismic activity is also increasing in the aseismic territory of Ukraine, but earthquakes are mostly man-made.

The table 1 presents the list of earthquakes in the Kryvyi Rih iron ore basin (Kryvbas), characterized by mining for 60 kilometers and a depth of more than 1,500 meters of underground works. The redistribution of stresses and deformations of the surface is due to a large size of dumps and tailings.

As we know from open sources of information there were a series of earthquakes after 2013. On 29th of August 2017 the earthquake in amplitude of 4.1 [2] and another on 20th of February

Table 1. Man-made earthquakes were registered in Kryvyi Rih by the seismic station of the Institute of Geophysics (IGP) of the National Academy of Sciences, in Kriviy Rih (Ukraine) from 2007 to 2013 [1].

№	Date	Latitude	Longitude	Magnitude	Depth
1.	25-12-2007 04:09:31	47.79	33.38	3.3	0m
2.	13-06-2010 03:58:17	48.02	32.35	4.3	447m – 527m
3.	18-09-2010 04:00:35	47.84	33.30	3.3	447m – 527m
4.	14-01-2011 05:03:12	48.10	33.40	3.5	1200m – 1300m
5.	26-06-2011 04:04:30	48.02	32.99	2.5	447m – 527m
6.	22-10-2011 04:06:45	48.89	33.24	3.1	1200m – 1270m
7.	31-03-2012 04:00:42	48.20	32.50	3.0	1200m – 1270m
8.	17-06-2012 04:03:16	47.70	33.57	3.0	1270m – 1300m
9.	28-11-2012 20:47:43	48.10	33.50	3.1	0 m
10.	23-06-2013 21:16:33	48.04	33.42	4.6	2 000 m

2018 in amplitude of 3.2 [3], and on 22nd of January 2022 the earthquake in amplitude of 3.3 [4]. The reason of earthquakes can be both the movement of lithospheric plates and mining. The authors [5] believe that the earthquakes №1,3,4,9,10, of the table 1 can be considered as a man-made. Also, authors classify [6] the earthquake № 1 in Table 1 as naturally-anthropogenic and believe that landslides in underground cavities are not the main cause, but may be an additional factor.

Mining in this area causes irreversible changes in the stress-strain state of the massif, which intensifies dangerous natural and man-made processes (landslides, floods, earthquakes, mountain strikes, etc.) The large-scale development of minerals of Kryvbas region is extracted by using of mass explosions in quarries and mines. Herewith, the depth of quarries reaches 450 meters and the mass of explosive substances up to 600 tons. The mass explosions in the mines are made at depths of 1300 meters and with the mass of explosive solutions up to 100 tons.

It should be mentioned that the Krivyi Rih city itself is situated on the junction of some tectonic plates. Due to these factors in Kriviy Rih iron ore structure the earthquakes in amplitude higher than 5 may be caused [7]. In addition to the general destruction of the basin, the seismicity of the zone is affected by industrial explosions and the presence of technological voids.

Except the impact of industrial explosions on the man-made seismicity of the region also affects the mining works, which increases the seismicity of this zone.

2. Method

Man-made seismic phenomena, namely the collapse of the mountain massif, the exit of the funnels occurs when the limit values of rock tension is reached. The graph in the (figure 1) it is the dependence of deformation on the load for the rocks of different geotechnical qualities [8].

Under the action of forces (loads), any rock goes through the next three stages of deformation..

The first stage of elastic deformation (segment OA in figure 1) – is reversible deformations, i.e., when the load is removed, the deformations disappear, and the rock completely restores its original shape and volume. The second stage of plastic deformation (segment AB in figure 1) is realized when the rock irreversibly changes the shape and volume, but without breaking the integrity of the rock. This stage is manifested when the forces exceed the elastic limit, but not above the strength limit of the rock. At this stage, the folds are created. The third

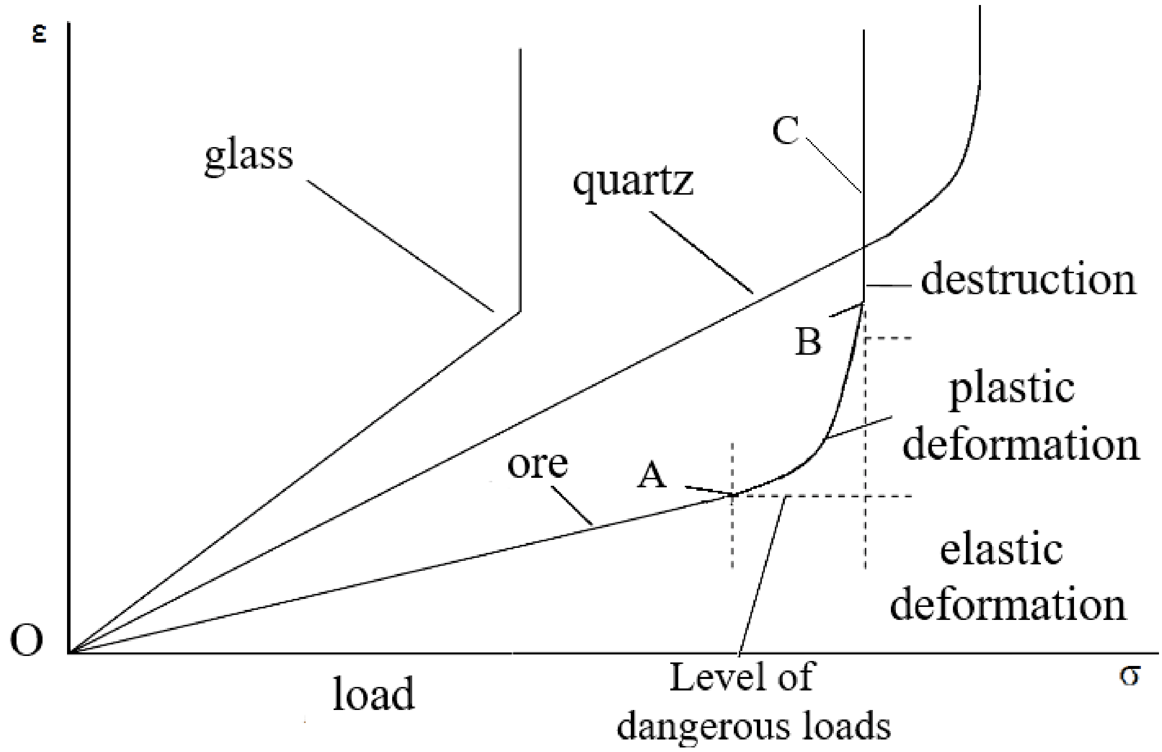

Figure 1. The strain-stress curves. The σ axis is the normal load. The ε axis is a strain.

stage of brittle or breaking deformation (segment BC in figure 1) is manifested when the forces exceed the strength limit of the rock and the rock is deformed with loss of integrity, with the formation of cracks of separation and chipping. Depending on the certain geological conditions, different stages of deformation can get different degrees of development, up to tectonic cracks [8]. Deformations for glass, quartz and ore are similar and depend on the load. Approaching the limit value of the stress-strain state of the massif (segment AB in figure 1)is a condition of the danger zone. This dependence is the basis of micro seismic control of the state of the massif. The task of control is to prevent the stress-strain state of the massif. Small cracks are registered with the help of microseismic monitoring, the number of cracks and their epicenter will indicate the stress of the massif. The increase in the number of cracks in time will indicate the second stage of plastic deformation (segment AB in figure 1) in which mining is a dangerous process. The registration of small cracks to predict powerful phenomena this is the task of microseismic monitoring. Therefore, this method is called micro seismic control. Due to a micro seismic activity, strong seismic phenomena can be predicted.

In the technical literature there are well-known example of determining the stress-strain state of a rock by the characteristics of the oscillation of the massif [9].

In order to be able to predict local earthquakes, landslides, mining strikes and safe mining operations at mining enterprises, it is necessary to introduce microseismic control. It will avoid material costs and increase the level of people's safety. It is important to control constantly or periodically the stress-strain state of the array for forecasting and prevention of dangerous natural and man-made processes.

Low-powered destruction in the form of cracks (unloading of the stress-strain state of the massif) in rocks causes seismic oscillations in the massif. This creates requirements for controlled parameters for measuring the speed or acceleration of microseismic oscillations of the massif [10].

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3. Investigation of massif oscillations

High sensitivity of measurement channels is required to control low-powered destructions. Along with the signals of destruction of random periodicity in the mountains massives there are a constant fluctuations - microseismics [11]. In most cases, the signals of microcracks are commensurate with the microseismics of the Earth. Due to the short distance to the expected phenomenon or to the monitoring area it is possible to separate the impact of both microseismics and man-made noise. On figure 2 is demonstrated the example of Earth's microseism.

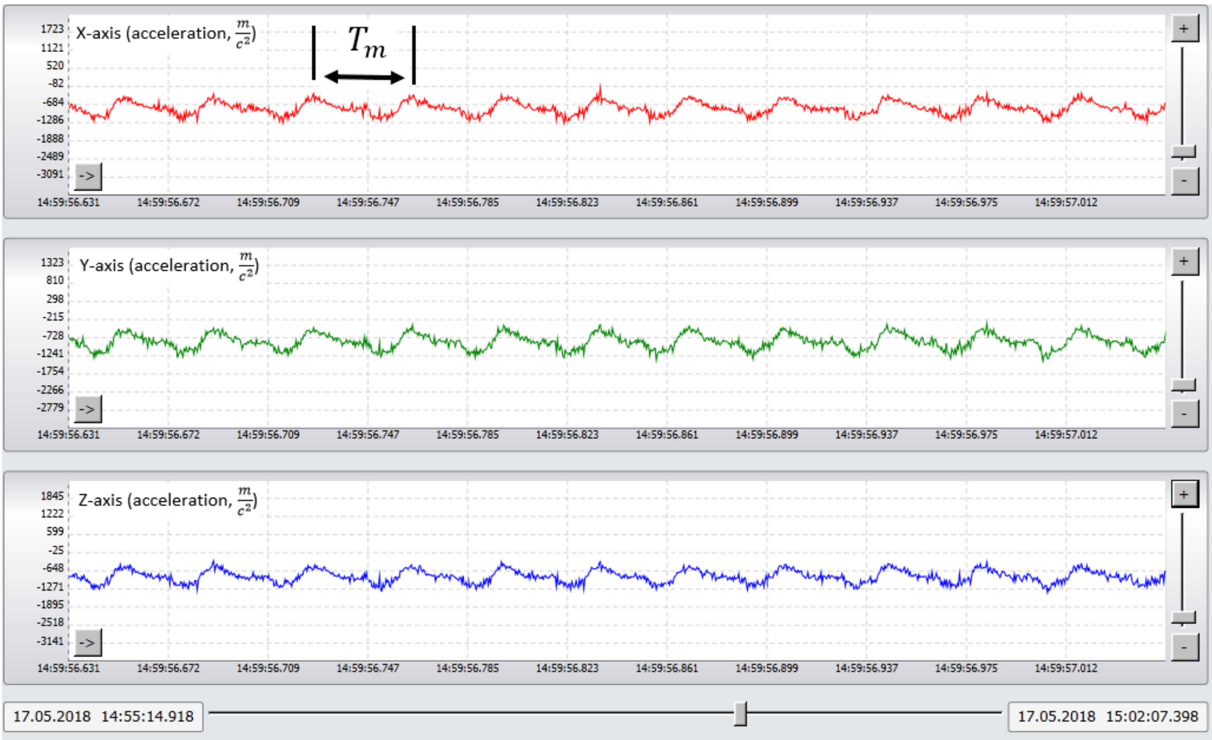

Figure 2. The sample of Earth's microseism in Artem's mine - 1, 17.05.2018 yr. $T_m = 38ms$, $f_m = 26.3Hz$; T_m – period of microseismic oscillations; f_m – characteristic frequency of microseismic oscillations.

The amplitude and frequency of the Earth's microseismic changes over time in a fairly significant range – 2,3 times [12]. The example of a microseismic on the surface of the mine Artem-1 in figure 3. It depends on several factors, for example: the seasons, the gravitational action of the Moon on the water, the distributed resonant qualities of the array and others. But due to the random components of fluctuations in the level of the microseismic in time, the influence of factors is insufficiently studied. The sample of a microseismic activity on the surface of the mine Artem-1 in figure 3.

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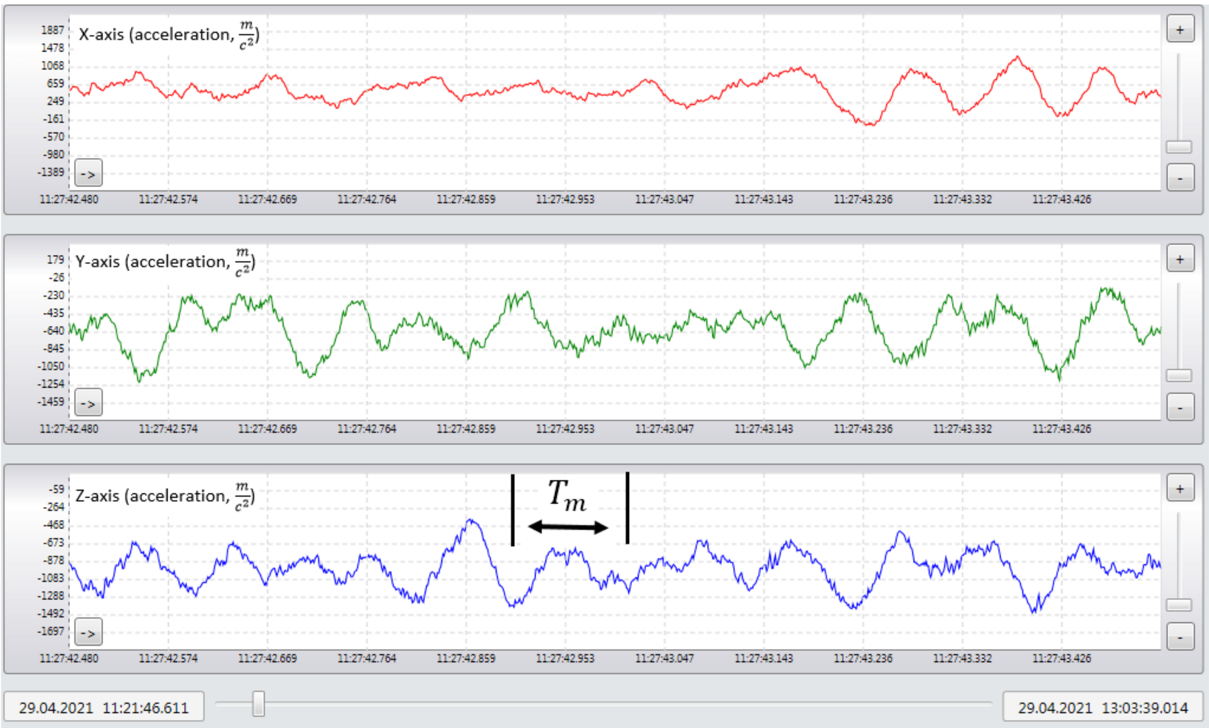

Figure 3. The sample of Earth‘s microseism on the surface of Artem‘s mine -1,29.04.2021 yr. $T_m = 94.3ms; f_m = 10.6Hz$; T_m – period of microseismic oscillations; f_m – characteristic frequency of microseismic oscillations.

Reducing of the influence of the microseismic on the measurement is achieved by limiting the minimal amplitude of significant signals at the level of three amplitudes of the microseismic in manual processing and ten amplitudes of the microseismic in automatic processing. And also at allocation of considerable signals it is expedient to use differences in a complex of characteristics of signals.

The low-power phenomenon differs from the Earth's microseismic in amplitude, frequency, duration, and shape, which can be seen in figure 4 [12]. To identify the phenomenon of the Earth a microseismic is considered an obstacle.

Any unloading of the massif is accompanied with creation of crack which is characterized on the recordings by sharp increasing amplitude and a certain frequency of oscillations. Examples of recording of the crack at the Frunze mine from 03.03.2020 are shown in figure 5.

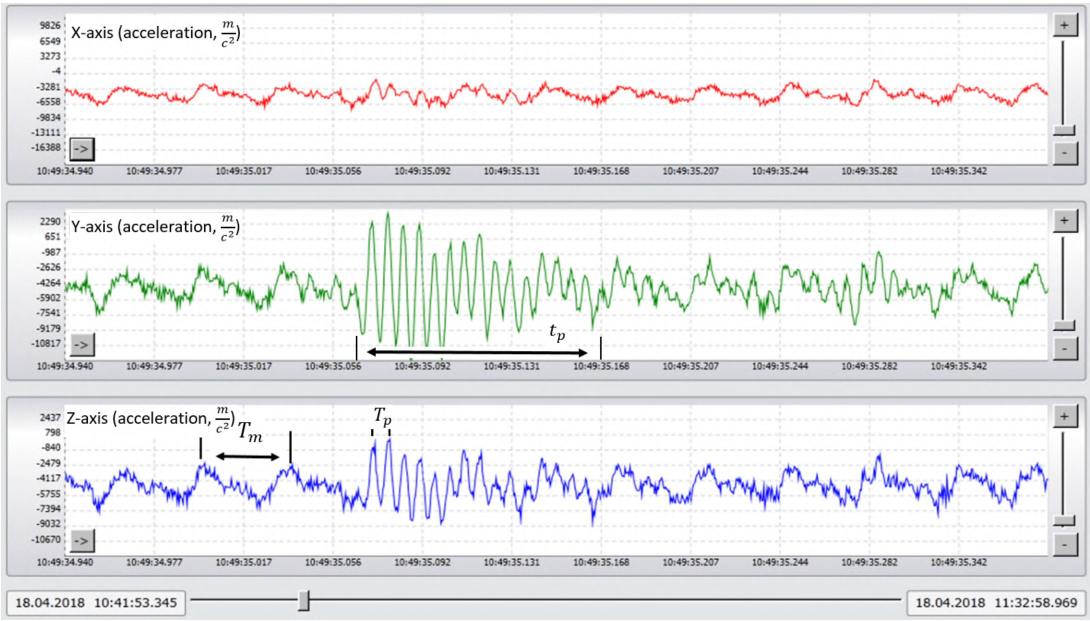

Figure 4. The sample of microseism with the the low-powered phenomenon in Artem‘s mine -1, 18.04.2018 yr. $T_m = 42ms$, $f_m = 23.8Hz; t_p = 100ms, T_p = 6.2ms$; $f_p = 161Hz$; T_m – period of microseismic oscillations; f_m – characteristic frequency of microseismic oscillations; t_p – duration of the phenomenon; T_p – period of oscillations of phenomena; f_p – characteristic frequency of oscillations of phenomena.

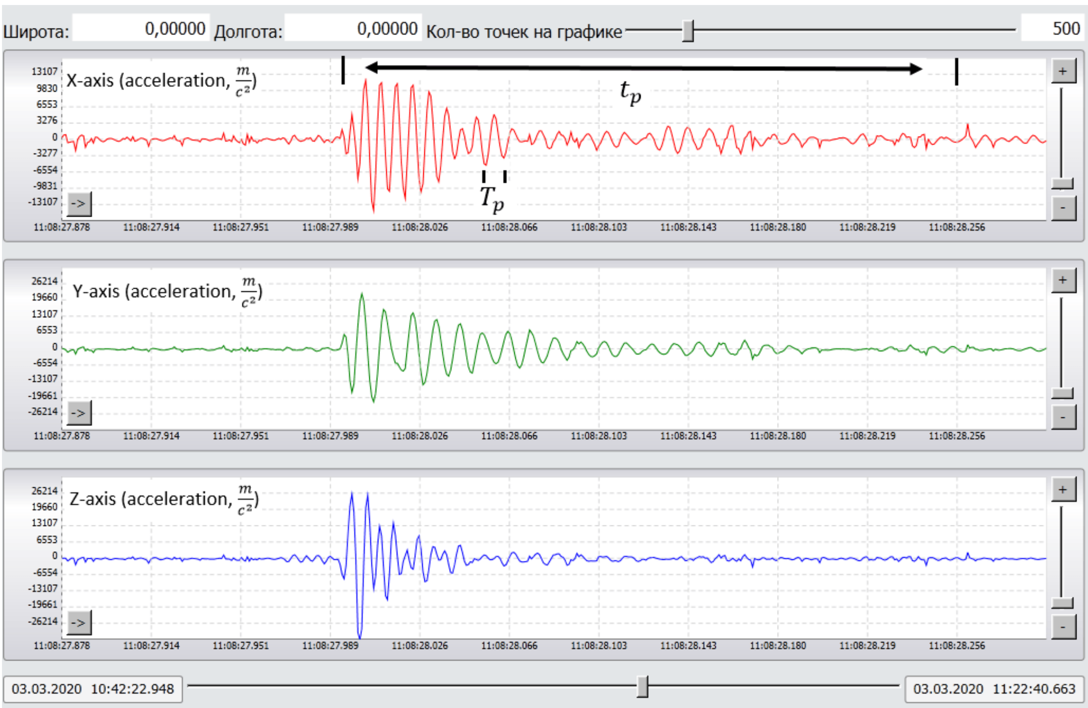

Figure 5. The sample of crack‘s signal recording in Frunze‘s mine, 03.03.2020 yr. $t_P = 250ms; f_P = 113Hz; T_p = 6.2ms$; t_p – duration of the phenomenon; T_p – period of oscillations of phenomena; f_p – characteristic frequency of oscillations of phenomena.

The authors made a spectral analysis of the frequencies of phenomena at the Artem-1 mine [13]. Directly in the epicenter of the crack formation with a conditional diameter of a few dozen meters has a length of about 1 ms and can be considered as a single impulse. At a distance from the epicenter due to the distributed resonant properties of the massif, oscillations occur with a certain frequency and a certain duration in (figure 4,5). The oscillations happen due to the distributed resonant qualities of the massif, and the frequency of oscillations depends on the elasticity and density of the rock.

Due to the filtering properties of the array with the distance from the phenomenon of the signal frequency decreases. With the distance from the phenomenon, the frequency of the signal decreases (figure 6) shows the most remote signal in accordance with the frequencies of 92 Hz.

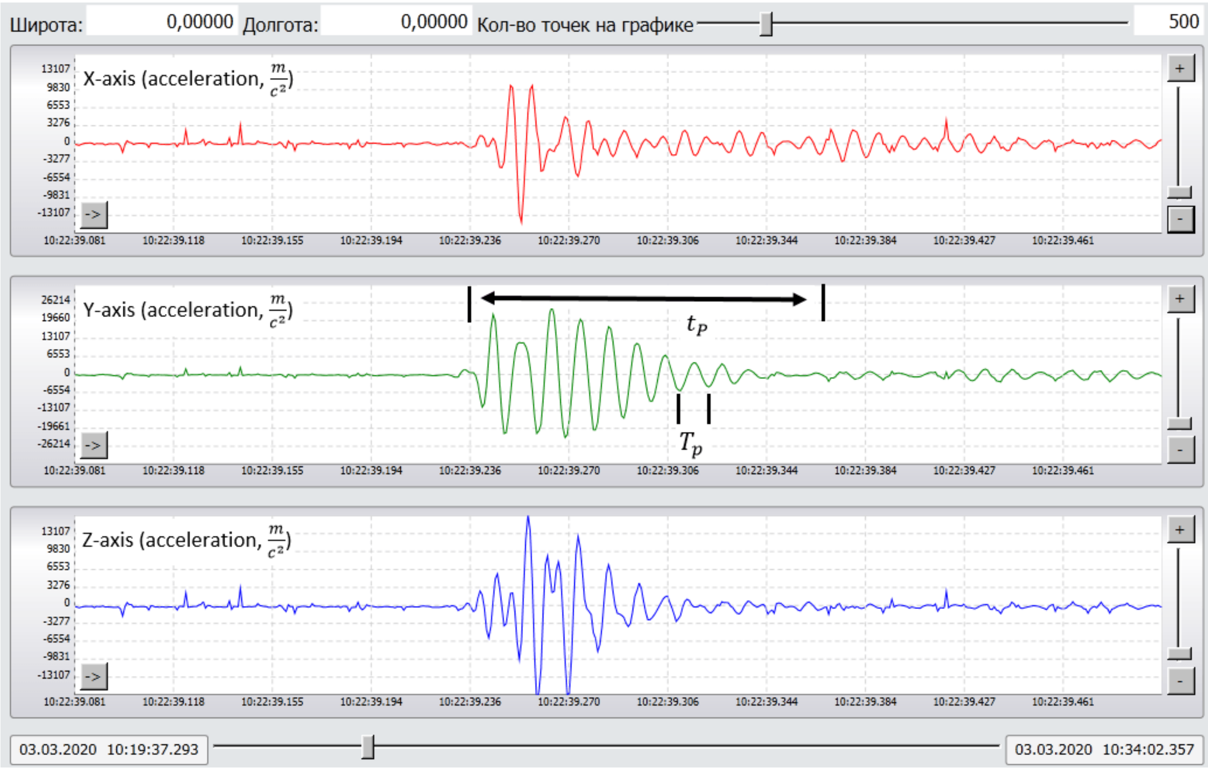

Figure 6. The signal of a crack on the distance of 40 m in Frunze‘s mine, 03.03.2020 yr. $t_p = 130ms; f_p = 92Hz; T_p = 6.2ms;$
t_p – duration of the phenomenon; f_p – characteristic frequency of oscillations of phenomena.
T_p – period of oscillations of phenomena;

In volume of geo-informational system of the mine , it is important to identify significant phenomena in terms of energy, territorial affiliation to the mine allotment (distance to the hypocenter) and the nature of the primary source - technical or natural [14]. The experience of the use of microseismic monitoring for iron ore mines and sizes of working horizons of most mines has shown the feasibility of a monitoring radius within 400 meters. The horizons of existing mines as a rule are usually have smaller width. The location of the measuring probe is chosen by compromising between the requirement to approach to the phenomenon and the requirement of safety of measurement. To increase noise immunity, it is advisable to use both physical filtration methods and software selection of significant phenomena on the background of man-made noise. This processing is called the primary processing of measurement results.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012007 doi:10.1088/1755-1315/1049/1/012007

4. Conclusions

To identify the stress-strain state of the massif by the microseismic method, it is necessary to collect an array of data which includes: the number of phenomena, the epicenter of the location of phenomena and their power.

High quality of primary data processing is achieved by using the identification of phenomena, namely: Earth microseismics, cracks, collapses, rock strikes, explosions, mass explosions, man-made earthquakes. This is done by processing 14-16 indicators or factors of microseismic signals, the main of which are: the frequency of oscillations of the array, the amplitude and duration of phenomena what presented on the figures 4,5,6. Along with the well-known complex methods for determining the coordinates of the hypocenter of phenomena (requires 4 spaced probes) in the GIS of mines, it is advisable to use simplified methods for estimating the location of the epicenter using a single probe. According to the amplitude of oscillations, we distinguish the power of the phenomenon and the distance. By the duration of the phenomenon we can estimate the distance to the epicenter.

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Iron ore underground mining under the internal overburden dump at the PJSC "Northern GZK"

To cite this article: S Pysmennyi *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012008

Iron ore underground mining under the internal overburden dump at the PJSC "Northern GZK"

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Abstract. Deterioration of mining conditions at mining deposits by open pit methods (increased mining depths, reduced ore deposit thickness) leads to an increase in mining costs. In Ukraine, to reduce open pit mining costs, overburden is disposed in temporary internal dumps located directly in the open pit over the ore reserves. Reactivation of pit areas with the temporary internal overburden dump located on them results in a surge of mining operations and deterioration of technical and economic indicators. Increased energy consumption, a decrease in working site parameters, an increase in angles of open pit slopes and stripping lags lead to unprofitability of open pit mining. One of the solutions to the mentioned scientific and engineering problem involves combined mining of deposits by integrated open pit and underground mining operations. The combined open pit-underground mining method enables reducing mining costs and enhancing technical and economic indicators. The suggested schemes for opening reserves located under the internal overburden dump enhance technical and economic indicators of deposit mining through making the internal dump a permanent one. This allows further disposal of overburden into internal dumps. Implementation of scientific recommendations and technological solutions resulted from the research performed (exemplified by the deposit *Hannivske*, Ukraine) reduces the cost of ore by 1.33 USD/t.At the same time, the total cost of building an underground mine makes16.4 M USD, which is 30% less than when applying traditional opening vertical shaft schemes.

1. Introduction

Hannivske deposit of ferruginous quartzites has been mined by open pit methods since 1963. The depth of the open pit reaches 252 m (the lower mark of the mining horizon is -120 m). The deposit is explored in detail to the depth of 300 m in the central and northern parts and 500 m in the southern part. According to the design, the width of the open pit is 1.4 km, the length is 7.2 km, the depth makes 300 m in the northern part and 450 m in the southern part. In 2020, the planned stripping ratio made 1.0 m^3/t, the average one was 0.84 m^3/t according to the data of the Northern GZK (ore mining and beneficiation plant) [1].

In terms of the geological structure complexity, the deposit is classified as group 2a (the southern part up to profile 28) and to group 1b (northwards of profile 28). The deposit is a northern continuation of the rocks of Kryvyi Rih iron ore basin [2–5]. The length of the explored part is 14.5 km; the length of the design contour of the open pit is about 8 km [1, 6, 7].

The productive thickness of the deposit is represented by ferruginous quartzites of the first ferruginous horizon. The horizon thickness varies from 300-500 m in the south to 180-250 m in the north. Country rocks (the footwall) consist of alumina-silicate schists of the first schistous horizon that overlap (the hanging wall) magnetite-silicate quartzites of the fourth ferruginous horizon (figure 1).

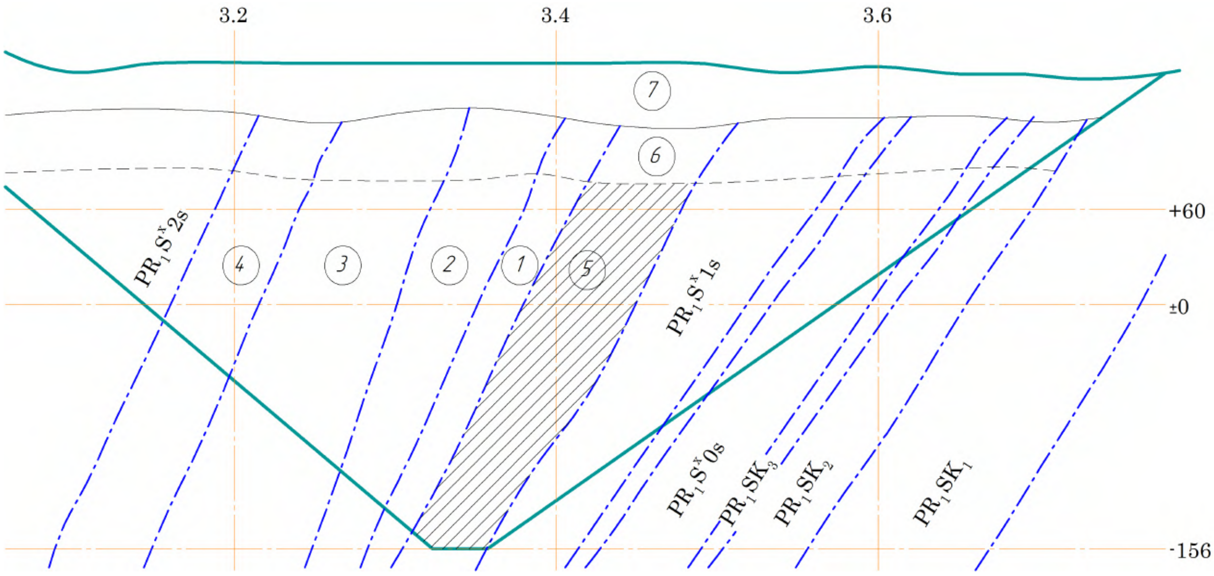

Figure 1. Geological cross-section by profile 33+170 (5.1 – 5.2): 1 – 4 – magnetite-silicate quartzites (substandard hanging walls); 5 – the footwall (magnetite quartzites); 6 – the area of underlying rock oxidation; 7 – loose Cenozoic sediments; PR_1S^x2s – quartz-magnetite-biotite schists; PR_1S^x1S – quartz-biotite-cummingtonite schists; PR_1S^x0s – magnetite-biotite-cummingtonite quartzites; PR_1SK_3 – quartz-biotite schists; PR_1SK_2 – quartz-sericite schists; PR_1SK_1 – mica quartzites.

The dip of rocks at almost the north-south strike is mainly westwards at angles 40 degree to 90 degree. In the southern part, the dip of rocks is steeper than in the northern part. As for the material composition of the textural-structural features and technological properties, the first ferruginous horizon is divided into two bands of approximately equal thickness – the footwall and the hanging wall.

The footwall which is 150–300 m thick in the south and 60–80 m thick in the north is composed of magnetite, hematite-magnetite quartzites with silicates and to a lesser extent of silicate-magnetite and magnetite-silicate quartzites. The latter two varieties occur in the form of thin layers (up to 20-40 m) in the hanging wall of the first ferruginous horizon [1, 8–10].

In accordance with the design and quality requirements, the cut-off value of the mass fraction of Fe_{mag} in quartzites of the footwall is 16%. The balance reserves also include less than 10 m thick substandard layers ($Fe_{mag} < 16\%$). In fact, quartzites of the hanging wall (especially in its northern and central parts) are used only for building hydraulic engineering structures of the plant [1, 9].

The tectonic structure of the deposit is different in different parts. Powerful ruptures divide the deposit into three parts - southern, central and northern - within the design contour of the open pit.

As is seen from practice, the actual structure of the deposit in certain areas, especially in its southern part appears much more complicated than it was apparent based on the exploration data. In the design contours of the open pit, the reserves of magnetite quartzites of the footwall within axes ±0÷1.8+120 m of the southern end make 175398 k t. This volume of ore accounts for 98190 k m^3 of overburden. The average stripping ratio is 0.55 m^3/t; the total volume of unoxidized quartzites of the southern part of the footwall makes 223.4 M t, and that of overburden is 128.1 M m^3 with the average stripping ratio of 0.57 m^3/t.

Reserves of quartzites in the central part within axes 2.0÷3.4 to the depth of 300 m make 63460 k t; in the northern part within axes 3.4÷4.8 to the depth of 300 m there remains 32482 k t; in the northern part within axes 4.8÷7.0 to the depth of 300 m balance reserves make 180000 k t with the average stripping ratio of 1.4 m^3/t. In total, within the design contours of the open pit, the remainder of the balance reserves of magnetite quartzites of the first ferruginous horizon makes 499340 k t [1, 6, 11].

Deterioration of mining conditions at mining deposits by open pit methods (increased mining depths, reduced ore deposit thickness as well as increased energy consumption) results in a decrease in working site parameters, an increase in angles of an operating pit wall and deactivation of the considerable part of the open pit due to the internal overburden dump building (figure 2). Reactivation of the open pit reserves after completion of another stage of mining leads to a surge of stripping and deterioration of engineering and economic indicators.

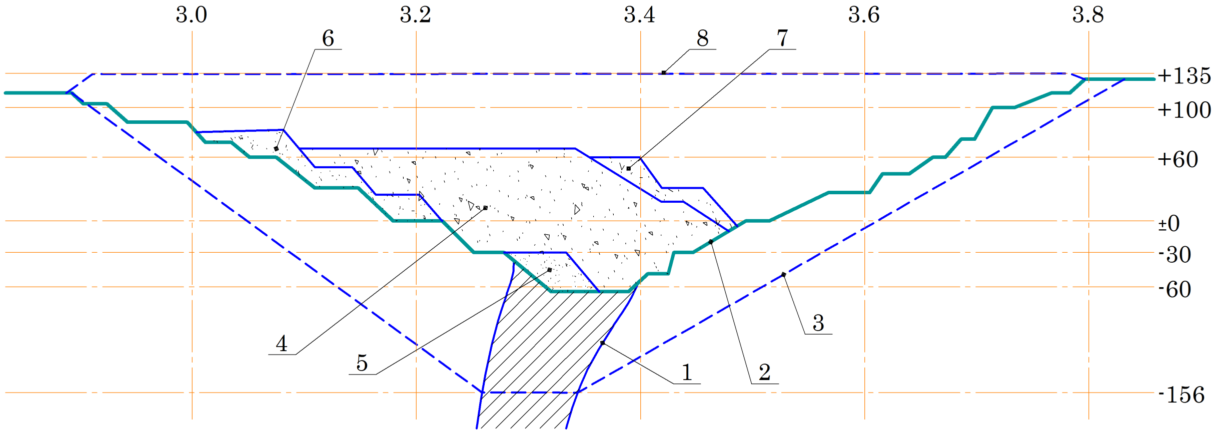

Figure 2. Cross section along axis 3.6: 1 – the ore deposit; 2 and 3 – the open pit contour at the end of the final mining stage and the design one respectively; 4, 5, 6, 7 – internal dumps within axes 2.6÷2.8 (I stage), 3.6÷3.8 (II stage), 3.0÷4.0 (III stage), 2.8÷4.0 (IV stage) respectively; 8 – the contour of the internal overburden dump.

In 2023, the open pit produced 6.50 M t of ore, 5.85 M m^3 of overburden was removed. In 2028, productivity of the southern part will make 6.2 M t of the first ferruginous horizon ore at the average stripping ratio of 1.30 m^3/t (table 1).

2. Purpose

One of the solutions to this scientific and engineering problem involves combined mining of the deposit by the integrated open pit and underground methods.

The combined open pit-underground mining method enables reducing mining costs and enhancing technical and economic indicators. Implementation of scientific recommendations and technological solutions to apply the combined mining method enables a number of foreign

Table 1. Calculated rock extraction volumes at the open pit.

Year	Ore, k t	Overburden, m^3	Stripping ratio with internal dumping, m^3/t	Stripping ratio without internal dumping, m^3/t
2023	6000	9600	1.60	1.60
2024	6500	9600	1.48	1.48
2025	7000	9600	1.37	2.04*
2026	8000	9600	1.20	2.43*
2027	9000	9600	1.07	1.32*
2028	10000	9600	0.96	0.96
Total	76500	99300	1.30	1.3

Note: * - *considering the internal dump liquidation.*

enterprises that traditionally use the open pit method to start intensive exploitation of deposit areas previously considered unpromising.

To implement advanced mining technologies at the deposit, the practice of a number of foreign mining enterprises with a combined open pit-underground method of deposit mining is analyzed.

3. Analysis of researches and publications

The sequence of application of open pit and underground mining methods is determined considering the required productivity of an enterprise and specifics of a deposit [2, 3, 12–15].

The most characteristic cases of combining open pit and underground mining operations in time are as follows: combined mining of reserves by open pit and underground methods within the same deposit; final extraction of deposit reserves by the underground method after finishing open pit mining operations (OPMO); mining of reserves on promising areas of the deposit by the open pit methods and final extraction on unpromising areas by the underground methods.

Depending on the location of mine and open pit fields within the deposit, three characteristic schemes can be distinguished: with a combination of vertical operations (underground mining operations (UMO) are performed under the open pit); with a combination of horizontal operations (UMO are in the open pit wall); with a partial combination in both vertical and horizontal directions [16–19]. *Kidd Creek* (Canada) is an example of a gradual transition from open pit to underground mining [20–22].

The deposit of base metals has been developed since 1966 by open pit methods. The combined technology with gradual transition to underground mining exclusively has been applied since 1968 (figure 3) [20, 23].

Underground mining began at the actual depth of the open pit of 150 m (the design depth -250 m), i.e. 7-10 years before completion of OPMO. The transition period from OPMO to combined open pit-underground mining lasted for about 10 years. During this period, the following tasks were performed: construction of the main and auxiliary shafts to the depth of 900 m; construction of surface and underground facilities; opening and preparation of two working levels developing; construction of the spiral ramp from the pit for delivering self-propelled equipment; construction of a complex of permanent orepasses and ventilation raises.

In the course of underground mining, the output of the open pit reduced. However, it maintained stable ore production and a constant level of workloads of the concentrating plant. The company applies powerful equipment “Ingersoll Rand”, “Mission”, “Cubex”, “Tamrock”.

Since 1996, the Australian copper-gold deposit *Osborne* has been mined by underground

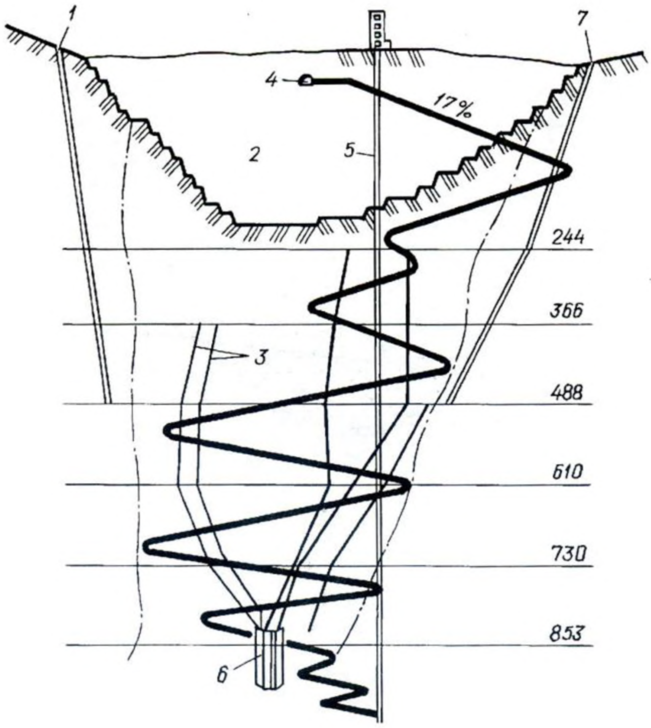

Figure 3. Scheme of opening *Kidd Creek* base metal deposit: 1, 7 – the ventilation raise; 2 – the final contour of the open pit; 3 – the orepass; 4 – the adit entry in the pit wall; 5 – the main shaft; 6 – the underground dump.

methods in the open pit wall [24–26]. The opening of the site of underground operations is carried out through the decline adit with an entry at the level 80 m of the depleted open pit) and by vertical shafts. The Australian *Northparkes* deposit operated by a group of underground mines is of particular interest as it is mined by underground methods not after completion of OPMO but parallel to them.

Considerable experience in the simultaneous open pit and underground mining operations has been accumulated at the largest copper and gold deposit *Grasberg* (Indonesia) [27]. The mine consists of an open pit and an underground mine. The open pit provides a high production volume at a low cost. The mine develops the under-pit ore massif and several individual ore deposits near the open pit.

Vihanti, *Hammaslahti*, *Pyhäsalmi*, *Haveri*, *Luikonlahti* and *Kotalahti* mines (Finland) develop a number of base metal deposits by open pit, underground and combined open pit-underground methods [28].

Pyhäsalmi mine develops a deposit of copper with the copper content of 3-4 percent as well as mining lead, zinc, sulfur and rare earth elements. The deposit thickness is 20-40 m and the dip is 70-80°. The upper part of the deposit is mined by the open pit method to the depth of 120 m, the lower part - by underground mining systems with backfilling [29].

Virtasalmi deposit of base metal ores performs open pit and underground mining operations to the full depth, (figure 4) [30]. To the depth of 175 m, both open pit and underground methods were applied with transportation of extracted rock mass from the underground part to the surface along the ramp. With transition to underground mining, ventilation raises were driven from the non-mining pit wall to air underground mining operations.

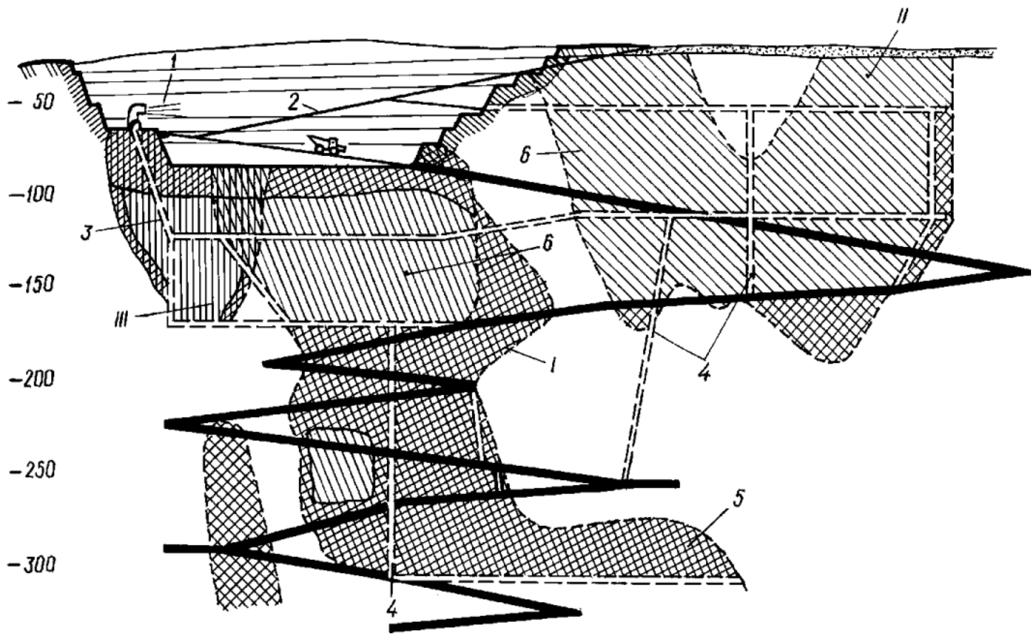

Figure 4. Scheme of mining *Virtasalmi* base metal deposit: I – the ore body A, partially mined by the open pit; II, III – the ore bodies B and C mined by underground methods; 1 – the open pit; 2 – the open pit ramp becomes the underground one for pit trucks to go up to underground workings; 3 – the ventilation raise driven from the non-mining open pit wall berm; 4 – ventilation raises; 5 – the ore body; 6 – the mined ore.

The open pit-underground method is also used at the copper-cobalt deposit *Kamoto* (Congo). The steep part of the deposit directly under the open pit is mined by stoping with back filling, and the low dip one – by the room-and-pillar system. To the depth of 170 m, the deposit was mined during 15 years, and 10 years later underground mining was started.

Tyshinske base metal deposit (Kazakhstan) is represented by two steep ore bodies "Main" and "Parallel" with an 80-85° dip and thickness of 10-70 m [31, 32]. Initially, the combined method was supposed to be applied to the depth of 380 m – by the open pit method and then by the underground method abandoning a 60 m high (equal to the level high) safety pillar in the pit bottom. To maintain productivity of the mine, it was decided to work out part of the deposit by the underground method with two levels simultaneously to the concentration level. This enabled creating favorable geomechanical conditions for relieving the ore mass, decreasing costs to maintain workings, reducing ore losses and dilution [33–35].

Uchalinske deposit applies the combined method to mine gold-containing iron ores. The reserves to be mined by the underground methods make 80%, and by open pits - 20%. Since ore bodies within the same level are of different thickness, dips and useful component contents, several mining systems are applied: the heading-and-stall method with sub level breaking for thick areas (specific weight 70%); the room-and-pillar method for 5-15 m thick ore bodies (15%); the horizontal layers method for thin areas of ore bodies (15%) [36–38].

Goroblagodatske iron ore deposit in Sverdlovsk region (Russia) is the largest [39, 40]. Ore bodies are represented by a series of sheet, tectonic, disturbed 200-1800 m long bodies with 30-75° dips and thickness of 2 to 84 m. The ores are exposed. The deposit is mined by open pit and underground methods. The depth of mining is 420 m and 200 m. The underground part of the deposit is mined by induced block caving with long hole breaking and back filling of the worked out area with self-caved rocks of the hanging wall. The height of the level varies from

60 m to 80 m. Average losses and dilution make 5-8%, up to 15% respectively [41–43].

The analysis performed enables ascertaining that in the world practice there is a steady trend of additional underground mining of deposit areas with unfavorable conditions for open pit mining operations.

The combined mining method enables reducing the level of environmental damage caused by open pit mining and increasing efficiency of underground operations [44–46]. Almost all considered enterprises that started mining reserves by open pit methods, implement gradual transition from open pit to underground mining, creating integrated geotechnological systems "open pit-underground mine" at the deposits.

All technological solutions at undegroud mines that are being built or operating focus on using highly efficient options of mining systems and types of self-propelled equipment. A characteristic feature of combined mining is the use of the general transport system "open pit-mine". In some cases, deposit areas are opened for underground mining operations by vertical shafts equipped with high-speed automated hoisting units.

Complexes of inclined and horizontal workings – ad its and spiral ramps – ensure efficient operation of self-propelled equipment and increase productivity of the mining enterprise. Experience shows that in most cases it is most efficient from the engineering and organizational points of view to drive horizontal and inclined transport transportation workings from the open pit side [47–49].

4. Methods

Determination of parameters of mining operations when applying the combined open pit-underground mining methods possesses certain specific features. They include the final depth of the pit (the open tier – OT), the boundary of transition from open pit to underground operations (the open pit-underground tier – OUT), the beginning of underground operations (the underground tier – UT) [50–52].

When determining the parameters of OT and OUT, the methods used for OPMO are applied [2–4] and technological features of determining parameters of mining operations in combined mining are also considered [53–55].

In combined mining, due to determined technological features [1,6,7], such concepts as "final depth of the open pit" and "boundary of transition from open pit to underground operations" are distingueshed. Obviously, the moment of transition to underground operations occurs long before reaching the maximum depth of the open pit and lasts long (up to 10–15 years). In addition, with a one-time assessment of the sequence of mining the reserves of the entire deposit, all the technological features of the design solutions should be considered [56–58].

The beginning of the transition [1] corresponds to the current depth of the pit which is determined by duration of complete mining of the deposit in a given range of depths and duration of construction of the underground mine to work with the reserves below the open pit bottom

$$H_{kt} = H_k + (M - B_d) \times 0.5 \times \tan\gamma - T \times h, \tag{1}$$

where H_k is the increase of the pit depth that depends on the slope angle of the operating wall, m; M is the thickness of the deposit, m; B_d is the pit bottom width, m; T is duration of underground mine construction, years; h is the rate of pit deepening, m/year.

The value of deepening open-pit ore mining operations without moving the pit walls apart is determined by thickness of deposits, slope dips and width of the pit bottom according to the formula

$$H_k = \frac{M - B_d}{ctg\beta_v - ctg\beta_1}, \tag{2}$$

where β_v, β_1 are the slope dips of the pit walls considering strength degradation of rocks in the transition zone of non-mining and operating walls respectively, degrees.

According to Starikov N and Novozhylov M, it is more accurate and scientifically justified to determine the value H_k considering possible losses and discrepancies between the calculated and actual losses when extracting ore pillars near the wall, and the cost of mining production in this area [59–61]

$$H_k = \frac{K \times (M - B_d)}{(1-K)(ctg\beta_v - ctg\beta_1)}. \tag{3}$$

where K is the coefficient characterizing the maximum permissible relative value of the ore volume remained in the wall pillars (it varies from 0.1 to 0.5). In general, the value H_k is the height of the transition zone, since it is in this zone that transition to parallel (simultaneous) production of open pit and underground mining operations and a single worked-out area can be created. The height of the transition zone is determined by the formula

$$\begin{aligned} H_k = {} & \frac{\sqrt{M(K_p - K_{op})^2 + H_k(K_p - K_{op})(M - B_d)(2 - K_{op} - K_o)(ctg\beta_v - ctg\beta_1)}}{(1 - K_{bz})(ctg\beta_v - ctg\beta_1)} - \\ & - \frac{M(K_p - K_{op})}{(1 - K_{bz})(ctg\beta_v - ctg\beta_1)}, \end{aligned} \tag{4}$$

where K_o, K_{op}, K_p, K_z are ore extraction ratios at open pit, open pit-underground, underground mining operations and at pillar extraction respectively.

Thus, the boundary of transition from open pit to underground mining operations is the boundary parameter of the combined (open pit-underground) mining of steep deposits determined by the total final depth of the open pit and the height of the transition zone that should be calculated considering technological features of the deposit.

When determining the boundary of transition for operating open pits, a preliminary assessment of the possibility and efficiency of transition to the combined method is first performed according to the criterion of the minimum estimated operating costs for mining the entire deposit. Then the obtained results are corrected and used to finally justify economic efficiency of transition (boundaries and terms) from open pit to underground mining. This task is solved at the stage of engineering design development considering additional factors: geological, hydrogeological, economic, technological, engineering, climatic, ecological, social.

As is seen from the design practice, the methods of large-scale assessment of the possibility and efficiency of transition to underground mining prove to be expedient. Analysis and consideration of indicators of the current open pit performance (primarily economic, the cost of production being the main of them) are a prerequisite for this assessment [62–64].

The cost of production both at open pit and underground mining methods is the most generalized, concentrated indicator of efficiency of mining enterprise performance. Despite the available reserves of reducing the cost of mining, it tends to grow as the depth of mining increases throughout the entire period of deposit operation.

The main reason for growth of the mining cost is a constant increase in the mining depth which leads to an increase in the volume of overburden rocks, especially hard rocks, an increase in the transportation distance, an iron content decrease in most cases. Correlation analysis of actual indicators of Kryvbas open pits demonstrates that the increase of the depth by 10 m results in the production cost increase by 11–12% and the cost of stripping – by 13–16% [65,66].

The final depth of the open pit is determined by minimizing the cost of mining to the depth H considering transition from open pit to underground mining operations and dynamics of the mining production cost

$$\sum K_v = C_r V_r + C_o V_o + C_{op} V_{op} + C_p V_p, \tag{5}$$

where K_v is the cost of mining, USD; C_r, C_o are the cost of 1 m^3 stripping and mining by open pit methods respectively, USD/m^3; C_{op}, C_p are the cost of open pit-underground and underground mining, USD/t; V_r is the volume of stripping, m^3; V_o is the volume of ore mining, m^3; V_{op}, V_p are volumes of ore production by open pit-underground and underground methods respectively, m^3.

In today's market economy, with self-financing of mining and capital works, performance efficiency of mining enterprises applying underground methods and carrying out reconstruction in order to maintain design production volumes should be provided by the condition

$$T_1 = T_2, \tag{6}$$

where T_1 is the time of mining the upper level, months; T_2 is the time of opening and construction of the lower level, months.

During construction of an underground mine from the open pit side, the time spent on preparation of the UMO start site should not exceed duration of additional mining of the open pit (a section of the open pit) to the maximum depth. This will allow maintaining production volumes and achieving the maximum economic effect.

In turn, the time spent on final extraction of reserves by open pit methods in the case of steep deposits can be presented as the function of the difference between the actual and final depths of the open pit and the rate of OPMO reduction.

Thus, the maximum profit received from mining and sales of useful minerals is due to timely provision of UMO area construction that excludes both early completion of open pit operations not related to the beginning of mining on the built level, and delay in construction of the underground complex

$$P = f(T_{lk}) \to \max \quad \text{at} \quad T_{actual} = T_{optimal}. \tag{7}$$

To ensure the optimal level construction time that corresponds to the rate of reduction of mining operations in the open pit, it is necessary to determine rates of constructing the underground complex.

5. Results

In underground mining in the zone of OPMO influence, choosing a scheme for opening and preparing the ore deposit considering mining conditions in the open pit is the most important factor. Main parameters of the opening scheme include the size of the mine field, location of main opening operations and ventilation workings, the scheme of haulage (transportation) levels [1].

Applying combined open pit-underground mining, the necessity to select opening schemes both for open pit and mine fields and the technological combination of open pit-underground mining processes often depend on efforts to make the most of the specific features of the deposit mining in order to increase its mining efficiency.

In underground and combined open pit-underground mining at *Hannivske* deposit beyond the contours of the OPMO stage, several technological schemes can be used within the design contours of the open pit. They differ in mining methods, loading, transporting the ore mass onto the surface, (figure 5).

Thus, the scheme (see figure 5 (a)), a provides for application of a system with bulk ore and country rocks caving, loading ore from the block into underground minecars by vibrofeeders and ore hoisting in a vertical shaft. The scheme (see figure 5 (b)) is distinguished by the method of transporting the rock mass from the stope to the shaft (underground trucks).

Traditional technological solutions (figure 5 (a) and figure 5 (b)) require building permanent ore hoisters and auxiliary ventilation shafts with appropriate surface complexes, transport and other communications, which is economically and organizationally impractical.

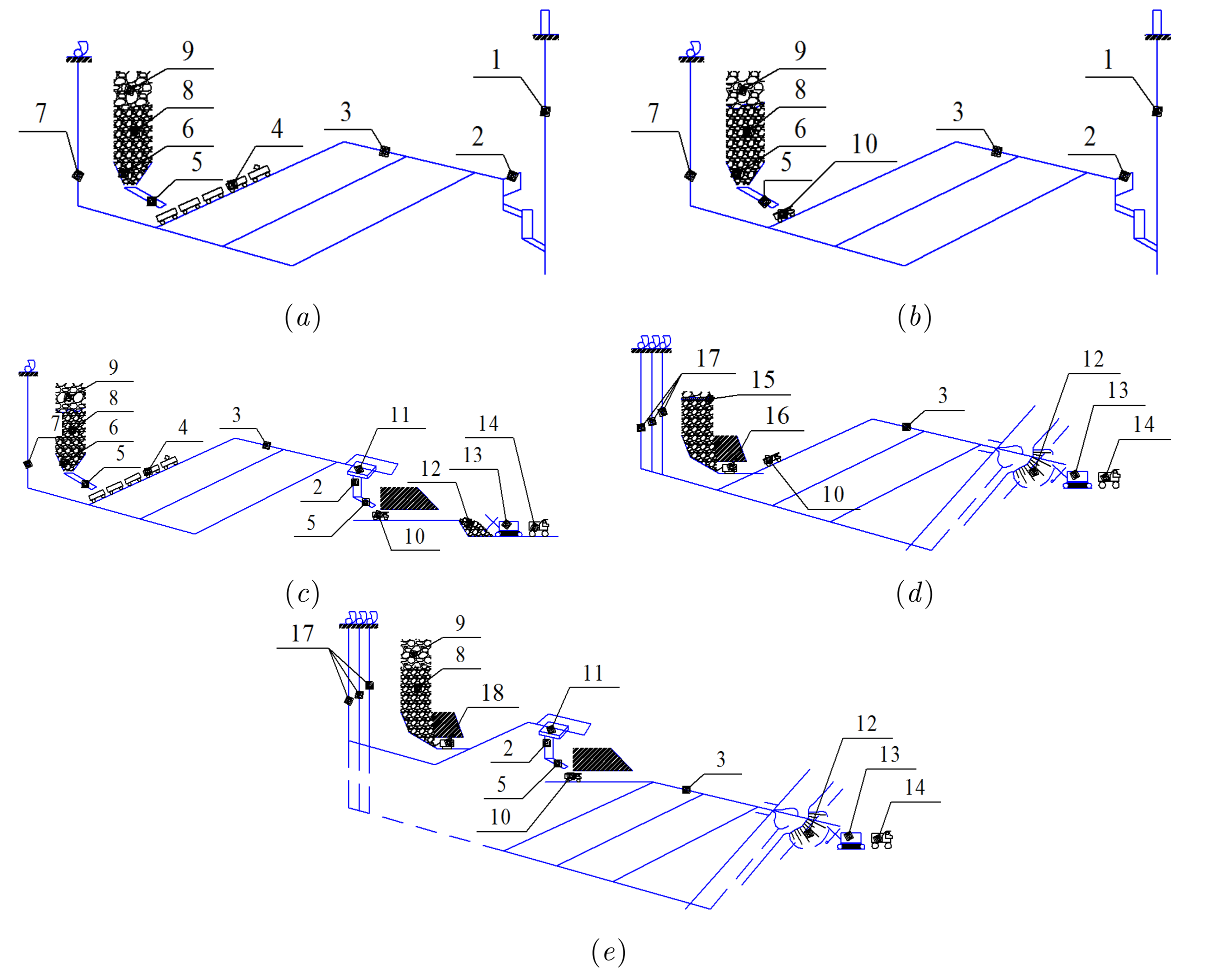

Figure 5. Schemes of opening and transporting the mined rock mass in combined open pit-underground mining. 1 – the vertical shaft with the skip winder; 2 – the crusher; 3 – haulage workings; 4 – the minecar; 5 – the vibrofeeder; 6 – the ore bell (drawpoint); 7 – the ventilation-auxiliary shaft; 8 – the broken ore; 9 – the permanent internal dump; 10 – the underground mine truck; 11 – the tippler; 12 – ore reloading yard in the open pit; 13 – the pit excavator; 14 – the pit truck; 15 – the protecting pillar; 16 – the underground hydraulic excavator; 17 – ventilation holes (trunks); 18 – the load-haul vehicle.

The most successful solution to the problem of combined open pit-underground mining of *Hannivske* deposit involves low-cost technological schemes. Their options, most suitable for these conditions, are presented (figure 5 (*c*) and figure 5 (*d*) and figure 5 (*e*)).

Scheme c provides for application of a system with bulk ore and country rocks caving, loading the ore from the block into underground minecars by vibrofeeders and transporting the ore in the adit on the open pit wall.

Scheme d provides for application of a system with bulk ore and country rocks caving and ore drawing under the protective pillar. The ore from the block is loaded into underground trucks by underground excavators and transported in the adit on the open pit wall.

Scheme e provides for application of a system with bulk ore and country rocks caving, loading the ore from the block into underground minecars by loaders and transporting the ore in the adit on the the open pit wall. These schemes involve various combinations of the following elements of the technology:

- at the stage of mining reserves – use of the room system with abandoned pillars within the mining blocks; use of induced block caving with a set of measures to prevent dilution of the broken ore with overlying rocks under the internal dump;
- at the stage of ore transportation and loading – use of high-performance vibrodrawing options (with twin vibrofeeders), implementation of excavator loading, use of high-performance load-haul vehicles;
- at the stage of ore transporting and hoisting onto the surface – use of self-propelled equipment with ore hoisting to reloading yards in the open pit.

At underground mines, when using high-performance self-propelled equipment, selection of a rational scheme of opening and preparation gains crucial significance for achieving the best results in terms of capital and operating costs reduction.

Application of self-propelled machines leads to a change in traditional opening schemes and conditions important features of deposit preparation. At the current level of mechanization, engineering indicators of underground production will be almost similar to those at OPMO. It is advisable to start mining from the southern flank of the site northwards, the transport adit is driven from the level -120 m, and the ventilation adit – from the level -20 m in the hanging wall of the deposit. Reserves of the level -165÷±0 m should be divided into two levels. The height of the first level is 105 m at the mark -105÷±0 m, and of the second one is 60 m, in the mark -165÷-105 m.

In this regard, opening, preparation and mining of levels are performed in two stages, (figure 6): the first stage – reserves are mined at the level -105÷0 m; the second stage – reserves are mined at the level -165÷-105 m.

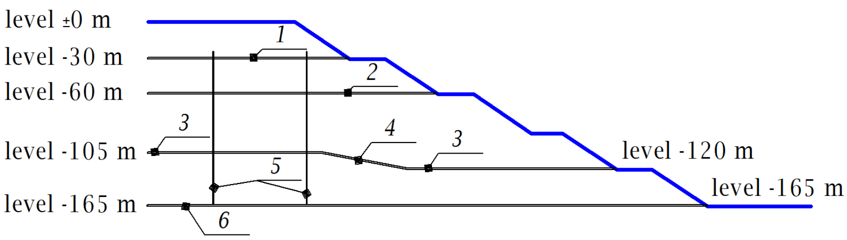

Figure 6. Deposit opening (option I): 1 – the ventilation adit; 2 – the drilling adit for mining the upper level; 3 – the loading and transportation adit for mining the reserves of the upper level and the drilling adit for mining the lower level; 4 – the ramp; 5 – the ventilation and manway raise; 6 – the loading and transportation adit for mining the lower level reserves.

Main opening workings in underground mining within the first stage are the transportation adit from the level -120 m to the level -165 m, the haulage adit from the northern end of the southern section of the open pit on the level -120 m to the level -105 m directly beyond the deposit. The drilling adit on the level -60 m, and the ventilation adit on the level -30 m, are located on the hanging wall of the deposit, (figure 7).

When mining at the second stage, the haulage adit of the -105 m level will become a drilling one, and the haulage and transportation adits will be located on the level -165 m. The transportation and ventilation adits are driven immediately from the northern end of the southern section to the southern end of the northern section. The length of the adits is 1500 m and 1150 m respectively.

Loaded and empty vehicles travel in the adit using a centralized signalling and communication system. Preparation of the mine field is of the ort kind at dead ends. Access orts are 40–60 m long (depending on the ore body thickness) and equipped with loading points. The length of the haulage and drilling adits is determined by mining and geological conditions.

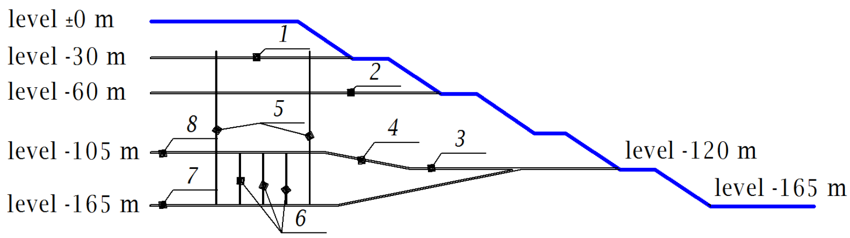

Figure 7. Deposit opening (option II): 1 – the ventilation adit; 2 – the drilling adit for mining the upper level; 3 – the loading and transport adit; 4 – the ramp; 5 – the ventilation and manway raise; 6 – the loading adit for mining the upper level reserves and the drilling adit for mining the lower level.

The total length of the haulage adit is 1500 m, and that of the drilling one is approximately 1000 m. Development and ventilation workings on areas of the second and subsequent stages of underground mining are driven as the reserves of previous areas are worked out. The mining blocks are prepared by 33 two-way access orts of 60 m each. Their total length makes 1980 m.

For effective ventilation of stoping in the hanging wall of the ore body, one ventilation-manway raise from the level -105 m to the level -30 m for every three blocks and a 1000 m long entry-collector on the level -105 m are built. The total number of raises is 16; their total length is 1200 m. Mining *Hannivske* deposit by the open pit-underground method will increase intensity of mining operations, efficiency of the enterprise and, accordingly, reduce the need for areas for external dumps. Therefore, the production capacity of the underground mine should be determined as the most possible according to annual production of minerals of the required quality.

When calculating the annual production value, operation indicators of the deposit are accepted for conditions of the most complete use of means of production, the rational mode of operation, application of the efficient technology and organization of activities of the mining enterprise which considers best practices and ensures compliance with safety requirements and technical operation rules.

Underground mining of the central part of *Hannivske* deposit is designed within axes 2.4÷3.4 ±0 m, with the level height of 165 m. According to calculations, the estimated economically feasible annual productivity of the underground mine is 3.18 M t/year, and by mining capabilities – 3.17 M t/year.

According to [6], optimization of the design productivity of the mine should be carried out on a scale of the mineral and raw material region where there is interrelation between consumption and production of this type of minerals. In the current economic conditions, considering possible iron ore product sales in the national and foreign markets, to compensate for the productivity loss due to the reduction in open pit mining volumes in the central part of the open pit, it is advisable to accept an annual productivity of 3 M t/year.

In this case, the service life of the underground mine t_p, considering final mining of the central part of the open pit within axes of 2.4÷3.4, level -165÷±0 m and the average loss factor $k_n = 0.85$, will make 18 years. The obtained value t_p meets the requirements [16, 17] for enterprises with a mineral concentration complex.

Technical solutions for the underground mine should be assessed on the basis of two main principles: the underground mine, despite a more complex technology and a relatively small share of the total production (15–20%), should provide an increase in efficiency of the main, open pit method; the technology of underground mining and the technical level of equipment should be as close as possible to those during open pit mining operations.

Broken rock mass is drawn and loaded using powerful loading and transporting equipment in the following combinations: hydraulic excavator – truck; load-haul units – truck; twin vibrofeeders – truck.

Based on the calculations performed, to ensure annual production of 3.0 M t/year, it is advisable to apply the following combination of transport equipment: load-haul units – truck. At the same time, six MT5010 trucks and three ST1810 load-haul units should operate simultaneously. For the specified mining and geological conditions, it is advisable to use an induced block ore caving system or room mining. It should be noted that when applying a room mining system with abandoned pillars, ore losses increase, and further disposal in the internal dump is not allowed. Thus, we finally adopt the system of induced block ore caving with breaking ore by parallel contiguous rings of longholes onto the vertical compensatory room.

The first 105 m high level is opened by horizontal adits driven from the open pit wall on the levels: -120 m (transportation), -60 m (drilling) and -30 m (ventilation). This option of the mining system is used, as a rule, for mining thick steep deposits.

In order to apply technological solutions that meet the minimum-operation principles, it is asvisible to draw ore from a panel through loading points. The panel and blocks are located with their long sides across the strike of the ore deposit, their length depends on thickness of the ore body (120 m), and the width of the panel is accepted 30 m. Ore reserves in the panel make $V_k = 1.28$ M t and the term of their mining is $T_0 = 0.43$ year.

To ensure the design annual productivity of 3.0 M t, three panels should be mined at a time. If the panel width is accepted to equal 30 m, the mining block width will make 90 m. Annual productivity is ensured subject to simultaneous operation of three blocks: 1 – preparatory, 1 – development and 1 – mine.

In conditions of intensive operation of self-propelled equipment, effective ventilation of stoping is provided by a forced ventilation system. It includes horizontal ventilation and manway workings on the level -30 m, ventilation raises from the level -165 m to the level -120 m and from the level -120 m to the level -30 m and a ventilation adit on the level -30 m.

Mining operations are aired according to the suction scheme. Fresh air is supplied through the adit entry, dilute exhaust gases of self-propelled equipment motors to the permissible sanitary standards and flow about workings.

According to the calculations, the period of building a start-up complex with the average per shift productivity of drifting faces of 40 m^3/shift and with the three-shift mode will make $T \approx$ 18 months. It should be noted that mining is carried out whenever required. At that, the total mining productivity can be increased by combining technological operations in several faces.

The total costs of mining operations required for commissioning the start-up complex is 2.5 M USD, the cost of mine equipment acquisition at the time of building the underground mine is 4.9 M USD. Considering the cost of equipment necessary for the construction, capital expenditures for the start-up complex will amount to 7.4 M USD. The total capital expenditures, considering the cost of additional equipment required to start stoping make 6.7 M USD, for mining and capital works – 2.3 M USD, and the total amount makes 9.0 M USD.

When mining a 90 m long and 105 m high area with the thickness of 120 m, the reserves to be mined will make 3.84 M t. Specific capital expenditures per tonne of ore reserves of the central section of the pit will be 0.26 USD/t.

The data characterizing efficiency of the underground mining enterprises of Kryvbas that apply elements of minimum-operation technology in their production cycle is used to determine the cost of extraction of 1 tonne of ore. In particular, a typical example of the above is *Ordzhonikidze* underground mine as part of the *Central Mining and Processing Plant* (Kryvyi Rih, Ukraine).

Similarly, on the UMO area of the open pit, the expected underground mine cost of ore production will make 13.69 USD/t, and the total cost will be 15.84 USD/t (table 2).

The consolidated technical and economic indicators of the combined (open pit-underground)

Table 2. Expected production costs of 1 tonne of ore during underground mining on the area of stage I of UMO.

Indicators	Costs, USD/t	Specific costs, %
Raw materials and basic materials	3.33	21.02
Remuneration of labor	2.16	13.61
Social Security deductions	0.78	4.93
Auxiliary materials	0.46	2.85
Energy costs	3.4	21.4
Fixed assets (deductions)	2.18	13.75
Service sector	0.3	1.95
Depreciation of fixed assets	0.25	1.57
Equipment maintenance repair costs	0.16	1.04
Other	0.68	4.26
Underground mine cost	13.69	86.38
General operating expenses	1.52	9.6
Non-production costs	0.64	4.02
Total cost	15.84	100

mining of the balance reserves of Hannisvke deposit are presented in table 3.

Table 3. Indicators by options under comparison.

Indicators	Option/t OPMO	Option OPMO + UMO
Annual production volume, including by areas, M t.:	10.0	10.0
-OPMO	10.0	7.0
-UMO		3.0
Cost of ore mining incl. transportation of overburden (excl. rocks removal from the internal dump), USD/t	9.93*	11.70**
Costs for liquidation of the internal dump (per 1 t of mined ore), USD/t	5.14*	
Specific capital investments, USD/t		0.26
Costs of mining 1 t of ore, USD/t	15.07	11.96

Note: * - *actual technical and economic indicators from open pit works for 2019;*
** - *weighted average indicator for OPMO + UMO.*

Comparison of the obtained indicators of open pit-underground mining with those of open pit mining confirms the viability of the open pit transition to application of the combined method of mining reserves under the internal overburden dump.

In this case, the central part of the open pit can be used to form a permanent internal dump with a capacity of over 300 M m^3. The total duration of mining and capital works, considering the previous period, is 2 years.

The first year accounts for 7.35 M USD for mining operations and acquisition of equipment necessary to start construction. Expenditures of the second year consist of costs of equipment necessary to start stoping and mining operations and amount to 9.05 M USD.

6. Conclusions

The analysis conducted enables ascertaining that the global practice of sustainable development demonstrates a trend to apply underground methods to additionally mine deposit areas with unfavorable conditions for open mining operations. Mining deposit by the combined method enables reducing environmental damages caused by open pit mining and increasing efficiency of underground operations.

Almost all considered enterprises that started mining reserves by the open pit method are implementing gradual transition from open pit to underground mining creating integrated geotechnological systems "open pit-underground mine" at the deposits. All technological solutions at underground mines that are being built or operating focus on using highly efficient options of mining systems and types of self-propelled drilling, haul and transportation equipment. In some cases, deposit areas are opened for underground mining operations by vertical shafts equipped with high-speed automated hoisting units.

The suggested complexes of inclined and horizontal workings ensure efficient operation of self-propelled equipment and increase productivity of the mining enterprise to 3 M t/year. Based on the calculations performed, it is advisable to apply the following combination of transport equipment: six MT5010 underground trucks and three ST1810 load-haul units.

When applying the combined method to mine reserves under the bottom of *Hannivskyi* open pit by underground methods, the cost of production will decrease by 3.11 USD/t, of which 0.26 USD/t are specific capital investments for underground mining. The total amount of capital expenditures will amount to 16.4 M USD.

Acknowledgments

The work was supported by the Ministry of Education and Science of Ukraine within the framework of the state scientific topics "Determination of regularities of the stress-strain state of rocks disturbed by workings with the purpose of developing resource-saving ore mining technologies" (State registration 0115U003179).

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IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: Vu Trung Tien 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012009

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012009 doi:10.1088/1755-1315/1049/1/012009

Determination of the movement and deformation areas of strata when exploiting longwall of Seam 11 under the open-pit mine at Ha Lam Coal Mine, Vietnam

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Abstract. Exploiting the face under the finished open-pit area always has potential risks of unsafety. It can be the risk of water flowing into the face or the occurrence of water cracking and mud, which is a very dangerous phenomenon in mining. The larger the dimension of the influence area of exploiting the face is, the greater the risk of water problems entering the face is. Through the assessment and analysis of the coal exploitation at the synchronized mechanized face of Seam 11 located under the open pits that have finished exploitation at the Ha Lam coal mine, the article has determined the movement and deformation areas of strata in the surrounding area to assess the influence of water in the open pit into the face. In order to avoid the risk of water cracking, the impact of these risks on the workers' safety and the exploiting process, the determination of the movement and deformation areas of surrounding rocks when exploiting the longwall face of the coal Seam 11 is very necessary for the Ha Lam coal mine. By collecting and analyzing geological conditions of the rocks around the face, combined with numerical modelling methods, the author has determined the dimension of the collapse and cracking areas when exploiting the face. The results of the research from this article have helped the Ha Lam coal mine take the initiative to choose and organize a rational mining solution. On that basis, it is possible to prevent the influence of water in an open-pit mine to ensure safety during exploiting the face of coal Seam 11.

1. Introduction

Ha Lam coal mine is one of the largest and most modern underground mines in Vietnam. Because the upper part of some coal seams are exploited by the open-pit mining method, when the mining part ends, open-pit pits will be formed [1]. According to calculations and forecasts, although the open pits have been dumped, they still contain a large amount of water, especially in the rainy season [2]. Therefore, when mining work continues by underground mining method in the area under these open pits, there will be many potential risks and insecurity, especially the risk of water cracking and mud [3, 4]. Currently, in a number of mines in the Quang Ninh coalfield, including Ha Lam coal mine, which is facing many difficulties in exploiting the seams, the coal reserves located under the open pit have finished exploitation. This is a problem that is not only concerned by the leaders of the mines, but also by the leaders of the Vietnam National Coal – Mineral industry Corporation [5, 6].

The longwall of Seam 11 in the Ha Lam coal mine is located under the area of open pits, including pit -54; -80; -60. The stratigraphic distance to the bottom of the pit is about 100 ÷ 120 m, the stratigraphy consists of a layer of siltstone lying on the coal seam with a thickness of about 5 ÷ 6m, followed by a layer of sandstone with a thickness of about 5 ÷ 18 m, above the sandstone layer is The gravel layer has a thickness of about 15 ÷ 35 m, above the gravel layer is a layer of siltstone mixed with sandstone with a thickness of about 12 ÷ 40 m [7]. The exploitation of this seam leads to unsafe risks such as: subsidence; surface deformation; the mine pressure in the mining area affecting the roadways are very complicated, as well as the phenomenon of the influence of the water contained in the open pit on the underground mine is very large, the risk of the water cracking, mud in the mine. In order to avoid potential water risks, it is necessary to observe, forecast and calculate the height of the collapse area and the fractured area when exploiting Seam 11 of the Ha Lam coal mine [8]. On that basis, it is possible to assess the level of influence of water on mining. In this paper, the author uses the numerical modeling method, by using UDEC software to monitor and determine the height of collapse and cracking of the roof when exploiting the longwall of Seam 11. Input parameters of rock and coal conditions are collected from the actual mine, build a model and conduct model analysis on the basis of the mining plan of the respective longwall.

The analysis and observation results from the numerical model have determined the height of the movement and deformation zones of the roof corresponding to the displacement in the strike direction of the longwall. This research result is also the basis for the Ha Lam coal mine to be proactive in deploying and choosing a reasonable mining plan for the conditions of the coal mine.

2. Characteristics of geological conditions of the longwall of Seam 11 and the current status of open pits of Ha Lam coal mine

2.1. Characteristics of geological conditions of the longwall of Seam 11

- Thickness of seams: 12 m;
- Average slope angle: 8^0;
- Exploiting height of the longwall: 2.6 m;
- The length of the longwall in the dip direction: 118.5 m;
- The length of the longwall in the strike direction: 550 m;
- Immediate roof: The Immediate roof is siltstone with a thickness varying from 5.0 ÷ 12.0 m, with an average thickness is 8.0 m. Compressive strength 110 ÷ 2104 kG/cm^2, average 613 kG/cm^2. Average volumetric weight 2.65 g/cm^3.
- Main roof: The Main roof is sandstone with a thickness is from 23 ÷ 48 m, the average is 30 m. Compressive strength 113 ÷ 3132 kG/cm^2, average 1188 kG/cm^2. Average volumetric weight 2.62 g/cm^3 [9].
- According to the current status of the mining area of Seam 11, the area with potential risk of water cracking of the longwall is located in the distance between the T40 and the T50 with a length of about 163m (figure 1), in which the area of the longwall is directly located at the bottom of the open pit -54 from the first position of the longwall, which is about 93 m [9].

2.2. Mining technology of the longwall of Seam 11 in the Ha Lam coal mine

In order to exploit the condition of thick seams, gently sloping, Ha Lam coal mine has applied the diagram of mining technology of the longwall advancing methods, cut coal by the shearer, protect the longwall by shield support, and transport coal by scraper conveyors (figure 2). The specific combination of equipment used in the longwall is as follows:

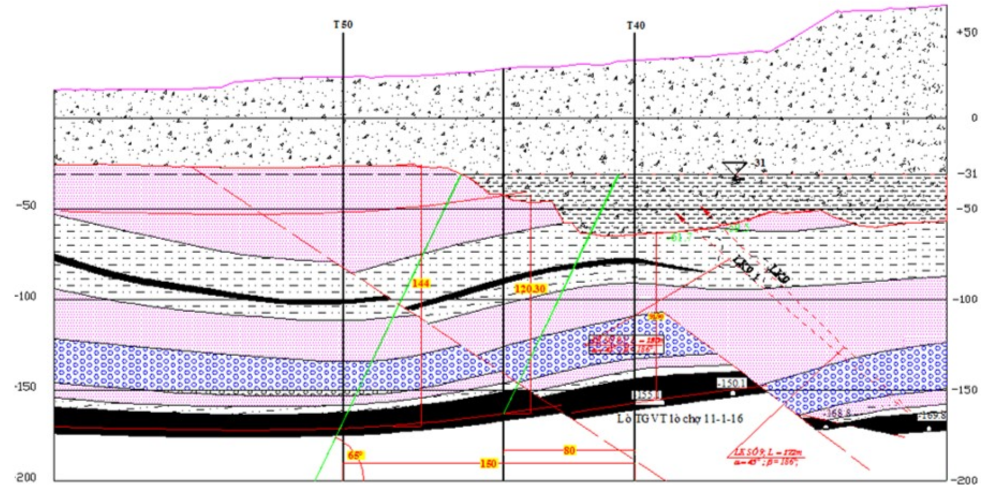
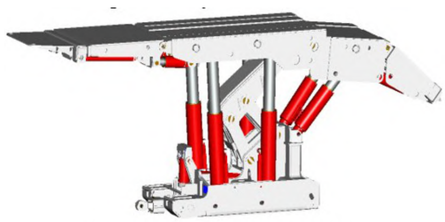
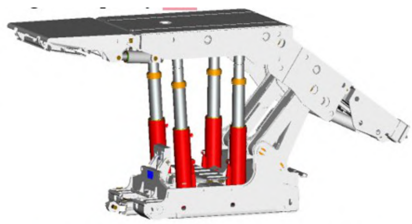


Figure 1. Cross-section IV-IV.



Shield of type ZF4400/16/28.



Shield of type ZFG4800/18/28.

Shearer of type MG150/375-W.

Scraper conveyors coded SGZ 630/264.

Figure 2. A group of equipment used in the longwall of coal Seam 11 – Ha Lam Coal Mine [10].

- Shield of type ZF4400/16/28, the height of the shield is 1.6 ÷ 2.8 m. The number is 73 shields;
- Shield of type ZFG4800/18/28, the height of the shield is 1.8 ÷ 2.8 m. The number is 6 shields;
- Shearer of type MG150/375-W. Designed capacity 500 tons/h;
- Scraper conveyors coded SGZ 630/264. Designed capacity 600 tons/h.
- In addition to the main equipment mentioned above, the synchronous equipment in the longwall also has a number of other equipment such as emulsifying pump station, winch, etc. figure 3 shows the actual coal mining process in the mechanized longwall of Seam 11 of the Ha Lam coal mine.

Figure 3. Coal mining in mechanized longwall of Seam 11 of the Ha Lam coal mine [10].

2.3. Current status of exploited open pits
The waste dump in the Seam 14 at West Side is dumped by Ha Lam and Nui Beo mines, which is currently at +160 m in the southwest, while the design level is +70 m. The waste dump area in the Seam 14 at West wing includes 03 open pits that have been finished and 01 open pits that is being exploited, specifically as follows:

- Open-pit mining of Seam 14 at West Side at level -80 has finished mining and dumped waste to the level of +30. Open-pit mining is located on the longwall CGH11-1.16, the stratigraphic distance from the longwall to the bottom of the pit is about 85 $\div$ 100 m, the stratigraphy consists of a siltstone layer lying on the coal seam with a thickness of about 5 $\div$ 12 m, followed by a sandstone layer, the gravel has a thickness of about 15 $\div$ 60 m, above the sandstone layer, the grit is a layer of siltstone with a thickness of about 20 $\div$ 60 m.
- Open-pit mining of Seam 14 at West Side at level -60 has finished mining and dumped waste to the level of +35. Open-pit mining is located on the longwall CGH11-1.16, the stratigraphic distance from the longwall to the bottom of the pit is about 120 $\div$ 150 m, the stratigraphy consists of a siltstone layer lying on the coal seam with a thickness of about 8 $\div$ 12 m, followed by a sandstone layer with a thickness of about 50 $\div$ 70 m, above the sandstone layer is a layer of siltstone with a thickness of about 40 $\div$ 50 m, above the sandstone layer is a layer of sandstone with a thickness of about 20 $\div$ 50 m.
- Open-pit mining of Seam 14 at level -53 has finished mining and dumped waste to +40 level. Open-pit mining is located on the longwall 11-3T-13, the stratigraphic distance from the longwall to the bottom of the pit is about 140 $\div$ 180 m, the stratigraphy consists of a siltstone layer lying on the coal seam with a thickness of about 5 $\div$ 11 m, followed by a layer of sandstone with a thickness of about 38 $\div$ 40m, above the sandstone layer is a layer of siltstone with a thickness of about 60 $\div$ 100 m.
- Open-pit mining of Seam 14 at West Side at level -54 (figure 4). Open-pit mining is located on the longwall CGH11-1.16, the stratigraphic distance from the longwall to the bottom of the pit is about 100 $\div$ 120 m, the stratigraphy consists of a siltstone layer lying on the coal seam with a thickness of about 5 $\div$ 6 m, followed by a sandstone layer with a

thickness of about 5 ÷ 18 m, above the sandstone layer is a layer of gravel with a thickness of about 15 ÷ 35 m, above the gravel layer is a layer of siltstone mixed with sandstone with a thickness of about 12 ÷ 40 m.

The work of dumping waste at this landfill in recent years has been carried out in the form of a circumference, dumping in the order of exploitation (when the mining is finished, dump the waste there), the height of the waste layer is from 30 ÷ 50m, almost no floor has entered the end position [11].

Figure 4. Open pit bottom of Seam 14 at West Side.

3. Characteristics of hydrogeological conditions around the area of the longwall of Seam 11

Within the study area, the reserves of Seam 14 are exploited by the open-pit method of the Nui Beo coal mine. Mining has destroyed the original topography, creating on the topography open pit and dumps that can be placed for water to accumulate. The reserve of Seam 11 below the upper pits has been mobilized by Ha Lam coal mine to exploit by the underground method according to the planning of the build mining investment project below -50 Ha Lam coal mine. The coal seam in this area belongs to the type of thick and gentle seams, exploited and using the roof control method by full caving, thus creating collapsed and cracked areas capable of developing from the ground to the topographic surface, if the mining depth is not too large [12–14].

Synthesized hydrogeological conditions in the area can be commented that the water source affecting underground mining is mainly water from open pits that have been exploited with a flow of about 500 000 m^3 [15]. Therefore, in the process of preparing and exploiting the longwall of Seam 11 in Ha Lam coal mine located under the open pits of Seam 14 in Nui Beo coal mine, it is necessary to have solutions to prevent the risk of water cracking into the longwall. In order to choose reasonable solutions, it is necessary to study and assess the risk of water cracking from the upper open pits into the longwall of Seam 11.

4. Determination of the movement and deformation areas of strata when exploiting longwall of Seam 11 under the open pit mine at Ha Lam coal mine

4.1. Proposing mining options to determine the movement and deformation areas

Option 1: the exploitation height of the longwall is 2.6 m, recovering 90 percent (equivalent to

9.4 m).
With a Seam 11 thickness is 12 m, the exploitation height of the longwall is 2.6 m, recovering 9.4 m (90 percent of top coal. Continuously cutting in 3 production shifts (one web cut for each), the longwall advance is 1.8 m/day (corresponding to 3 web cuts/day).

Option 2: the exploitation height of the longwall is 2.6 m, recovering 50 percent (equivalent to 4.2 m).
With a Seam 11 thickness is 12 m, the exploitation height of the longwall is 2.6 m, recovering 4.2 m (50 percent of top coal. Continuously cutting in 3 production shifts (one web cut for each), the longwall advance is 1.8 m/day (corresponding to 3 web cuts/day).

Option 3: the exploitation height of the longwall is 2.6 m, not recovering of top coal.
With a Seam 11 thickness is 12 m, the exploitation height of the longwall is 2.6 m, not recovering of top coal. Continuously cutting in 3 production shifts (one web cut for each), the longwall advance is 1.8 m/day (corresponding to 3 web cuts/day).

4.2. The basis for determining the movement and deformation areas corresponding to the above options

- Determine the distance of the collapsed and the fractured areas in the roof area of the longwall of Seam 11, corresponding to the above options, and compare it with the distance from the bottom of the pit to the mining location of the longwall. From there, assess the risk of water cracking into the longwall from the open pit mining above Seam 11.
- Determine the caving step of the roof in order to propose mining solutions to ensure safety when mining the longwall face of Seam 11 under the open pit at Ha Lam coal mine.
- Ensure the safe height from the cracked area when exploiting the longwall to the bottom of the open pit.

4.3. Building simulation numerical model

Based on geological conditions, the results of determining the physico-chemical parameters of the roof and floor rock in the mining area (shown in table 1 [16]), using UDEC 3.1 software (Universal Distinct Element Code) to build numerical modeling monitoring the state of the roof when mining the longwall. Based on the physicochemical parameters of the roof and floor rock in the mining area, UDEC software is applied to build numerical modeling to monitor the mining process of the longwall of Seam 11 with dimensions of 210 x 210. Corresponding to the three options proposed in Section 4.1 above, exploiting the height of the longwall is 2.6 m with the recovery rates of top coal including 90 percent; 50 percent and not recovering. figure 5 shows the simulation of UDEC 3.10 software and the CGH48 borehole stratigraphic column of Seam 11 in the Ha Lam coal mine. figure 6 shows the simulation of the monitoring process of the roof when exploiting the longwall.

Based on the analysis results from UDEC 3.1 software, determine the distance of the collapse area, the distance of the fracture zone of each of the above options, compare with the distance from the bottom of the pit to the mining location to evaluate the influence of the water from the open pit on mining work at the Seam 11 in Ha Lam coal mine.

4.4. Analyze the results from the numerical model

Based on the analysis results from UDEC 3.1 software, determine the distance of the collapse step of the roof, the height of the collapse and the cracking of the roof of the longwall of Seam 11. Based on the results of the monitoring model, the dimension shows collapse and cracking of the

Table 1. Analytical results of the roof and floor rock of Seam 11.

Rock unit	Value	Compression resistance strength	Tensile strength (kG/cm^2)	Internal friction angle (^{0})	Cohesive force	Volumetric weight (g/cm^3)	Specific weight (g/cm^3)
gravel stone (Roof)	Max	3255.00	149.06	$35^0 00'$	590.00	2.63	2.67
	Min	1052.80	89.18	$33^0 30'$	339.00	2.50	2.62
	Medium	1595.49	118.26	$34^0 50'$	436.71	2.58	2.65
Sandstone (Roof)	Max	1559.02	164.00	$35^0 30'$	525.00	2.80	2.81
	Min	173.01	26.88	$26^0 00'$	39.00	2.53	2.60
	Medium	927.35	93.64	$33^0 34'$	311.14	2.65	2.70
Siltstone (Roof)	Max	1726.00	128.00	$38^0 27'$	330.00	3.06	3.12
	Min	110.84	24.21	$16^0 00'$	38.50	2.47	2.54
	Medium	521.78	55.38	$32^0 27'$	145.42	2.66	2.74
Claystone (Roof)	Max	230.68	30.45	$32^0 06'$	68.00	2.80	2.86
	Min	166.88	24.52	$30^0 00'$	53.00	2.62	2.68
	Medium	206.22	27.35	$31^0 12'$	62.00	2.70	2.75
gravel stone (Floor)	Max	1536.91	139.19	$35^0 00'$	460.00	2.65	2.69
	Min	800.13	77.71	$33^0 56'$	244.00	2.56	2.64
	Medium	1198.45	107.24	$34^0 22'$	361.00	2.60	2.67
Sandstone (Floor)	Max	2811.42	238.00	$35^0 35'$	900.00	2.79	2.81
	Min	127.00	42.00	$31^0 45'$	138.00	2.52	2.63
	Medium	1061.93	102.37	$34^0 16'$	347.26	2.66	2.71
Siltstone (Floor)	Max	1402.80	106.20	$38^0 56'$	420.00	3.57	3.59
	Min	172.55	5.86	$27^0 30'$	53.00	2.02	2.35
	Medium	472.90	51.12	$32^0 37'$	134.75	2.65	2.73
Claystone (Floor)	Max	1987.00	76.50	$33^0 54'$	116.00	2.76	2.84
	Min	103.00	22.30	$29^0 30'$	43.00	2.44	2.55
	Medium	460.18	34.66	$31^0 49'$	71.14	2.60	2.69

options for depreciation and recovery when the longwall moves in the corresponding direction, specifically as follows:

Option 1: the exploitation height of the longwall is 2.6m, recovering 90 percent (equivalent to 9.4 m)

When the longwall is cut in the strike direction corresponding to specific lengths, the movement of the longwall is monitored, and the model shows the results of the roof collapse and the corresponding crack formation process. In figure 7 the process of collapse and cracking of the roof when the longwall moves 95 m.

The results from the model show that when the longwall is cut in the 95 m strike direction, the height of collapse and cracking of the roof is from 65 ÷ 70m. However, in this option, some cracks develop to the bottom of the open pit, potentially posing

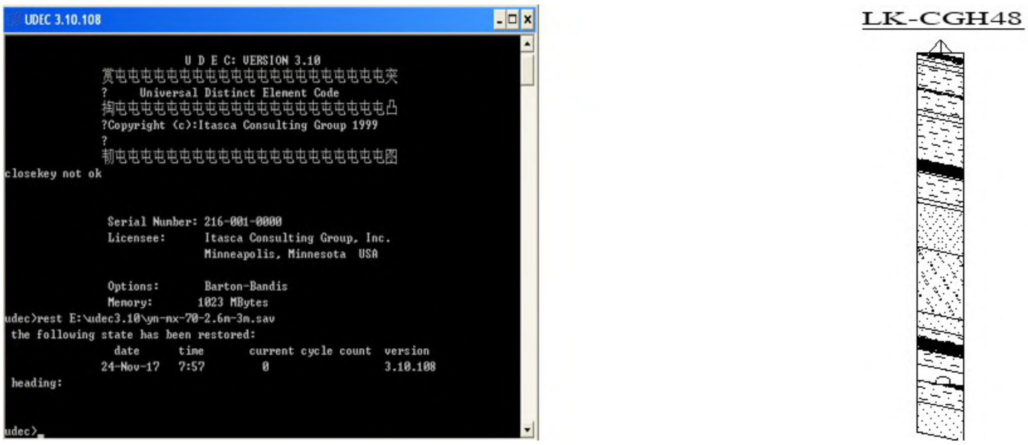


Figure 5. Simulation of UDEC 3.10 software and CGH48 borehole stratigraphy column of Seam 11 in Ha Lam coal mine.

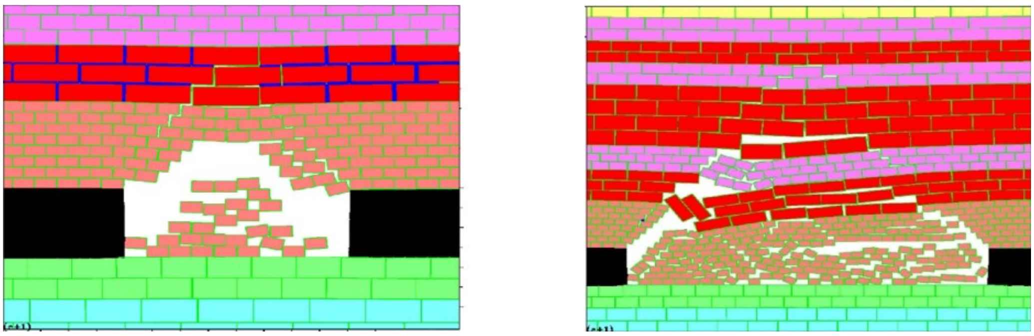


Figure 6. Simulation of the process of monitoring the longwall when mining [12].

a risk of unsafety when mining.

Option 2: the exploitation height of the longwall is 2.6m, recovering 50 percent (equivalent to 4.2 m). The monitoring results on the model of this option are shown in figure 8.
The results from the model show that when the longwall is cut in the 95 m strike direction, the height of collapse and cracking of the roof is from 55 ÷ 60m. However, in this option, some cracks develop to the bottom of the open pit, potentially posing a risk of unsafety when mining.

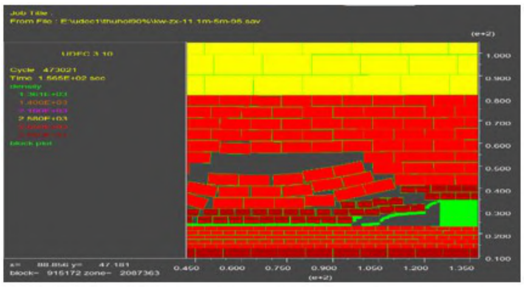
Option 3: the exploitation height of the longwall is 2.6m, without recovering of top coal. The monitoring results on the model of this option are shown in figure 9.
The results from the model show that when the longwall is cut in the 95 m strike direction, the height of collapse and cracking of the roof is from 50 ÷ 55 m.

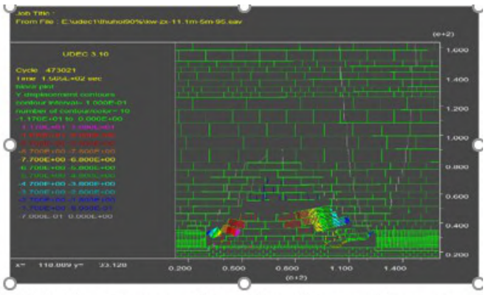
5. Results and discussion

Based on the results of the monitoring model, the height of collapse and cracking of the mining and recovery options when the longwall of Seam 11 when cutting 95 m in the strike direction is shown in table 2.

However, in option 2, and option 3, when cutting 95 m in the strike direction, there is a crack that develops to the bottom of the open pit -80, which will pose a potential risk of unsafety in exploitation.

Option 3 exploits the height of the longwall is 2.6 m, does not recover the top coal, this option


(a) The process of forming the collapse zone.


(b) The process of forming the cracking zone.

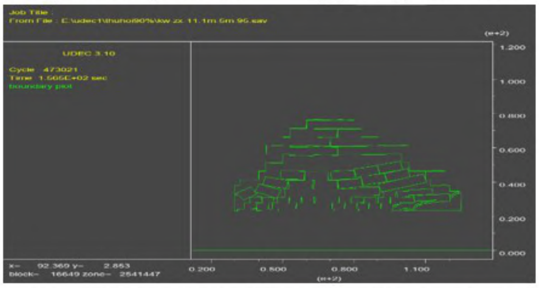
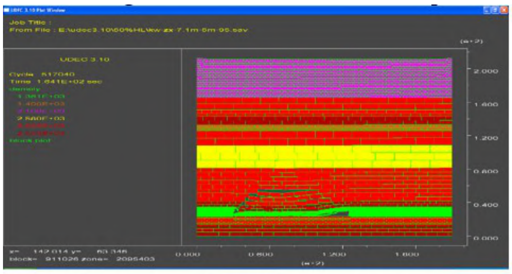
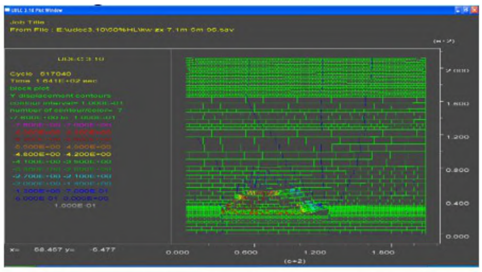

(c) The process of forming the height of the collapse and cracking zone.

Figure 7. Status of the roof of the longwall of Seam 11 when cutting 95 m in the strike direction (Option 1).


(a) The process of forming the collapse zone.


(b) The process of forming the cracking zone.

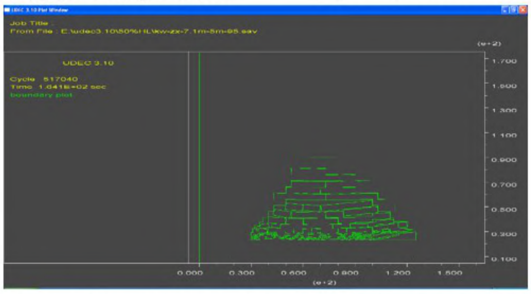
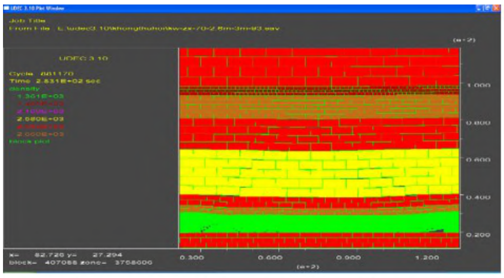
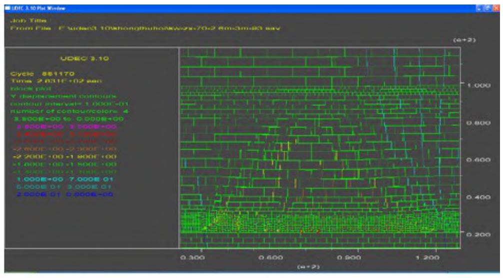

(c) The process of forming the height of the collapse and cracking zone.

Figure 8. Status of the roof of the longwall of Seam 11 when cutting 95 m in the strike direction (Option 2).

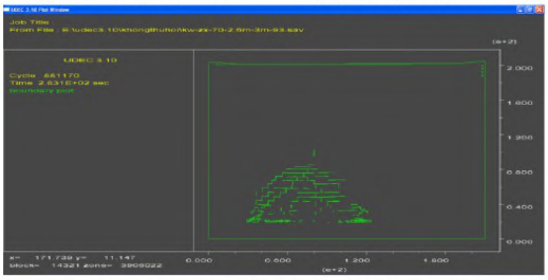
has the monitoring results on the model indicating that it is safer than the two options above. However, this is the option with the largest coal loss among the three options.



(a) The process of forming the collapse zone.



(b) The process of forming the cracking zone.



(c) The process of forming the height of the collapse and cracking zone.

Figure 9. Status of the roof of the longwall of Seam 11 when cutting 95 m in the strike direction (Option 3).

Table 2. Height of collapse and cracking of three options 1, 2 and 3.

Option	The length of the longwall when cutting in the strike direction (m)	The height of collapse and of the roof of the longwall of Seam 11 (m)
1	95	65-70
2	95	55-60
3	95	50-55

6. Conclusions

Through the combined results of the article, the author analyzed the actual conditions of the longwall using the mechanized mining technology of Seam 11 in the Ha Lam coal mine. Based on the proposed 3 mining options, the author calculated and forecasted the height of the movement and deformation zones of the roof. This result is observed for each mining option of the longwall by numerical modeling method, the documents for building the numerical model are provided by the Ha Lam coal mine, so it has the necessary reliability.

The research results of the article can serve as a basis for the Ha Lam coal mine to consider forecasting the movement and deformation height of the roof when exploiting the longwall of Seam 11 for each of the above mining options. Based on the assessment and monitoring of hydrogeological conditions, as well as the calculation of the water flow stored in the open pit, Ha Lam coal mine can choose a reasonable exploitation plan for the longwall of Seam 11. In the process of exploiting the longwall, it is necessary to continue to monitor and evaluate the water appearing in the longwall, and at the same time maintain an appropriate drainage solution, if any abnormality is found, it is necessary to have timely solutions.

The rational exploitation plan applied at the longwall of Seam 11 in the Ha Lam coal mine will bring high efficiency and meet the requirements of actual production. On that basis, improve the ability to use the equipment effectively, improve the safety in the mining operation of the longwall, and prevent the occurrence of water and mud problems. Therefore, the exploitation of coal seams under the open pit area is an extremely necessary problem. The combined results of the article can also serve as a document for researchers in the field of coal mining technology in the Quang Ninh coalfield.

Acknowledgments
The author would like to thank the Board of Directors of two Ha Lam and Nui Beo coal mines in Quang Ninh coalfield, Vietnam for creating favorable conditions, providing data, and surveying the field for the author to complete this study.

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A study of rock response to failure in the context of the bending properties and comparison with uniaxial tensile and compression behaviour

To cite this article: K Tomiczek 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012010

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012010 doi:10.1088/1755-1315/1049/1/012010

A study of rock response to failure in the context of the bending properties and comparison with uniaxial tensile and compression behaviour

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Abstract. The phenomenon of rock bending occurs during underground exploitation, construction of underground excavations and tunnels, and even rising heading – shafts. It is also common in building engineering, e.g., in the case of floors. Rocks and concretes as granular materials on the aggregate scale are fractured as a result of exceeding shear and tensile strength. In a complex state of stress – bending, crack propagation occurs from tensioned to compressed fibres. Three-point bending tests of medium-grained quasi homogeneous and isotropic sandstone were tested for strength and deformation properties of rocks. The E deformability modules for compressed and tensioned fibres as well as strains at failure were determined. The results of three-point bending were compared with the results of uniaxial compression and direct tension. Clear differences were found in the values of strengths, moduli of deformation and strains at failure. The bending strength B of about $9.5 MPa$ is almost 3 times greater than the direct tensile strength σ_T of about $3.2 MPa$ and is 1/10 of the ultimate uniaxial compression strength σ_C. With three-point bending, the values of the moduli E are equal to: for tensioned fibres about $6.7 GPa$, for compressed fibres $14.6 GPa$; in uniaxial compression tests about 13.0GPa and in direct tensile tests $4.8 GPa$. Rock material was also failure at various strains values at the ultimate strength. In the case of three-point bending tests, the strains at failure were equal to: for tensioned *fibres* about 0.125%, and for compressed *fibres* 0.065%; in uniaxial compression tests ε_z were equal to about 0.63% and in direct tension tests 0.07%.

1. Introduction

A commonly used material constant describing the strength properties of rocks, but also concretes, composite granular materials and cohesive soils is the one- (and three-) axial compression strength σ_C. The use of this constants as a strength parameter is usually sufficient to solve most problems in the field of geomechanics, geotechnics and strength at the engineering level. However, materials such as rocks and concrete are in fact fractured by shearing and/or tensioning, which already occur at the level of grain aggregates [1].

Compression and shear tests are in common use, while uniaxial tensile tests are much less common. Failure of rocks is often due to *flexure*. Bending of rock layers occurs in the case of underground chamber roofs, mining excavations, tunnels and even rising headings at high horizontal stress values. Also in building engineering, the problem of bending of floors is key when designing ground-based and underground structures.

Bending tests of rock beams are rare, e.g., [2]. This is primarily due to the difficulty of obtaining and making rock samples with recommended accuracy, as well as the need to compare with the results of other strength tests, e.g., uniaxial tensile tests. In the case of rocks in Poland, the phenomenon of bending of rocks was analysed only in the context of the bending strength and bending of roof layers near mining excavations. Such analyses were conducted by: in 1955 Salustowicz [3], Salustowicz and Galanka [4]. Borecki and Chudek [5] and later Kidybinski [6]. They gave the values of bending strength of rocks as one of the three basic material constants. In turn, Hobler [7] and Nagaraj [8] write about the tests of bending strength of rocks in the context of equating it with tensile strength.

Although the phenomenon of rock damage and failure occurs in many cases as a result of their *flexure*, issues related to rock stability are solved primarily on the basis of compression and shear constants. Constants of elasticity are used, e.g., Young's modulus E, volumetric modulus K and shear modulus G. Similarly, in the numerical modelling the basic constants are already mentioned constants and constants related to shear strength such as cohesion c or angle of internal friction ϕ.

Few tests of rocks indicate, however, that bending strength B should not be equated with tensile strength σ_T, and $\sigma_B = (1.42.0)\sigma_T$. According to Kidybiński [6], the σ_B/σ_T ratio is equal: for coarse-grained sandstones 1.7, for fine and medium-grained sandstones 1.4, for slates and coals 2.5. It also turns out that the properties of rock material subjected to bending are definitely different from that characteristic of rocks under compression or tension.

2. Materials and methods

Samples of medium-grained homogeneous and isotropic *Brenna* sandstone were tested. The properties of this sandstone have been well known as a result of research conducted in previous years, including uniaxial compression- and direct tensile-, *Brazilian*- and shear under compression tests, e.g., [9, 10].

Brenna sandstone is a medium-compactness light grey sandstone with a green, fine-grained shade with a random texture. A standard testing machine (compression/tension, $400kN$) EDZ-40 by Werkstoffprufmaschinen Leipzig (DDR) was used for the tests. The piston pressed out from the machine's working cylinder at a constant velocity of $0.003mm/s$. Cuboid samples with dimensions of $1555cm$ (hab) were placed on a steel plate with hardness above 45HRC on two cylindrical pins. Samples were made in 2017-2019 in accordance with the recommendations of the *International Society of Rock Mechanics* [11]. They were made in the sample preparation workroom of the Department of Geomechanics and Underground Construction. The distance between the supports was $11.5cm$. The sample was loaded halfway through its ball-and-socket joint (figure 1).

Axial (longitudinal) strains ε_z were measured by latticed strain gauges type RL350/30/2.15 (made of Spoldzielnia Pracy "Techno-Mechanik", Gdansk, Poland) and by the 16-channel MGCplus strain gauge bridge (Hottinger Baldwin Messtechnik, HBM). For the acquisition of measurement data, the Catman v. 5.0 (HBM) program was used. A system of six independently connected strain gauges glued in the middle of the sample height, vertically to its longitudinal axis on the left, right and the bottom side of sample walls, taking into account the position of sample in the device, was used (figure 2).

Some authors, e.g., Hobler, equate bending strength σ_b with tensile strength (in bending test) and state that σ_B is calculated as:

$$\sigma_T(=\sigma_B) = \frac{2}{3} * \frac{F * l}{b * h^2}, Pa \tag{1}$$

where: $\sigma_T(=\sigma_B)$ – tensile strength determined in the three-point bending test, Pa, F- point load, N, l – distance between supports, m, h – beam height, m, b – beam base (width), m.

As already mentioned, laboratory tests show, however, that bending strength σ_B should not be equated with tensile strength, and $\sigma_T = (0.50.7)\sigma_B$.

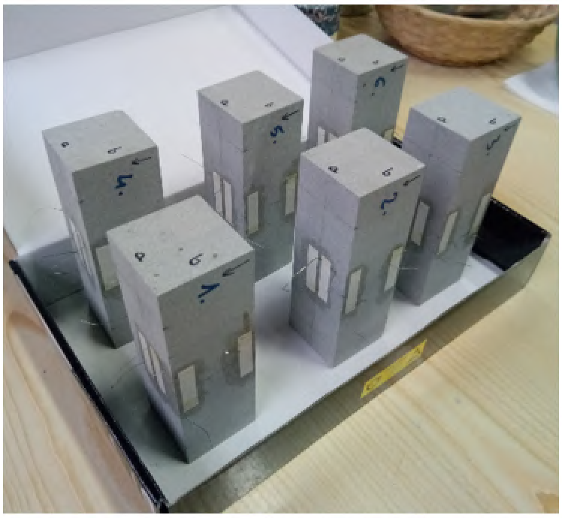

Figure 1. *Brenna* sandstone samples with strain gauges before testing.

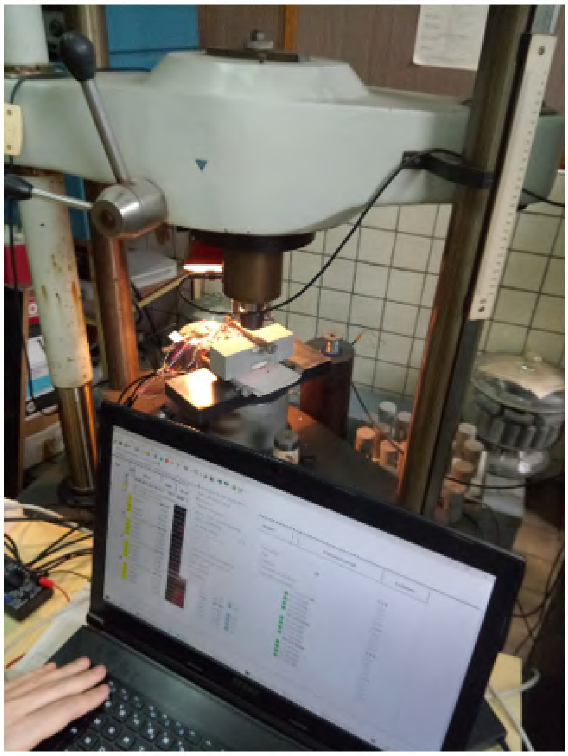

Figure 2. Test stand for three-point bending tests of *Brenna* sandstone beams.

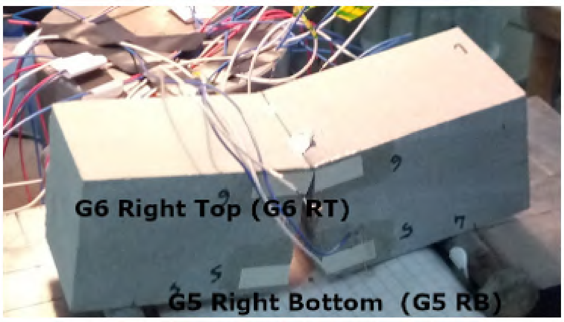

Figure 3. Method and places of gluing electro-resistance strain gauges; *right* side of sample.

Figure 4. *Brenna* sandstone beams after bending tests.

Jastrzebski et al. [12] describe the phenomenon of bending such as "the originally straight axis of the beam is curved, whereby the longitudinal fibres of the beam from the convex side are elongated, and from the concave side they are shortened". If in the cross section except to the bending moments there are no lateral forces or they are negligible, we can talk about *pure* bending. Tasks related to the determination of beam deformations and stresses can be easily solved in the case of simple symmetrical bending. "It occurs when all forces act in one plane, called the plane of forces, which is also the plane of symmetry of the beam". Then, only normal stresses σ_n occur in the cross-section of the beam relative to this cross-section. There are no tangential stresses τ. Stresses and strains can be determined strictly only in a few simple load cases; the simplest is three-point bending. Nagaraj [8] writes that in the case of pure bending, by determining the strength and deformation modulus for tensioned *fibres* of rock beam sample, one can (probably) talk about determining the tensile strength and modulus for tensioning the rocks.

If the *elongation* (deformation) of longitudinal fibres lying on the tensile bar's wall (figures 5-6):

$$\varepsilon_x = \frac{z}{\delta}, \tag{2}$$

where: δ – radius of curvature, m, z – distance from neutral axis (NA); for rectangular cross-section $z = 0.5h$, m. If the maximum normal stresses σ_x change linearly at the beam cross-section

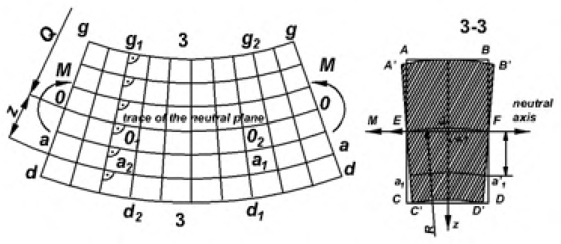

Figure 5. Enlargement of the central part of the bar and cross-section $3-3$; A, B, C, D, E, F, G – characteristic points before loading, " ' " – during loading. In practice, it can be assumed that the lateral deformations are so small that the shape and dimensions of the neutral ABCD surface (cross-section) remain unchanged [12].

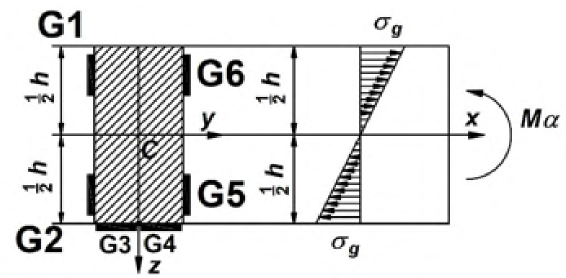

Figure 6. Stress graphs σ_g of the rectangular cross-section; $M\alpha$- bending moment in cross-section, corresponds to M_g [12].

height and their extreme values are in the *fibres* clearance line from the neutral axis, we can write that:

$$\varepsilon_x = \frac{E * z}{\delta}, \tag{3}$$

Therefore:

$$\varepsilon_x = \frac{\sigma_x * \delta}{z}, \tag{4}$$

where: E_b – modulus of elasticity of tensioned fibres, GPa, $\sigma_x = \sigma_B$ – concurrently, (after [12]). Knowing the value of bending strength $\sigma_B(= \sigma_x)$, one can determine the value of the elastic modulus E_b of tensile beam *fibres*.

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3. Results of laboratory tests

The results of the *Brenna* sandstone bending tests were compared with the results of other tests carried out in previous years. *Brenna* sandstone has already been subjected to uniaxial compression (figures 7a, 7b and 7c), uniaxial tension ([9, 10]; figure 7d) and tensile tests using the *Brazilian* method (figures 8a and 8b). In the first series of bending tests, conducted a 3 years earlier, tests were carried out by measuring the strains of tensioned *fibres* on the bottom wall of the sample at the failure strength (tensile stresses in tables 1 and 2, [13]).

Figure 7. The servo-operated research laboratory where uniaxial compression and tensile tests were carried out: laboratory view (a), *Brenna* sandstone sample before (b) and after (c) the uniaxial compression test and before the uniaxial tensile test (d).

The mean constant values were calculated based on the laboratory tests:

- uniaxial compression strength $\sigma_C = 94.86 MPa$,
- axial strains at failure under uniaxial compression $\varepsilon_{zmax} = 0.63\%$,
- axial elasticity modulus under uniaxial compression $E_C = 12.99 GPa$,
- uniaxial tensile strength $\sigma_T = 3.18 MPa$,
- axial strains at failure under uniaxial tension $\varepsilon_{zmax} = 0.07\%$,
- axial elasticity modulus under uniaxial tension $E_T = 4.81 GPa$,
- tensile strength under *Brazilian* test $\sigma_{TB} = 5.68 MPa$,
- strength under three-point bending $\sigma_B (= \sigma_T) = 9.32 MPa$,
- axial strains at failure under bending $\varepsilon_{xmax} = 0.17\%$,
- modulus of elasticity of tensioned fibres $E_b = 5.62 GPa$.

(a) (b)

Figure 8. Brazilian test of *Brenna* sandstone samples: sample in the *Brazilian* test apparatus and view of the samples after typical tensile failure under lateral compression (*Brazilian* test).

This means that the fracture of *deflectioned* rock material occurs at tensile strain values for tensioned fibres almost 1.5 times greater than at failure of rock material under the direct tensile tests (see tables 1 and 2).

The three-point bending tests carried out in the 1st series clearly pointed differences in the constants describing the strength and deformational properties of the rock material in simple (uniaxial compression and uniaxial tension tests) and in the complex state of stress (three-point bending test), both for compressed and tensioned *fibres*.

In the 1st series of three-point bending, the strains ε_x was gauged using a system of three in series-connected strain gauges glued to the bottom walls of the samples (similar to G3 and G4 strain gauges, figure 6). It can be said in a simplification that such a strain gauge system measured (as in a serial array) the average strains over the entire width of the sample.

In the case of the 2nd, the latest series of three-point bending tests, tensile strains ε_x were also measured in the middle bottom part of the sample (strain gauges G3 and G4) and were equal to 0.14%. They were smaller than the average (measured in the 1st series of test) by about 21%, but clearly by about 142% greater than the tensile strains at the failure strength measured in uniaxial tensile tests.

Table 1. *Brenna* sandstone constants calculated on the basis of uniaxial compression, uniaxial tension and tensile *Brazilian* tests. Constant values calculated in the three-point bending test: ε_{xmax} - strains along the x axis (axial) at the failure, $\sigma_B(=\sigma_T)$- tensile strength under the three-point bending test , E_b - modulus of elasticity of *fibres* under tensile stress along the x axis (1st series of tests, [13].

Uniaxial compression test				**Uniaxial tension test**				**Brazilian test**		**Three point bending test**			
	$h:d=2$, $h=84mm$				$h:d=4$, $h=168mm$				$h:d=0.5$, $h=21mm$		**(1st series)**		
	σ_C	ε_{zmax}	E_c		σ_T	ε_{zmax}	E_T		σ_{TB}		ε_{xmax}	σ_B	E_b
No.	[MPa]	[%]	[GPa]	No.	[MPa]	[%]	[GPa]	No.	[MPa]	No.	[%]	[MPa]	[GPa]
B1	95.80	0.65	12.76	B20	3.15	0.07	4.89	B41	5.48	Bb21	-	8.98	-
B2	97.40	0.62	13.85	B21	3.54	0.09	4.13	B42	6.42	Bb22	0.16	9.16	5.67
B10	92.30	0.62	12.96	B23	3.63	0.08	4.46	B43	5.10	Bb23	0.17	10.14	5.98
B11	93.70	0.62	12.44	B30	2.74	0.04	6.65	B44	5.74	Bb24	0.16	9.34	5.75
B13	95.10	0.63	12.96	B31	2.84	0.09	3.93	B45	5.67	Bb25	0.17	9.00	5.37
μ	94.86	0.63	12.99	μ	3.18	0.07	4.81	μ	5.68	Bb26	0.17	9.29	5.32
										μ	0.17	9.32	5.62

The average (μ) values of the axial deformation modulus E_b determined for tensioned *fibres* for the 1st series of tests (3 strain gauges on the bottom sample wall, table 1) was equal to $5.62GPa$, and for the 2nd series of tests (2 strain gauges G3BL and G4BL on the bottom sample wall sample, table 2) about 19% higher and equal to $6.7GPa$. The E_b values determined at bending (tables 1 and 2) for tensioned fibres were definitely higher, by approx. 30% than the E_T values determined under direct tensile tests (table 1, see figure 9).

Comparing the values of strains at the failure strength obtained on the basis of three-point bending tests ε_x and uniaxial compression and tensile ε_z (tables 1, 2 and 3), several interesting conclusions can be drawn:

- the absolute value of compressive strains of compressed *fibres* at the failure strength in the upper part of the sample under bending is lower than the value of tensile strains (tensioned *fibres*) in the bottom part of the beam; these values are 0.07% and 0.11% respectively it means that in the case of rocks where is no symmetry of deformation (and probably stress

Table 2. Constant values calculated on the basis of three-point bending tests for a system of 2 strain gauges measuring tensile strains of the bottom beam wall (see Figure 2.8, 2nd series of tests): ε_{xmax} - strains along the x axis (axial) at the failure strength, σ_B - bending strength under the three-point bending, E_b - modulus of elasticity of fibres under tensile stress along the x axis.

Sample No.	**Bottom strain gauges (bottom beam wall, tensioned fibres)**	ε_{xmax} [%]	$\sigma_B[MPa]$	$E_b[GPa]$
1	Left G3 BL	0.147	9.02	6.14
	Right G4 BR	0.141	9.02	6.40
2	Left G3 BL	0.156	8.63	5.53
	Right G4 BR	-	-	-
3	Left G3 BL	0.146	9.40	6.44
	Right G4 BR	0.107	9.40	8.79
4	Left G3 BL	0.172	9.49	5.52
	Right G4 BR	0.139	9.49	6.83
5	Left G3 BL	0.150	9.47	6.31
	Right G4 BR	0.127	9.47	7.46
6	Left G3 BL	0.154	9.55	6.20
	Right G4 BR	0.118	9.55	8.09
	Average	0.142	9.48	6.70

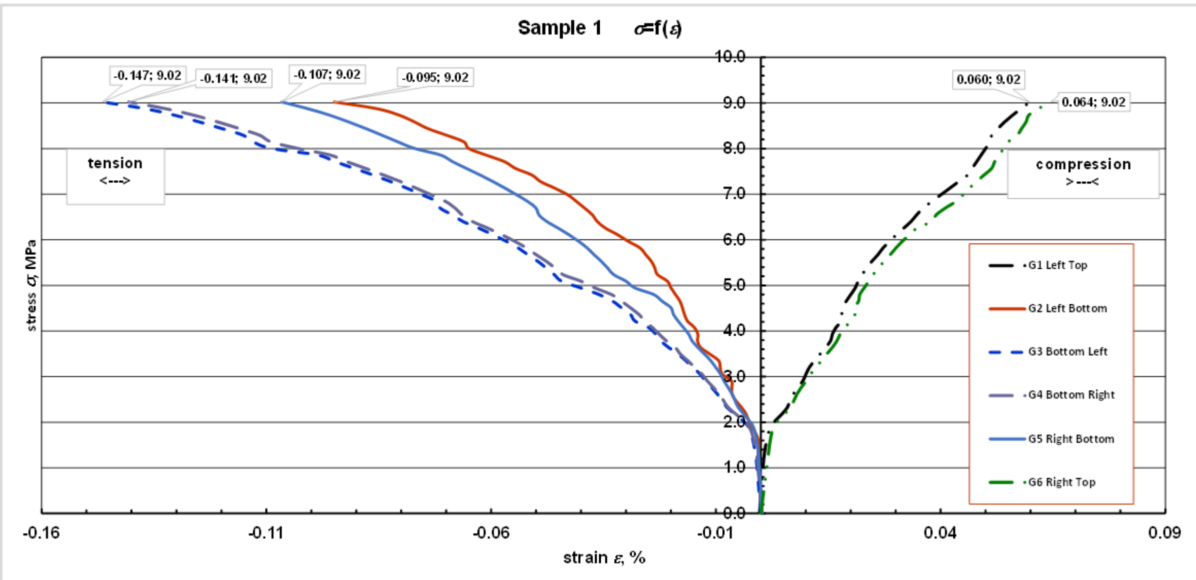


Figure 9. Stress σ - strain ε characteristics for different parts of the *Brenna* 1 beam sample under three-point bending.

Table 3. Tensile and compressive strains at the failure strength ε_x measured on the side walls of the beam. G1LT and G6RT strain gauges measured compressive strains, while G2LB and G5LB strain gauges measured tensile strains. For determined constants: $\sigma_B = 9.26MPa$ - average bending strength, $\sigma_C = 94.86MPa$ average uniaxial compression strength, $\varepsilon_z = 0.63\%$ maximum strains at failure under uniaxial compression, $\sigma_T = 4.81MPa$ average direct tension strength, $\varepsilon_z = 0.07$ average maximum strains at failure under direct tension.

Strain gauge	Sample	Position/ part	Strains	ε_{bmax} %	Strain gauge	Sample	Position/ part	Strains	ε_{bmax} %
G1 LT	1	Left upper	Compressive (+)	0.060	G2 LB	1	leftlower	Tensile (-)	0.095
	2			0.070		2			0.095
	3			0.048		3			n.d.
	4			0.080		4			0.119
	5			0.080		5			0.104
	6			0.068		6			0.114
G6 RT	1	Right upper	Compressive (+)	0.064	G5 RB	1	Right lower	Tensile (-)	0.107
	2			0.061		2			0.118
	3			0.053		3			0.107
	4			n.d.		4			n.d.
	5			n.d.		5			n.d.
	6			0.068		6			n.d.
			Average	0.065				Average	0.107

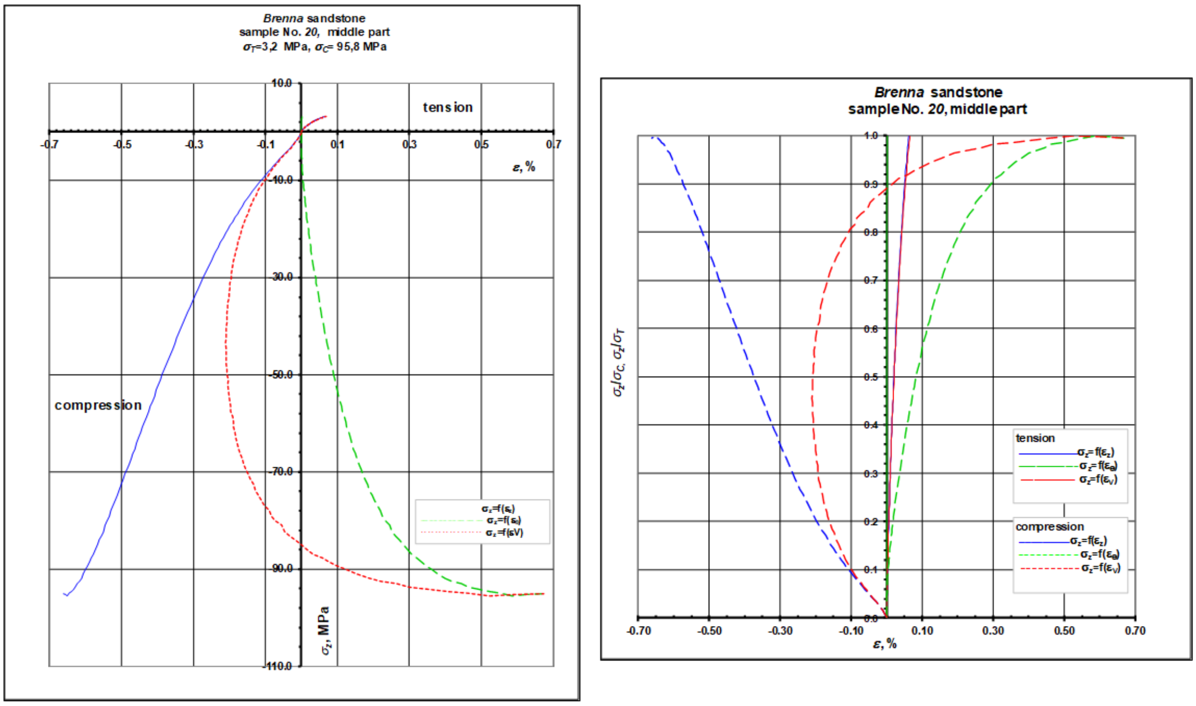
values; compare Figure 8) relatively to the neutral axis, as described by theoretical solutions based on the mechanics of continuous and elastic media, the neutral axis is probably not the axis of symmetry of beam, and it is displaced upwards;

- all stress σ - strain ε characteristics of samples under bending, for both compression and tension *fibres*, are non-linear over the entire stress range (figure 10). Such non-linear behaviour was characteristic of direct tensile tests (figure 10a), whereas in the uniaxial compression tests there were intervals of linear (elastic) behaviour (figure 10b).

To sum up, bending tests carried out on well-known homogeneous and isotropic sandstone clearly show significant differences in the values of constants calculated on the basis of bending compared to constants based on compression and tensile tests. These differences relate not only to strength and deformability, but also to strains for which the process of material failure starts.

4. Conclusions

Rocks are granular materials. Mineral grains are bound by a binder. Their behaviour in the field of compressive stress is well known. Shear and tensile tests are also carried out. Tensile tests are



(a) (b)

Figure 10. Typical characteristics of normal stress σ_z - strain ε of *Brenna* sandstone: comparison of the characteristics $\sigma_z = f(\varepsilon)$ for uniaxial compression (bottom) and uniaxial tension (top) (a) and the stress level σ_z/σ_C and $\sigma_z/\sigma_C(b)$; ε_z- axial strain, ε_o – lateral strain, ε_V- volumetric strain.

most often carried out by indirect methods, e.g., the *Brazilian* test. It is the properties of rocks under conditions of direct tension that are most free of faults resulting from test technology.

However, rock damage and failure often occur when rock layers bend. Rock layers are always bent as a result of underground mining, underground excavations, chambers and tunnels. We also encounter the phenomenon of bending in the case of other granular materials, e.g., concrete.

Two series of tests were conducted on the deformation and strength properties of homogeneous and isotropic fine-grained *Brenna* sandstone under three-point bending conditions. It is well-described and known sandstone. In previous years, research was conducted on it, including uniaxial compression, direct tension and shear under compression tests.

The presented results of laboratory tests clearly indicate the differences between the values of constants calculated on the basis of three-point bending, direct tension and uniaxial compression tests. For the tested Brenna sandstone, these differences are very clear. The bending strength σ_B of about 9.5MPa is almost 3 times greater than the direct tension strength σ_T of about $3.2MPa$ and is 1/10 of the uniaxial compression strength σ_C.

Differences also occur in the case of deformability moduli E. Under three-point bending, E is equal to: for tensioned *fibres* about $6.7GPa$, and for compressed *fibres* $14.6GPa$. For the same sandstone, the E values were equal: in uniaxial compression tests around $13.0GPa$, and in direct tensile tests $4.8GPa$. The deformability is therefore very different.

Rock material was also failured at various strains values ε. In the case of three-point bending tests, the ε_x strains were equal: for tensioned *fibres* about 0.125%, and for compressed *fibres* 0.065%. In uniaxial compression tests, failure occurred at a ε_z value of about 0.63%, and in direct tensile tests 0.07%.

The stress σ - strains ε characteristics for both compressed and tensioned *fibres* of sandstone samples under bending were non-linear over the entire stress range. Until now, the properties of rocks under bending were most often equated with their properties under tensile conditions. As it results from the conducted tests, rocks in the conditions of a complex state of bending stress show different properties than those in compression and tension, and the failure occurs at different strains values.

These rock material properties are important, especially from the point of view of researching and forecasting the development of damage zones in the excavation ceilings and underground structures, mining excavations and tunnels, and in the description of the rock material during numerical analysis and simulations.

Acknowledgments
The research was carried out as part of the statutory work (No.06/040/BK_19/0092/BK265/RG-4/2019) of the Department of Geomechanics and Underground Construction, Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, Poland.

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PAPER • **OPEN ACCESS**

Stress environment around head entries with pillarless gobside entry retaining through numerical simulation incorporating the two type of filling wall

To cite this article: I G Sakhno *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012011

Stress environment around head entries with pillarless gobside entry retaining through numerical simulation incorporating the two type of filling wall

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Abstract. Longwall mining is the most productive system for underground extraction of coal. Many coal mines use a pillarless mining. Reserving a gateroad for the usage of next panel mining is a popular gob-side entry retaining. Thus, the conventional entry retaining method requires an installation of filling walls. The mechanical properties of filling materials largely determine the quality of job-side entry retaining. Stress field evolution study around head entries when main roof console length increase with two variants of filling wall. Ansys code was used to analyze the stress evolution law under different mining conditions. As a result of numerical simulation, it was found that in the case of gob-side entry retaining, the localization of maximum stresses in surrounding rock is determined by the length console of the main roof, which hanging on the border with the gob, and the filling walls deformation module. Potential location of roof cutting, stress gradient and extremum stress in the main roof define the stability of entries. Main roof console length and filling material parameters control can help to the formation of a stable structure around the entry to meet the requirements of the next working face.

1. Introduction

Active mining of mineral resources was carried out during last century by many countries. This has led to a significant increase in the depths at which minerals are mined. Coal mining in USSR, Poland, Germany, Britain and France had reached deeper than 1000 m as early as the XX. At present the depth of coal mines has reached 1500 m, the average depth of metal mines has reached 2000 m, the depth of non-ferrous metal mines has reached around 4500 m [1]. An increase of the mining depth leads to a number of negat ive phenomena in mines: rockbursts, large-scale caving, large inrush of mixed coal, etc. One of the typical phenomena observed at great depths is damage to and failure of the surrounding rock masses of mine roadways.

Mine roadways are a very important element of a coal mine. Their condition largely determines the safety and rhythm of the mine, the stability of ventilation, total cost of extracted mineral resources.

A common underground coal mining technique used in the United States, China, Poland, Russia, Ukraine is the longwall method. Longwall mining, a safe and highly productive coal mining method, has become more frequently used for extracting coal seams. In the longwall method, the overlying strata are allowed to cave behind the working face after the coal is extracted, creating a gob.

Most commonly, U.S. and Australia longwalls use three- or four-entry gate roads for panel mining. Two-entry gates are often used under deeper cover to achieve better pillar stability. Wide pillars in coal mines of Europe and Asia were replaced to narrow ones back in the 80s.

Size of the narrow coal pillar in Ukraine is generally 1.5-3 m, as shown in figure 1a. In recent years the pillarless technology was vigorously developed, as shown in figure 1b. In this technique, the former entry is artificially retained as the tailgate for the next mining panel by using pigsties, concrete blocks, paste-like backfill material, high-water packing material, and other fill materials [2]. Many coal mines of China, Poland, Russia, Ukraine use a pillarless mining [3], [4], [5], [6]. Many scientists believe that it is necessary urgent to implement and popularize the pillarless mining technology with reasonable economy and high safety (figure 1).

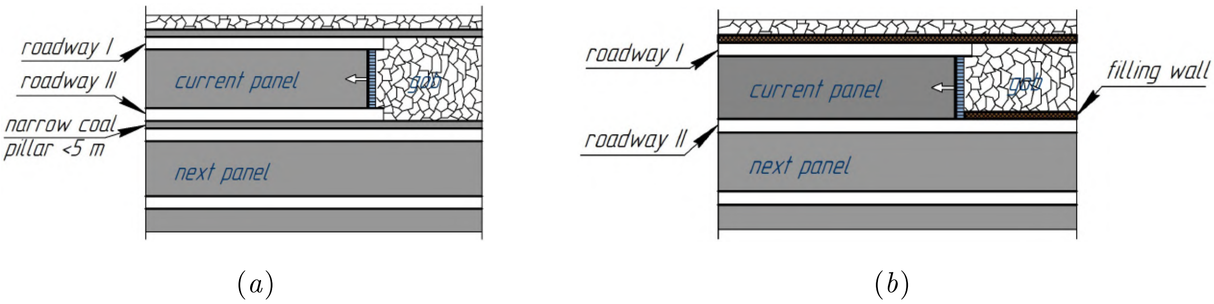


Figure 1. Typical coal mining modes: (a) mining with a narrow coal pillar; (b) gob-side entry retaining by filling artificial material.

As can be seen on figure 1b the gob-side entry retaining method requires an installation of artificial filling walls. The mechanical properties of filling materials largely determine the gob-side gate road stability. Many scholars researched in fields for improved efficiency filling wall, optimizing the entry-in support parameters. The varieties of wall types have been tried, such as timber cribs, dense pillar, gangue piling, and masonry walls [7], [8], [9], [10]. However, due to low support force and large deformation most conventional construction have been greatly affected.

Bai et al. [11] developed high-water quick-setting materials and pasty materials as new filling wall materials. The advantages of them include high-support force, quick force-increase speed, good gob-side gate road maintenance performance, mechanized creation, and good isolation of the gob.

Li and Hua [12] by taking Xieyi coal mine in Huainan as project background, established a mechanical model of key blocks and immediate roof, and analyzed the interaction mechanism between key blocks and surrounding rock around the gob-side entry retaining. As a result, determined reasonable width of roadside backfill, calculated stability coefficients of key blocks, and obtains sensitive coefficients of influencing factors on the stability of key blocks.

Chen et al. [13] researched method combining entry-in basic support with reinforced support, which is successful in gob-side entry retaining method practice for easy caving and medium caving roofs. Jiang et al. [14] presented a case study of the failure mechanisms and support design for deep composite soft rock roadway in the Yangcheng Coal Mine of China. Based on the failure mechanism, a new combine support was proposed that consisted of bolting, cable, metal mesh, shotcrete, and grouting.

In [15] the load-bearing capacity of mine roadway supports with flexible concrete formwork is studied to create a new integrated supporting control system. This approach is combined a flexible concrete formwork, bolt and anchor cable support with a wire mesh for retaining the surrounding rock of a roadway. As a result, retained roadways are formed in the surrounding rock.

Mentioned technologies that came out in recent years has been applied in gob-side entry retaining engineering in which roofs are managed using the caving method, but the high cost limits its wide application.

In [9], [16], [17] proposed the using of gangues as a filling wall material, that can help remove gangues on the ground. This reduces the cost a filling wall and solves the problem of rock wastes. It [18] have studied the performance of gangue concrete for its application as material of filling walls. Coal gangue is a concrete material utilizing gangues as a coarse aggregate and cement as a cementing material, mixed with a certain amount of additives. Through laboratory tests, Gong et al. [18] focused on the study of the influence of the water-cement ratio, aggregate content on the compressive strength, and the post peak carrying capacity of gangue concrete. An economical filling walls gangue concrete material is provided for the development with fully mechanized gangue backfilling mining.

Scientists for different application fields have recently researched the properties of gangue concrete. These concrete materials are gaining popularity when applied in farmland drainage ditches [19], in building [20], [21], as road base material [22].

The use of gangue concrete in China mining as filling walls material is mainly associated with the application on backfilling working faces [23], [24], [25], but similar technologies applied in mining in which roofs are managed using the caving method are of interest. Such an experience is of interest in full-mechanized mining of coal seams with a thickness of 0.8-2.0 m. Such seams are mainly mined in Ukraine. The use of conventional gangue piling is impossible on longwalls with a high advance rate due to the poor mechanization of the process and the low bearing capacity of filling walls, which does not allow reusing gateroad for the next panel mining. At the same time, filling walls from new high-water quick-setting materials and pasty materials are limited in their application due to their high cost.

Thus, the analysis carried out indicates that the opportunity of job-side entry retaining by longwall mining is primarily determined by the material and parameters of the filling wall. At the same time, combined fastening technologies are becoming increasingly popular. Usage of one or another filling wall design option is determined by mining and geological conditions and technological parameters of seam excavation, because they will determine the stress field around entry gate roads, which form the loading of the surrounding rocks and support system.

In this paper, based on the geological conditions typical for the Ukrainian Donbass, through numerical simulation stress field evolution around head entries when main roof console length increase with two variants of filling wall: high-support cemented filling and gangue concrete wall, was controlled. This study provides a reference on which filling wall design to choose in the gob-side entry retaining for coalmines that have similar geological conditions.

2. Methods

We used methods of computer simulation to investigate stress field evolution around head entries. The general scheme of the model is shown in figure 2. Finite element analysis software system Ansys was used. The modeling was carried out in a volume setting on a natural scale. The solution used a standard method for simulating the stress-strain state of an array near various mining structures using the principle of forces superposition.

The geometric and physical nonlinearities typical for the problems of mining geomechanics were taken into account. Therefore, the numerical analysis was carried out by the iterative Newton-Raphson method.

The model simulated geological conditions typical for the Ukrainian Donbass. In the numerical simulation model, the thickness of coal seam is 1.5 m. The immediate roof was

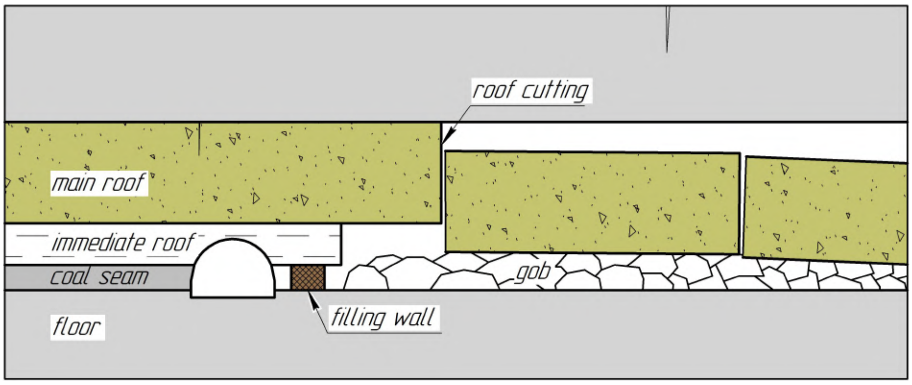


Figure 2. The gob-side entry retaining method of gob roof managed by caving method.

represented by siltstone with a thickness of 2.5 m and a uniaxial compressive strength of 40 MPa. The main roof is sandstone with a thickness of 6.0 m and a strength of 70 MPa. The floor rocks are mudstone with a uniaxial compressive strength of 40 MPa.

To simulate the behavior of rocks, a Drucker-Prager deformation model was used. The adequacy of the deformation model was established by simulation experiments [26]. According to the described structure, each layer was assigned a deformation modulus, Poisson's ratio, an angle of internal friction, an adhesion coefficient, and a dilatancy angle (table 1).

Table 1. Initial data for numerical modeling.

№	Density, kg/m^3	Elastic modulus, GPa	Poisson's ratio	Angle of internal friction, deg	Dilatancy angle,deg	Cohesion value, kPa
			Mine roof			
1	2500	27.5	0.25	27	25	135
			Immediate roof			
2	2400	22	0.25	32	30	106
			Coal seam			
3	1350	3	0.3	30	27	96
			Floor			
4	2400	22	0.25	32	30	106
		High-support	cemented filling	wall [27]		
5	2300	32	0.25	-	-	-
		Gangue	concrete filling	wall [18]		
6	2000	5.2	0.22	-	-	-
			Cribs			
7	1200	1	0.25	-	-	-

The dimension of the model is length x width x height = 256 m x 145 m x 10 m. The load at the upper boundary is calculated with the assumption that the mining depth is 800 m. The bottom boundary is vertically fixed. The left and right boundary is horizontally fixed. Arched entry gates were modeled. The dimension of the roadway is width x height = 5 m x 3.5 m. The bearing capacity of the lining arches was assumed to be 600 kN and was simulated by a distributed rebound over the area of the roof and sides.

The geomechanical situation corresponded to the state of the massif behind the longwall after coal seam was excavated and the immediate roof collapsed. The finite element model is shown in figure 3.

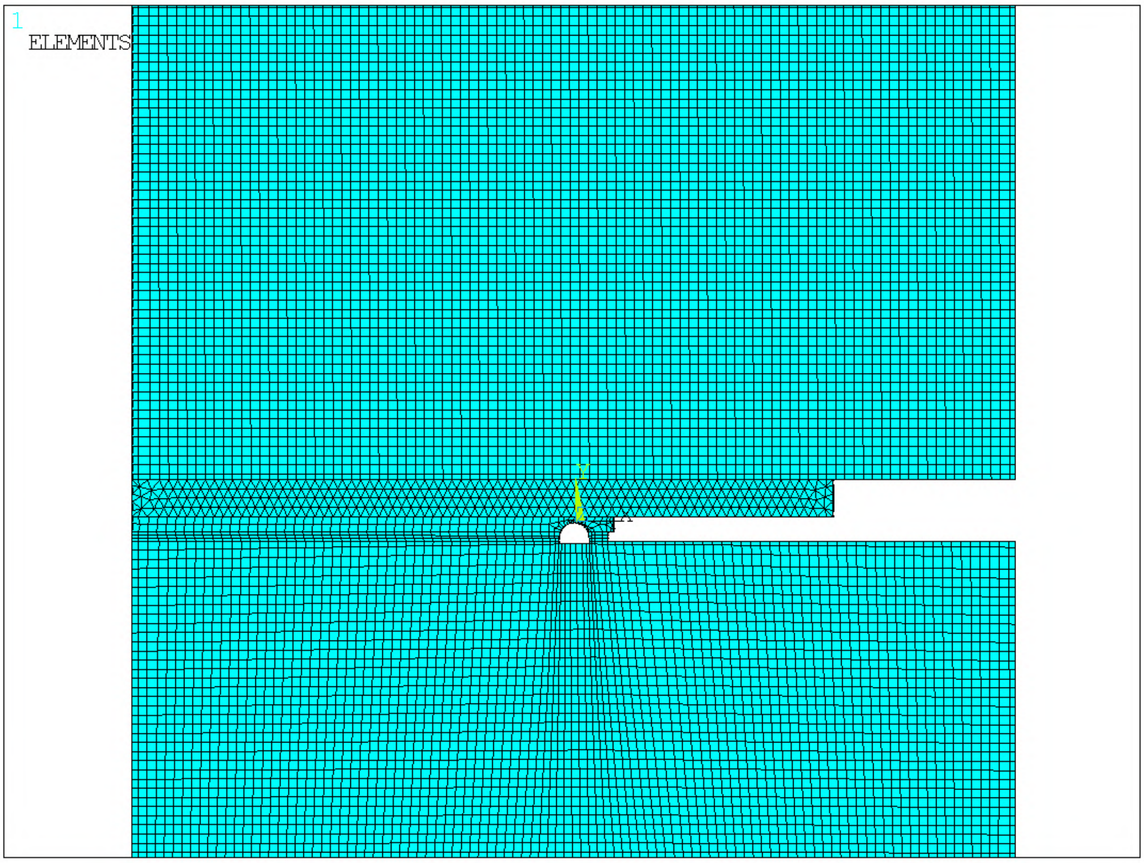


Figure 3. General view of the finite element model.

The properties of two variants of filling wall: high-support cemented filling and gangue concrete wall are given in table 1. The parameters of filling wall are taken from studies by Gong [18] for gangue concrete. The reported modulus of the HD C-S-H phase in the pure cement paste varied from 29.1 ± 4.0 GPa to 36.1 ± 3.4 GPa [27], [28], [29]. For comparison, a simulation was also carried out using wooden cribs.

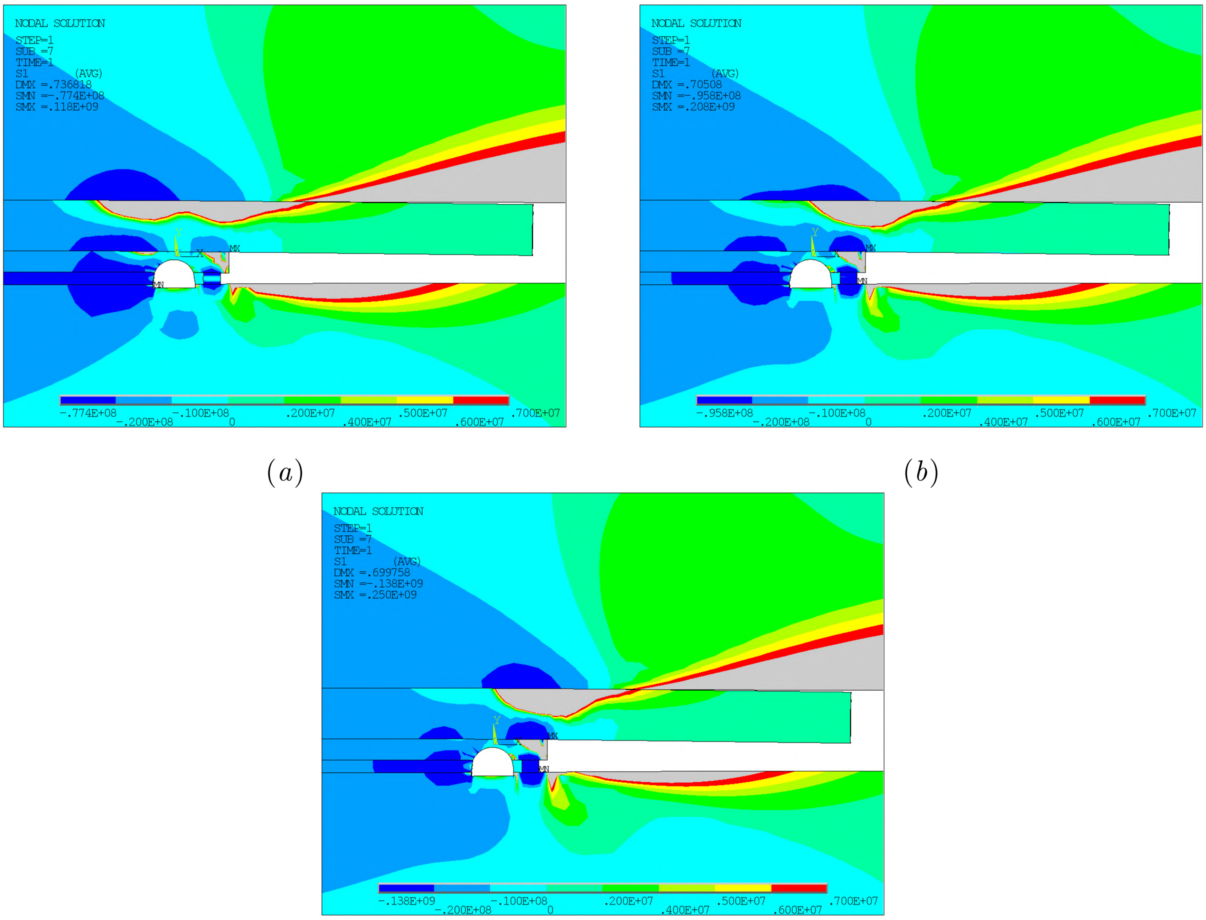
3. Results and discussion

To study the stress environment around head entries, simulation modeling of the deformation process was carried out. Main roof console length was varied from 18.5 to 57.5 m. At the same time, three tasks were successively solved:

- analysis of the massif stress-strain state (SSS) with a wooden cribs;
- analysis of the massif SSS with a gangue concrete filling wall;
- analysis of the massif SSS with a high-support cemented filling wall.

Distributions of the maximum principal stresses around the head entries, with 42.5 m main roof console length are shown in figure 4.

Gray color in figure 4 highlights the areas in which the resulting stresses exceed the tensile strength of the rocks. It can be seen from the figures that areas of maximum stresses are formed in the main roof near the entry, which are higher than the ultimate strength of rocks. These



(a) (b) (c)

Figure 4. Distribution patterns of the maximum of the principal stresses σ_1 around the head entries with a wooden cribs (a), a gangue concrete filling wall (b), high-support cemented filling wall (c).

areas are large, which may indicate a high probability of cutting the main roof console there. The localization of the mentioned zones is different when using wooden cribs (figure 4a) and filling walls (figure 4b, c). In the case of using cribs, the maximum of the principal stresses σ_1 in the main roof is on the coal seam side. Here is probably the cutting of the main roof. When using filling walls, the maximum stress is above ones, which contributes to the cutting of the main roof above the wall and is more favorable for the stability of the head entries.

To quantify the influence of the type of filling wall and main roof console length on the localization of the area of maximum stresses in the main roof and, accordingly, the probable place of main roof cutting, the stresses that form in the upper part of the hanging console of the main roof were analyzed. The stress control points are shown in figure 5.

Figure 6, figure 7 shows graphs of changes in the maximum of the principal stresses σ_1 in the model along line 1 of the main roof. The Y-axis on the graphs corresponds to the cross-sectional axis of the reusing entry. The positive direction of the X-axis coincides with the direction from the entry to the goaf.

Figure 6 shows that a decrease in the rigidity of the filling wall (case cribs) leads to a shift of the stress extremum in the main roof relative to gateroad towards the untouched massif. This

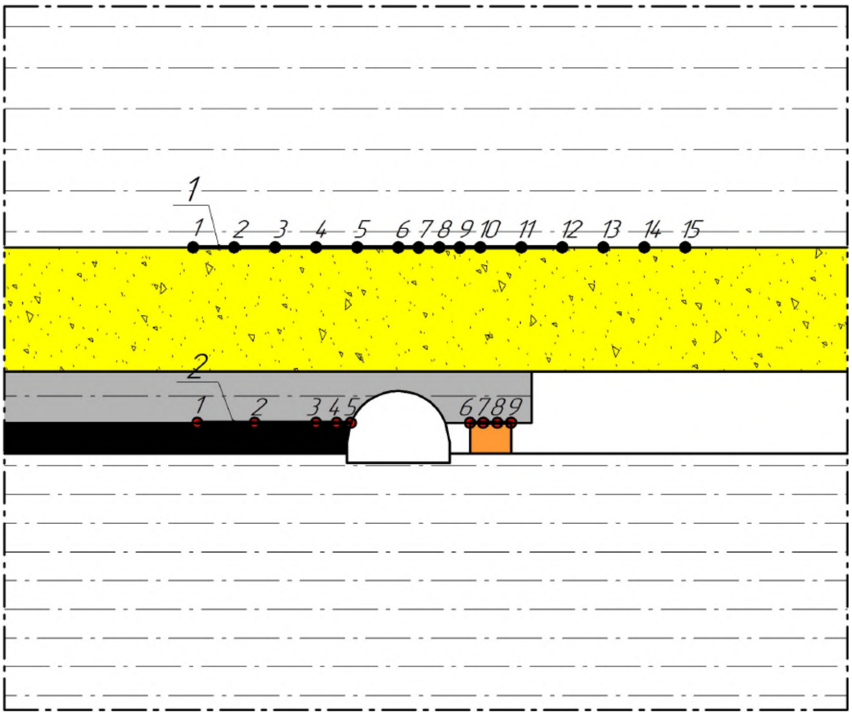


Figure 5. Scheme of the model with stress control points: 1 – line in the upper part of the hanging console of the main roof; 2 – line along the contact surface of the filling wall with the immediate roof.

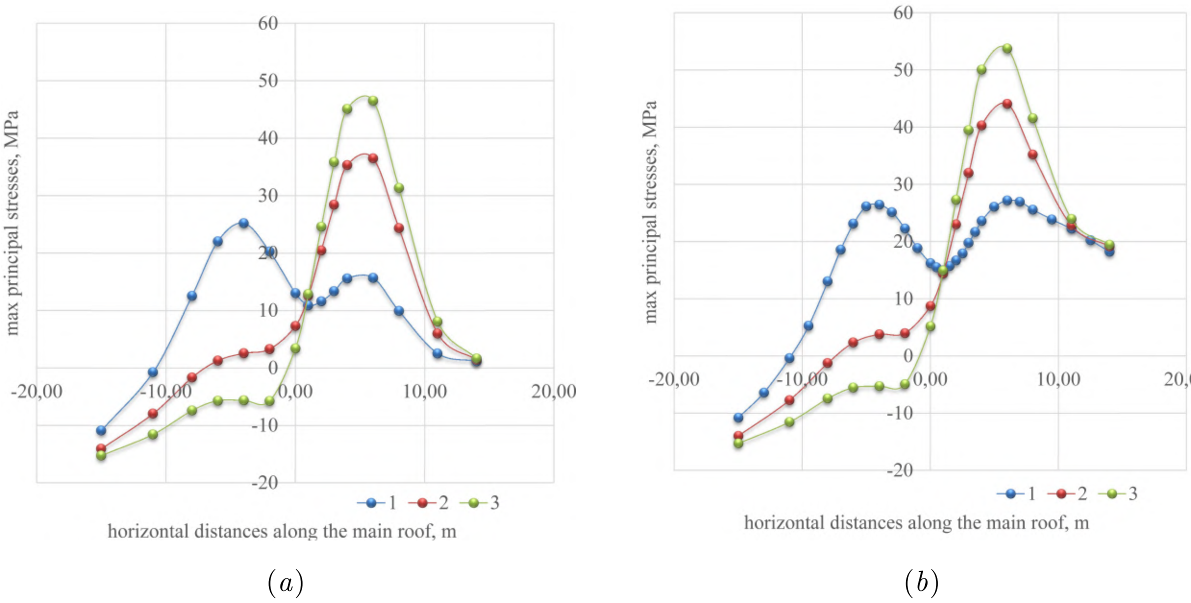
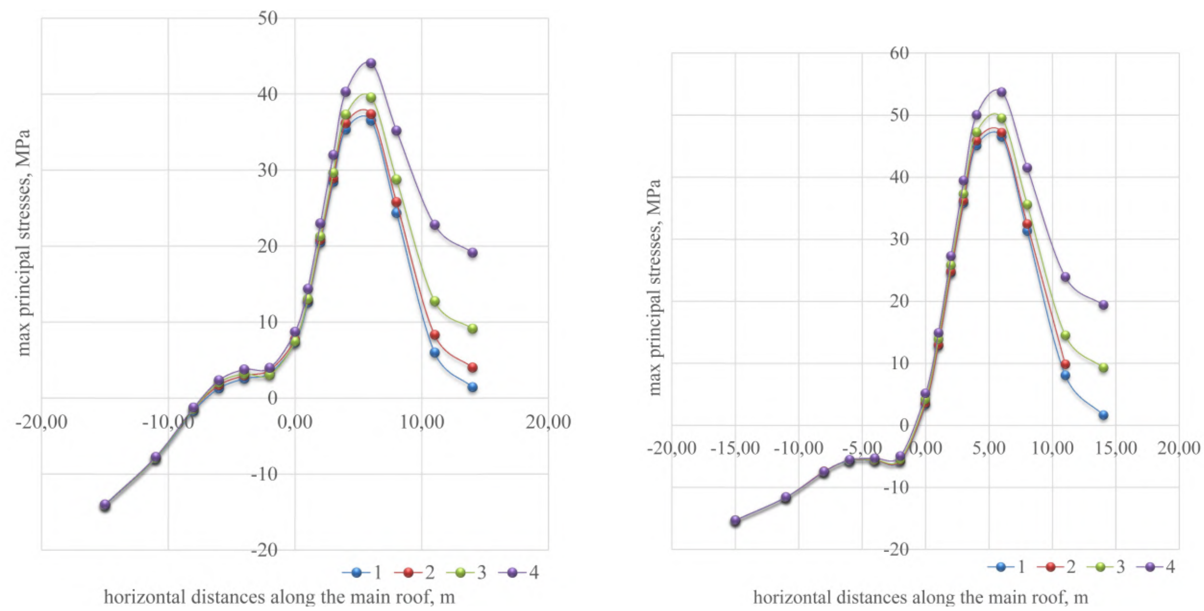


Figure 6. Maximum of the principal stresses σ_1, with console length 18.5 m (a), 57.5 m (b) and using: 1 – cribs, 2 – gangue concrete filling wall, 3 – high-support cemented filling wall.

increases the probability of cutting of the main roof from the side of the massif. In this case, the weight of the roof rocks rests on the lining of the entry and leads to its deformation, which does



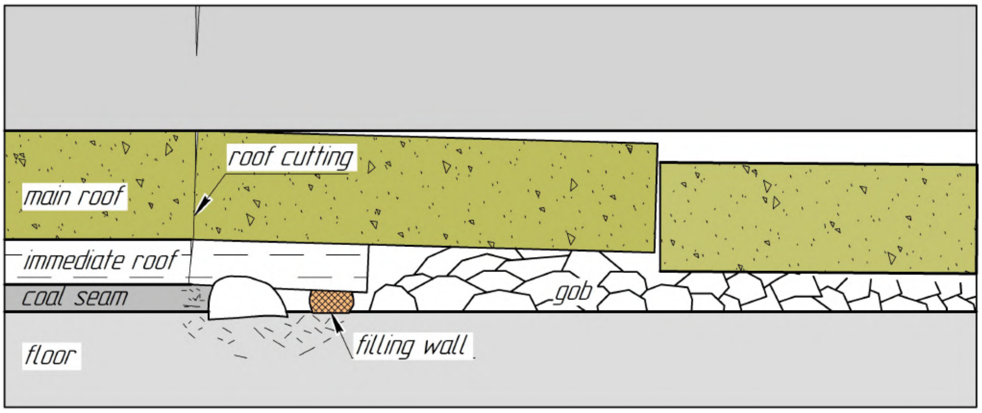
(a) (b)

Figure 7. Maximum of the principal stresses σ_1, when using gangue concrete filling wall (a), high-support cemented filling wall (b) and console length: 1 – 18.5m, 2 – 30.5, 3 – 42.5, 4 – 57.5m.

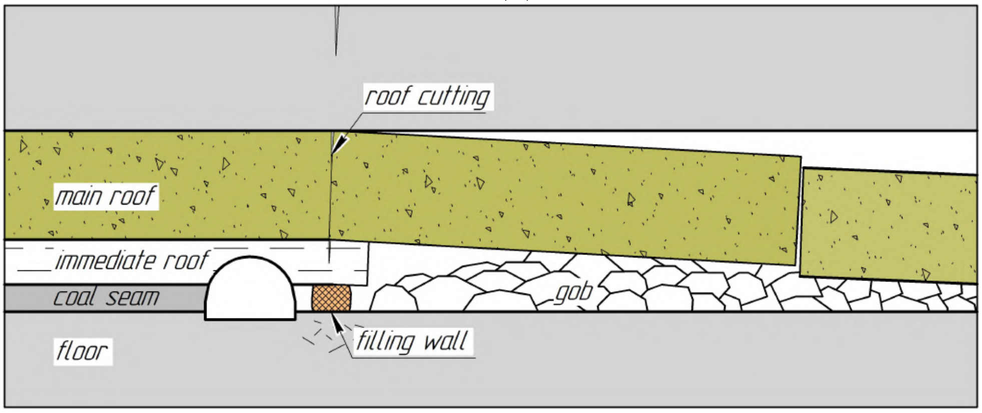
not allow saving the gateroads for reuse. In the case of using both types of filling wall (figure 6), the maximum stresses are located above the wall, which contributes to the cutting of the roof and its fall to the goaf. The described process is shown in figure 8. Thus, the fact that gangue concrete can replace high-support cement when creating a filling wall is confirmed. However, it is also seen that filling wall with a higher modulus contributes to the formation of higher principal stresses in the main roof. Therefore, with a console length of 18.5 and 57.5 m, the stress extremes for gangue concrete filling wall are 36.5 MPa and 46.5 MPa, and for high-support cemented filling wall – 44.0 MPa and 53.7 MPa. That is, an increase in the length of the console of the main roof from 18.5 to 57.5 MPa causes an increase in stresses by 22-27percent. Figure 7 shows that an increase in the length of the main roof console leads to an increase in stresses in the main roof, which is generally logical. The maximum influence of the console length on the principal stresses σ_1 is observed in the section between points 6-15 along line 1 (Figure 5), that is, above the entry and the filling wall, where the maximum stresses are formed. This influence naturally grows in the direction from entry to gob. An increase in the length of the console also causes an increase in min principal stresses σ_3. It leads to rock and coal disintegration around the entry and also determine the deformation of one. Thus, the reserve for increasing the stability of the entry is to reduce the length of the hanging roof console. At the same time, it should be taken into account that the filling wall must withstand the load from the bending and the weight of the roof rocks without destruction.

The distribution of vertical compressive stresses surround of the entry with different types of filling wall with a console length of 18.5 m are shown in figure 9.

Figure 9 shows that an increase in the deformation modulus of the filling wall leads to an increase in compressive vertical stresses in the roof above the wall and in the floor below it. Accordingly, the loads on the filling wall also grow. Cutting of the roof from the goaf side will only occur if the compressive strength of the filling wall is higher than that of the main roof.



(a)



(b)

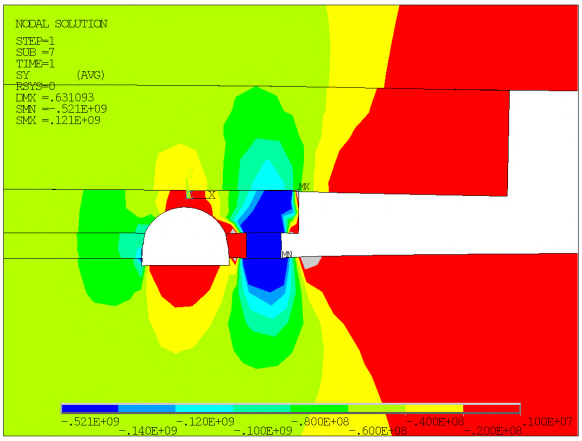
Figure 8. Maximum of the principal stresses σ_1, when using gangue concrete filling wall (a), high-support cemented filling wall (b) and console length: 1 – 18.5m, 2 – 30.5, 3 – 42.5, 4 – 57.5m.

The compressive stresses from the coal seam side decrease with an increase in the filling wall deformation modulus. They are greatest when using wooden cribs, as can be seen from figure 9a. In this case, the destruction zone around the gateroad from the side of the formation is much larger, respectively, the convergence in the entry is also. The lowest formation stresses are observed when using high-support cemented filling wall figure 9c.

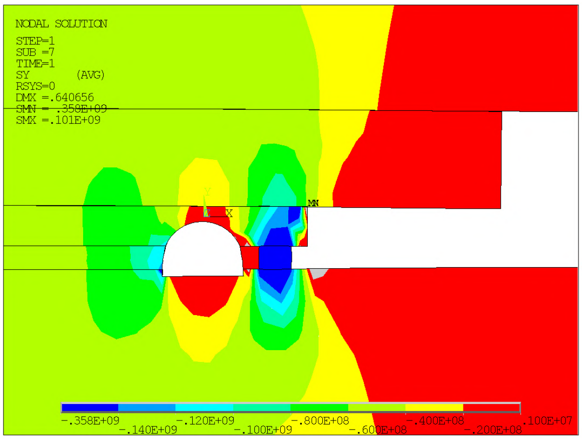
To estimate of compressive stresses around of the entry and the dependence of the pressure on the filling wall on its type and the length of the console, the vertical stresses in the model were analyzed along the contact surface with the immediate roof (line 2 in figure. 5) presented in figure 10.

Figure 10 shows that the stresses from the coal seam side are maximum at a lower value of the deformation modulus and decrease with an increase in the filling wall deformation modulus. It can also be concluded that the filling wall is loaded unevenly. The pressure from the goaf side is much greater than the pressure from the working side. This unevenness is the greater, the greater the modulus of deformation of the filling wall material. It is maximum for high-support cemented filling wall. In this case, the pressure difference across the width of the wall is 123 MPa between 308 and 185 MPa at the edges of the wall.

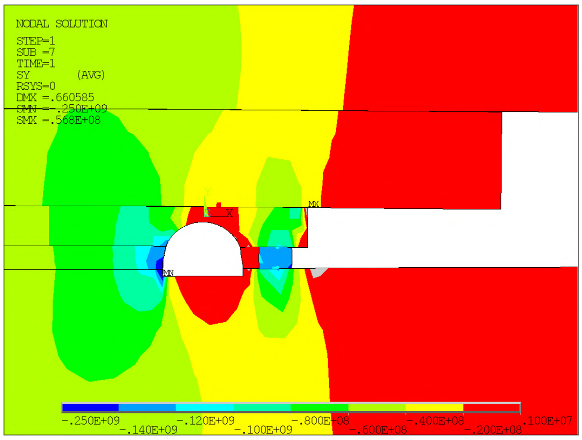
Since the filling wall in the case under consideration works for uniaxial compression, the



(a)



(b)

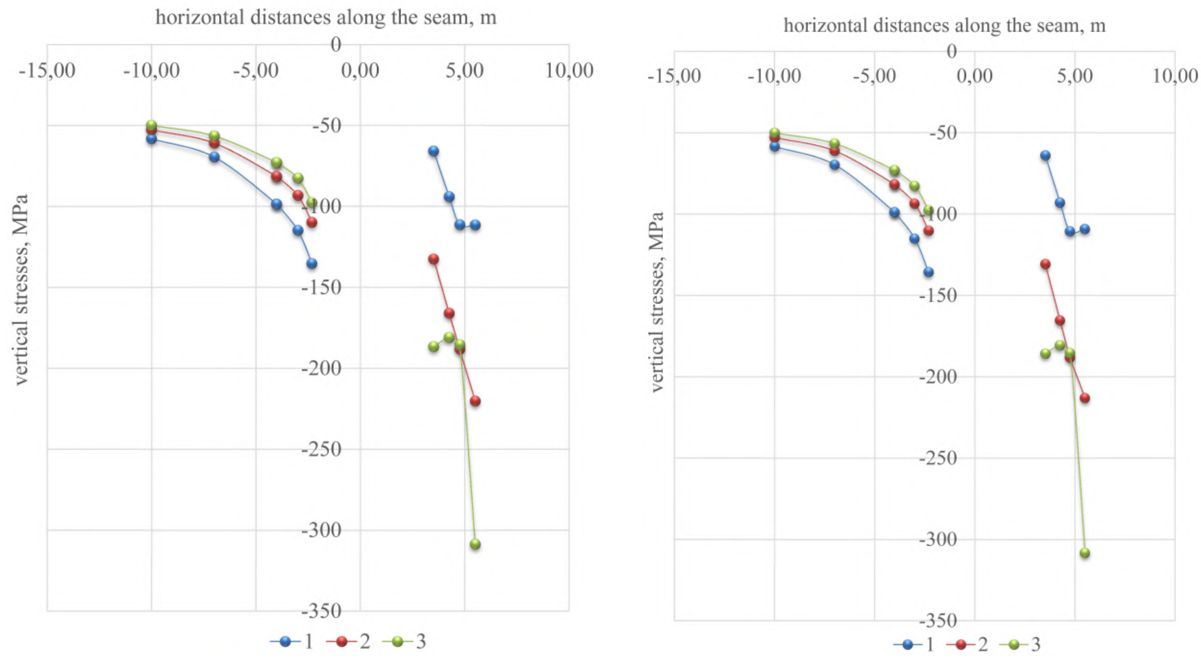


(c)

Figure 9. Distribution patterns of the vertical stresses around the head entries with a wooden cribs (a), a gangue concrete filling wall (b), high-support cemented filling wall (c).

minimum (in the algebraic sense) principal stresses in the wall are close to the values of vertical stresses, which makes it possible to determine the required strength of the filling wall material by comparing the calculated stresses with the limiting ones. In this case, the least stable is the edge part of the protective structure from the gob side.

Since the vertical stresses in the wall significantly exceed the stresses in the roof, the probability of the primary destruction of the wall remains quite high. At the same time, despite the higher bearing capacity of the high-support cemented filling wall, the risk of its destruction is higher than the gangue concrete filling wall, since the excess of the compressive stresses of the corresponding tensile strength is much greater. In the case of filling wall destruction, its



(a) (b)

Figure 10. Vertical stresses along the contact surface between the massif and the immediate roof, with a console length of 18.5m (a), 57.5m (b) and using: 1 – cribs, 2 – gangue concrete filling wall, 3 – high-support cemented filling wall.

deformation modulus will decrease and the main roof will most likely be cut not above the filling wall, but above the coal seam. It will lead to significant deformation of the entry and make it impossible to reuse it. To avoid the destruction of the filling wall, it is necessary to provide appropriate measures. This may be an increase in the size of the wall, an increase in its bearing capacity, or an artificial cutting of the main roof console.

4. Conclusions

Trends of coal mining are directed to implement and popularize the pillarless mining technology with reasonable economy and high safety. Reserving a gateroad for the use of next panel mining is a popular gob-side entry retaining. At the same time, it is important to improve efficiency filling wall, optimizing the entry-in support parameters. Current research proposes the using both high-support cement and gangue cement as a filling wall material. A study of the stress-strain state of the massif was carried out using the listed types of filling walls in comparison with conventional cribs. Ansys code was used. The influence of the deformation modulus of filling wall and the length main roof console on the localization of maximum stresses in surrounding rocks and respectively area of roof cutting is shown.

It is shown that when using wooden cribs, it is impossible to achieve the reuse of gateroads, since the convergence in the entries is too large. At the same time, gangue concrete can replace high-support cement when creating a filling wall. With gangue concrete filling wall, more favorable conditions are created in terms of stresses in the roof. However, filling walls are only effective if there is a cutting roof over them. If the cutting roof area is localized from the side of the rock massif, then the weight of the rocks falls on the entry and critically deforms it. Cutting of the roof from the gob side will only occur if the compressive strength of the filling wall is higher than that of the main roof. In case of primary destruction of the filling wall, its deformation modulus will decrease, which will lead to a significant deformation of the entry and make it impossible to reuse it. To avoid the destruction of the filling wall, it is necessary to provide appropriate measures. This may be an increase in the size of the wall, an increase in its bearing capacity, or an artificial cutting of the main roof console.

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Dissipative structure suppression as a way to increase the sustainable improvement of the frame support bearing capacity

To cite this article: V V Nazimko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012012

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012012 doi:10.1088/1755-1315/1049/1/012012

Dissipative structure suppression as a way to increase the sustainable improvement of the frame support bearing capacity

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Abstract. Introduction. A yield frame support is a basic means of providing the underground roadways' stability in the deep mines operating in the hard ground control condition when the ratio of the ground pressure to the unconfined strength of surrounding rock mass exceeds 0.33. The operators adjust the nominal bearing capacity of the frames at 0.55 of their maximum or peak resistance F_{max} because the frames operate in a dry friction mode spontaneously generating oscillation, which causes variation of the resistance in the range from 0.1 up to 0.9 of F_{max}. Aim/tasks. We intended to reduce the dynamic oscillation of the support resistance that allows for increasing their bearing capacity. Methodology. We used a computer simulation by FLA3D model, indoor testing of the frames, and actual measurements in an underground coal mine. Results. We revealed a specific behavior of the frame support that reduced the limit of the bearing capacity by 45%. During yielding, the frames generate dissipative structures (DS) that become apparent due to the dynamic nature of stick-slip friction following the yielding process. We demonstrated that DS control and especially its suppression provides a sustainable increase in the frame bearing capacity. Conclusions. Improvement of the yield frames design and especially their clamps are the prospective way to control DS and provide sustainable enhancement of the frame bearing capacity.

1. Introduction

World mineral resources have been depleted at shallow depth, which is recently increasing progressively due to intensive mineral deposits development. Consequently, geologic and mining conditions deteriorated because the growing ground pressure increased deformation of the rock mass surrounding underground roadways augmenting the tremors and rock bursts. This complicated the roadways maintenance that recent publications highlighted [1, 2].

High level of the stress state in the rock mass surrounding underground roadways at the great depth renewed the relevance of technologies based on the ground pressure relief [3]. Ground pressure diminishes when a roadway support yields and allows essential displacement to occur. As a result, the importance of the yieldable frame supports (YFS) implementation increased especially in coal mines, which extract coal seams at the depth 800 m and more [4–6] where ratio of the ground pressure to the unconfined strength of surrounding rock mass exceeds the critical level of 0.33 and negative effects of ground pressure increase dramatically.

Recently, a combination of YFS and rock bolts/cables has become popular [7–9]. YFS consists of several (for example three) overlap segments 1,2,3, which are joined with the clamps 4,5 (figure 1). The clamps grip adjacent segments firmly with the tightening the bolts and nuts. Resilience of YFS is provided due to reciprocal sliding of the adjacent segments. The more the tightening of the bolts the more friction forces are generated in the clamps and joints, hence YFS increases its resistance to the ground pressure.

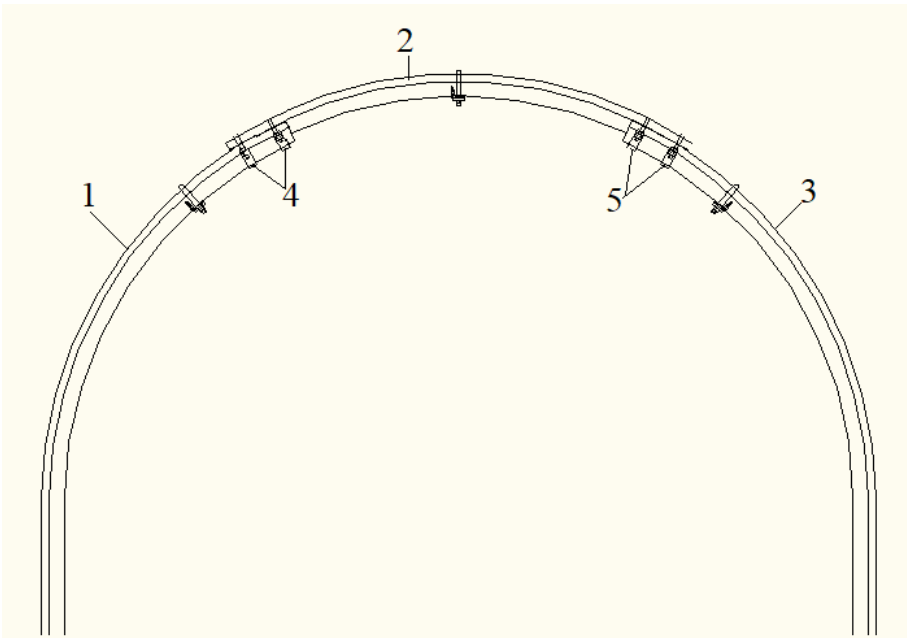

Figure 1. Structure of the YFS: 1,2,3 are overlap segments; 4,5 are clamps.

Despite YFS has been designed in 1950s, it still has a great reserve for improvement of the bearing capacity (figure 2). The resistance of YFS periodically varies during its operation while the variation may range from zero up to the maximal bearing capacity of the frame. This capacity YFS demonstrates in the rigid mode of loading when its clamps are blocked. Then YFS starts to deform plastically and transits to a failure state. Such a dynamic oscillation of YFS resistance is nonstationary because the level of the average current resistance drifts during support yielding and peak resistance usually grows as the overlap of adjacent segments expands [10]. An evident illustration of this effect is depicted in figure 2 which presents the results of testing a frame SVP 27. The resistance of serial peaks grew from zero to 202, 252, 294, 336, 365, and 407 kN as the height of the frame reduced by 152 mm. The intermitted line demonstrates an ideal diagram, which would reproduce the maximum of the frame bearing capacity when the adjacent segments slide relatively each other under maximum possible resistance without the drops. After replacing the timeline with a motion scale we may asses energy, which was dissipated by the frame during its yielding. The actual useful work done by the frame was 42.6% of the possible maximum which apparently demonstrates that the reserve of the frame bearing capacity exceeds 50%.

The same tendency has been reported by Pytlik [11]. Eleven tests from 12 demonstrated a steady growth of peaks resistance as YFS was yielding. For example, Pytlik tested LP10/V32 frame having two clamps on every overlap of the frame segments. At the first stage, the frame is tested in the rigid mode with blocked clamps until evident signs of plastic deformation will

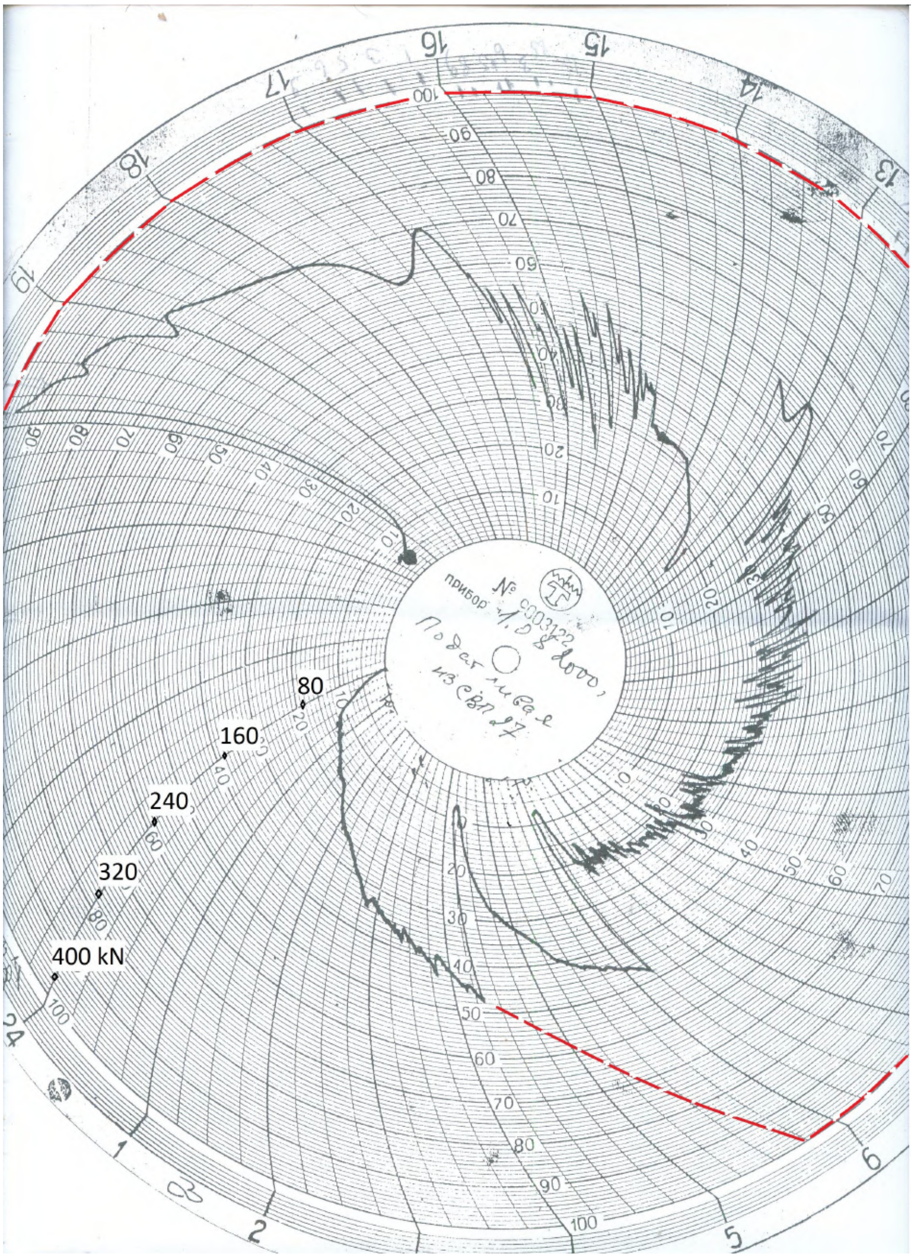

Figure 2. Diagram of YFS resistance.

appear. In this case, an ultimate load applied to the frame or its bearing capacity F_{max} was 1069 kN. During the second stage, the frame was tested in the yielding mode, tightening torque in the clamp bolts was 500 Nm which provided permissible load $F_n = 325$ kN.

As Pytlik [11] reported, an initial 100 mm of resilience YFS fulfilled steadily: peaks of the resistance were in the range from 300 to 400 kN whereas minimum counteraction varied about 100 kN. Then consistency of the diagram was broken and the frame transited to a non-stationary mode with a chaotic unpredictable variation of the resistance, which eventually jumped up to 714 kN that is definitely less than $F_{max} = 1069$ kN. In other words, the probability of the clamp jamming could be neglected. As a rule, YFS is tested until its height reduces by 20% that is in a range from 700 to 800 mm for a frame having cross sectional area from 17 to 20 m^2. However, the test was interrupted at 315 mm presumably because of the threatening ascending tendency of the test diagram when initial F_n increased almost twice as much.

Paczesniowski [12] showed that dynamic and poorly stabilized variation of YFS resistance may dramatically reduce its actual bearing capacity. He calculated index k_4 as the relation of a permissible load F_n for YFS to its maximal bearing capacity F_{max}. The Author determined the percentage of the tested frames, which survived until their vertical deformation reached 20%. Database contained 121 case of YFS indoor testing; 76 frames survived whereas the other 45 frames failed before their vertical size reduced by 20%. The adjacent segments of some frames were blocked with clamps although the first peak of all tested frames resistance matched a predetermine level called 'permissible load' that ranged from 0.3 up to 0.8. However, as it was noted before, YFS characteristics is not stationary and its parameters – such as the current peak of the resistance, its variation, and sliding interval between sequential peaks – usually float during testing (figure 2). That is why YFS may eventually fail during testing even if $k_4 < 1.0$. According to Paczenoivsky [12], not a single frame having index in the range of $0.7 < k_4 \leq 0.8$ survived. The less the index was the more percentage of the tested frames survived although even the frames having $k_4 \leq 0.4$ could fail in the long run as in example of [11] when $k_4 = 0.304 \ll 1.0$. The main reasons of this were dynamic oscillation of the frame resistance, stochastic and nonstationary nature of the oscillation. Therefore, aim of this paper was to reduce the dynamic oscillation of the support resistance that allows increasing their bearing capacity and reduces the risk of the failure.

2. Analysis of the YFS resistance oscillation dynamics

YFS operation involves the dry friction mechanism, which is followed by so-called stick-slip auto-oscillation. Stick-slip regime of friction is widely spread in technics [13–15]. Usually, stick-slip friction causes harm producing fretting of the frictional surface and even blocking of the mechanisms. On the other hand, it facilitates accurate positioning [16] in precision machinery. Incorporating dry friction in YFS structure, designers had a goal to reduce cost of the frame supports. In addition, components of the frame are made with high tolerance. Finally, surfaces of the frame components, which contact and slide reciprocally, are rough. All these factors invest in uncertainty of the YFS physical parameters and increase randomness of the friction process. These factors rise the variation of the peak resistance of YFS that should be considered in more detail.

Also, F_n is determined as the very $first$ peak of a frame resistance. However, it should be borne in mind that the majority of the test diagrams are usually nonstationary and the peaks of YFS resistance show a discrepancy.

We digitized the diagrams of our tests and presented these results in figure 3. The analysis showed that this histogram may be approximated by truncated normal distribution having average of 195 ±131 kN, namely the standard deviation is 67%.

It should be stressed that testing any frame is a time - and labor-consuming procedure because of the big mass and sizes of the frame. Therefore, F_{max} is tested one time and an ultimate bearing capacity of YFS is considered as a definite constant. However, constant F_{max} does not comply with probability theory. Even extremely simple detail such as a piece of wire has indefinite strength. For example, the ultimate tensile strength of a steel sample variates according to normal law with standard deviation (STD) of 4.38% [17]. However, a frame support is a more complex structure that consists at least of 19 details. Therefore statistical testing of a representative set of the same frame would provide STD at least 10%. Thus $F_{max} = 704 \pm 70$ kN in our case. Both the normal distributions of the frame in the yielding and rigid modes are depicted in figure 4.

Clearly, these distributions overlap. This does mean that there is a certain risk – several percent in the case – of the frame failure although as far as we know standards of the frame

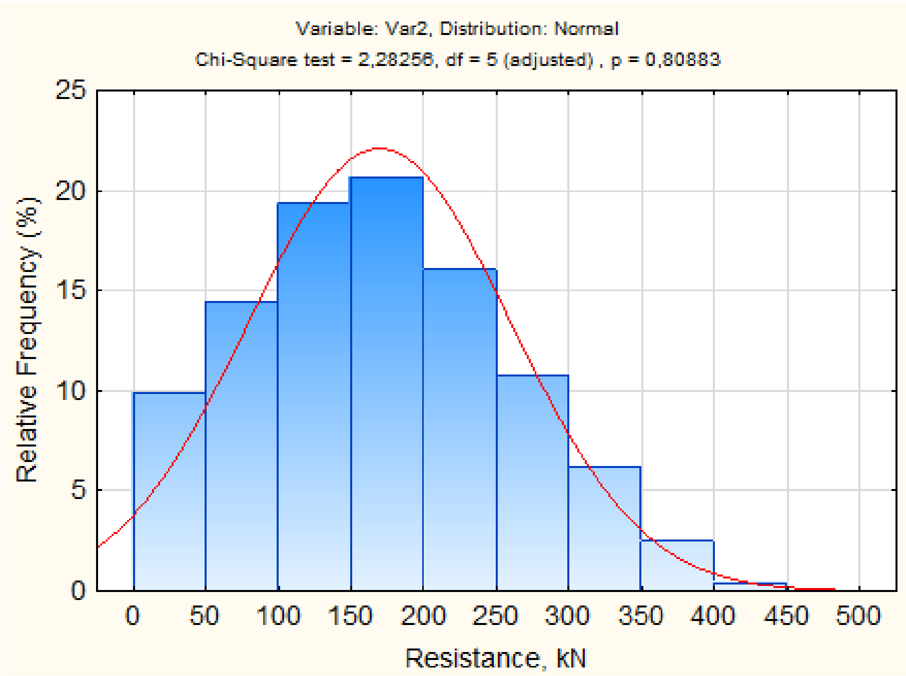

Figure 3. Histogram of the YFS resistance.

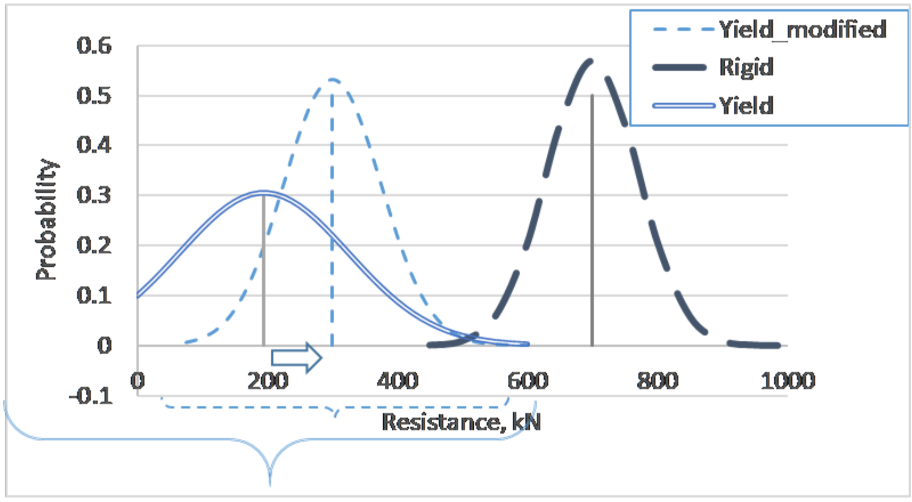

Figure 4. Normal distributions of the frame resistance in the resilient (yieldable) mode and strength of the frame or its ultimate resistance (rigid mode) with blocked clamps.

testing do not account for the variation of F_{max} and nonstationary property of the test diagram. Paczenovsky [12] proved the risk indirectly demonstrating the negative effect of k_4 increase. The diagrams in figure 4 demonstrate how to control the risk. In order to increase the level of acceptable load to a frame, variation of the frame resistance should be reduced. For instance, to lift the acceptable average load from 195 to 300 kN, STD of the frame resistance should be reduced to 75 kN or 25% (intermitted line in figure 4). Simple increase of the tightening in the clamps expands the overlap of the frame resistance distributions in yieldable and rigid modes. Increase of the distributions' intersection rises risk of the YFS failure and reduces resilience interval, shortening the period when the frame survives. So far, the only recognized way to secure and control the survivability of the YFS is to keep $k_4 \leq 0.5$. However, this approach is reactive and not reliable because the frame behavior is not stable during the yielding process that is reflected by the nonstationary test diagram. Our analysis allowed suggesting new proactive tactics to control the survivability:

(i) The most important method is controlling stick-slip friction to stabilize peaks of YFS resistance in resilience mode. This makes yielding of the frame predictable, reduces uncertainty and enforces stability of the process in the predetermined interval of YFS deformation.

(ii) The ideal approach is to suppress stick-slip mode of the friction completely but, in reality, variation of YFS resistance should be reduced as much as possible. Subject to condition (a), this will allow increasing the permissible load over 50% threshold of k_4 without raising the risk of surveillance limit reduction.

(iii) Sensitivity of the stick-slip mode to the tightening of the clamp bolts should be minimal. For example, a situation when the stability of YFS behavior depends on the amount of the clamp's tightening is inadmissible. An increase in the tightening should not impair the stability.

3. Investigation of the stick-slip friction during resilience of YFS

3.1. Selection of the method

Recently, YFS functioning has been mostly investigated using special indoor testing facility [6, 9, 11, 18–20]. The most informative data were accumulated from laboratory testing of YFS. All researchers registered the auto-oscillating behavior of the frames during their yielding. They analyzed mechanic energy and heat, which dissipate due to resilient process. Pytlik [20] tested YFS under dynamic load. Horst et al. [19] demonstrated that corroded frames blocked or loses its bearing capacity. Brodny [18] concluded that such components of the clamps as clevises or yokes have crucial impact on functioning of friction joints and safety of YFS operation. We used these findings to substantiate and interpret the resilience of YFS as the stick-slip process, which has the nonstationary nature.

Several researchers carried out underground experiments [1, 21–26]. Lubosik and Walentek [22] emphasized that the most intensive plastic deformation of YFS occurs in underground openings at the great depth especially 1000 m and deeper. Rotkegel et al. [6] proved this conclusion and recommended to supply the frames with secondary support such as a 'spreader' beam being hung to the cable bolts along a roadway. Wang et al. [5] modified YFS implementing tubes filled with concrete instead of traditional U-shape profile.

In recent times, computer simulation became popular to investigate YFS behavior although the problem of friction and reciprocal sliding of the frame segment remains unsolved [6, 27–32]. Horyl et al. [28] simulated by finite element method (FEM) vibration of YFS due to its dynamic loading. Later, Horyl et al. [29] managed to simulate explicit reciprocal sliding of the YFS segments and demonstrated by FEM that loading capacity of YFS is proportional to the friction coefficient. This simulation was carried out on a symmetrical half of the profile, and reciprocal sliding of the segments was quasi-static because the researchers did not mention dynamic oscillation of the YFS resistance. In [30], Horyl et al. used FEM model that accounted for nonlinear behavior of the frame. However, the Authors managed to trace the first peak of the frame resistance only in limited range of deformation 60-70 mm. Lia et al. [31] proposed a new criterion that helped to simulate separation of the arch from the rock exposure, but they did not simulate yield of the clamps as an explicit slide. Rorkegel et al. [6] and Mazurek et al. [27] investigated stress and bending moment distribution in a frame using FEM but explicit reciprocal sliding of the frame segments remained behind the scope of the research works.

In this paper, computer simulation has been used to investigate the stick-slip friction process during operation of YFS. We used FLAC3D commercial code [33], which enables explicit simulating of irreversible movement and reciprocal sliding in particular. A stick-slip process consists of two phases, namely elastic-plastic deforming that accumulates potential energy in contacted parts of a frame and abrupt relief of this energy, which is followed with its transformation to kinematic one. Indoor testing has demonstrated that acceleration of certain YFS segments may increase at the second stage as much as 2000 m/s^2 [11]. Therefore, operation of YFS is a non-equilibrium dynamic process, which can be described by second Newton law:

$$\sigma_{ij,j} + \rho b_i = \rho \frac{dv_i}{dt}. \tag{1}$$

where ρ is the mass-per-unit volume of the medium, b is the body force per unit mass and $\frac{dv}{dt}$ is the material derivative of the velocity [33].

Plastic deformation of the frame was simulated using von Mises constitutive model. Contact between adjacent segments and clamps was imitated by special interface (figure 5).

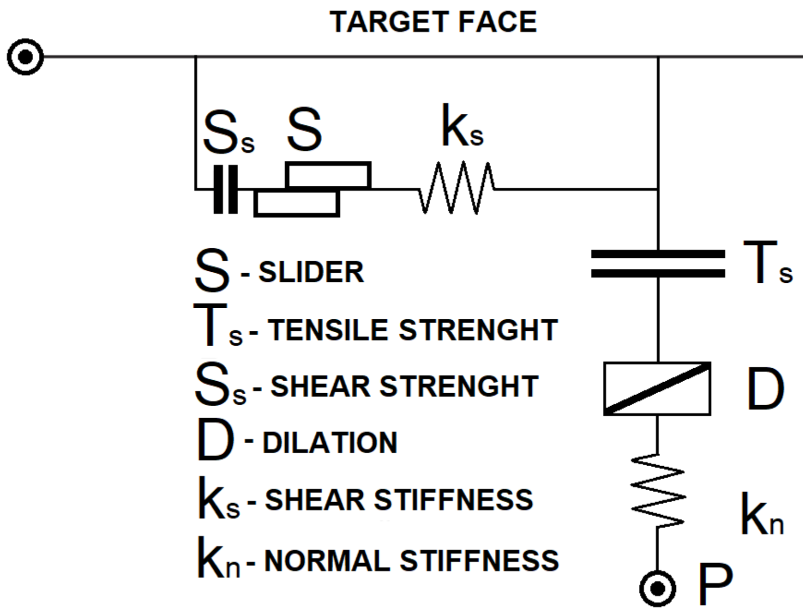

Figure 5. Schematic of the interface [33].

According to [33] the normal and shear forces describing the elastic interface response are determined at calculation time $(t + \Delta t)$ using the following relations:

$$F_n^{(t+\Delta t)} = k_n u_n A + \sigma_n A. \tag{2}$$

$$F_{si}^{(t+\Delta t)} = F_{si}^t + k_s \Delta u_{si}^{(t+(1/2)\Delta t)} A + \sigma_{si} A. \tag{3}$$

where $F_n^{(t+\Delta t)}$ is the normal force at time $(t + \Delta t)$ [force]

$F_{si}^{(t+\Delta t)}$ is the shear force vector at time $(t + \Delta t)$ [force]
u_n is the absolute normal penetration of the interface node into the target face [displacement]
Δu_{si} is the incremental relative shear displacement vector [displacement]

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σ_n is the additional normal stress added due to interface stress initialization [force/displacement]
k_n is the normal stiffness [stress/displacement]
k_s is the shear stiffness [stress/displacement]
σ_{si} is the additional shear stress vector due to interface stress initialization [force/displacement]
A is the representative area associated with the interface node $[length^2]$

The Coulomb shear-strength criterion limited the shear force by the following relation

$$F_{smax} = cA + F_n \tan\phi. \tag{4}$$

where c is cohesion between contacting parts of YFS.

Itasca introduced a local non-viscous damping to dissipate energy of unbalanced forces, which are produced by dynamic processes [33]. A damping-force term is added to the equations of motion that reads

$$F_i^{<l>} + F_{(i)}^{<l>} = M^{<l>}(\frac{dv}{dt})^{<l>}, \tag{5}$$

where $l = 1, n_n$
$F_{(i)}^{<l>}$ is the damping force and is given by

$$F_{(i)}^{<l>} = -\alpha|F_i^{<l>}|sign(v_{(i)}^{<l>}). \tag{6}$$

$$sign(y) = \begin{cases} +1, & \text{if } y > 0; \\ -1, & \text{if } y < 0; \\ 0, & \text{if } y = 0. \end{cases} \tag{7}$$

expressed in terms of the generalized out-of-balance force, $F_i^{<l>}$, and generalized velocity, $v_{(i)}^{<l>}$. The damping force is controlled by the damping constant, $\alpha = 0.8$.

We simulated reciprocal sliding of adjacent segments having profile of YFS (ŁP10/V36 modification). These segments were griped with SD36W double-yoke clamps (figure 6). In order to exclude additional effect of curvature, we used straight segments of the YFS profile. Such an approach is widely accepted in the practice of YFS testing. Physical parameters of the steel and interfaces are presented in the table 1.

Table 1. Physical parameters of the simulated YFS.

Metal			**Interface**			
Bulk modulus, Pa	Shear modulus, Pa	Yield strength, Pa	Normal stiffness, N/m^3	Shear stiffness, N/m^3	Friction coefficient, degree	Cohesion, Pa
$140 * 10^9$	$84 * 10^9$	$550 * 10^6$	$26 * 10^9$	$26 * 10^9$	13.0	5.0

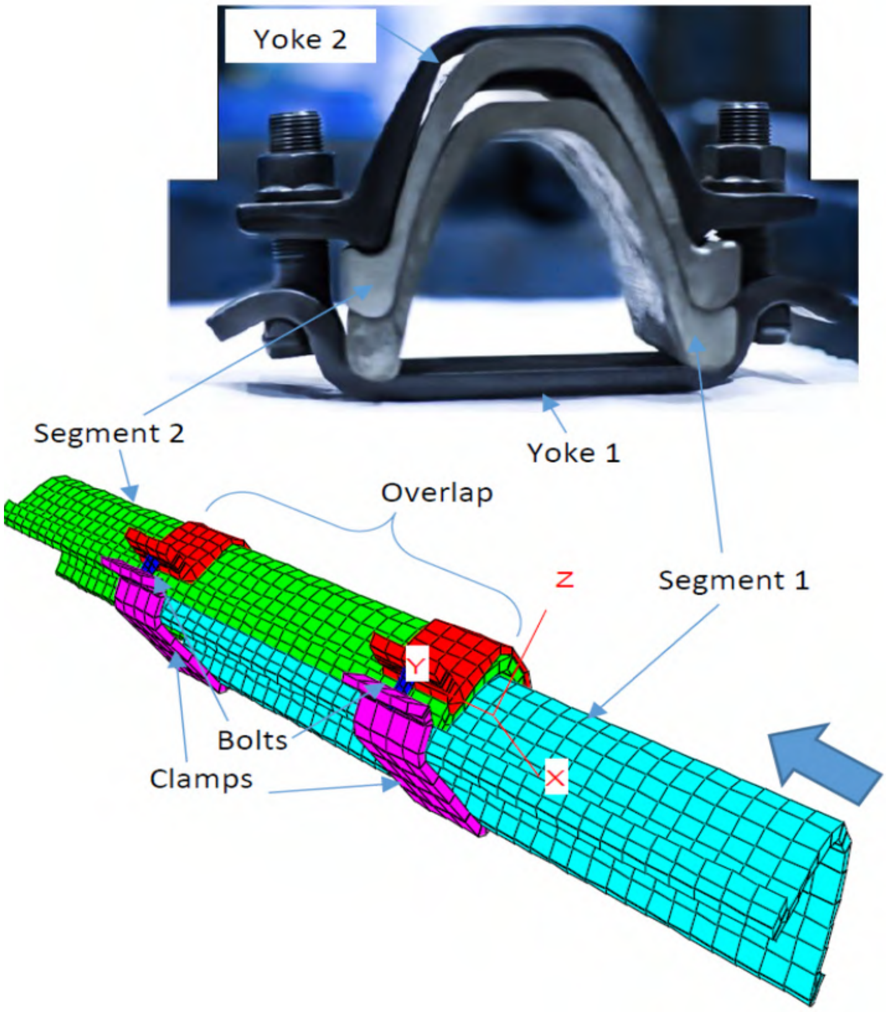


Figure 6. Schematic of the simulated YFS fragment.

3.2. Substantiating of boundary conditions
According to previous experience, all researchers loaded an experimental frame with hydraulic rams, which have been anchored in a base that was another big frame surrounding the tested frame. These loading facilities have essential elastic resilience. Besides, the hydraulic system serving the testing facilities had limited capacity. Therefore, pliability of the loading facility is commensurate with the tested frame flexibility, and they influence each other. By default, indoor testing of YFS is considered as in a set load mode, although the real loading facility cannot keep the stable load. Furthermore, amplitude of YFS resistance variation can be overestimated during indoor testing.

Rigidity of the surrounding rock mass strongly depends on geologic structure and physical properties of the rock. Thus, behavior of YFS may variate essentially depending on the surrounding rock properties. Anyway, it may be expected that soft surrounding rocks will apply more stable load to YFS in comparison with hard rock mass, which may accumulate essential amount of potential energy. However, real boundary conditions applied to YFS in an underground roadway are worse than those in a laboratory are because laboratory facility provides minimum of degrees of freedom. That is why YFS demonstrates the most efficient behavior and dissipates the maximum external energy due to friction of the overlayed segments in a laboratory. In the real environment of an underground roadway, YFS may dissipate the energy of ground pressure not only because of friction mechanism but also due to plastic deformation that reduces integrity and the bearing capacity of the frame. Finally, there is uncertainty in this problem and the best way to solve it is to choose a simple and definite boundary condition.

Therefore, we fixed the protruded end of the segment 2 and applied constant velocity to the opposite end of the segment 1 (figure 6). This velocity was selected at 0.001 so that damping algorithm kept up with the dissipation process. To end with, we tested YFS in a set displacement mode. Pretention of the bolts in the clamps was varied in the range from 200 to 400 MPa to prevent plastic deformation of the bolts.

As has been said earlier, an indoor facility limits the degrees of freedom to the minimum that provides a favorable condition of YFS testing, hence it usually demonstrates maximum of bearing capacity.

4. Results of simulation

Testing of YFS in the set displacement mode provides movement of the rear end of segment 1 with constant velocity that should provide a smooth sliding of the segment 1 relatively segment 2. As a result, we should not have expected an apparent variation of the YFS fragment resistance. Nevertheless, we registered a periodic oscillation of unbalanced forces in the whole model during YFS fragment test (figure 7).

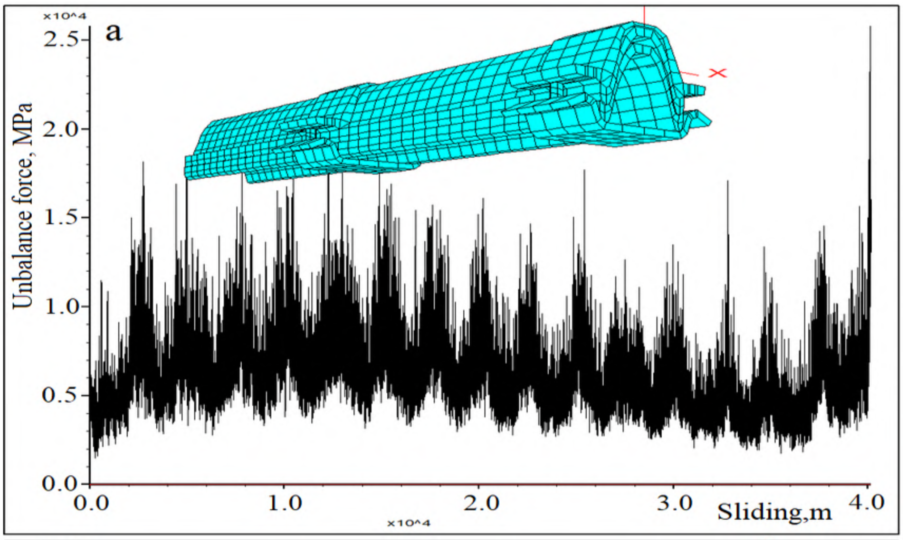
Two evident modes of fluctuation may be noted, namely low and high frequent. We consider the high frequency oscillations as those having stochastic nature because our model consisted of 1976 zones and 4228 nodes. Kinematic energy of the dynamic interaction among the zones and nodes during sliding movement dissipated according to (5), (6), (7) and the frequent oscillation of the unbalanced forces may be explained by error of calculation based on float numbers rounding. However, low-frequency oscillations are natural, should be qualified as an effect of self-organization, and addressed to the stick-slip mode of friction. Seventeen low-frequency fluctuations were registered during sliding of segment 1 to 0.4 m. As a result, the average step of the oscillation was 23.5 mm along sliding direction, which falls within the experimental range from 2.9 mm [20] to 37.5 mm [11]. The diagram in figure 7,a demonstrates the dynamic of reciprocal segments friction for the pretension of the clamps' bolts to 300 MPa, whereas fragment (b) of this figure shows the diagram for the tightening of the bolts to 400 MPa, whereby the bolts transited to plastic state at the end of the experiment. The average level of the unbalance forces grew 1.46 times in the second case that corresponds to a common sense and matches the results of simulation by Horyl et al. [29].

5. Possible ways to control the stick-slip friction in YFS

The great number of conventional clamps are used in the industries and it is expedient to maintain the YFS reliably. Physical methods have been proposed and tested to suppress the stick-slip using vibration [34]. Another approach to damping the stick-slip regime is implementation of a deforming sliding layer [35].

Chemistry proposes different means, which might eliminate stick-slip friction. Spraying of an inhibitor on the surface of YFS profile can reduce their adhesion [31]. Friction coefficient can be reduced at the stick spot using surfactant [36]. Such treatment of the YFS profile surface may be done by separate sections remaining gaps between them. Those sections, which have been treated, will carry out stabilizing function in order to keep the yielding process in the stationary mode. Parameters of this technology such as width of the sections, intervals between them, chemical components are the subject of the future investigation.

A method should be developed to forecast and reveal the moments when an individual YFS is going to stick at the dangerous threshold of its resistance. A single peak of the YFS resistance can damage the whole frame. This is expedient to diminish the resistance at some limited intervals



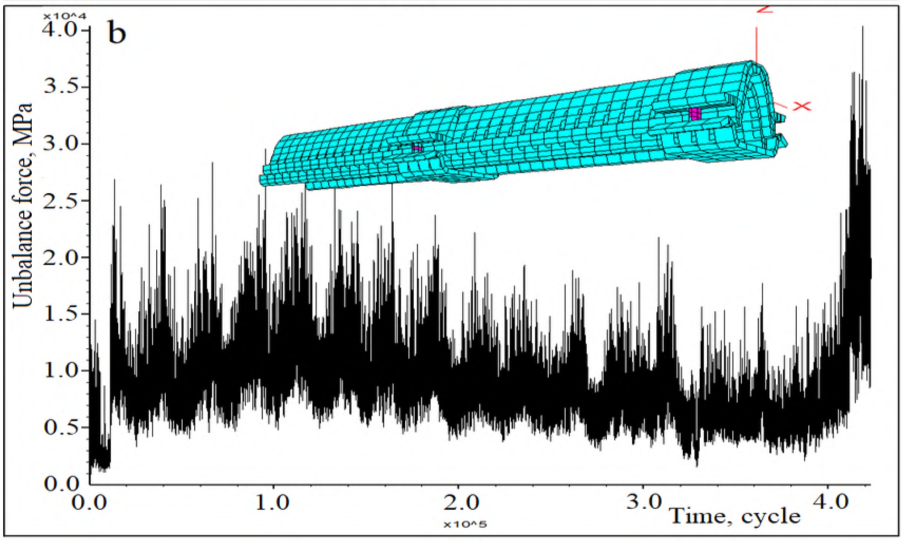


Figure 7. Unbalance force diagrams: (a),(b) – tightening of the clamps to 300 and 400 MPa correspondingly.

in order to save YFS bearing capacity during its yielding through the whole working range, namely 20% vertical deformation of the frame and might be more. YFS main duty is to control ground deformation around the underground opening but not to prevent it. Synchronous radial irreversible movement of the ground inevitably causes self-wedging effect when discrete adjacent pieces of the surrounding rock mass block and jam each other [37]. This behavior generates a self-supporting effect [38] resistance of which is by two orders more than YFS resistance.

6. Conclusion

The standard of YFS survivability testing envisages comparison of maximal resistance of the testing frame in predetermined yielding range and the ultimate bearing capacity of the frame previously tested in the rigid mode with blocked clamps. YFS operates on the principle of the dry friction in the stick-slip mode and the frame are made with high tolerance, surfaces of the frame components, which contact and slide reciprocally, are rough. All these factors invest in the uncertainty of the YFS physical parameters and increase randomness of the friction process.

These factors rise the variation of the peak resistance of YFS and frequently change the steady friction to non-stationary auto-oscillation process. To account for this uncertainty, we introduced the natural variation of the ultimate strength of YFS and matched two distributions, namely normal distribution of the ultimate strength of the frame, and truncated normal distribution of the frame resistance. Such an approach facilitated not only to reduce the uncertainty but assess the risk that the tested frame fails. So far, the only recognized way to secure and control the survivability of the YFS is to keep $k_4 \leq 0.55$. However, this approach is reactive and not reliable because the frame behavior is not stable during the yielding process that is reflected by the nonstationary test diagrams. Our analysis allowed suggesting new proactive tactics to control the survivability:

(i) The most important method is controlling stick-slip friction to stabilize peaks of YFS resistance in yielding mode. This makes yielding of the frame predictable, reduces uncertainty and enforces stability of the process in the predetermined interval of YFS deformation.

(ii) The ideal approach is to suppress stick-slip mode of the friction completely but, in reality, variation of YFS resistance should be reduced as much as possible. Subject to condition (a), this will allow increasing the permissible load over 55% threshold of k_4 without raising the risk of surveillance limit reduction.

We used FLAC3D commercial code to investigate the stick-slip friction process in the set displacement mode during operation of YFS. Validation of this model has shown that results of our simulation are not in contradiction with the independent computer simulation and indoor experiments. We simulated reciprocal sliding of two straight overlapped segments of YFS profile, which were gripped by two clamps. Despite we applied constant velocity to the rear end of the moving segment, certain dissipative structures emerged, which appeared as spontaneous auto-oscillation of the unbalanced forces in the model. We proposed new design solutions, methods and technologies to control the stick-slip friction process increasing the bearing capacity and reliability of YFS.

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To cite this article: Yu L Zabulonov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012013

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012013 doi:10.1088/1755-1315/1049/1/012013

Modern technical and software-analytical tools for solving problems of radiation and technogenic-ecological safety of Ukraine

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Abstract. Nuclear energy in Ukraine is provided by the operation of four operating nuclear power plants (15 reactors). For the next decades it is planned only to increase the capacity of this according to the "Energy Strategy of Ukraine until 2035" industry. Nuclear power plants are objects of increased danger. So, conditions should be provided to maintain environmental balance in Ukraine, innovative developments for radioactive waste management should be implemented, methods of wastewater treatment must be developed/improved, prevention and elimination of natural and emergency emergencies should be provided. It is important to create variety of scientific, technical and innovative developments to solve these problems. Their development is carried out by institutions and organizations, including the National Academy of Sciences of Ukraine. The study analyzes and summarizes activities of the State Institution "The Institute of Environmental Geochemistry of National Academy of Sciences of Ukraine" on innovative developments to improve nuclear, radiation and technogenic environmental safety. The developments of the Institute are defined, described and systematized. The performed research was aimed to solve problems of sustainable development of nuclear energy, environmental problems of nuclear fuel cycle, handling of radioactive materials at all stages of their life cycle.

1. Introduction

Ukraine is among the top ten countries in the world in the field of nuclear energy. However, along with the prospects for the development of nuclear energy, it is important to solve urgent problems of safe and efficient operation of nuclear fuel cycle facilities. At the same time the principles of ensuring its individual components – natural and man-made and environmental security are laid down at the state level in forming the national security strategy. This is reflected in the Law of Ukraine "On Basic Principles (Strategy) of State Environmental Policy of Ukraine until 2030" [1].

Since 2014 there is a shortage of coal as a result of the military conflict in eastern Ukraine. So, the role of nuclear energy increased significantly. However, another problem is arised - any nuclear power plant can become a target for terrorists. Also an important problem in nuclear energy is radioactive waste and spent nuclear fuel which need safe disposal or storage. Not all Ukrainian nuclear power plants (NPPs) have facilities for the processing of radioactive waste. So, it is important to conduct research related to waste management and protection of population and environment from radiation.

Various institutions and organizations (including research institutes of the National Academy of Sciences of Ukraine) function to solve problems related to improve Ukraine's nuclear, radiation, and technogenic environmental safety. Scientific support of the above tasks is provided by the institutes of the Department of Nuclear Physics and Energy of the National Academy of Sciences of Ukraine [2], including the State Institution "The Institute of Environmental Geochemistry of National Academy of Sciences of Ukraine" (IEG NAS of Ukraine) [3].

IEG NAS of Ukraine is one of the leading scientific institutions of Ukraine in the field of environmental and radiation safety [4]. In 2021 IEG NAS of Ukraine celebrated its 25th anniversary [5]. We will analyze and summarize scientific achievements and innovative hardware and software created by employees of the Department of Nuclear Physics Technologies and the Department of Environmental Protection and Radiation Safety to address current issues of nuclear, radiation and man-made environmental safety of Ukraine.

We analyzed scientific publications and systematized research in the following areas: 1) radiation and technogenic environmental safety [6–14]; 2) environmental monitoring of technogenic-loaded territories [15–22]; 3) introduction of innovative developments in practice and in training and advanced training of specialists in the field of nuclear energy, etc. [23–27]. However, it needs separate analysis and coverage of scientific achievements and innovative hardware and software created by the staff of IEG NAS of Ukraine to address current issues of nuclear, radiation and man-made environmental safety of Ukraine.

The aim of the work is to analyze, summarize and highlight innovative developments of IEG NAS of Ukraine to improve nuclear, radiation and technogenic environmental safety of Ukraine.

2. The research results

In 2021 Ukraine celebrated 30th anniversary of independence. The analytical publication [28] states that there was a need for intensive development of some modern areas of basic and applied research in a number of fields in the first years of our country's independence. It includes computer science, nuclear and electronic physics, space and aerospace research, materials science, general and renewable energy, energy saving, geochemistry, ecology. Accordingly, new scientific institutions were established and work of existing organizations was expanded. Some research institutions of the sector were included in the structure of the NAS of Ukraine, and activities of certain institutes were reoriented to scientific and technical support of basic industries and energy.

We should not forget tragic event occurred in our country on – the Chernobyl accident noting the role of scientists in the formation of the Ukrainian state. The Chernobyl disaster affected the environmental, economic and socio-psychological aspects of life not only in the 30-kilometer exclusion zone, but also far beyond. It caused number of complex scientific and technical, medical, biological and environmental problems. It should be noted that participation of scientists of the NAS of Ukraine in overcoming of the Chernobyl disaster consequences began in the first days after the accident and continues today. In addition, the catastrophe scale of the necessitates a scientific assessment of intensity and specificity of the distribution of radionuclides in all chains of natural ecosystems. It is rightly considered the world's greatest technogenic and environmental catastrophe of the twentieth century Therefore, maximum possible elimination of the consequences of this catastrophe was and remains to this day one of the most important scientific tasks of institutions and organizations of the NAS of Ukraine [28].

New scientific institution was established – the State Research Center for Environmental Radiogeochemistry in order to eliminate the consequences of the Chernobyl disaster and minimize the risks of radiation pollution on humans and the environment. The Institute in 2001 was renamed into IEG NAS of Ukraine. Currently, the IEG NAS of Ukraine conducts fundamental and applied research in the following main scientific areas: scientific support of the nuclear fuel cycle; instrumentation in the field of nuclear, radiation and environmental safety; mathematical modeling and forecasting of natural and technogic processes. Also, the Institute has state license to conduct geological, hydrogeological, engineering-geological, environmental-geological and laboratory works. The laboratory base of the Institute has state accreditation. It includes set of analytical equipment for the analysis of toxic, heavy and radioactive elements.

There are 4 NPPs operating in Ukraine with 15 power units – 13 of them are WWER-1000 type and 2 WWER-440 type. Measures to improve the safety of existing NPPs are implemented on a systematic basis in accordance with the requirements of national norms, rules and standards on nuclear and radiation safety, recommendations of the International Atomic Energy Agency (IAEA) and taking into account many years of experience and international practice. The activities of the SNRCU (State Nuclear Regulatory Committee of Ukraine) to regulate safety of nuclear installations are aimed to ensure nuclear and radiation safety at all stages of the life cycle of nuclear installations, protection of personnel, population and environment. Main focus was on improving safety of existing Ukrainian nuclear power plants [29]. Results of scientific research of the Department of Nuclear Physical Technologies and the Department of Environmental Protection and Radiation Safety of the Institute are main scientific and technological base of innovative developments of methods, techniques, technologies and means of control of radiation and sanitary environment, cleaning environmental components from man-made pollution [5]. Accordingly, basic and applied researches in recent years were aimed to solve problems of sustainable development of nuclear energy, environmental problems of the nuclear fuel cycle, handling of radioactive materials at all stages of their life cycle.

Systematization of performed scientific researches and innovative developments created by the employees of IEG NAS of Ukraine was carried out in two directions:

1. radiation safety;
2. technogenic and ecological safety.

2.1. Radiation safety

In this area, employees of the IEG NAS of Ukraine created number of technical and software-analytical tools and implemented them in the work of various organizations and enterprises:

- plasma-chemical installation of liquid radwaste treatment generated during the operation of NPPs and NFC (nuclear fuel cycle) facilities (figure 1);
- for control the movement of radioactive materials, a mobile system for detecting neutron and gamma radiation, which works in real time;
- "ASPEC-O" spectrometric complex for radiation detections and monitoring based on an unmanned aerial vehicle (octocopter) (figure 2). More about this development is described in [5];
- system of radiation control and identification of ionizing radiation based on solid-state detector with high metrological and operational characteristics for effective control of specific activity of liquid, viscous, bulk food and non-food samples at permissible concentrations and below, identification of their radionuclide composition;
- "FoodLight" – a portable workstation that allows you to measure the field activity of gamma-emitting radionuclides in the field (figure 3);

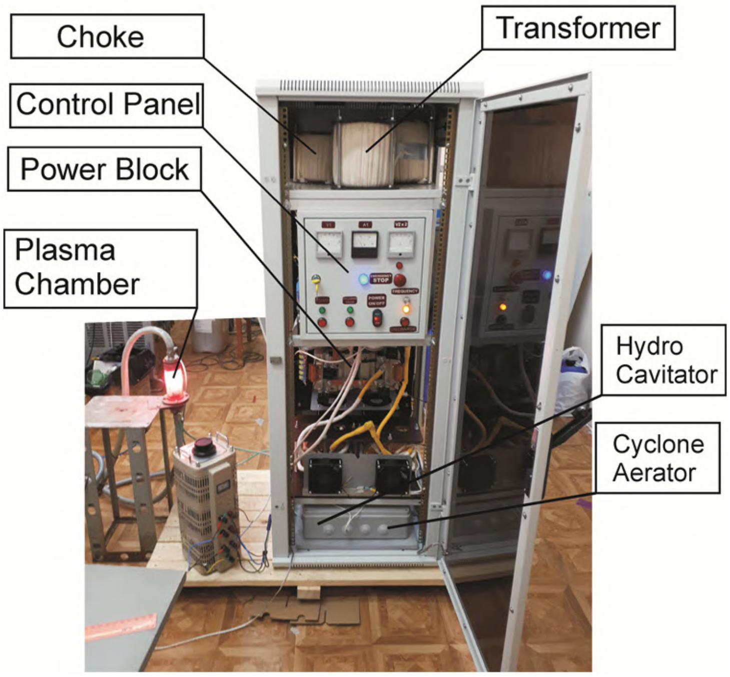

Figure 1. Plasma-chemical installation of purified contaminated drinking water by cold plasma.

(*a*)

(*b*)

Figure 2. Spectrometric complex "ASPEK-O" for radiation reconnaissance and monitoring on the basis of unmanned aerial vehicle type octocopter.

- "G-Scrin" – an automated complex that allows you to measure the content of incorporated radionuclides in the human body (figure 4);
- software and modeling complex that allows to determine dynamics of concentrations distribution of radioactive substances in all components of environment as a result of an incident with spillage of liquid radioactive media in radiation-hazardous facility or outdoors, assess health risks personnel and population, determine annual effective doses from all routes of exposure, identify worst-case scenarios of such dangerous events, generate recommendations to support effective management decisions to respond quickly to such emergencies and minimize their consequences, faster and better develop relevant project documentation , to conduct its examination (figure 5).

Figure 3. Portable workstation “FoodLight”.

Figure 4. Automated complex “G-Scrin”.

The developed experimental technical means are recognized in the world. They provide real-time operational search, detection, localization and identification of nuclear radiation materials.

Also, scientists of IEG NAS of Ukraine performed number of research works marked “Secret”. They are related to the prevention of emergencies at critical infrastructure.

Figure 6 summarizes and schematically presents hardware and software created by the staff of the Institute to address pressing issues of nuclear, radiation and technogenic environmental safety.

2.2. Technogenic environmental safety

Environmental security is a component of national security that guarantees protection of vital interests of man, society, state and environment from real or potential threats posed by natural or technogenic factors. In addition environmental component of each of these types of security can be an integrator that integrates them into the national security system. It will help to find their optimal ratio in this system. Moreover, today there is no doubt that any aspect of national security, whether economic, technological or defense loses its meaning in the case of unsuitability of the environment for human life and activity [30].

There is atendency Ukraine to increase number of emergencies of technogenic nature due

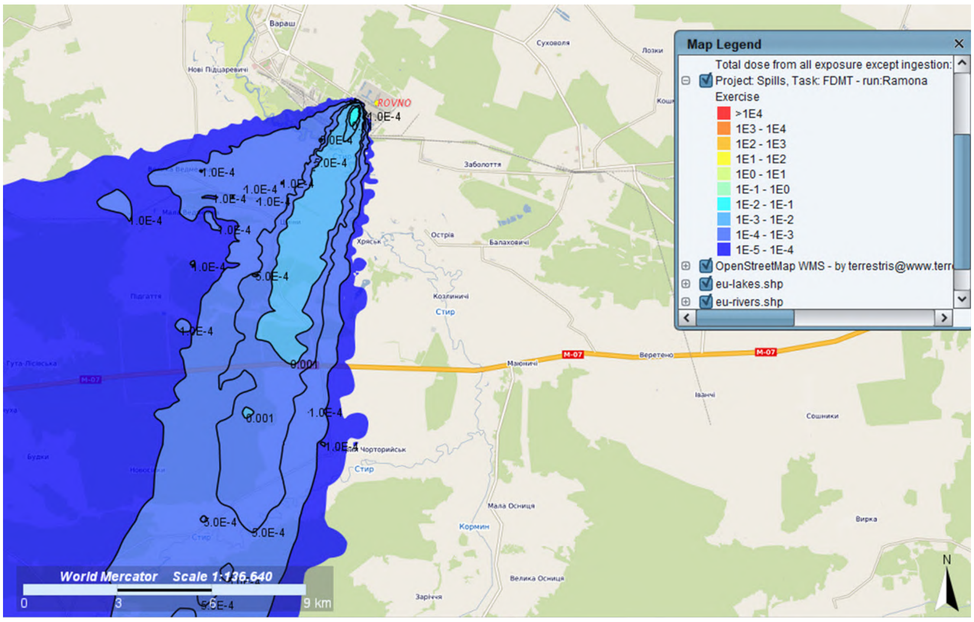

Figure 5. Example of the software-modeling complex.

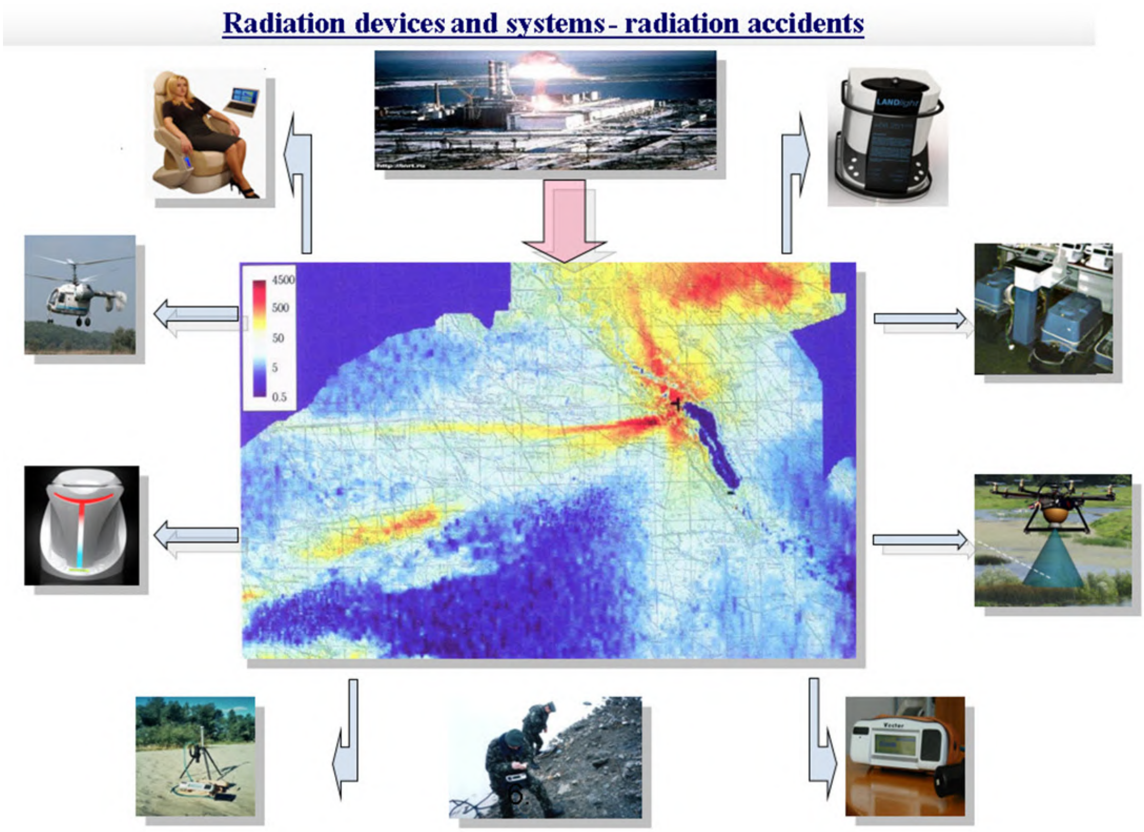

Figure 6. Hardware and software to solve current problems of nuclear, radiation and technogenic environmental safety.

to the use of outdated technologies in many sectors of the economy. Causes of emergencies of technogenic nature include: large amount of transportation, storage and use of hazardous substances; obsolescence of fixed assets, in particular environmental protection; emergency condition of significant part of utilities networks (water and gas pipelines); insufficient investment support for implementation of resource-saving and environmentally friendly technologies in environmentally hazardous industries, namely chemical, metallurgical and energy. For example, nuclear power plants have been operating for over 40 years, new nuclear reactors have not been built and old ones are constantly being extended. Also important is problem of harmful emissions from industrial enterprises into the atmosphere and lack of strict sanctions due to refusal to install special filters to reduce emissions of harmful substances.

The publication [31] emphasizes that status of security problems in modern society is changing due to the impact of different levels of threats: global, regional and national; natural, technogenic and increasingly – socio-ecological. Currently, environmental situation in Ukraine as a whole can be described as tense. Level of environmental safety is defined due to extremely high technogenic load which is constantly growing. Ensuring environmental safety at potentially hazardous sites requires technical re-equipment of production with introduction of the latest resource and energy-saving technologies. It is important to strengthen supervision over the strict satisfaction of industrial safety needs at potentially dangerous facilities, to ensure comprehensive processing, disposal, removal and disposal of industrial waste.

Outlined above problems are paramount importance for conducting research and creating innovative developments which are implemented by the staff of the Institute to improve technogenic environmental safety. As a result of the analysis, the results of scientific research were systematized. We will present the scientific achievements of scientists of IEG NAS of Ukraine and created innovative developments:

- software-modeling system is developed. It allows comprehensive assessment of chemical impact of energy facilities on air and population of adjacent areas with appropriate accumulation, storage, systematization, processing, analysis, exchange and visualization of monitoring data, as well as modeling and forecasting layer of the atmosphere in the controlled areas. More about this development is described in [5];
- mathematical and software tools for optimizing the network of observation posts for air pollution in man-made areas of Ukraine is developed;
- the newest technology of manufacturing of elements of anode and cathode lithium-ion accumulators of the increased capacity for tasks of conversion of peak loadings on power system is created and introduced;
- a new method for the synthesis of highly dispersed nanosorbent has been developed on the basis of magnetically sensitive thermally expanded graphite. This nanosorbent is used to eliminate spills of oil and petroleum products in water bodies;
- indirect method of measuring the concentration of air components on the basis of basic gas laws and taking into account the meteorological characteristics of atmospheric air is developed;
- prototype of the measuring module was developed as an element of the air pollution monitoring system. Figure 7 presents working prototype of the measuring module as an element of the air pollution monitoring system. Such a measuring module may include sensors for measuring the concentration of various pollutants (PM1, PM2.5, PM10, CO_2, CO, SO_2, NO_X, CH_2O, etc.) and meteorological parameters (temperature, humidity and pressure) [32];
- new mathematical tools for modeling air pollution due to dust formation on ash and slag dumps were developed. They unlike existing ones take into account particle parameters,

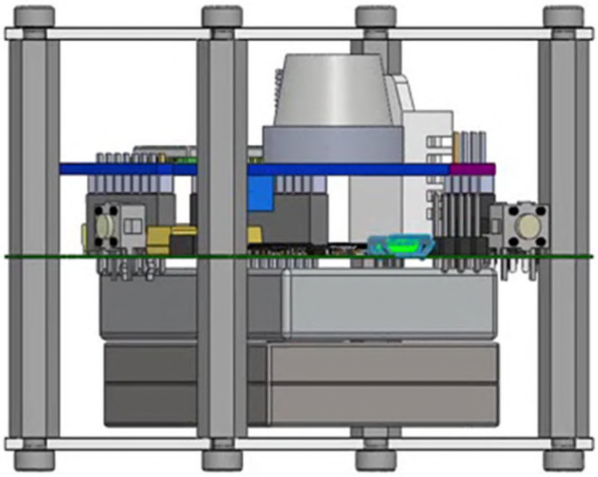

Figure 7. Module of the monitoring system.

spatial and technogenic surface features, meteorological factors, dust suppression and wind erosion intensities. ash slag enterprises of the fuel and energy complex on the state of atmospheric air and the population of the surrounding areas. Specialized software and modeling complex was developed on the basis of the mathematical apparatus. It allows to analyze data of atmospheric air monitoring on the territory of ash and slag dumps, to determine the distribution of pollutants in space and time in atmospheric air during dusting of this man-made object, to protect health of personnel and the population, to solve problems of preventive forecasting and generate recommendations to support effective management decisions to respond quickly to such emergencies and minimize their consequences;

- new mathematical models of air and surface water pollution as a result of emissions and discharges from NPPs and mathematical model of soil pollution by chemical emissions from NPPs due to the deposition of impurities from the surface layer of the atmosphere were created. Computer tools were developed for comprehensive assessment of the non-radiation impact of Ukrainian NPPs on the environment on the basis of mathematical software;
- prototype of drinking water treatment plant for persistent organic pollutants by plasma-chemical method was developed. The method of cold plasma does not require additional chemical treatment. It is used for purification of technogenic polluted waters. This is developed under a UK Grant;
- multifunctional laser computer complex with 8 channels system was developed for treatment of wounds and trophic disorders of participant of Antiteroristic Operation and Operation of Joint Forces, as well as their rehabilitation;
- new mathematical tools for optimizing the air monitoring system of man-made areas was developed. This unlike existing ones takes into account technogenic, environmental, socio-economic factors, level and consequences of air pollution. Its application allows to determine coordinates of stationary and mobile posts depending on current monitoring tasks for a specific network/territory. Mathematical tools are implemented in the form of a specialized software package.

Scientific results and innovative developments created by employees of the Department of Nuclear Physics Technologies and the Department of Environmental Protection and Radiation Safety of IEG NAS of Ukraine are of great practical importance for environmental safety, as evidenced by the acts of implementation in various enterprises and organizations. Also number of patents for copyright certificates for the above developments is received.

3. International cooperation and implementation of scientific results

Another important achievement of IEG NAS of Ukraine is successful integration into the international scientific system. It contributed to the promotion of Ukrainian inventions abroad and increased importance of the contribution of our scientists to the achievement of world science. Employees of IEG NAS of Ukraine are experts of: Pure Earth International Organization (USA); Pegasus Environmental and Nuclear Services, Inc. (USA); Ministry of Ecology and Natural Resources of Ukraine and others, etc. [5]. The Institute also cooperates with various international organizations and universities: PLEJADES Independent Experts (Germany), Clemson University (USA), Indra Scientifc SA (Belgium), Blacksmith Institute (USA), etc.

Employees of IEG NAS of Ukraine fruitfully cooperate with domestic and foreign research centers and production associations. Priority areas of such cooperation are within the framework of international scientific cooperation under EU programs “Horizon 2020”, NATO “Science for Peace and Development”. These are creation of new functional materials and nanocomposites for elements and devices used in telecommunications and engineering; research of new coordination compounds for the needs of medicine and agriculture; development of resource-saving technologies for efficient processing of metal-containing natural and man-made substances. They will certainly help to reduce technogenic load on the environment.

The Department of Nuclear Physical Technologies and the Department of Environmental Protection and Radiation Safety Technologies employ qualified scientific personnel with many years of positive experience in conducting scientific research. The Institute gained authority and respect not only through the work of scientists, but also through tireless work of large number of engineers, graduate students, talented youth, support departments and services. They all love their profession, are proud of their Institute and develop domestic science.

Process of creating innovative developments is accompanied by discussion, testing and description of their benefits by presenting scientific results and innovative developments at various scientific and exhibition events and publishing scientific articles, monographs and more. Also, employees of these departments initiated, annually organize and conduct international workshop “Innovative Approaches for Solving Environmental Issues (IASEI)” in the framework of the International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters (ICSF) [33]. Figure 8 presents photo of international workshop, which was held in 2021 in online format, more details on the materials of workshops and conferences can be found in [33, 34].

As a result of analysis and systematization of the work of scientists of the Department of Nuclear Physics Technologies and the Department of Environmental Protection and Radiation Safety of IEG NAS of Ukraine in recent years it is determined:

1. The Institute has reputation of leading scientific institution of Ukraine on the development of nuclear and physical technologies and radwaste management. This promotes interest of foreign investors in cooperation and financing of various projects.
2. The results of scientific research are unique (carried out at the intersection of different branches of science). Therefore, innovative projects are attractive for investment and competitive for world science.
3. The Institute is a leading research institution in the development of plasma-chemical technologies, in particular, developed innovative plasma-chemical reactors for the purification of liquid radwaste from radionuclides of objects.
4. Scientists of the Institute for the first time carried out radiation mapping of territories, including the Chornobyl Exclusion Zone, using the developed technology on the basis of

Figure 8. International workshop "Innovative Approaches for Solving Environmental Issues (IASEI-2021)".

unmanned aerial vehicles.

5. Reviews and responses of scientific papers from leading scientists at Clemson University, Khazar University, Vilnius University and other organizations indicate a high level of technical and software-analytical tools for solving problems of radiation and technogenic-ecological safety.

4. Conclusions

Importance of conducting research on the issue of technogenic environmental safety was exacerbated by the pandemic caused by coronavirus disease (COVID-19) and the military situation in eastern Ukraine. Our country has large number of potentially dangerous facilities. Nuclear power plants occupy the first positions among such facilities.

Thus, the Institute is one of the recognized research institutions, whose employees are able to solve pressing problems environmental and radiation safety. The Department of Nuclear Physics Technologies and the Department of Environmental Protection and Radiation Safety provides solutions to pressing problems of national security of Ukraine in the following areas: comprehensive environmental monitoring of technogenic areas; radiation and technogenic-ecological security; civil protection of territories, population and environment.

For the needs of the nuclear energy complex of Ukraine, scientists of IEG NAS of Ukraine performed a number of studies on scientific and technical support of nuclear energy development and application of radiation technologies. Their main task is scientific and technical support of safe and reliable operation and development of nuclear energy, broadening of resource base, development of new generation nuclear physics facilities and applied research in promising areas of nuclear physics, plasma physics, radiation materials science and instrumentation, development of mathematical and software tools for modeling and forecasting the impact of radiation-hazardous objects on the environment.

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Immobilization of boronic acid derivative onto the magnetic Gd-containing composites

To cite this article: Ie V Pylypchuk *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012014

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012014 doi:10.1088/1755-1315/1049/1/012014

Immobilization of boronic acid derivative onto the magnetic Gd-containing composites

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Abstract. Aiming to develop new magnetic materials for neutron shielding applications, B- and Gd-containing magnetic nanoparticles were synthesized. Following bottom-up synthetic approach, core-shell Fe_3O_4/Gd_2O_3 nanocomposite particles were synthesized at the first stage. In the next stage, magnetic core-shell particles were modified with amino groups followed by grafting onto their surface of the boronic acid derivative. Such a multifunctional material, containing both boron (B) and gadolinium (Gd) atoms is a promising candidate for developing films and membranes, strongly interacting with neutrons. Due to the presence of boronic acids and bound to the indicator (Alizarin Red S), the material can induce color changes while immersed in sugar-containing solutions. Such a feature enables a possibility to estimate the number of boron atoms left after interaction with neutrons, thus allowing to check composite neutron-capture recourse.

1. Introduction

Research aimed at creating supramolecular, composite, nanostructured, and consolidated materials that effectively absorb ultrahigh-frequency electromagnetic and neutron radiation for use in technical, medical-biological, environmental, etc., has become significant in our time. Nanocomposites that are sensitive to effectively adsorb neutron radiation are promising for practical implementation in radiation medicine, engineering, ecology, biology, and more. However, there is still a need for development, not just efficient materials, but materials from sustainable sources.

In this view, gadolinium, and boron, chemical elements with high neutron capture cross-sections, are attractive due to their versatile chemistry and ability to be incorporated into re-processible composites. In the case of boron, it interacts with epithermal neutrons with the release of gamma-quants and alpha-particles, as shown in the scheme below (figure 1).

Alpha-particle have free path lengths in the range of micrometers, and thus, to avoid secondary radiation damage to the material caused by alpha-particles, boron components can be incorporated into a layered matrix, preferably of inorganic oxide origin. Such an inorganic matrix can be an iron oxide, due to its good radiation-scavenging properties. Also, if such an

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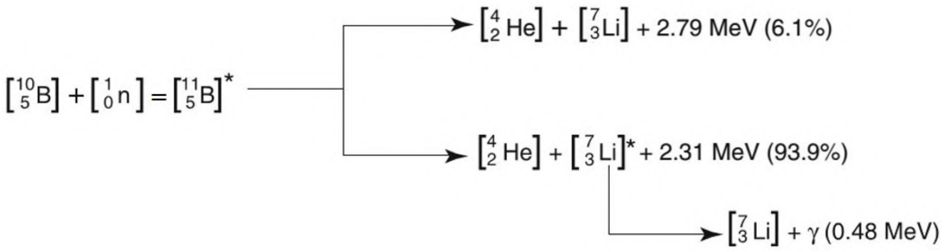

Figure 1. Interaction of boron with epithermal neutrons.

oxide contains gadolinium components, it can work as a secondary barrier for the neutrons. For instance, the enhancement of neutron attenuation and reduction in secondary gamma by combining Gd_2O_3 and B_4C has been shown in work [1].

In literature, a gadolinium oxide Gd_2O_3 was used for the preparation of self-healing poly (vinyl alcohol) hydrogels for thermal neutron shielding [2]. Also, a Gd_2O_3 based thermal neutron attenuating paint with an oxide mass fraction of 0.4 has been produced using commercial polyurethane and has shown good neutron protection properties [3]. In another example, nano-boron carbide (B_4C) and boron nitride (BN) particle-reinforced polymer composites were developed for neutron shielding [4]. However, to increase the interfacial adhesion between BN and the polymer matrix, additional modification with coupling agents is needed [5], which might cause additional expenses. For this purpose, a B_4C/epoxy composite was developed [6]. However, the thickness of such a coating for 80% absorption of neutron fluence was almost 9.8 mm at 3 wt% of B_4C (particles 150µm). This result proves that high loading of neutron-shielding materials is needed. To another publication [7], a nanoamorphous B_2O_3 layer was designed and fabricated between B_4C particles and an Al matrix. The authors claim that good corrosion resistance makes $B_4C@B_2O_3/Al$ composites a potential neutron shielding material. Also, the addition of medium-heavy metal powders to epoxy-based composited was proposed as an effective way to improve the neutron-shielding properties of materials [8].

Thus, a hierarchical structure, containing layers of boron components alternating with mixed gadolinium/iron oxide seems to be most attractive in terms of scavenging neutron radiation, and such a material was developed in this work.

2. Experimental part

Synthesis of magnetic Gd-containing nanosized carrier. Doping of magnetite's surface with gadolinium ions was carried out with gadolinium nitrate. Briefly, the solution containing ferrous and ferric salts (1M: 2M), and 1 mole of $Gd(NO_3)_3$, was heated to 90 °C, and slowly precipitated by the addition of ammonia solution under vigorous stirring. Precipitated Fe_3O_4/Gd_2O_3 nanocomposite particles were washed with distilled water until a neutral pH and separated with a permanent magnet and sonicated twice for 5 minutes. The average particle size was ∼13 nm. The particles were stabilized either with sodium oleate or oleic acid.

Modification of the surface of magnetic Gd-containing by γ-aminopropylsiloxane. The surface of magnetic Gd-containing nanoparticles was coated with γ-aminopropylsiloxane (γ-APS) in toluene [9]. The reaction of polycondensation is carried out according to the scheme in (figure 2).

Transmission electron microscopy (TEM) of magnetite nanoparticles was performed using transmission electron Microscope JEOL 2010.

γ-APS was dried over molecular sieves and purified by distillation in a vacuum. Magnetic Gd-containing particles were exposed to a solution of γ-APS (10% vol.) in toluene for 8 h, precipitated in a centrifuge, washed with toluene and acetone, and dried at 293 K. Contents

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$$|-OH + (C_2H_5O)_3Si(CH_2)_3NH_2 \rightarrow |-O-Si(CH_2)_3NH_2 + 3C_2H_5OH$$

Figure 2. Polycondensation reaction scheme.

of functional groups on the surface of magnetite were measured with X-ray photoelectron spectroscopy (XPS) and differential scanning calorimetry (DSC) combined with differential thermogravimetric analysis (DTA). The thermal graphs were recorded in the temperature range 293–1273 K at the heating rate of 0.16 °/s on a Q-1500D thermal analyzer purchased from the company MOM (Hungary) [10, 11].

Immobilization of boronic acid derivative. 5-formil-2-furyl boronic acid (furyl borate) was immobizlied on the surface of Magnetite/3-APS composite in ethanolic solution. Immobilization of Alizarine Red S was performed in phosphate buffer (pH=7.4).

3. Results and discussion

To create neutron-shielding materials which are safer for the environment, we have selected a boronic acid derivative. This is due to their relatively low toxicity and their degradation into the environmentally benign boric acid [12].

From the DTA data was calculated, the concentration of the hydroxyl groups on the magnetic Gd-containing nanoparticles (specific surface area Ssp= 90 m^2/g) was equal to 2.4 mol/m^2 or 2.2 mmol/g [9]. On the surface of magnetite forms Si-O-Si use polymeric coating a with high degree of polymerization which, in its turn, can further provide magnetic carriers with certain chemical or biochemical properties.

The nano-dimentsinality of synthesized magnetite particles was confirmed by electron microscopy (figure 3a). The presence of the amino groups at the surface of the obtained nanocomposite was confirmed with XPS [9]. The obtained samples were tested by Fourier-transform IR-spectroscopy. Figure 3b shows the Fourier-IR spectrum of magnetite, modified by γ-APS. Pronounced absorption bands at 1037 and 1130 cm^{-1} of approximately equal intensities indicate the formation of a polymer layer of Si–O–Si at the magnetite surface resulting from hydrolytic polycondensation of the modifier molecules. Intensive doublet at 1037 and 1130 cm^{-1} is caused by the formation of polymer structure with a high degree of polymerization, i.e., on the surface of magnetite occurs hydrolytic polycondensation of molecules of modifier with the formation of polymer structure of the bonded layer of a modifier [9, 10].

Thus, having modification of magnetic Gd-containing nanosized carrier confirmed, we have proceeded with immobilization of the boronic acid derivative (figure 4). Synthesis of Fe_3O_4/3-APS/furfurylborate nanocomposite showed below.

FTIR-spectra (figure 5) shows AB at 1732 and 1811 cm^{-1}, that corresponds to a formyl residue of initial furfurylborate. Splitting to two AB can be explained by a possible intermolecular interaction of formyl residue with hydroxyl groups of boronic acid. After furfurylborate interaction with amino group of modified magnetite, AB of formyl residue disappears, that confirm formation of Fe_3O_4/3-APS/furfurylborate nanocomposite. AB of -B-C bond can be observed at 900 cm^{-1}, AB of -B- bond appear at 1350 cm^{-1}. Adsorption bands of -C=N bond can be observed at 1630-1690 cm^{-1}. Thus, IR spectroscopy confirms that furfurylborate has been successfully immobilized on the surface of Gd-containing magnetic particles.

Boronic acids contain trivalent boron atoms bonded to one alkyl/aryl substituent and two hydroxyl groups ($R - B(OH)_2$) [13]. Unique and versatile reactivity [14] and stability [12] of boronic acids have led to uses in numerous areas, including C-C bond formation, acid

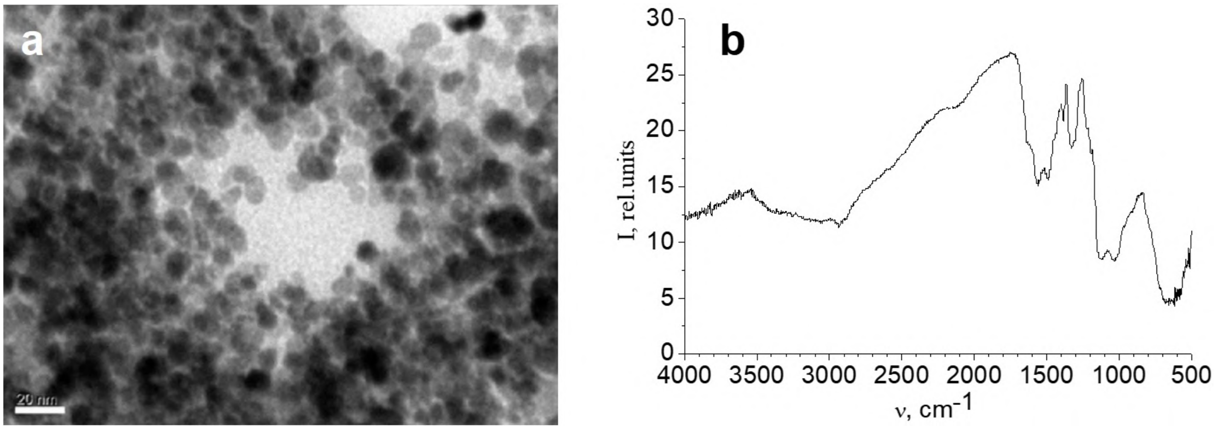

Figure 3. TEM image of initial magnetite particles (a), and FTIR spectra of magnetic Gd-containing nanosized carrier modified by γ-aminopropylsiloxane (b).

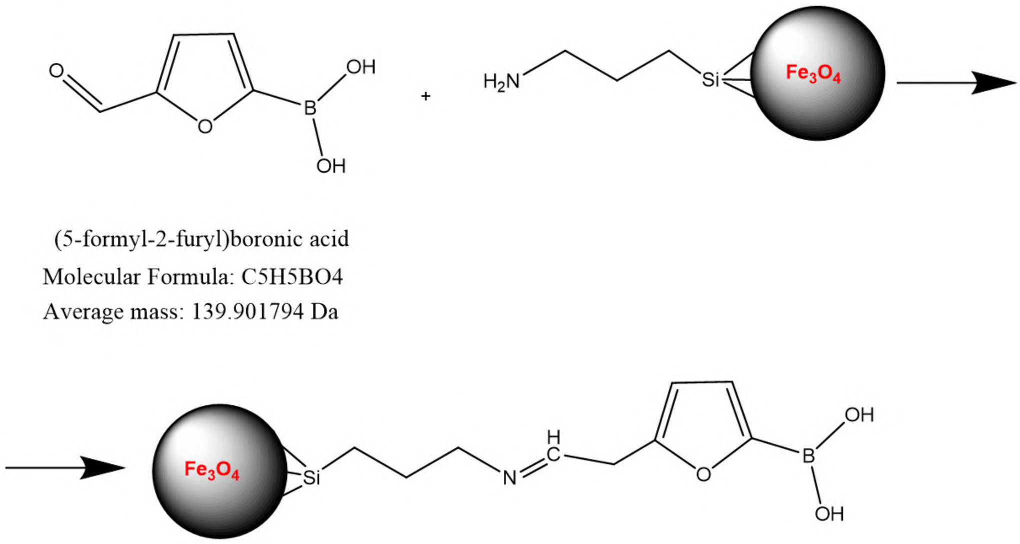

Figure 4. Scheme of immobilization of boronic acid derivative.

catalysis, asymmetric synthesis, carbohydrate analysis, metalcatalysis, molecular sensing, and as therapeutic agents, enzyme inhibitors, and novel materials [13]. Perhaps the most important chemical characteristic that has led to boronic acids finding utility in a plethora of biomedical applications is the ability to form reversible covalent complexes with 1,2- or 1,3-diols [12] (figure 6).

For instance, ARS dye (figure 7), an a cis-diol has been used as a reagent for the fluorometric determination of boric acid interactions with cis-diols [15].

ARS displays a dramatic change in fluorescence intensity and color in response to the binding of boronic acid [16]. Thus, there is a "switch" of ARS molecules from a non-fluorescence condition to a fluorescence one, and the content of cis-diols in the solution can be quantitatively evaluated with the fluorescence of obtained conjugate. In addition, there is a shift of the maximum absorption band of cis-diol derivate in the visible range. The scheme of ARS interaction with boronic acid is shown in figure 8.

In our work it is demonstrated with the formyl-furylboric acid and ARS in phosphate buffer

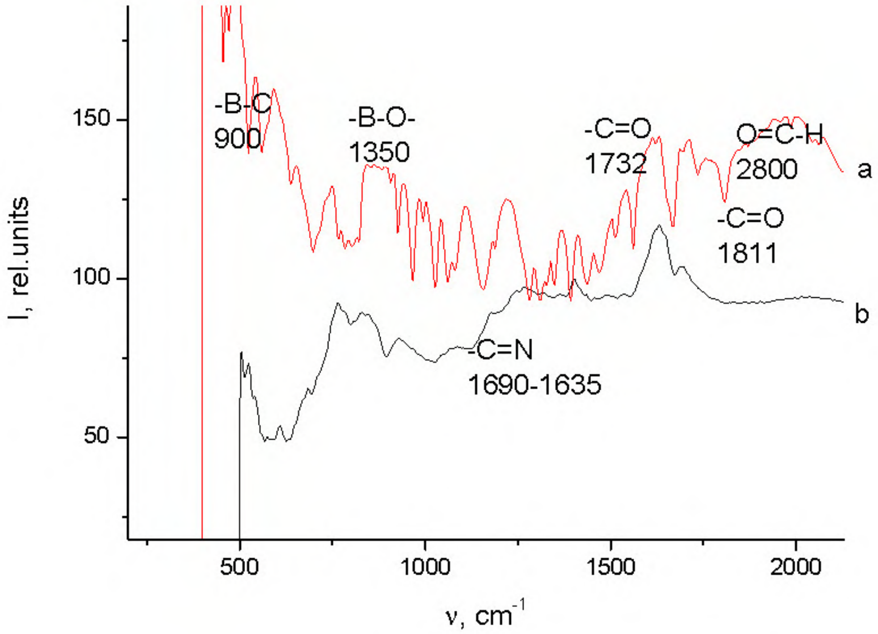

Figure 5. FTIR-spectra of furfurylborate (a) and Fe_3O_4/3-APS/furfurylborate nanocomposite (b).

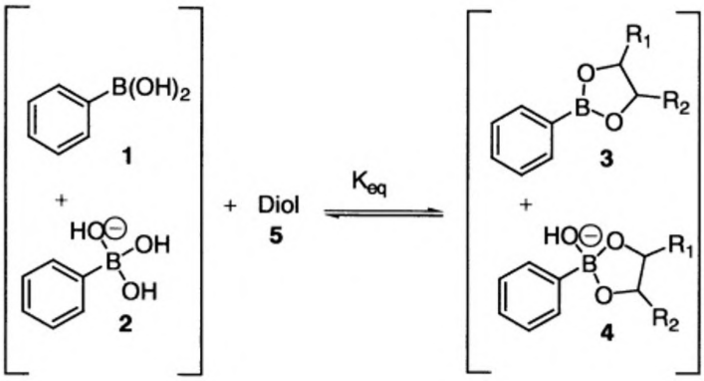

Figure 6. Reaction of diols with phenyl-boronic acids.

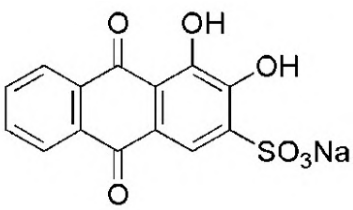

Figure 7. Chemical structure f ARS dye.

(figure 9). A typical solution for the study of binding fluorescence dye ARS and boronic acids consisted of phosphate buffer at pH=7.4, ARS (0.01 mM) and boronic acid ranging in concentrations from 0.01 to 1 mM. ARS show acidic properties: pKa1 = 5.5; pKa2 = 9.5.

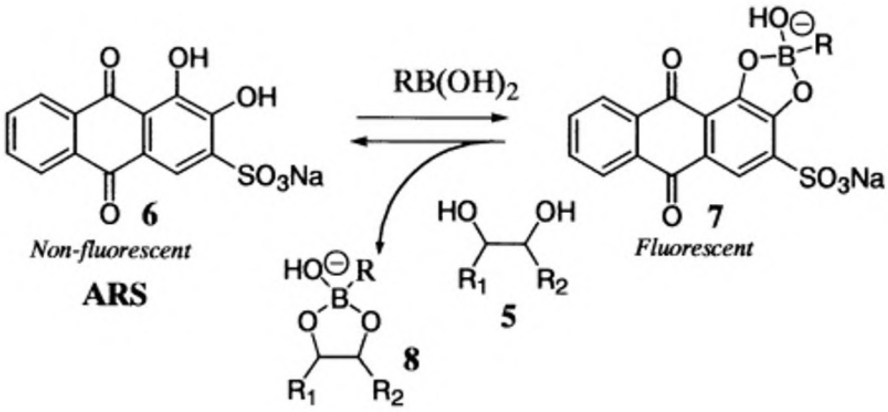

Figure 8. Competitive binding of a Boronic acid with ARS and a 1,2-diol.

$\lambda_{max} = 515$ nm (figure 9).

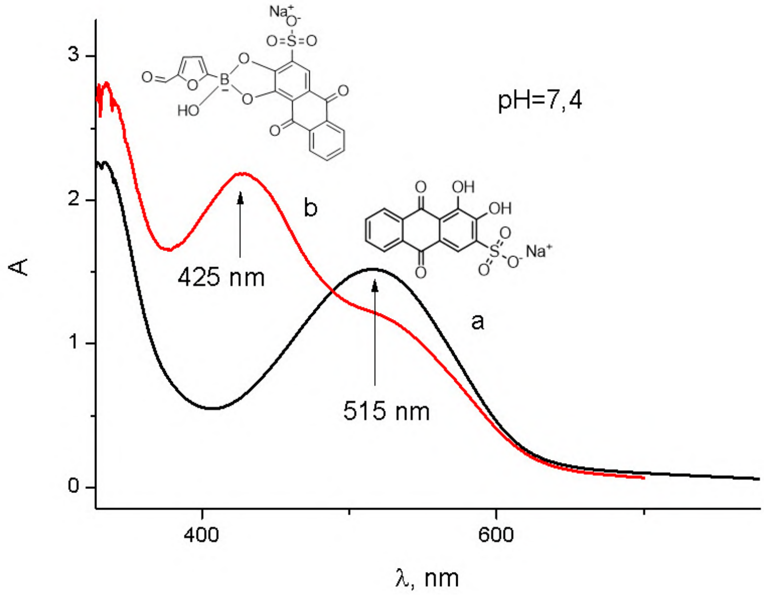

Figure 9. UV-Vis spectra of ARS (a) and furfurylboronic acid/ARS conjugate (b).

The formation of ARS-Fe_3O_4/3-APS/furfurylborocnic acid conjugate occurs according to the scheme in figure 10.

After the chemisorption on boronfurfurol, the ARS molecule switches from a non-fluorescent to a fluorescent state. Immobilization of ARS on Fe_3O_4/3-APS/furfurylborate nanocomposite allows creation fluorescent probe on nanocomposite surfaces. In our work, it has been demonstrated by the formation of conjugate formylfurfuryl boronic acid with ARS in phosphate buffer (pH=7.4). A shift of ARS adsorption maximum from 515 nm to 425 nm in ARS-furfurylboronic acid conjugate indirectly confirms changes in the electronic state of the ARS molecule, necessary for fluorescent state switching.

Based on published data [17], in case of the addition of carbohydrates in the form of cis-diol form the competitive replacement ARS on the surface of the composite to sugar molecules should

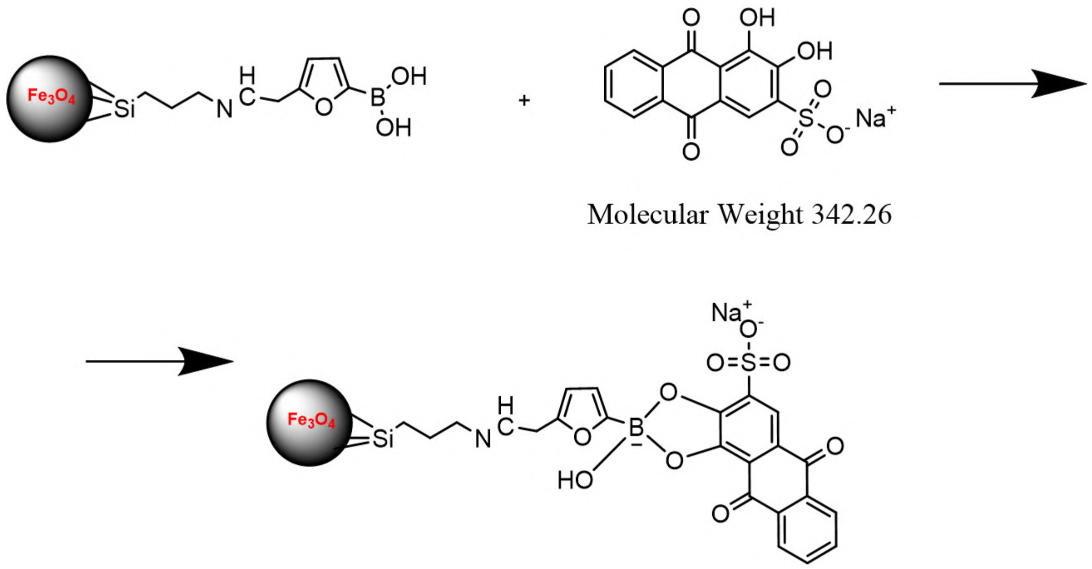

Figure 10. Scheme of the interaction of ARS with boronic acid immobilized on the surface of magnetic Gd-containing particles.

happen. Recognition of different simple sugars in human blood is an important task for current medicine. The most promising way to construct fructose-sensitive materials is to use the ability of boronic acid to form reversible covalent complexes with 1,2- and 1,3-diols [16, 18, 19]. Boronic acids have relatively small toxicity and can be considered "green" compounds [16]. The release of ARS was confirmed by photocolorimetric method (λ = 440 nm). A model experiment was being conducted that based on competitive sorption phenomena between ARS at the surface of nanocomposites and fructose. It passes according to the scheme in figure 11.

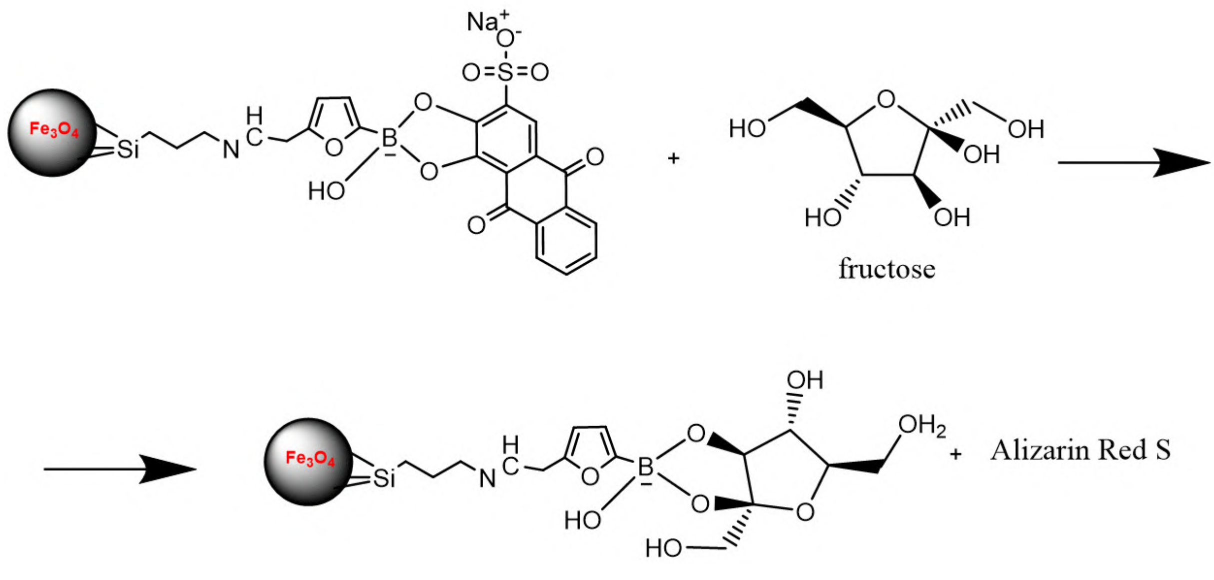

Figure 11. Scheme of fructose interaction with ARS on the surface of boronic acid/magnetic Gd-containing particles.

We have estimated the amount of available boronic groups on the surface using a reaction composite with sugar. As it can be seen from figure 12, the amount of released ARS is proportional to the concentration of sugar in the added solution. The maximum amount of released ARS corresponds to the calculated boronic acid content of 1.76 mmol/g. Taking into account the number of amino groups in the initial composite (2.2 mmol/g), one can conclude that the immobilization efficiency for the boronic acid derivative is 80%. However, not all the boronic acids moieties on the surface can be available for the reaction with sugar due to steric hindrance.

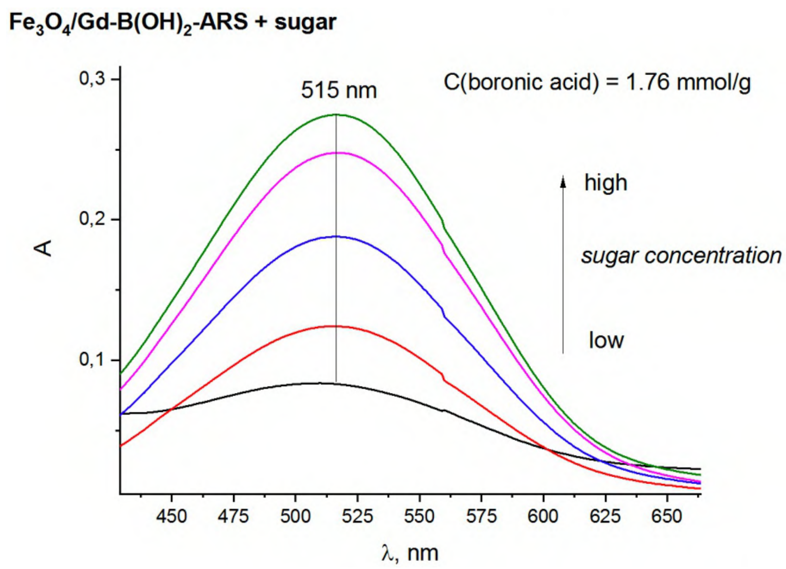

Figure 12. The optical density of sugar-containing solutions after reaction with boronic acid/magnetic Gd-containing particles bound with ARS.

4. Conclusions

Aiming to develop new magnetic materials for neutron shielding applications, we have used a bottom-up approach for the synthesis of promising boron-containing nanocomposites on a Fe_3O_4/3-APS basis. Performed formation of Fe_3O_4/3-APS/furfuryl boronic acid conjugate with ARS which opened up the path for fluorescent determination of these kinds of nanocomposites due to inherent changes in the electronic structure of the dye adsorbed on the surface. Due to the presence of boronic acids on the composite surface, the composite changes the color of the sugar-containing solutions, allowing to control of the amount of immobilized boronic acid derivative.

We can propose the use of such multifunctional B/Gd-containing magnetic nanocomposites as a magnetic actuator membrane, providing efficient shielding "on-demand" maintaining strong interaction with neutrons. This work, we believe, is contributing to sustainable development goals 9 (industry and innovation) since it offers an innovative approach for neutron shielding and 12 (responsible production) due to the possibility to extract recycle such a magnetic material using strong magnetic field.

Acknowledgments

The work is performed in the frames of Ukrainian state fund program "Support of the development of prior scientific researches" as a winner of the projects for laboratories/groups initiated by the National Academy of Sciences of Ukraine (KPKVK 6541230).

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To cite this article: Yu L Zabulonov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012015

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012015 doi:10.1088/1755-1315/1049/1/012015

Mathematical aspects of remote assessment of the radiation state of contaminated areas

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Abstract. The use of radioactive materials is widespread in scientific investigations and various sectors of the economy. There are also extremely radiation-hazardous objects, for instance the well-known Chornobyl Exclusion Zone (Chornobyl, Ukraine) covering the large contaminated areas and the Shelter Object containing the materials of huge radioactivity of about 20 MCi. To safe handling with such objects and materials, the correct their monitoring, detection and characteristics evaluation are vital. The modern development of small flying machines, measurement equipment, and information technologies allow one to increase the amount of measurement data and their accuracy, and to reduce the processing time. On the other hand, the requirements to accuracy, quickness, and correctness of data interpretation increase as well. To solve these problems effectively, the mathematical tools of data processing should be improved. The main mathematical problem at the remote evaluation of radioactive fields relates to the solving the inverse problem for the Fredholm integral of the first kind. In this research, we consider the reconstruction of surface density of gamma radiation on the ground using the data of aerial shooting. We survey the methods for solving the inverse problem, their advantages and disadvantages. The adaptation of the methods to the reconstruction of nonstationary discontinuous radioactive fields is presented. We modify the numerical algorithms using the opportunities of modern calculating software. In particular, it is considered the task when the algorithm reconstructs the density distribution very well.

1. Introduction

The energy of radioactive decay [1] can be useful supporting the high level of human societies development but conventionally also possesses unpleasant often dangerous effects.

In few recent decades the issues of radiation safety are becoming increasingly important. This is caused by the various reasons [2] including essential increasing the nuclear waste, expansion of the areas of contaminated land, intensive use of nuclear materials in military [3] and civilian purposes, operation of power plants containing the nuclear reactors (nuclear plants, submarines, missiles, and etc.), increasing a number of terrorist attacks and level of their preparation. Moreover, due to the prevalence of radiation materials, negative consequences of technogenic and natural disasters (Chornobyl and Fukushima nuclear accidents [4]) can be multiplied.

To organize the effective control and correct handling of radioactive materials and to provide the radiation safety, small flying machines or so-called unmanned aerial vehicles (UAVs) began to apply widely. The advantages [5–11] of this approach are well known. Among them are:

- rapid gathering of data extracted from the large areas;
- in contrast to the manned vehicles, UAVs do not require special strict regulations or permissions, there are less problem with pilot's safety;
- UAVs can provide more detail explorations of the areas with complicated reliefs or obstacles [2, 12, 13];
- their exploitation is less expensive;
- they are less dangerous for environment (accident does not lead to substantial injury or damage of surrounding structures);
- there is a possibility to use them in particularly unfavorable conditions (strong radioactive, magnetic, temperature fields);
- in general, UAVs can get as close to the source as possible and, in turn, decrease the influence of attenuation effects;
- multipurpose application (relatively easy to change equipment).

When radiation fields are considered, special attention is paid to the development of procedures for identifying the array of detector's readings [8, 9, 14, 15]. The choice and details of the implementation of such procedures depend on the problem's specifics, but, as a rule, they are based on the statistical nature of the signals being recorded. The latter leads to the need to solve the inverse integral problem, which belongs to the class of ill-posed problems and can demonstrate the multi-valudness of solutions or instability. Starting with the works of Tikhonov and Lavrentyev, with the subsequent contribution of many others [16, 17], a number of algorithms [18, 19] have been proposed to regularize the problems including variational, Friedman, weighted singular schedule.

It is intensively developed the methods for solving the inverse problem arising in statistical statement [2, 20, 21], i.e. the problems which do not possess exact solutions due to containing, for instance, data with measurement errors or the problems in which the amount of in-coming data is restricted, while a model requires the assessment of huge number of model's parameters.

However, their implementation for a specific task is not easy, in particular in the case of multidimensional, singular or dynamic problems that arise during aerial photography, visualization of areas of high radiation.

2. Research aim and objectives

It is important the increase of the algorithm's stability, the choice of the optimal procedures for a particular task, ensuring the accuracy of reproduction of the characteristics of the studied system, speed and ease of obtaining results. The aim of this report is to consider integral direct and inverse problems arising in the task of remote monitoring of distributed radioactive fields. In this research we investigate the problem of remote sensing of ground surface to reveal the distributed gamma ray emission and estimate its characteristics.

3. Statement of the problem

Let us start from the mathematical description of the problem omitting some technical and physical details [9, 12–14]. In particular, the simplified scheme of remote sensing is depicted in figure 1. Suppose we have a detector (the point D with the coordinates x^d and the altitude h^d) mounted on a small flying machine providing us the counting of gammas produced on the ground surface. The detector's eyeshot is formed by the collimator with rectangular cross-section and the aperture 2θ rad. Hence, on the ground surface it is appeared the view window (almost rectangular), the gammas from which reach the detector. It is obvious that the size of the window depends on the detector's altitude h^d and θ, i.e. the window side $2\Delta x = 2(h^d - h)\tan\theta$, where h is the relief altitude. For instance, when the detector with $\theta = \pi/3$ rad is located at a height of 55 m above the ground surface, the view window size is $2\Delta x = 190$ m.

Next, the detector traps gammas during the time interval $[t_{i-1}; t_i]$. We can also assume that the exposure time of the detector is $t_i - t_{i-1} = \tau = const$. At the end of this time, the number of gammas W is fixed. Note that, during the time τ, UAV moves with the velocity v m/s along the horizontal axis and the view window is shifted on the distance $v\tau$ m as shown in figure 1, i.e. when $\tau = 1$ s and $v = 100$ km/h, the window displacement is 28 m. As a consequence, if UAV flies the distance about $L = 4000$ m, we obtain $L/(\tau v) \approx 140$ values of W.

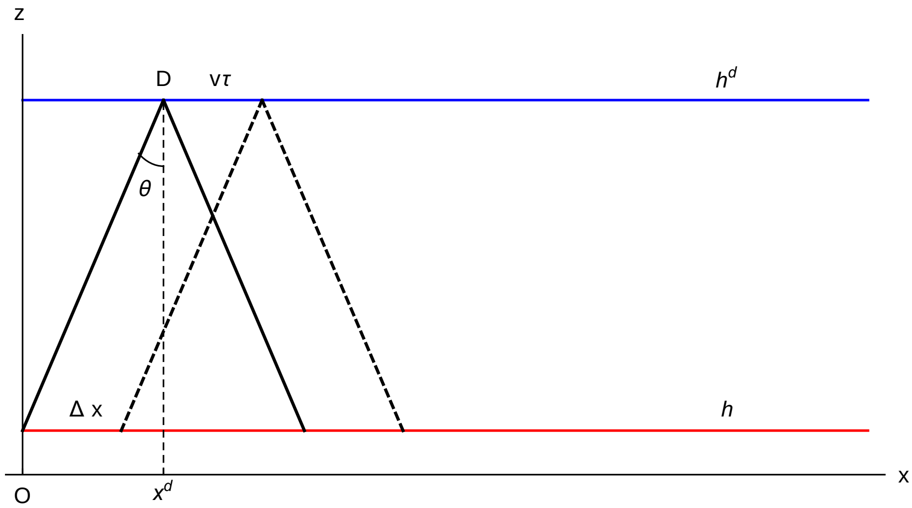

Figure 1. The simplified scheme of remote sensing.

Thus, in general, to evaluate the number of trapped gamma rays at a time moment t_i, it can be used the following integral [14, 19] equation

$$\int_{t_{i-1}}^{t_i} dt \int_\Omega w(x^d, x)d\Omega = W(t_i), \tag{1}$$

where w is the density of gammas, $x^d \in R^n$ is the detector's position and $x \in R^n$ is a point in the domain Ω representing a radioactive material. The quantity

$$w = \sigma(x)sg(x^d, x)\frac{e^{-r\mu}}{4\pi r^2},$$

where σ is the density of gamma sources; X^d is the detector position; s is the effective area of detector's inlet; $\mu = 1/\ell$ is the coefficient of attenuation in air (ℓ stands for the mean free path of the gamma rays [22]); the function $g = (h^d - h)/r$ coincides with the cosine of angle between the vertical and the direction from the detector to the point x; r is the distance between detector and the point x lying on the surface.

Thus, two problems arise: the former is to estimate the number of events W registered by the detector for a given distribution of σ (*direct* or *forward* problem); the latter is to restore the distribution σ, when the data W are given (*inverse* problem).

In this report, we consider the one-dimensional problem (1). Thus, from equation (1) and taking into account that $t_i = i\tau$ it follows

$$\int_{(i-1)\tau}^{i\tau} dt \int_{vt}^{vt+2\Delta x} \sigma(x) \frac{s(h^d - h)}{4\pi r^3} e^{-r\mu} dx = W(i), \qquad i = 1, \dots, N, \tag{2}$$

where $r = \sqrt{(h^d - h)^2 + (x^d - x)^2}$.

Using the substitution $vt = x^d$, relation (2) can be written in equivalent form

$$\frac{1}{v} \int_{x_{i-1}^d}^{x_i^d} dx^d \int_{x^d}^{x^d+2\Delta x} \sigma(x) \frac{s(h^d - h)}{4\pi r^3} e^{-r\mu} dx = W(i), \qquad i = 1, \dots, N. \tag{3}$$

Thus, below we are going to solve the direct problem evaluating the integral in (2).

4. Direct problem

To solve the direct problem represented by relation (2) (or (3)), we fix the UAV speed $v = 27.7$ m/s, its profile movement $h^d = const = 75$ m, and the surface profile $h = const = 20$ m. The density of gamma radiation

$$\begin{aligned} \sigma(x) =& 20(\cos[x/400] + 1.1) + 20UnitBox[(x - 3500)/50] + 20UnitBox[(x - 3250)/50] + \\ &+ 20UnitBox[(x - 1000)/50] + 20UnitBox[(x - 1250)/50], \end{aligned} \tag{4}$$

the parameter $\mu = 0.001$ 1/m. We also assume that $\tau = 1$ s and, thus, a number of W-values is $N = 140$. The *Mathematica* software contains the in-built function for the numerical integration W[s_?NumberQ] := NIntegrate[]. Using this functions, integral (3) is evaluated.

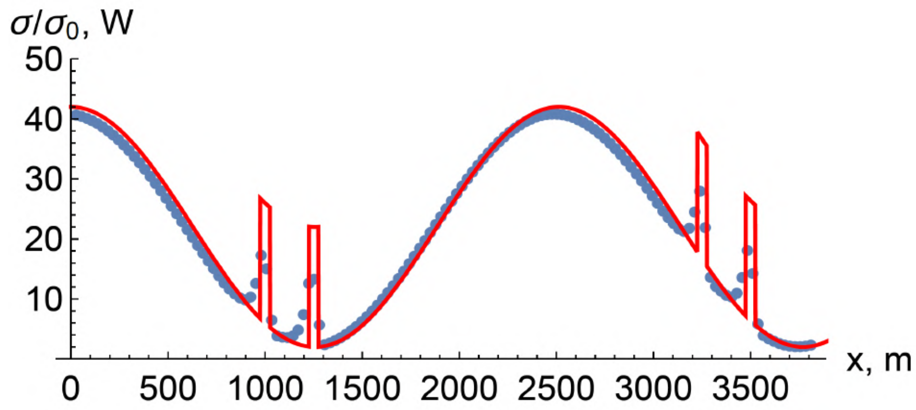

Figure 2. Comparison of the specified profile of density $\sigma(x)$ (solid curve) and detector's readings W (filled circles).

Note that integral (3) can be calculated by means of conventional rectangle method. Recall that, to approximate the integral of $f(x)$ over the interval (a, b), it can be used the following version of the rectangle method:

$$\int_a^b f(x)dx = \Delta_0 \sum_{i=1}^{n} f\left(a + \frac{2i-1}{2}\Delta_0\right), \qquad \Delta_0 = \frac{b-a}{n}. \tag{5}$$

Applying formular (5), the approximation of integral (3) can be cast in the following form

$$W(i) = \Delta_2 \sum_{k=1}^{N_2} \Delta_1 \sum_{j=1}^{N_1} \sigma \left((i-1)\tau v + \frac{2k-1}{2}\Delta_2 v + \frac{2j-1}{2}\Delta_1 \right) \\ G\left((i-1)\tau + \frac{2k-1}{2}\Delta_2, \frac{2j-1}{2}\Delta_1 \right), \tag{6}$$

where $\Delta_1 = 2\Delta x/N_1$, $\Delta_2 = \tau/N_2$. The function G reads as follows

$$G(t,x) = \frac{s(h^d - h)}{4\pi r^3} e^{-r\mu}. \tag{7}$$

Comparison of specified density $\sigma(x)$ and results obtained with the in-built function NIntegrate... and via the relation (6) is depicted in figure 2. The profile of $W(i\tau v)$ is stretch (each W value is multiplied by 60) over the vertical axis. In this figure, we can see that the doublet structures are distinguished on the resulting profile of W.

Analyzing the structure of the right part of relation (6), it is worth to note that the discretizations over t (adds with k) and x (adds with j) are, to some extent, equivalent. Thus, we can take N_2 not small but arbitrary, whereas N_1 can be chosen 1. Plotting the profile of W at $N_2 = 7$ and $N_1 = 1$, we obtain the indistinguishable W profiles.

5. Inverse problem

The solution of the inverse problem is related to the reconstruction of the function σ, when the values of $W(i)$ are known. As it was mentioned above, such problems are more complicated [17, 18] in comparison with the direct problems due to their ill-posedness. To examine these problems, it has been developed a wide range of approaches but there are examples when we can avoid the ill-posedness, as in our case.

In the case of equation (2), we find the function $\sigma(x)$ in the discrete form. Namely, the rectangle method gives us the natural way to discretize the spatial variable x. Before the application of relation (6), it is worth to note that the argument of σ is not suitable for using since it depends on many parameters. Thus, let us assume that $\tau v = \Delta_1 N_2$ and rewrite it in the following form

$$(i-1)\tau v + \frac{2k-1}{2}\Delta_2 v + \frac{2j-1}{2}\Delta_1 = (i-1)\tau v + \frac{2k-1}{2}\tau v/N_2 + \frac{2j-1}{2}\Delta_1 = \\ = [(i-1)N_2 + k + j - 1]\Delta_1.$$

Since i, N_2, k, j are natural numbers, then the set of unknown values $\sigma(x)$ is defined for the multiple values Δ_1.

Next, putting $\sigma([(i-1)N_2 + k + j - 1]\Delta_1) = \sigma_q$ and now $q = (i-1)N_2 + k + j - 1$ are natural, the relations (6) can be presented in the form

$$Weq(i) = \Delta_2 \sum_{k=1}^{N_2} \Delta_1 \sum_{j=1}^{N_1} \sigma_q \cdot G\left((i-1)\tau + \frac{2k-1}{2}\Delta_2, \frac{2j-1}{2}\Delta_1 \right), \tag{8}$$

which is the linear system of algebraic equations with respect to σ_q. The function G is defined by (7).

To study how the procedure works, we fix $N_1 = 1$, $N_2 = 7$, $\tau = 1$, and $v = 2\Delta x N_2/\tau = 27.2179$m/s. The typical length of the spatial interval is about 4 km, so we have $N = 140$, i.e.

there are 140 elements of W. Then for instance the equation of the system (8) at $i = 1$ is as follows

$$0.00777701\sigma_1 + 0.00434966\sigma_2 + 0.00204783\sigma_3 + 0.00100755\sigma_4 + \\ +0.000540804\sigma_5 + 0.000314641\sigma_6 + 0.000195592\sigma_7 = Weq(1).$$

It is obvious that the equations for $i \in [135; 140]$ contain the extraquantities $\sigma_{141,\dots,146}$. All these unknowns are assumed to be zero.

So, using the in-built *Mathematica* functions, the numerical procedure is constructed. At first, we specify the vector of data W writing them into the array Y = Table[W[i], {i, 1, 140}]. We also define the vector of variables var = Table[σ [i], {i, 1, 140}]. Finally, the system of algebraic equation is introduced by means of command syst = Table[Weq[i] == Y[[i]], {i, 1, 140}] /. Table[σ[j] − > 0, {j, 141, 146}] . The system's solution written in the form of array can be obtained via the command Z=var /. Solve[syst, var]. Analyzing figure 3, it is worth to notice that there is a point at the right edge lying slightly beyond the theoretical curve $\sigma(x)$. It is obvious that this does not influence on the other points.

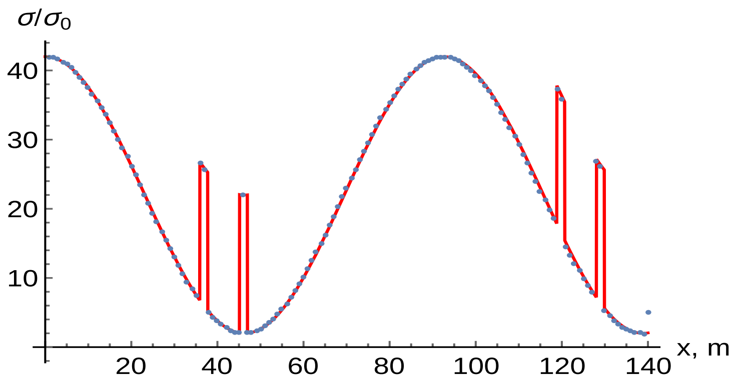

Figure 3. The reconstruction of the profile of density $\sigma(x)$. Solid curve stands for function (4), whereas dots mark the reconstructed values of σ, i.e. values of array Z.

6. Concluding remarks

Thus, in the research presented above we considered the mathematical issues related to the remote sensing of ground surface. Modern achievements of software, numerical methods, UAVs provided additional opportunities to improve and understand more deep the problem we encounter during remote sensing. In particular, using the tools offered by the software package *Mathematica*, we constructed the solutions of direct and inverse problems in a simple way.

It turned out that the solution of the direct problem conveys very well the localized sources of emission including of doublet type. Furthermore, in these studies we developed the procedure for the inverse problem solving which restored the theoretical distribution perfectly. It is possible that this is related to the specific choice of the quantities h^d, h, v, and τ. But this issue requires additional studies.

Presented and similar investigations are useful to consider in connection with other ways of monitoring of the territories affected by accidents at nuclear facilities such as at Chornobyl or Fukushima NPPs. Huge amount of contaminated materials, complex contamination of areas, large temporal scales of radioactive decay highlight novel regularities the nature's evolution and adaptation [1,4,23,24]. A systematic approach to solving existing problems and preventing new ones is the key to sustainable development of human society.

The findings presented can be useful for the problems of revealing and specification of weak ionic radiation occurring in homeland security, ecology, nuclear medicine, and etc.

Acknowledgments
The work is performed in the frames of Ukrainian state fund program "Support of the development of prior scientific researches" in the National Academy of Sciences of Ukraine (KPKVK 6541230).

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To cite this article: A O Zaporozhets *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012016

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012016 doi:10.1088/1755-1315/1049/1/012016

Electronic circuits of measuring modules of air pollution monitoring system based on low-cost sensors

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Abstract. Currently, the state system for monitoring atmospheric air pollution in Ukraine is obsolete both in terms of technical and methodological support. In Ukraine, air pollution measurement standards have not been updated for more than 30 years, which led to gradual degradation of the monitoring system. Although relatively new technical means for measuring the concentration of various pollutants are partially used in certain industrial cities, the data they generate do not allow to make a full conclusion about the level of local pollution, the full range of pollutants, the localization of pollution sources, etc. This led to the need to create modern measuring modules of the air pollution monitoring system capable to generate large data sets and solving a number of modern methodological problems of the monitoring system. The hardware complex of the measuring module of the atmospheric air monitoring system based on low-cost sensors has been implemented. It is designed to receive, process, accumulate data, transmit and visualize the necessary information of the air pollution monitoring system. Connection diagrams of various hardware elements of the measuring module of the air pollution monitoring system (STM32F103C8T6 microcontroller, HC-12 module, SIM800C module) are shown. Printed circuit board in Altium Designer CAD, the drawings and the layout of the printed circuit board also are shown. The proposed technical prototype of the measuring modules of the monitoring system can become an addition to an existing monitoring system, or, in the case of creating a large-scale network of such tools, completely replace it.

1. Introduction

Atmospheric air is one of those natural environments that have a significant impact on the state of well-being and human health. In modern conditions of vigorous activity of industrial enterprises and urbanization of territories, the impact on the environment is increasing [1–5].

One of the factors of this impact is appeared in increasing the volume of harmful substances emissions into the atmospheric air from stationary and mobile sources. Since today most of the population of Ukraine lives in urban areas, the problem of urban air pollution has become extremely urgent and requires an immediate solution [6, 7]. The existing monitoring system has a number of disadvantages, is technically and morally outdated, does not correspond to the appropriate level of providing the governing bodies with detailed information for them to make effective management decisions in order to reduce the level of atmospheric air pollution [8–12].

To ensure the implementation of the basic principles of the functioning of the state system for monitoring environmental air pollution, it is necessary to involve the existing potential of all subjects of monitoring, primarily on the basis of consistency and progressiveness of the technical, regulatory, legal and methodological support of observation networks.

Each developed monitoring system should contain the following main components: observation of both distant and short-term trends; assessment of compliance with air quality standards; assessment of public health and negative impact on the environment; planning; approval of dispersion models using mathematical modeling approaches to predict air pollution levels; effectiveness of management measures.

As a result of atmospheric air monitoring, the following is obtained: primary data on monitoring and monitoring the state of pollution; generalized data on the level of pollution in a certain area for a certain period of time; generalized data on the composition and volumes of pollutant emissions; assessment of the levels and degree of danger of environmental pollution and the life of the population; assessment of the composition and volumes of pollutant emissions.

The purpose of this work is to obtain qualitatively new data by developing new measuring modules for an air quality monitoring system with a high update rate.

2. Modern state of the air pollution monitoring network in Ukraine

Atmospheric air monitoring is an integral part of the state environmental monitoring system, which is carried out in order to obtain, collect, process, store and analyze information on the state of atmospheric air and develop scientifically based recommendations for making decisions in the field of atmospheric air protection [13–16].

Atmospheric air monitoring subjects place observation posts, monitor concentrations of pollutants. Enterprises, institutions and organizations whose activities lead or may lead to deterioration of the atmospheric air may establish observation posts and monitor the concentrations of pollutants [17–19].

The number of observation posts and their location for assessment are determined in the program of state monitoring in the field of atmospheric air protection for each zone and agglomeration.

To ensure the accuracy of measuring devices, all subjects of atmospheric air monitoring that monitor the concentration of pollutants, assess the quality of atmospheric air, provide calibration and maintenance of measuring equipment used for monitoring atmospheric air.

According to [6], in Ukraine there were 162 posts in 53 cities, among them: 16 – in Kyiv; 10 – in Kharkiv; 8 – in Odesa; 6 – in the Dnipro, 5 – in Zaporizhzhya, Mariupol, Kryvyi Rih. In other regional centers, the number of observation posts did not exceed 4.

The mandatory air pollution monitoring program includes seven substances: suspended dust particles, sulfur dioxide, nitrogen oxides, carbon monoxide, formaldehyde, benzo(a)pyrene and lead [20, 21]. Some observation posts may monitor other pollutants. This depends on local or regional emissions as well as the industrial potential of the area.

In general, the quality of atmospheric air is determined by 33 indicators, according to the approved list for each of the 53 cities of Ukraine. Other substances may be included in the monitoring program in accordance with the decision of local authorities.

At 81 stationary posts, such heavy metals are monitored: iron, cadmium, copper, zinc, lead, nickel, manganese, chromium.

Sampling is carried out at certain time intervals according to one of 4 observation programs: complete, incomplete, reduced or daily. The full program provides for 4 measurements during the day: 01:00, 07:00, 13:00, 19:00; incomplete involves 3 measurements: 07:00, 13:00, 19:00; the reduced program provides 2 measurements: 07:00; 13:00; the daily program implies continuous observations. As measuring instruments on the observation network, such types of stationary observation posts of domestic production as "POST-1", "POST-2", "POST-2a" are used.

The development of the environmental monitoring system in Ukraine in recent years has led to the development in large industrial regions of networks of monitoring posts for the state of atmospheric air using automated monitoring posts. They complement the existing monitoring network. Such automated observation posts are already operating in the city of Kryvyi Rih, projects have been developed for the Nikopol and Kharkiv cities.

At present, a large number of software has also been developed for processing measurement results and forming specialized educational complexes for ecologists, engineers, scientists, and various specialists on their basis.

Since the control of atmospheric air pollution and emissions from industrial enterprises is one of the main elements of the environmental monitoring system, the creation and development of local networks using automated observation posts should be the main direction in the development of the atmospheric air quality monitoring system.

This article is devoted to the development of hardware for measuring modules of the atmospheric air pollution monitoring system, which will allow obtaining up-to-date information on the level of air pollution using modern microprocessor technology.

3. Electronic circuits of measuring modules

As a microcontroller, a microcircuit of the STM32F10x family (STM32F103 series) was chosen, which provides the best 32-bit efficiency in the class of microcontrollers (figure 1). The microcontroller has a high-performance RISC core with a frequency of 72 MHz, fast memory, extended I/O ranges and peripherals connected to APB buses. The STM32F103C8T6 is equipped with a 12-bit A/D converter, a timer, standard and advanced communication interfaces: up to two I2C and SPI, three USART, USB and CAN. Power saving mode allows to use it in low power devices.

The 32-bit microcontroller is made according to the Harvard architecture (program and data memory are separated), has several separate buses and a 3-stage pipeline and more than 10 general-purpose registers, which allows to perform operations in parallel and (most) in one cycle. The instruction set is Thumb-2 (a mix of 16-bit and 32-bit instructions, targeted at C/C++ compilers).

Microcontroller connection is typical:

- power is supplied through capacitors C7-C11, respectively, to each foam VBAT, VDD and VDDA;
- boot through the resistor is brought to the ground;
- restart button is programmable;
- quartz QZ1 with a frequency of 32.768 kHz.

The measurement module also includes SIM800C, HC-12 transceivers and BME-280, DHT-22, MQ-9, PMS7003, ZE08-CH2O, GP2Y1010AU0F, DS18B20 sensors.

The device is powered by a Li-Pol battery with standard size 54×34×10 mm, nominal voltage 3.7 V, capacity 2 Ah, operating temperature -20…60 °C. The device is charged via a Micro-B USB connector.

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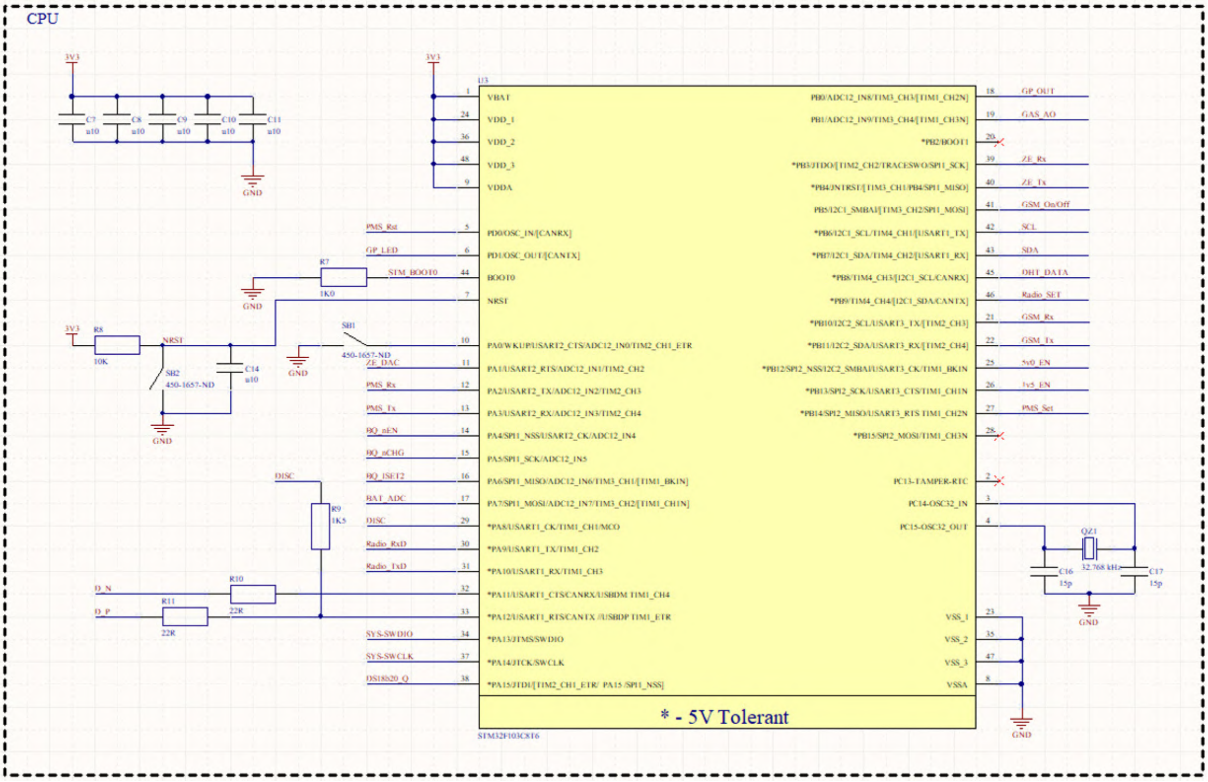


Figure 1. Microcontroller electrical diagram of STM32F103C8T6 connection.

The HC-12 module was selected as a transmitter for peer slave modules, which is a wireless half-duplex UART module that allows to transmit and receive data in the frequency range from 433.4 MHz to 473 MHz at a speed of 1200 to 115200 Bd, has the ability to select channels from 1 to 100, has the ability of choice of 8 transmitter power options from -1 dBm to 20 dBm. At the same time, the transmission distance can reach 1000 meters in the open area at a data speed of 5000 bps. The module connection diagram is shown in figure 2.

The module is built on the basis of the SI4463 chip, a 30 MHz quartz resonator is connected to the same chip, which is necessary for operation. This chip has an SPI interface, but the module is connected via UART. The fact is that there is another microcontroller on the module – STM8S003F3, it acts as an interface converter. In addition, the STM microcontroller simplifies interaction with the SI4463. The STM microcontroller implements all necessary commands and simplifies the configuration and control of the HC-12 module using native AT commands. The role of the master is played by the SIM800C transmitter module, this is a model of a full-featured quad-band GSM/GPRS module from SIMCOM figure 3. The module is a semi-finished product with 16x18mm size, designed for surface mounting on a printed circuit board. The module contains interfaces for connecting a SIM card, analog audio circuits, USB, UART, and general-purpose digital inputs/outputs. Power is supplied from a stable voltage source of 3.5–4.2 V, which can be a standard lithium battery. The current consumed from the power supply is on average 100–200 mA (several milliamps in standby mode), but pulsed currents can reach 2 A, so to prevent a short-term drop in the supply voltage, it is necessary to use low-impedance blocking capacitors, placing them in close proximity to the module. The antenna circuits of the module have an impedance of 50 ohms in the operating bands of 900 and 1800 MHz.

The data exchange interface with the module is represented by two functions: a function for reading data from the driver intended to be sent to the module, and a function for sending

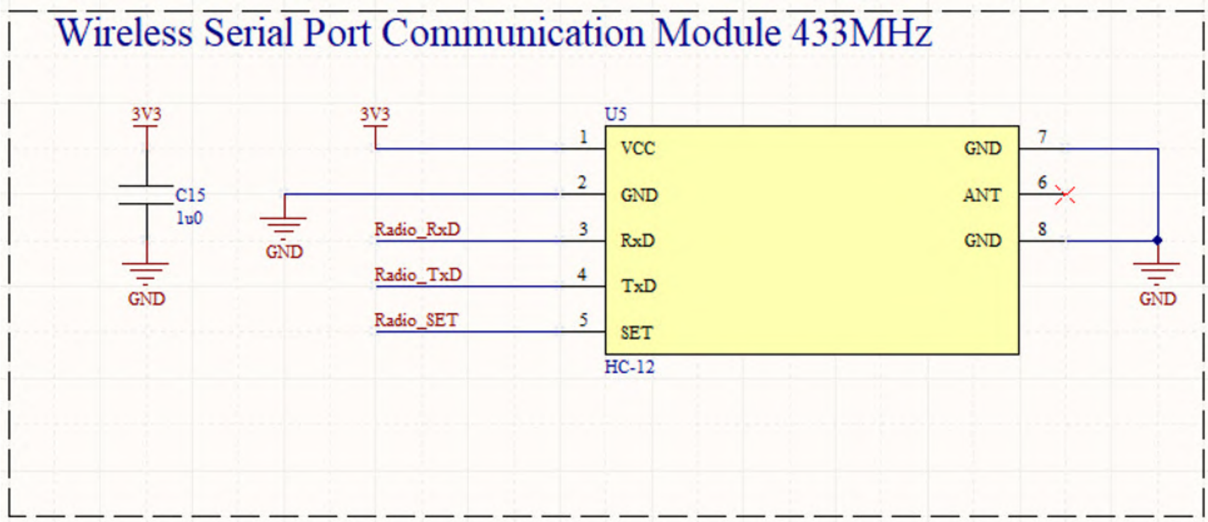


Figure 2. HC-12 module electrical connection diagram.

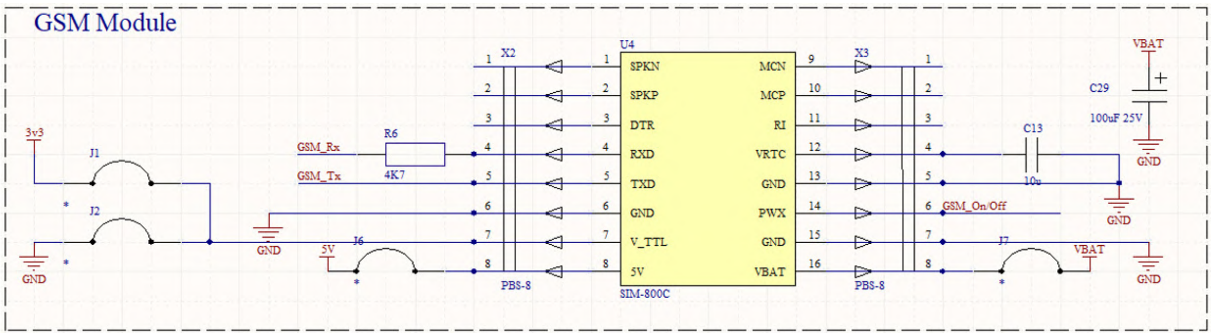
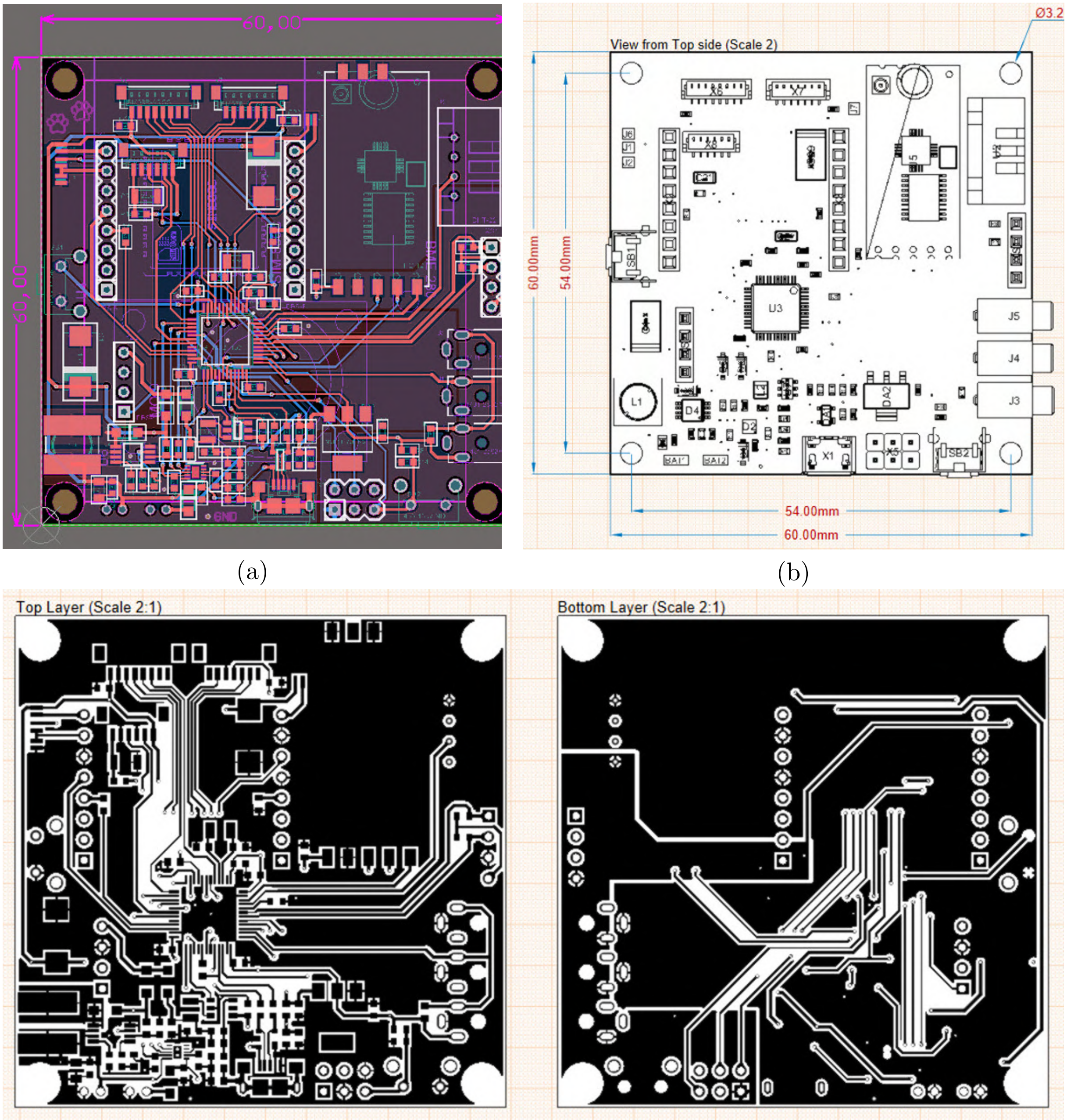


Figure 3. Electrical diagram of SIM800C module connection.

data to the driver received from the module. The latter function can be safely called with the microcontroller's interrupt handler and is capable of passing 1–255 bytes of data to the driver. This makes it easy to implement a "module-driver" channel using an interrupt from UART RX or from DMA microcontroller, transferring 1 byte or variable length data blocks at once. The reverse data channel "driver-module" must be implemented depending on the platform used, for example, using UART TX or DMA interrupt. The driver can generate a data block up to 600 bytes long (MTU+ headers), so the user must provide an appropriately sized buffer to store the data during its byte or block output.

The exchange interface with the user program is represented by two groups of functions: reading and writing (control). The functions of the first group should be called by the user when certain events occur in the driver. They are designed to receive data from the driver (for example, SMS text or data received via TCP). The functions of the second group can be called if the driver is free (not busy processing the previous command) and are used to control the module and transfer data. Figure 4 shows the printed circuit board in Altium Designer CAD, the drawings (used to design the VM case) and the layout of the printed circuit board (to check the compliance of the manufactured printed circuit boards with gerbera files).

Figure 5 shows the wiring boards of the measurement module (3D model in Altium Designer CAD and manufactured at the JLCPCB factory). Figure 6 shows a working prototype of the measurement module as an element of an air pollution monitoring system.



(a) (b)

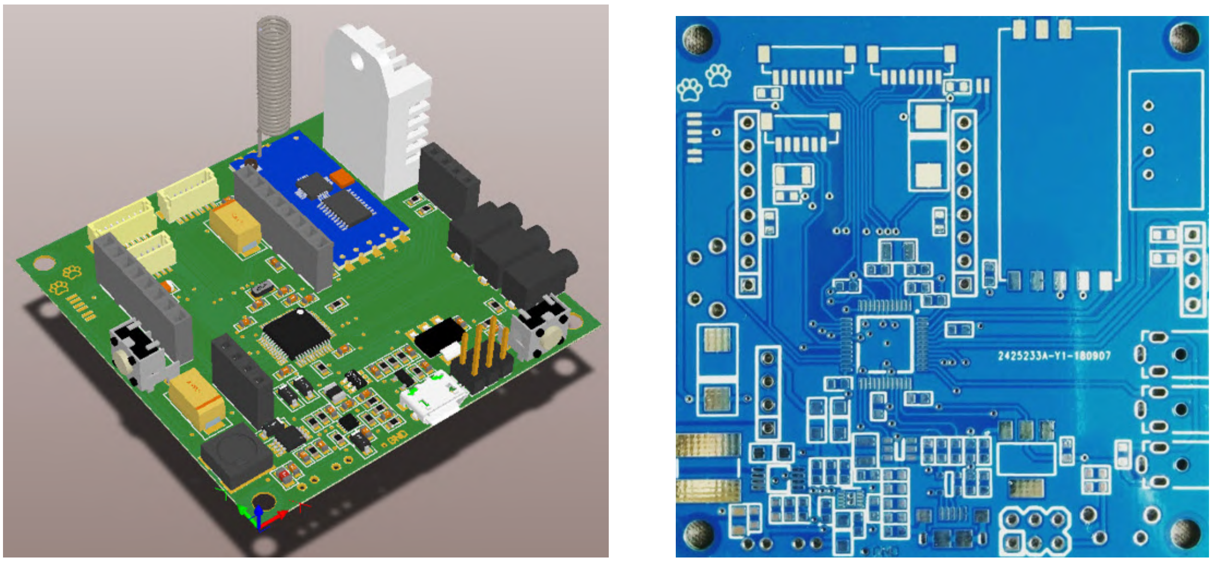
(c)

Figure 4. Printed circuit board of the measuring module: (*a*) printed circuit board in CAD; (*b*) drawing of the printed circuit board; (*c*) PCB topology.

4. Information-measuring channel and system sensors

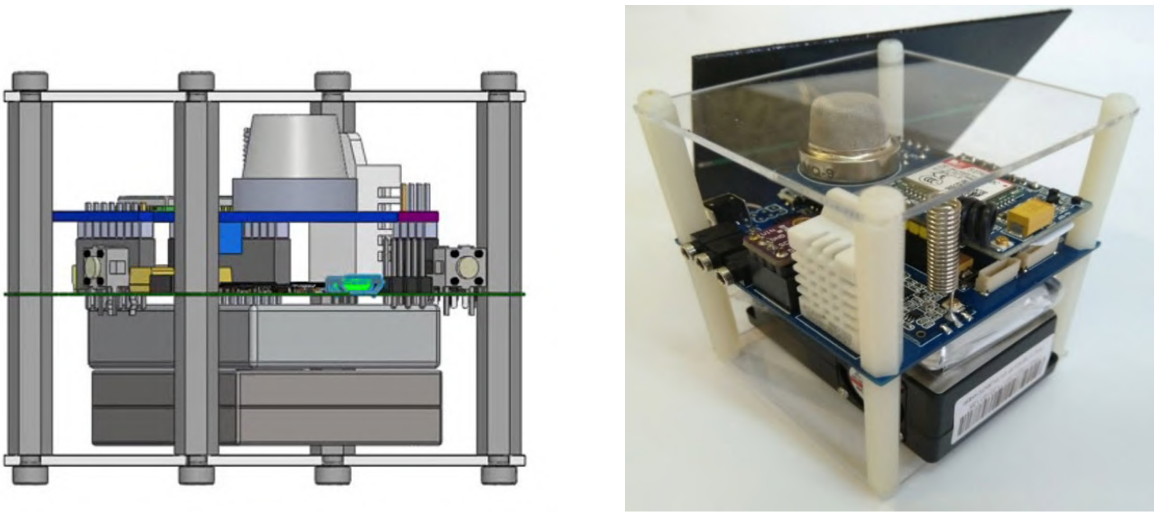
Sensors of various physical quantities can be included in the air quality monitoring system. Depending on the needs, up to 15 analog sensors, and 256 digital sensors via the 1-WIRE bus and up to 127 via I2C can be connected to the base module, including:

- particulate sensor: PMS 5003 and/or GP2Y1010AU0F;
- meteorological sensors: BME 280, DHT-22, DS18b20;



(*a*) (*b*)

Figure 5. Measurement module board: (*a*) 3D model of the board; (*b*) PCB manufactured by JLCPCB factory.



(*a*) (*b*)

Figure 6. Working prototype of the measuring module of the air pollution monitoring system: (*a*) 3D model; (*b*) appearance of the studied sample of the module

- sensors for monitoring the concentration of the following substances: formaldehydes (CH_2O); carbon monoxide (CO); carbon dioxide (CO_2); nitrogen dioxide (NO_2); ozone (O_3).

Table 1 shows the parameters and characteristics of the sensors. Table 2 shows parameters of the measuring module.

Thanks to the provided wide range of sensors, it is possible to expand the range of use of

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Table 1. Parameters of sensors of the measuring modules of air monitoring system.

Name	Parameter	Unit	Measuring range	Resolution	Error	Reaction time
SDS011	PM10, PM2.5	$\mu g/m^3$	0-1000	0.1	±15%	1 s
BME280	Temperature	°C	-40…+85	0.01	±0.01 °C	1 s
	Humidity	%	0-100	0.01	3%	1 s
	Pressure	hPa	300-1100	0.01	±0.01 hPa	1 s
MH-Z19	CO_2	ppm	0-5000	1	50 ppm±5%	<60 s
ZE08-CH2O	CH_2O	ppb	0-5000	1	<10 ppb	<60 s
MICS-6814	NH_3	ppm	0.1-300	0.001	±20%	1 s
	CO	ppm	0.1-1000	0.001	±20%	1 s
	NO_2	ppm	0.02-20	0.001	±20%	1 s
RadKit	Radiation	$\mu R/h$	0-999	1	±10%	60 s
ZE03-SO2	SO_2	ppm	0-20	0.1	<0.1 ppm	<90 s
ZE25-O3	O_3	ppm	0-10	0.1	<10 ppb	<90 s

Table 2. Parameters of the measuring module of air monitoring system.

Parameter	Value
Power supply	5 V, USB compatible battery (3.7V, 2000 mAh)
Connection	GSM and 433MHz module
Dimensions	60x60x70 mm

measuring modules and the system as a whole.

Figure 7 and figure 8 show graphs of PM2.5 dust concentration and radiation background obtained as a result of the operation of the measuring module for 7 days. The location of the measuring module is shown in figure 9. The measurements were carried out within one week – from April 5, 2022 to April 12, 2022. Significant excess of these parameters was not recorded. The measurement range of sensors was 20 minutes. Thus, a data base of more than 500 measurements was formed. Compared to the existing monitoring system, the network built on the developed measuring modules is able to increase the amount of received data by 18 times.

5. Conclusions

The current state of the existing air pollution monitoring system in Ukraine is shown. The features of air pollution monitoring in different cities of Ukraine are presented. The actual task of creating a modern information-analytical system for monitoring atmospheric air pollution, based on low-cost sensors, is considered. The electronic circuits of the measuring modules of the air pollution monitoring system implemented on the basis of modern microprocessor technology are proposed. The features of connecting individual components (STM32F103C8T6 microcontroller, HC-12 module, SIM800C module) as elements of the measuring module are presented. The use of a number of meteorological parameters (temperature, humidity, pressure) and pollutants (PM10, PM2.5, CO_2, CH_2O, NH_3, CO, NO_2, SO_2, O_3, radiation) as the basis of the monitoring system is proposed. Experimental data were obtained from measuring the concentration of PM2.5 dust and the radiation background of the area where the measurements

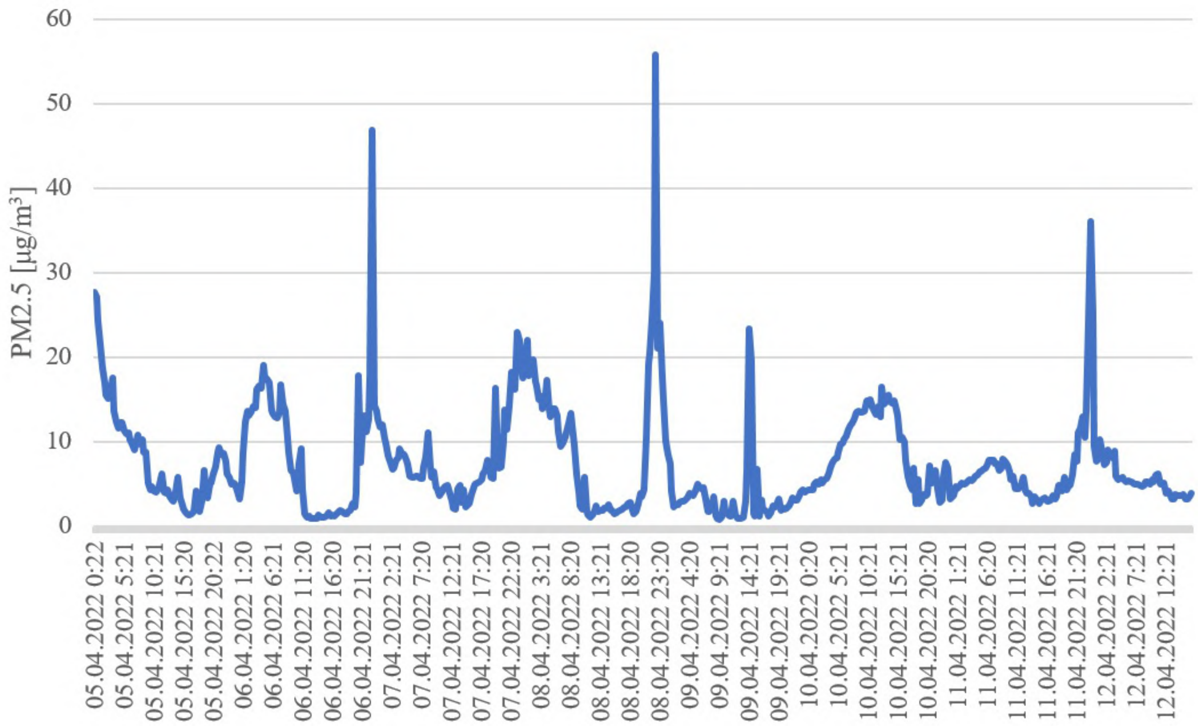

Figure 7. PM2.5 dust concentration during April 5-12, 2022.

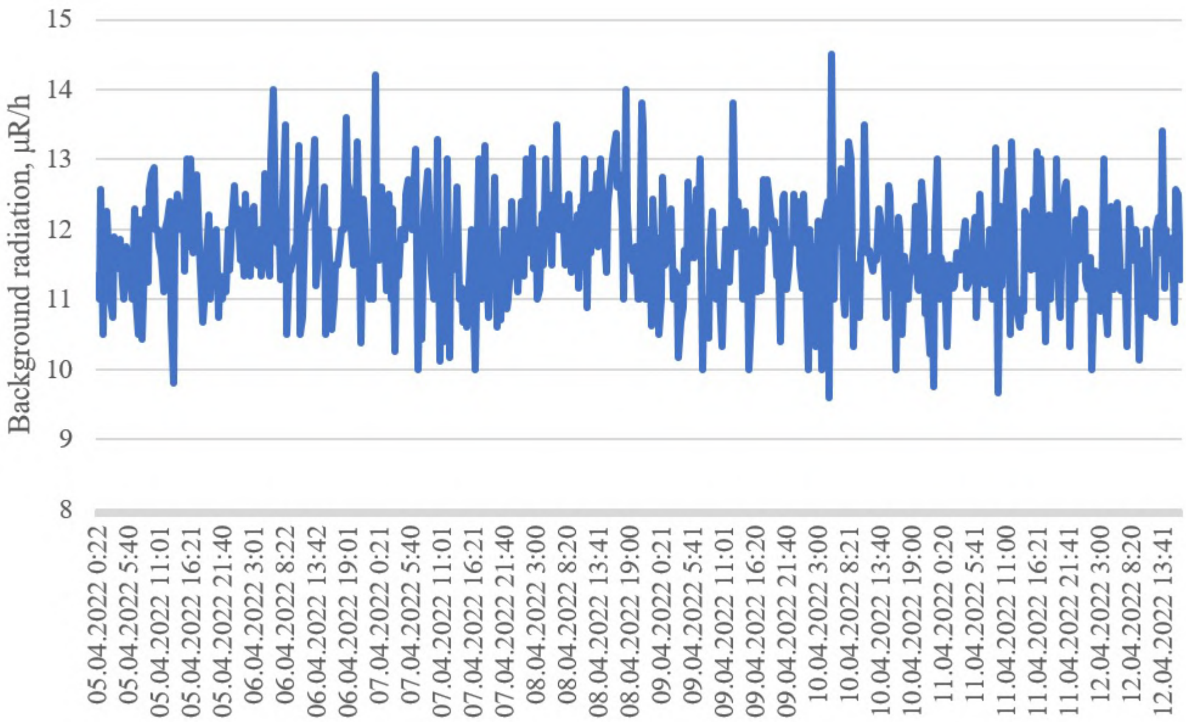

Figure 8. Radiation background during April 5-12, 2022.

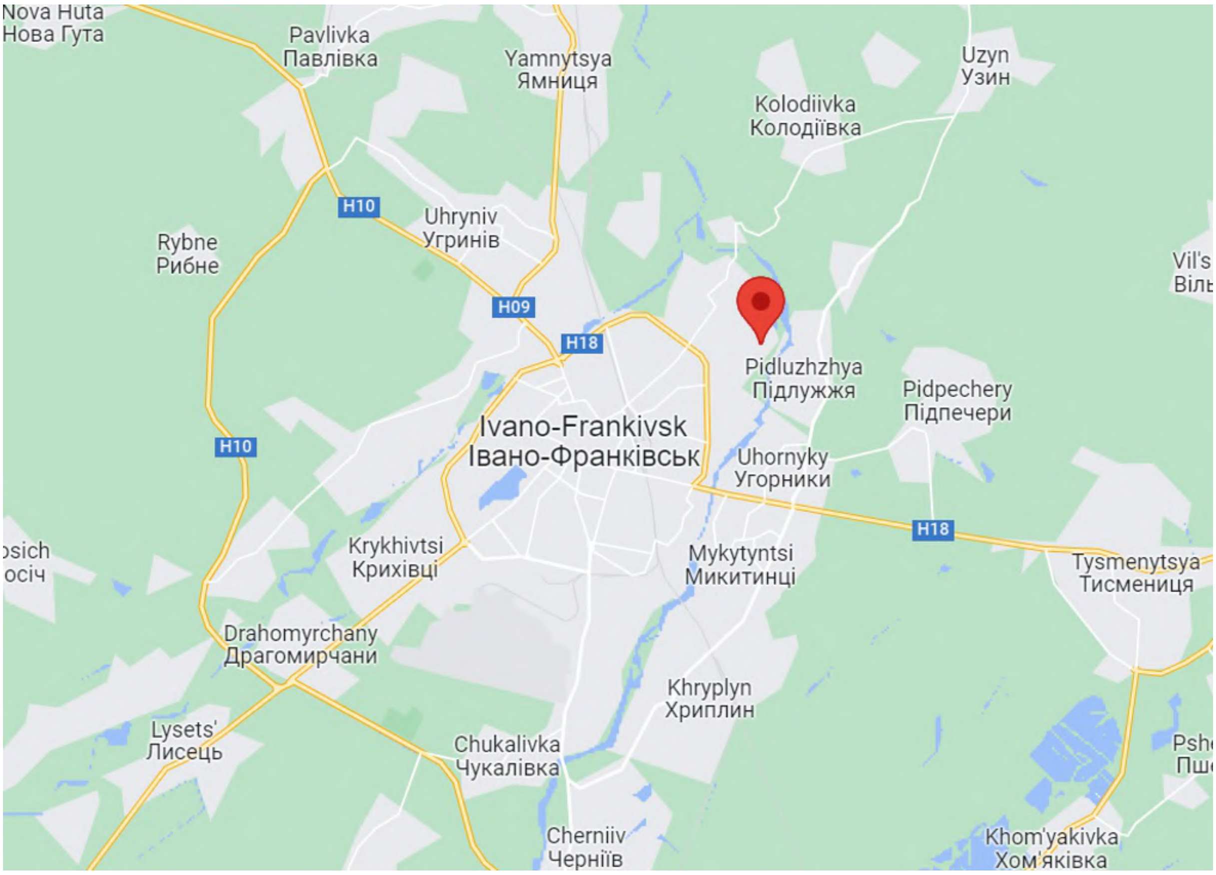

Figure 9. Location of the measuring module.

were made. In comparison with the existing system, the information base of the developed module has been increased by 18 times.

Acknowledgments
The work is performed in the frames of Ukrainian state fund program "Support of the development of prior scientific researches" as a winner of the projects for laboratories/groups initiated by the National Academy of Sciences of Ukraine (KPKVK 6541230, 0121U111148).

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IOP Conference Series: Earth and Environmental Science

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Decisions to prevent pollution and restore the environment within the impact of abandoned oil and gas wells

To cite this article: T M Yatsyshyn *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012017

Decisions to prevent pollution and restore the environment within the impact of abandoned oil and gas wells

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Abstract. Decommissioned oil and gas wells that pose a danger to the environment due to emissions of methane, which is a powerful greenhouse gas and one of the man-made factors that weaken the stability of the planet in the context of global climate change. The prospects of using resistant plants common in natural phytocenoses to the influence of oil contaminants in phytoremediation practice are analyzed. The bioindication suitability of oil-sensitive plant species, which are recommended for use in monitoring studies of the quality of technogenic-transformed environment, is revealed. The choice of equipment for the restoration of abandoned wells has been made.

1. Introduction

Currently, the planet is exacerbating the negative effects of global climate change: a significant number of extreme weather conditions, floods, increased geodynamics and more. The danger is growing due to the fact that the ecological balance is disturbed as a result of the existing consumer format of human life: growing needs, depletion of resources, waste accumulation, etc. The transition to alternative energy sources does not allow to obtain the expected effect during extreme weather conditions. For example, wind power generators are not able to operate at wind speeds greater than 25… 28 m/s due to the fact that the automation of the wind turbine specifically "takes it out of the wind" for safety reasons. With even more intense hurricanes there is a possibility of destruction of the wind turbine structure [1]. Therefore, increasing the volume of hydrocarbon production and geological exploration of new deposits remains an important area of socio-economic development to ensure reliable energy sources. At the same time, the development of innovative alternative energy sources continues [2].

Oil and gas facilities pose a potential environmental hazard, both due to the presence of aggressive chemicals in technological processes and due to the large number of these facilities in all regions of the planet. The consequences of oil and gas production, which occur during the life cycle of wells, cause significant environmental damage and in many cases form irreversible changes in the natural environment. Thus, in the process of oil and gas extraction, the air, water bodies and soil are polluted. This causes discharges, emissions and vapors of harmful gaseous substances, the inflow of a significant amount of associated reservoirs of high mineralization and spills of hydrocarbons destroy the biota of water bodies, disrupt the soil cover [3, 4]; tens and hundreds of barns with drilling mud remain unliquidated; torches burn about 35 billion a year of associated gas [5]; gas and oil manifestations and open fountains, which can occur at all stages of construction and operation of wells.

Decommissioned wells need special attention. Decommissioned oil and gas wells pose a danger to the environment, as most of them produce methane, which is a powerful greenhouse gas and one of the man-made factors that weaken the stability of the planet in the context of global climate change. The number of abandoned oil and gas wells is not fully established. Determining their number is complicated by the fact that many of the abandoned wells are "lost" without any evidence of their existence on the surface.

2. Literature analysis and problem statement

The problem of abandoned oil and gas wells is common on all continents. A recent investigation by Reuters estimates that the United States could have more than 3.2 million orphaned and abandoned wells. Some states have a few hundred; others have a few thousand. And some have a staggering number of them: Pennsylvania reportedly has more than 330,000 of these wells within its borders [6]. The website of the Department of Environmental Protection Commonwealth of Pennsylvania contains information on abandoned wells, orphaned wells and plugged wells (figure 1) [7].

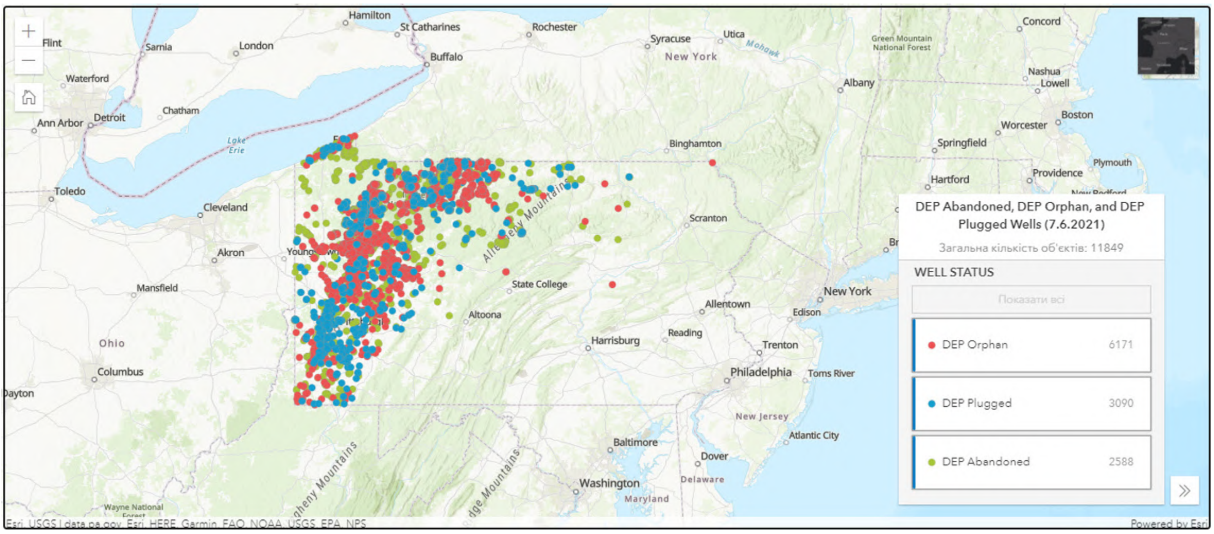

Figure 1. Accounting for decommissioned wells abandoned and plugged in Pennsylvania [7].

"Orphaned" wells are those for which no former owner or operator can be located, while the term "abandoned well" typically refers to an unproductive well with a known owner/operator. They are essentially open holes in the ground that need to be cleaned and plugged with cement to stop their pollutants from escaping into the environment [6].

The authors of the article [8] note that millions of abandoned oil and gas wells are scattered across the United States, causing methane emissions and other environmental hazards. Governments are increasingly interested in decommissioning these wells but want to do so efficiently. And to provide cost estimates for decommissioning oil and gas wells and key cost drivers. It is also noted that older wells are more costly than newer ones. The closure of orphan

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012017 doi:10.1088/1755-1315/1049/1/012017

sites is a multi-year process. Therefore, it is important to determine the correct list of equipment for restoration work in such wells and the choice of environmental restoration technologies within their influence.

Phytocenotic diversity is one of the key indicators of stability of functioning and development of any ecosystem, and the nature of location and projective coverage of the species in the phytocenosis are the most important parameters for assessing the impact of environmental factors on the ecosystem [9,10]. Plants play the role of primary absorbers of man-made pollutants and phytomeliorants of the environment, and at the same time can reflect at different levels of biological organization the degree of anthropogenic transformation of the environment.

The toxic effects of petroleum components on living organisms are known, in particular the ability of heavy metals and hydrocarbons to block vital biochemical processes in cells and migrate through trophic chains [11, 12]. Oil has an inhibitory effect on plant growth and development, especially at the stage of seed germination, so most seeds of plant organisms can not germinate in conditions of high oil concentrations [13, 14].

3. Purpose and objectives of the study

The global negative impact of the oil and gas industry consists of the local impacts of individual facilities. Therefore, addressing the environmental issues of individual facilities, including decommissioned wells, is one of the main tasks to improve the environmental safety of the industry. The main tasks of this article are:

- to analyze of the probable environmental impact of the old stock of decommissioned wells;
- to investigate the species composition of phytocenoses and the taxonomic characteristics of the oil-contaminated ecosystem plant groups phyto objects to offer a range of equipment methods for decommissioned wells restoration;
- to offer a range of equipment for abandoned wells restoration;
- to determine the principles of environmental safety management of the old fund abandoned wells.

4. Research methods

The choice of separate types of equipment for restoration works is conducted, in particular: the device for unscrewing of pipes, the device for cleaning of the tool which rises from a well, metal catcher and foam generating device. Identifying the stages in the life cycle of a well with the highest risk to the environment involved the use of a life cycle assessment method. The methods of biological monitoring of the environmental state are used in the work: observation, surveys and field researches, which provide the description, study of plant groups as components of ecosystem, in natural conditions, research of their functioning, structure and development. Field research includs preliminary preparatory, field and in-house methods.

5. Research results

5.1. Analysis of the potential environmental impact of decommissioned wells old fund

The global negative impact of the oil and gas industry consists of the local impacts of individual facilities. Therefore, solving environmental issues of individual facilities, including decommissioned wells, is one of the main tasks to improve the environmental safety of the industry [15, 16].

On the location of the man-made object, in our case oil and gas wells, the degree of environmental risk from the conducted activity depends. It is important to consider the length of the life cycle of the object.

In the western part of Ukraine, oil and gas facilities are located near natural recreational areas of national importance (Truskavets, Skhidnytsia, Morshyn, Bukovel resorts), which creates a high risk of man-made disturbance of valuable areas. Since the main negative impacts are on the surface layer of the atmosphere and surface and groundwater, the areas of distribution of pollutants may become transboundary. Factors of natural origin can also increase the degree of risk, in particular for mountainous areas where there is a high risk of mudslides.

Seismic movements can activate these wells and provoke accidental oil and gas emissions. The result is the transformation of large areas into areas of ecological disaster. Tightness of wells during their conservation is designed for 20-30 years. Over time, the cement bridges in the well may collapse, the mouth equipment and the column itself may corrode, causing the well to depressurize. There are research data and there are real facts of hydrocarbons from the deep layers, which causes uncontrolled leakage of fluid or gas into the environment during the depressurization of the well structure. Sources of information systematically publish information about oil leaks and the destruction of conservation structures in abandoned wells around the world. Therefore, the problem of handling wells in the post-operational period is currently extremely acute.

The Association Agreement between Ukraine and the EU, the Paris Agreement on Climate Change, the provisions of Directive 2003/87/EU and the Concept for the implementation of state policy in the field of climate change until 2030, approved by the Cabinet of Ministers of Ukraine from 07.12.16 №932-r, Ukraine provides for the introduction of a system of monitoring, reporting and verification of greenhouse gas emissions [17]. Emissions must be controlled at all stages of the life cycle, so one element of eco-efficiency is the choice of technologies based on the use of equipment that minimizes environmental impacts both during the technological process and in the process of manufacture, delivery and disposal. European Union Directives 2008/50/EU on ambient air quality and cleaner air for Europe and 2010/75/EU on industrial emissions essentially set out prevention principles, complemented by restrictions, quality monitoring and control of air emissions. The Directives also state that preference should be given not to traditional measures (treatment facilities, etc.), but to measures that prevent pollution at technological facilities and do not increase the burden on other natural environments [18, 19].

Pollution prevention is currently a top priority in most countries around the world. Thus, in section 6602(b) of the Act, the US Congress establishes a priority national policy:

- contamination should be prevented or reduced at source, if possible;
- uncontrollable pollution should be involved in the recycling cycle (recycling) in an environmentally sound way, if possible;
- contamination that cannot be prevented or cannot be involved in the re-use cycle should be treated in an environmentally sound manner, if possible;
- location, storage or other release into the environment should be used as a last resort and carried out in an environmentally sound manner.

5.2. The analysis results of the phytocenoses species composition and taxonomic characteristics of plants groups of the oil-contaminated ecosystem

The urgent task of environmental science is to find effective remediate plants that are resistant to oil pollution. However, the isolation of plants with valuable bioindicative properties is necessary for timely monitoring of changes in the ecosystem in oil-contaminated areas. The study of plants at the population-species level, which is one of the key structural components of the biosystem organization of living organisms, allows to assess the bioproductive potential of the autotrophic block of the ecosystem, and hence its ability to self-sustain and self-restore.

The analysis of phytocenotic diversity was performed on three sites with an area of 25 m^2, located around the source of oil pollution according to the tested method (figure 2). The nature of the location and projective cover of the species in the phytocenosis was determined by the Brown-Blanke method, and the identification of species was conducted using the electronic determinant

Plant Snap and reference books. Taxonomic characterization of species was performed in the laboratory.

Figure 2. Experimental area of phytocenotic diversity analysis of oil-contaminated area.

The phytocenotic diversity of the study area is represented by 13 species of herbaceous plants, 12 genera, 7 families, 7 orders, 2 classes and 1 division of Angiosperms. The class of Monocotyledons includes two families found in the territory of oil pollution Poaceae and Cyperáceae, represented by two species *Poa pratensis L.* and *Carex hirta L.*, respectively. The class Dicotyledons includes five families Asteraceae (6 species *Helianthus annuus L., Taraxacum officinale Wigg., Erigeron canadensis L., Atremisia vulgaris L., Artemisia absinthium L., Achillea millefolium L.*), Fabaceae (2 species *Medicago sativa L., Trifolim pratense L.*), Apiaceae (1 species *Daucus carota L.*), Linaceae (1 species *Linum usitatissimum L.*), Polygonaceae (1 species *Fagopyrum esculentum L.*).

The highest projective coverage is characterized by *Poa pratensis L., Carex hirta L., Daucus carota L., Achillea millefolium L.*, which are resistant to oil pollution and can be used as promising objects in phytorecultivation practice table 1.

Linum usitatissimum L., Heliánthus ánnuus L., Fagopyrum esculentum L., which are very scattered in the phytocenosis with a projective cover of up to 25%, were the most vulnerable to stressful growth conditions. These species can be used in bioindication studies of oil-contaminated environments. Intermediate place is occupied by the following species that have adapted to living in an oil-contaminated environment *Taraxacum officinale Wigg., Erigeron canadensis L., Atremisia vulgaris L., Artemisia absinthium L., Medicago sativa L., Trifolim pratense L.*

Thus, in the conditions of oil pollution, a stable phytocenosis was formed, represented by a small number of species of herbaceous plants, most of which have adapted to adverse living conditions. Further studies of morphological, physiological, biochemical and accumulative

Table 1. The nature of the location and projective coverage of herbaceous plant species in the phytocenosis of the oil-contaminated area.

Score	Nature of the species placement in the phytocenosis	Projective cover	Plant species
1	very scattered	up to 25%	*Linum usitatissimum L., Heliánthus ánnuus L., Fagopyrum esculentum L.*
2	scattered	26-50%	*Taraxacum officinale Wigg., Erigeron canadensis L., Atremisia vulgaris L., Artemisia absinthium L., Medicago sativa L., Trifolim pretense L.*
3	groupped	51-75%	*Poa pratensis L., Carex hirta L., Daucus carota L., Achillea millefolium L.*
4	thicketed	76-100%	-

parameters of these plants will reveal the range of response rates of phytoobjects as bioindicators and bioremediates of man-made environment.

5.3. The choice of equipment for restoration of abandoned wells

Abandoned wells, the number of which is not clearly recorded on the planet and in Ukraine, pose an increasing threat to the environment every year. The danger is the breach of the casing due to corrosion and, as already mentioned, due to the increasing frequency of seismic oscillations. Conditions are being created for the inflow of oil and gas product in abandoned wells, which enters the upper aquifers and pollutes large areas. Such wells are a source of methane in the environment.

To be able to develop technical and technological solutions to reduce risks to the environment from abandoned oil and gas wells it is necessary:

- to collect data on the location of wells;
- to form a database of passport data or other information sources about the well;
- to conduct a study of the location of the well;
- to establish the condition of the well and the possibility of further work.

All wells that are abandoned or decommissioned must be under constant supervision. This leads to the creation of a structure that can give a "second life" to such wells and should be responsible for the environmental safety of such facilities. Due to the need to establish relations with the owners of areas where abandoned wells are located, it is necessary to develop a plan and strategy for the use of abandoned wells. The work should be aimed at obtaining a positive effect, both environmental and economic. At this stage, there are cases of restoration of wells and oil or gas receiving. In addition, it is possible to obtain thermal energy from these wells.

Most of the abandoned wells are low flow due to complications and accidents, which led to their abandonment or conservation. Therefore, one of the first stages of technical and economic decisions should be research and repair work of these wells. It is necessary to select modern, reliable, highly efficient devices, equipment and special tools for cleaning wells from destroyed equipment and other unnecessary items and dirt. Indicative options for selecting individual items of equipment and devices will be discussed below.

In the process of descent into the well of long-term equipment (eg: pipes, rods) it is necessary to monitor the condition of this equipment. To do this, it is advisable to use a rod magnetic flaw detector. The essence of the device is explained by the drawing (figure 3), which shows a general view of the rod magnetic flaw detector in working condition when passing through the protrusion and coupling of the rod or pipe when descending into the well. Figure 3 shows the moment of passage of the flaw detector through the landed end of the rod with the coupling.

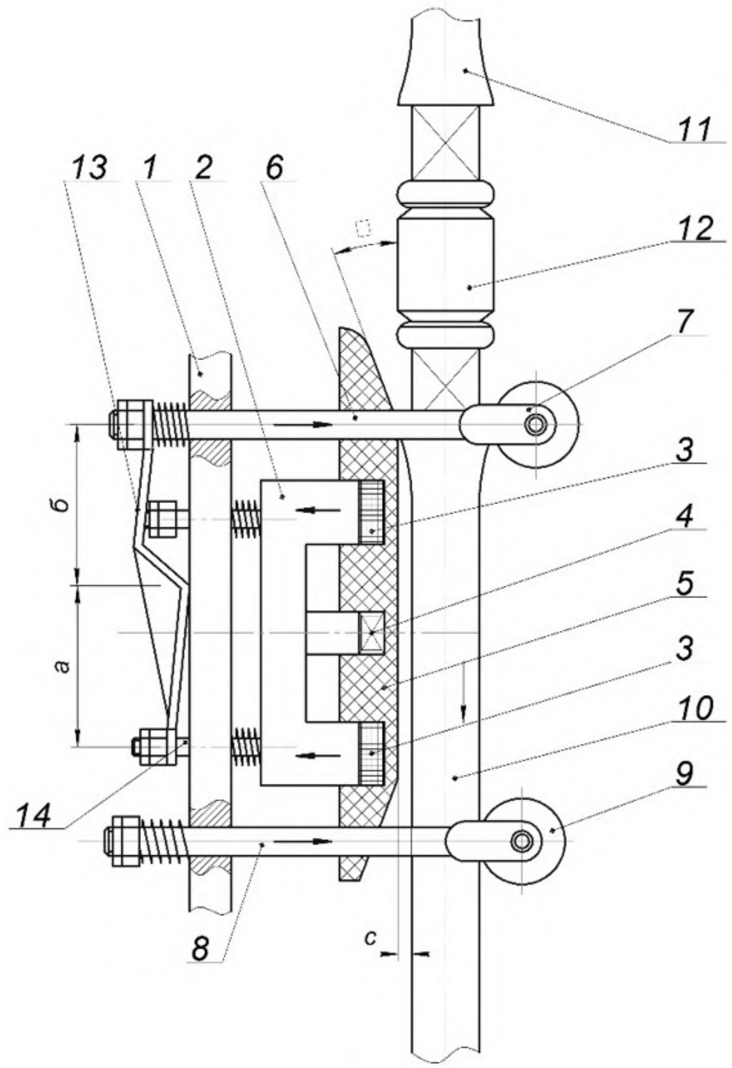

Figure 3. General view of the rod magnetic flaw detector in working condition.

The rod magnetic flaw detector consists of a frame 1 and a magnetizing system mounted on it. This system is made in the form of a U-shaped magnetic circuit 2 with permanent magnets 3 and a magnetic field sensor 4, located between the permanent magnets 3. The sensor is also connected to electronic recording equipment (shown in figure 3). The protective element 5 of non-magnetic material (e.g. polyurethane) is present to protect the permanent magnets 3 and the magnetic field sensor 4. In the holes in the frame 1 and the protective element 5 mounted upper spring rods 6 with roller 7 and lower spring guide rods 8 with roller 9. Protective element

5 with landed ends 11 at an angle in contact with the controlled surface of the rod 10. Between the landed ends of the rod 11 is a coupling 12, and on the frame 1 is a lever balancing mechanism 13 in contact with one end with the upper spring rods 6 and the other end with the lower guide spring rod 14 of U-shaped magnetic conductor 2.

This control will prevent damaged elements from flowing into the well, which could cause additional complications.

To accelerate the unscrewing of pipes or rods left in the well, it is advisable to use a device for unscrewing the pipes in the well [19]. Figure 4 shows a laboratory experimental sample of the device.

This device for unscrewing pipes in the well contains a hollow cylindrical body with a left adapter located in the lower part, and a right adapter located in the upper part of the device. Anchor assembly with locking elements, reversible mechanism in the form of a planetary gearbox, consisting of a hollow gear shaft, a carrier with satellites, which are installed to interact with a hollow gear shaft and a toothed surface made on the inner cylindrical surface of the hollow cylindrical body of the device. The hollow gear shaft itself is mounted on rotatable bearings with respect to rotation relative to the device body, and the means for actuating the anchor assembly comprises a housing which is fixedly connected to the carrier and mounted on the middle part of the gear shaft. Fixing elements that are rotatable about axes parallel to the axis of the device. And the outer working cylindrical surface of the fixing elements is made by moving the generating along the part of the Archimedes spiral. The means for triggering the anchor assembly includes a spacer sleeve, which is installed with the possibility of limited axial movement on the splined surface made on the upper part of the gear shaft. The anchor assembly also contains thrust carriers, which are fixed on the upper end surface of the fixing elements and made in the form of cylindrical rods with spherical ends. Adjusting nut screwed on the threaded surface made on the gear shaft below the splined surface. The anchor assembly also includes a spring mounted between the upper end surface of the adjusting nut and the spacer sleeve, the lower end surface of which is made in the form of a cone arranged to interact with the spherical ends of the thrust bearings.

Execution of the outer working cylindrical surface of the fixing elements by moving the generating along the part of the Archimedes spiral and enabling the rotation of the fixing elements around axes parallel to the axis of the device to change the outer diameter of the device, provides more interaction with the inner surface of the casing. This prevents it from being damaged by contact, which could be a source of future damage. In addition, the proposed design of the locking elements allows the device to be used in casings of different diameters without replacing the locking elements themselves.

To capture ferromagnetic parts that have accumulated in the well, it is necessary to use the end and peripheral magnetic metal traps.

In a peripheral magnetic trap, placing the paws on top of each other with belts allows you to cover the entire gap between the drill string and the well walls, providing simultaneous centering of the trap and protection of magnetic systems from destruction. The placement of the lower belt paws between the upper belt paws provides full coverage of the flushing fluid flow by the action of the magnetic field. The flux that is not exposed to the magnetic field in the lower belt falls within the range of the magnetic field in the upper belt. The formation of magnets and magnetic conductor systems allows to create different combinations and ensure their performance removable and autonomous. Making magnetic systems removable allows you to quickly replace them on the surface when replacing the bit or layout of the drill string, which significantly reduces the time to clean the metal trap from ferromagnetic particles and reduces time spent during lowering and lifting operations. Execution of autonomous systems ensures their independence from external energy sources, as well as the independence of their performance from the conditions of formation of the magnetic circuit with the body of the metal catcher.

To prevent the absorption of liquid in the process of washing the well, it is advisable to carry out foam washing. And to obtain a fine stable foam, it is necessary to use a foam-generating device (figure 5).

Figure 4. Laboratory experimental sample of a device for unscrewing pipes.

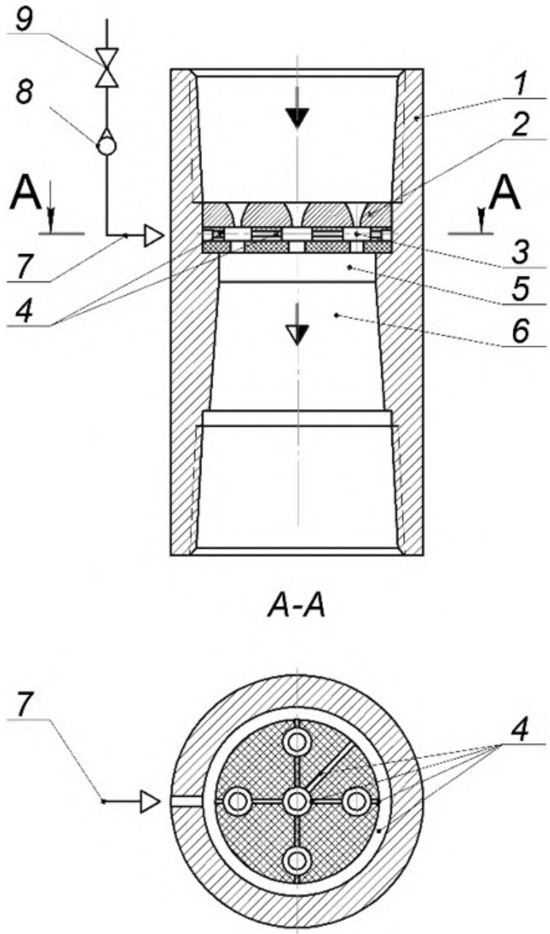

Figure 5. Foaming device.

This foam generating device has a positive effect due to the introduction of a multi-nozzle insert, instead of one nozzle, allows to increase the productivity of the device and its efficiency due to increased contact surface area of liquid jets in pre-mixing chambers with air or gas, from many nozzles in the cavitation chamber of intermediate mixing, where the dispersion takes place, which contributes to the effective mixing of air or gas with liquid and the formation of a foamy solution. In the chamber of turbulent motion of the flow of the mixture placed in the diffuser is the process of consolidation of the obtained effect a stable controlled foamed mixture is obtained.

5.4. Definition of environmental safety management principles of the old fund abandoned wells
Decommissioning and abandoned oil and gas wells are currently being accumulated, some of which are not accounted for anywhere, posing a potential risk to the environment. At the same time, there is an increase in inflows and outflows in the later stages of field operation. Therefore,

there is a need to develop strategic solutions based on the principles of eco-efficiency to prevent environmental pollution during the life cycle of oil and gas wells [20].

The main positions of the Strategy are:

- to analyze each stage of the life cycle for the possibility of reducing not only output flows (emissions, discharges, waste etc.), but also reduce input flows, which involves resource conservation and efficient use of energy. Achieving such effects is possible with the modernization of existing technologies and equipment;
- constant control of wells decommissioned by developing innovative tactics for their involvement in the life cycle of energy flows;
- reduction of the risk of emergencies by monitoring the condition of equipment: timely diagnosis and selection of criteria for equipment perfection;
- development of forecast estimates in emergency situations, in particular in gas and oil pipelines and open fountains, which will allow to make effective management decisions for rapid localization of the accident and reduction of negative environmental effects on the environment;
- formation of an environmental safety management system at all stages of the life cycle of oil and gas wells, based on the principles of sustainable development, eco-efficiency and continuous improvement by adapting best practices of developed countries and developing their own management approaches.

6. Discussion of the results

The process of well restoration is complex and requires a significant number of specialists and resources to achieve the expected effect. The work should be carried out systematically with the planning of successive stages. Equipment and methods of restoration of abandoned wells should be determined individually according to the characteristics of each well and the specifics of the landscape. Selection of plant bioindicators and bioremediators of technogenic-changed territories should take into account climatic zonation and their phytodiversity.

7. Conclusions

The problem of abandoned wells significant number presence, where there is insufficient or no control over their condition and processes occurring in the wellbore space, which can pose a threat to the environment. The prospects of using resistant plants common in natural phytocenoses to the influence of oil contaminants in phytoremediation practice are analyzed. The bioindication suitability of oil-sensitive plant species, which are recommended for use in monitoring studies of the quality of technogenic-transformed environment, is revealed. The selection of equipment that allows for the effective restoration of abandoned wells is done.

The solutions proposed in the work will allow to monitor these wells condition, to reduce the uncontrolled flow of fluids into the environment and to restore areas affected by long-term exposure to hydrocarbon pollution.

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To cite this article: O Yu Bogoslavska *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012018

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012018 doi:10.1088/1755-1315/1049/1/012018

The impact of fuel delivery logistics on the cost of thermal energy on the example of biofuels boilers in Ukraine

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Abstract. One of the important directions for achieving the goals of sustainable development and decarbonization is to increase the share of biofuels, including in heat supply systems. In this case, an important factor in deciding on the use of biofuel boilers is the cost of fuel, which is affected by the delivery logistics. The authors determined the impact of logistics for different types of fuel for low-power boilers (0.5 and 1 MW, burning biofuels) on LCOH. The calculations take into account the existing rates of environmental tax. The paper considers the transportation of biofuels by road to small consumers over short distances (within a radius of several hundred kilometers). The study showed that the cost of delivery of pellets from producer to consumer can be up to 20% of their cost. It is established that the transportation of a ton of pellets per 1 km increases the cost of this ton by about 1.35 UAH, therefore, the logistical component in the final cost of pellets can be significant.

1. Introduction

One of the important directions for achieving the goals of sustainable development and decarbonization is to increase the share of biofuels, including in heat supply systems.

Recently there have been significant changes in the energy sector of Ukraine, including the use of renewable energy sources, as well as individual and centralized heating. The issues of energy safety of the country, reduction of dependence on imported energy carriers, especially natural gas, are becoming increasingly important. A number of documents have been adopted, strengthening the legislative field for the introduction of renewable energy sources (RES), in particular the use of biomass, as well as stimulating the replacement of natural gas in heat supply with other energy carriers [1]. The actuality of biomass energy and fossil fuel substitution

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012018 doi:10.1088/1755-1315/1049/1/012018

projects has increased significantly. Biomass is a renewable local fuel that, if used sustainably, is a virtually inexhaustible source of energy.

Water heating boilers on biomass are widely used for heating individual structures and private houses, as well as several structures and even micro districts when they are used in the centralized heat supply. The main types of fuel for such heating equipment are anthracite, peat, wood, wood pellets, sunflower husk pellets, straw briquettes, wood chips and wood waste.

Boilers for biofuels are usually projected on the thermal capacity of not more than 1 MW, because with a higher capacity significantly complicates their operation.

It is not only the procurement prices for different types of wood and agro-biomass that are an important factor in the choice of fuel. The logistical component also makes a significant and sometimes decisive contribution. Transportation of biofuel over long distances leads to high freight costs, as well as significant costs for handling operations, which significantly increases the final cost of fuel.

For instance, burning sunflower husks in the boiler of an oil extraction plant, or using wood waste for CHP at a woodworking plant, because the logistics expenses in this case are minimal and no money is spent on waste disposal [2].

Papers [3–9] are devoted to the study of the impact of biofuel delivery on the cost of heat.

The most relevant for this study is the paper [3], in which the heat supply problem of the city of Baikalsk is considered. The most environmentally friendly solution to this problem is using timber, which was felled during forest sanitation outside the Anchuk village. Environmental friendliness and other advantages of biofuel are the main reason for using this type of heat source. The article [3] presents a comparative analysis of the production and delivery costs of the fuelwood chips and pellets for Baikalsk. Pressed fuel wood chips and chips with standard bulk density are considered. The Levelized cost of heat, unit cost, and capital costs are used as indicators of the economic efficiency of pellets and fuelwood chips.

Authors of [4] show, that combined heat and power (CHP) production in combination with a district heating (DH) grid gives an energy-efficient use of wood fuels.

Paper [7] discusses alternatives for biofuel-based district heating using simulation analysis in a real-life case example and illustrates the current supply chain structure of forest chips from harvest to the heat energy plant. Also, the study demonstrates how a regional bioenergy system could be developed with the help of a simulation model for evaluating the feasibility of different wood fuel supply chain options. The model mimics a real-life example of an industrial area in a small Finnish municipality planning to invest in a CHP plant.

Given that Ukraine is the largest country in Europe, the transportation of biofuels in it can be carried out over long distances. Thus, the aim of this study is to investigate the impact of delivery logistics of biofuel on the cost of thermal energy, which will develop practical recommendations for the use of remote sources of biofuels for low-power solid fuel boilers.

2. Methods

2.1. Features of biofuel transportation

The profitability of a boiler plant depends on a well-functioning logistics system. After all, delivery requires certain costs, and if this process is not optimized, these costs can be too high. It is important to ensure full protection of fuel, especially pellets, from moisture, precipitation and other damages during transportation. Therefore, the best option will be closed bodies, hoppers, wagons. The use of fuel pellets or granules was chosen for analysis only in this article.

Pellets for solid fuel boilers can be loaded:

- in bulk;
- in big-bags;
- in bags of different volumes.

Types of packaging depend on two factors. The first - how exactly is planned to provide transportation of fuel. The second - how it will be used.

The high bulk density of pellets is a positive feature, which reduces the cost of transportation, in contrary to packaging in big-bags and bags. In fact, loading and unloading of pellets in bulk, as well as their feeding into the boiler, is easily automated, which reduces the cost of these works.

Bulk delivery of pellets is used in most European countries, which allows significant savings on packaging and loading and unloading operations. More than 50% of pellets are burned in the boilers of large boilers and CHP plants in Europe. Therefore, it is much easier and more profitable for them to purchase such fuel in bulk from vehicles, to reload it from wagons, ships or motor vehicles into hoppers from which it will be fed directly to the boiler.

Packaging in big-bags. Fuel pellets, like many other bulk products, are often packaged in large, most often propylene bags - the so-called “big-bags”. Such packaging is quite convenient for transportation, provides protection of the product from physical effects, allows the use of conventional techniques for loading and unloading operations (crane, forklift). In some cases, delivery of pellets to consumers is also made in big bags, which are then loaded into the furnace with a crane or forklift. In addition, big-bags are suitable not only for transportation of pellets, but also briquettes. In relatively small industrial boilers, large bags play the role of storage, from which fuel is automatically fed to the boilers.

Packing in ordinary bags. Ordinary polyethylene bags of different volumes are often used for transportation. Most often small packaging is a practical choice for private households. Such bags are mostly designed for weights of 10 to 20 kilograms. That is, they can be easily carried by hand and put pellets in the boiler. The bags with pellets are placed on pallets for easy loading and unloading onto trucks. Most often the bags are packed with extra-class pellets intended for private consumers who burn them in special stoves and fireplaces or use them for barbecues instead of traditional charcoal.

The choice of specific transport for delivery of solid biofuel depends on the location of the consumer. Let’s take a look at several options.

River and sea transportation is an inexpensive way to transport biofuel over long distances. Depending on customer requirements and plant capabilities, pellets can be loaded on a ship in bulk, in big-bags or in consumer packaging. Many European customers prefer to receive fuel in bulk. Most customers who consume pellets in large volumes, have their own terminal complexes in sea and/or river ports. Transportation to specific customers is carried out from these complexes.

Transportation by river within one country is performed if the producer is located in the immediate vicinity of the waterway. However, this method of delivery has its disadvantages - one of them is that not all rivers are navigable in winter. And it is the winter time of the year that is the most important for the solid biofuel market.

Trucks is one of the most expensive, but also the most flexible method of delivery. This type of transport is used if you need to deliver pellets for a relatively short distance (the best option if you need transportation for a few hundred kilometers, no more). Handling can be done in bulk, if a covered crate. If the products are packed, cranes or forklifts are used. If the company’s production facilities are located far from railroads or river (sea) ports, it is also more reasonable to use trucks [2, 10, 11].

Selection of a specific transport for the delivery of solid biofuel. Let’s look at how the process of biofuel delivery is organized in Germany and Austria [12, 13]. The specialized truck equipped with a pneumatic unloader is used in most cases, for the transportation of pellets. Such truck has a large tank, which is divided into several parts (the container can be mounted directly on the truck chassis or on a trailer attached to the truck). The tank is divided into four chambers, so it can be unloaded at different locations, at different consumers. When delivery of solid biofuel is required, the vehicle loads the chambers. The pellets are fed by a conveyor belt. At the end of the transporter there is a sleeve made of synthetic materials. It is lowered into the chamber and the pellets are poured into this chamber of the tank. The unloading process is not complicated. The machine has a hose that connects to the pellet storage unit. The driver of the vehicle with the help of the control panel starts the compressor. The average pressure of the compressor reaches a mark of 0.5 bar. Such pressure is enough to pump over a hose up to 400 kilograms of pellets in a minute. If the hose is too long, the pressure drops to about 0.3 bar, and the fuel transfer rate drops to 340 kilograms a minute. The truck can carry from 15 to 28 tons. It usually takes one working day to load, deliver and unload. The popularity of solid biofuels has provoked a significant expansion of the network. That is why the warehouses are designed to cover the largest radius of 150 km.

Such transportation technology is not used, primarily because consumers do not have the necessary equipment in Ukraine. Indeed, unloading must be carried out in a specialized container, from which the fuel is automatically transferred to the furnace chamber of the boiler. As soon as Ukrainian consumers will actively install boilers that run on alternative energy sources and start equipping their homes accordingly, modern equipment will appear in Ukraine.

Rail transportation is the best option for transporting large amounts of biofuel to industrial consumers, who usually have rail infrastructure, i.e.: sidings; shunting locomotives; hoppers unloading devices, etc. Pellets are transported by railroad both in covered wagons - in bags or big-bags, and in special hopper wagons designed for transportation of bulk cargo [2, 10, 11].

For a product, the retail price of which rarely exceeds 250 Euros per ton, and the production cost is 60-80 Euros per ton, the efficiency of transport and logistics operations is one of the key factors of profitability. The cost of delivering pellets from the manufacturer to consumers can be up to 50% of the cost of production. Savings of 1 euro per ton for a large producer will save tens of thousands of Euros over a year and will amount to only 3-4% of logistics costs [2].

2.2. Delivery of solid biofuel within Ukraine

Pellets and briquettes are commonly used in the Ukrainian market. They are made from different raw materials:

- in bulk;
- wood;
- sunflower husk;
- husks of other crops;
- straw;
- peat.

Often the supplier announces the price of pellets EX-works (warehouse) in terms of INCOTERMS-2020, without taking into account the loading and unloading of vehicles, delivery to the place of unloading, as well as transporting pellets to the boiler hopper.

Delivery can be carried out as indirectly from the manufacturer's warehouse, as well as from the industrial warehouse. Of course, delivery from the manufacturer's warehouse without reloading is better, since the reloading of pellets does not improve their quality, and the conditions of storage in the secondary warehouse may not meet the requirements (above all for the indicators of volatility).

Most manufacturers deliver pellets packed in plastic or papery bags. Delivery of pellets with the help of specialized transport in Ukraine to the country we have not yet seen.

Also, it should be noted that any reloading increases the number of harmful particles of pellets, not given for combustion. According to the [14] one "hard" reloading of 25 kg of pulp (eg, warehouse-machine) reduces the amount of waste approximately by 0.15-0.3% of the total mass of the pulp.

If the pellets were brought in an open car (without a tent) in the autumn-winter period and some of the bags are blocked by the road pond, there is a chance that these pellets are not suitable for use, because where the pond, there is often water.

Terms of storage of pellets depend primarily on the conditions of their packaging. As a general rule, pellets are not subjected to direct exposure to water, but on the other hand, pellets actively absorb moisture from the ambient air. In addition, in winter, when you put pellets in a warm room can create condensation, so the question of how the pellets are packed, comes to the fore [14].

In this work, we will consider biofuel in the form of pellets, which are packed in a trolley of 1 ton. The size of this bag is 90×90×190 cm. The volume of the package is 1.54 cubic meters.

2.3. The levelized cost of heat

For economic efficiency comparison of heating projects with different biomass types boilers, the method of levelized cost of heat was used [15, 16].

The levelized cost of heat (LCOH) is widely used for determining optimal projects in heating [17–25]. In particular, work [18] proposed a new dynamic price model based on the LCOH and the predicted hourly heat demand.

Sometimes the term LCOH is used when it comes to burning fuel and producing energy as heat. This method is universal and convenient when comparing different types of heat production technologies and is used by many organizations, including the International Energy Agency (IEA). The general formula of this method is as follows:

$$LCOH = \frac{\sum_{t=1}^{N} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_t}{(1+r)^t}}, \tag{1}$$

where

I_t is investment expenditures in year t;

M_t is operations and maintenance expenditures in year t;

F_t is fuel expenditures in year t;

H_t is energy (heat) generation in year t;

r is discount rate;

N is lifetime of the technology.

The use of LCOH makes it possible to specify prospective heat generation technologies for implementation. This in turn is needed to forecasting the structure of fuel and energy consumption for heating systems [25].

The environmental factor in the LCOH it is necessary to take into account as both the environmental requirements for incinerators and the environmental tax rate are constantly growing. Therefore, when determining the LCOH for small combustion plants, it is necessary to take into account the environmental tax [26].

For a more accurate calculation of LCOH it is also necessary to take into account the cost of delivery of biofuels, therefore it is proposed to calculate the average cost of thermal energy for the life cycle, taking into account the delivery logistics, by the expression:

$$LCOH_{F^{log}} = \frac{\sum_{t=1}^{N} \frac{I_t+M_t+F_t+F_t^{log}}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_t}{(1+r)^t}}, \tag{2}$$

where F_t^{log} is fuel delivery logistics expenditures in year t.

Thus, the logistic component of LCOH ($\Delta LCOH_{Flog}$) can be defined by expression:

$$\Delta LCOH_{Flog} = LCOH_{Flog} - LCOH. \tag{3}$$

3. Results

We chose biofuel boilers of Ukrainian production by KZOT and Gefest 500 and 1000 kW capacities, which burn such fuel: straw pellets, sunflower husk pellets and wood pellets. Calculations were made for three distances - for 100, 300 and 500 km. Such distances are selected as averages within different types of administrative units of Ukraine - within one district, one region, and between regions.

Fuel price is taken from online ads: wood pellets is 5000 UAH/t, straw pellets is 3300 UAH/t, sunflower husk pellets is 3980 UAH/t. Usually the cost of fuel is indicated without the cost of delivery. The cost of delivery is 27 UAH/km by truck with a capacity of 20 tons [27].

The discount rate is 10%, salary of boiler house employees - 6500 UAH/month.

The cost of boilers is taken from the Internet ads as follows (table 1) [28, 29]. Due to the significant increase in natural gas, which took place in autumn 2021, pellets became more expensive too, for example, in autumn 2020 wood pellets cost 2100 UAH/t, sunflower husk pellets - 1200 UAH/t. The cost of motor fuel and delivery [27] has grown less rapidly over the same period.

Table 1. Boilers and their main characteristics in January 2022.

The boiler	The boiler's power, kW	Efficiency, %	The boiler's cost, UAH
KZOT ARS 500 Comfort	520	85	294579
KZOT BRS 500 Comfort BM	500	92	293980
Gefest Profi-P 500	500	92	248400
KZOT ARS 1000 Comfort	1000	85	446344
KZOT BRS 1000 Comfort BM	1000	92	430883
Gefest Profi-P 1000	1000	91	465000

The exchange rate of the national currency - the hryvnia (UAH) - is constantly unstable and has fluctuated in the last 5 years in the range of 25.24-35.35 UAH/EUR [26]. The exchange rate of the National Bank of Ukraine is 31,74 UAH per 1 euro on 1 February 1, 2022.

Using the formula (1) is calculated LCOH, using the formula (2) - levelized cost of heat taking into account the cost of fuel delivery $LCOH_{Flog}$ for 3 cases - delivery of pellets at 100, 300 and 500 km, as well as using the approach of [26] calculated levelized cost of heat taking into account the environmental tax $LCOH_{T_{eco}}$ (table 2). The fuel component of LCOH, which takes into account the cost of fuel and electricity, was also calculated. Environmental tax rates have increased since January, 2022 and their values are given in [30].

The results of calculations show that at a transport distance of 100 km the logistics component $\Delta LCOH_{Flog}$ is 2.6-3.9%, for a transport distance of 300 km - 7.7-11.7%, for a transport distance of 300 km - 12.8-19.5%. The minimum value is for boilers burning wood pellets, the maximum is for boilers burning straw pellets. Taking into account the cost of delivery increases LCOH by 34.95-44.81 UAH/Gcal for a transport distance of 100 km, by 104.85-134.42 UAH/Gcal for a transport distance of 300 km, by 174.75-224.04 UAH/Gcal for a transport distance of 500 km. The minimum value is for boilers burning sunflower husk pellets, the maximum is for boilers burning straw pellets.

Table 2. Levelized cost of heat (LCOH) with and without taking into account the cost of fuel delivery and environmental tax from boilers that burn different types of pellets UAH/Gcal.

The boiler, fuel type	LCOH	Fuel component LCOH	$LCOH_{T_{eco}}$	$LCOH_{F^{log}}$ 100 km	$LCOH_{F^{log}}$ 300 km	$LCOH_{F^{log}}$ 500 km
KZOT ARS 500 Comfort, wood pellets	1549.3	1448.7	1555.7	1589.0	1668.2	1747.5
KZOT ARS 500 Comfort, sunflower husk pellets	1189.7	1089.1	1198.7	1227.6	1303.5	1379.3
KZOT ARS 500 Comfort, straw pellets	1179.5	1079.6	1187.9	1224.3	1313.9	1403.5
KZOT BRS 500 Comfort BM, wood pellets	1442.2	1338.5	1447.0	1479.8	1555.1	1630.4
KZOT BRS 500 Comfort BM, sunflower husk pellets	1260.9	1157.2	1270.6	1300.3	1379.2	1458.1
KZOT BRS 500 Comfort BM, straw pellets	1101.2	997.5	1107.9	1142.4	1224.9	1307.3
Gefest Profi-P 500, wood pellets	1434.7	1338.5	1439.5	1472.4	1547.7	1622.9
Gefest-Profi P 500, sunflower husk pellets	1102.5	1006.2	1109.6	1138.3	1210.0	1281.7
Gefest-Profi P 500, straw pellets	1104.7	1008.4	1111.5	1147.7	1233.7	1319.8
KZOT ARS 1000 Comfort, wood pellets	1526.6	1448.7	1537.5	1566.0	1644.8	1723.7
KZOT ARS 1000 Comfort, sunflower husk pellets	1154.0	1089.1	1167.5	1191.6	1266.9	1342.2
KZOT ARS 1000 Comfort, straw pellets	1157.5	1079.6	1170.5	1202.3	1291.9	1381.5
KZOT BRS 1000 Comfort BM, wood pellets	1415.0	1338.5	1424.8	1451.7	1525.2	1598.7
KZOT BRS 1000 Comfort BM, sunflower husk pellets	1146.4	1004.1	1158.5	1181.3	1251.2	1321.1
KZOT BRS 1000 Comfort BM, straw pellets	1074.0	997.5	1085.6	1115.2	1197.7	1280.1
Gefest Profi-P 1000, wood pellets	1432.8	1353.2	1442.7	1469.5	1543.0	1616.5
Gefest Profi-P 1000, sunflower husk pellets	1096.9	1017.3	1109.2	1131.8	1201.7	1271.6
Gefest Profi-P 1000, straw pellets	1088.0	1008.4	1099.9	1130.2	1214.4	1298.6

The fuel component is 91-95% of LCOH.

The value of environmental tax is calculated for 2022 for the following pollutants -

CO_2, NO_x, SO_2, solids. Now in Ukraine exist an environmental tax for CO_2 emissions from the combustion of all biomass [31]. According to the Tax Code of Ukraine, business entities that carry out such emissions in the amount of not more than 500 tons per year are not payers of the environmental tax for carbon dioxide emissions, i.e. the tax base for carbon dioxide emissions is reduced by such emissions of 500 tons per year. $\Delta LCOH_{T_{eco}}$ is 0.33-1.12% of LCOH, in monetary terms this component is 4.77-13.52 UAH/Gcal. The minimum value is for boilers 500 kW burning wood pellets, the maximum is for boilers 1 MW burning sunflower husk pellets.

4. Discussion and conclusions

In the autumn of 2021, the cost of natural gas and biofuels increased many times over. Fuel delivery also became more expensive, but the increase was not so significant. The high cost of gas encourages the use of other sources for heat supply, including using biofuels more widely. Ukraine is a large country, and at current natural gas prices, customers buy pellets with delivery not only within one or two regions, but also within half of the country. The results of calculations show that under the condition of pellets transportation for 500 km the cost of heat increases by 13-20%. The minimum value is for boilers burning sunflower husk pellets, the maximum is for boilers burning straw pellets.

The results of calculations show that the environmental tax component is many times smaller than the fuel delivery component and at current environmental tax rates is 1% of LCOH, which does not significantly affect the Levelized cost of heat. An approach in which biofuels are considered CO_2-neutral and no tax is paid for CO_2 emissions from their combustion will not significantly affect LCOH.

Different types of pellets have different calorific value and cost. Wood pellets are 20-30% more expensive than other pellets, but have the lowest calorific value. The highest cost has heat produced from wood pellets - an average of 20% more expensive. Taking into account the cost of logistics does not change this - heat produced from wood pellets remains 20% more expensive. Even with pellet delivery over 500 km, the LCOH will be lower for boilers burning sunflower husk pellets and straw pellets compared to wood pellets and no shipping charges.

Thus, it is most economical to use sunflower husk pellets and straw pellets. Decarbonization is a separate issue, in many countries biofuels are considered carbon-neutral in addition to the cost of producing and transporting fuels. And from this point of view it is most expedient to use fuels with the shortest way of transportation.

Although biofuels are considered to be more environmentally friendly because they are considered CO_2-neutral, their combustion produces emissions of other pollutants and ash. It is obvious that biofuel ash has a different composition and physicochemical properties than coal ash, but all ash dumps from solid fuel combustion have a negative impact on the environment and human health [31–44]. Further research should consider the ways and costs of handling pellet ash in the LCOH.

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To cite this article: V V Kovalenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012019

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012019 doi:10.1088/1755-1315/1049/1/012019

Problem of municipal solid waste of Ukraine and ways to solve it

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Abstract. Currently, Ukraine is among the countries with the largest absolute volume of waste generation and accumulation. Situation with landfills in Ukraine is uncontrolled. This is evidenced by unspecified landfills. The situation is constantly worsening due to harmful chemical emissions of landfills. The paper describes how pollution by landfills affects environmental components. Foreign experience, domestic waste management and methods of waste disposal were analyzed. The publication contains statistical data about dumps, landfills of household waste in Ukraine and describes normative-legal acts regulating issue of waste management. This paper outlines several recommendations for decreasing of environmental pollution from landfills on the territory of Ukraine. Following measures should be taken to solve the problem: sorting municipal solid waste; recycling; control and landfills registration; landfill placement; construction of waste-recycling and waste-burning plants; increasing awareness through environmental education on responsible attitude to waste.

1. Introduction

Currently, almost continuous production provides modern citizens with necessary needs such as food, clothing, household things and technics. It leads to overconsuming which causes waste amount increasing. Almost all this waste go to landfills and its amount is increased every year. New problem appears - we just throw out things and buy new ones instead of fixing.

Environmental pollution issues are growing drastically every year all around the world. It leads to environmental catastrophe of global scale. So, it needs fast-decision-making process or at least measures implementation that can minimize damages to the environment. Most developing countries constantly try to solve problems with pollution at all possible levels.

Ukraine is not a difference. Problem of environmental pollution became large-scale. Therefore in 2017 the "National Waste Management Strategy for Ukraine until 2030" was approved. It is aimed at addressing problem of environmental pollution in Ukraine. This Strategy is addressed to critical situation with formation, accumulation, storage, processing and disposal of waste. It is characterized by the further development of environmental threats.

The main problem is annual increase in the household waste amount and its irrational use. Ukraine is ranked ninth among the countries with the highest amount of waste produced per

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012019 doi:10.1088/1755-1315/1049/1/012019

capita. Thus, annual amount of household waste per person is 10.6 tons; the total annual amount of waste is 474.1 million tons. Among them 448 million tons are hazardous [1].

In general, problem of waste in Ukraine is large and significant due to dominance of resource-intensive multi-waste technologies in the national economy, and due to lack of long-term adequate response to its challenges. Significant scales of resource use, energy and raw material specialization of the national economy together with the outdated technological base determined and continue to determine high rates of waste generation and accumulation. Such circumstances lead to deepening environmental crisis and aggravation of the socio-economic situation in society. It necessitates reform and development taking into account domestic and international experience of the entire legal and economic system governing use of natural resources in general and waste management in particular. The problem of waste is one of the key environmental problems and is more important in terms of resources [2].

During 2020-2021, the amount of household waste is increased as a result of coronavirus COVID-19. Plastic bags, disposable masks and rubber gloves were added to waste. Importance of protective means use is emphasized everywhere, and no information about their features.

2. Analysis of research and publications

Number of legislative documents, scientific publications and information resources were analyzed while researching the problem of solid domestic waste (SDW) and ways to solve it. Result of the analysis showed that outlined by us problem is considered and described in the following areas:

- administrative and legal regulation in the field of waste management [1, 3–5];
- analysis of foreign experience in waste management [2, 6, 7];
- modeling of domestic waste generation process for planning of management system and forecasting impact on the environment [7–10];
- collection and transportation of solid waste, solving problems of processing and disposal of it [11–13];
- reclamation of solid waste landfills [1, 14, 15].

Thus, it is clear that solid waste problem and its disposal is relevant for different countries. In Ukraine there are number of legislative documents. Also there are gross violations of these regulations and insufficient control by government agencies, especially mass emergence of unauthorized landfills. So, SDW sorting is almost non-existent. It directly affects increase in waste in landfills and increase landfills area.

3. Research aim and objectives

The aim is to investigate problem of solid waste management in Ukraine and to describe the landfills impact on environmental components. Tasks:

(i) *D*escribe impact of landfills on environmental components;
(ii) *A*nalyze foreign experience in household waste management and ways to dispose them;
(iii) *C*onsider solid waste landfills on the territory of Ukraine;
(iv) *O*utline recommendations for reducing pollution of environmental components by landfills in Ukraine.

4. Impact of landfills on humans and environment

Industrial revolution was precondition for environmental pollution. In contrast there are a lot of shortcomings along with achievements of technological progress. One of the main is global pollution of the planet with various wastes [16].

Emergence of plastic and other synthetic materials exacerbated the environmental situation on the planet. Such materials are almost non-degradable and cause great damage to flora and fauna within radius of hundreds of kilometers from the territory of organized landfills. The amount of plastic waste discharged into the ocean is shown in figure 1.

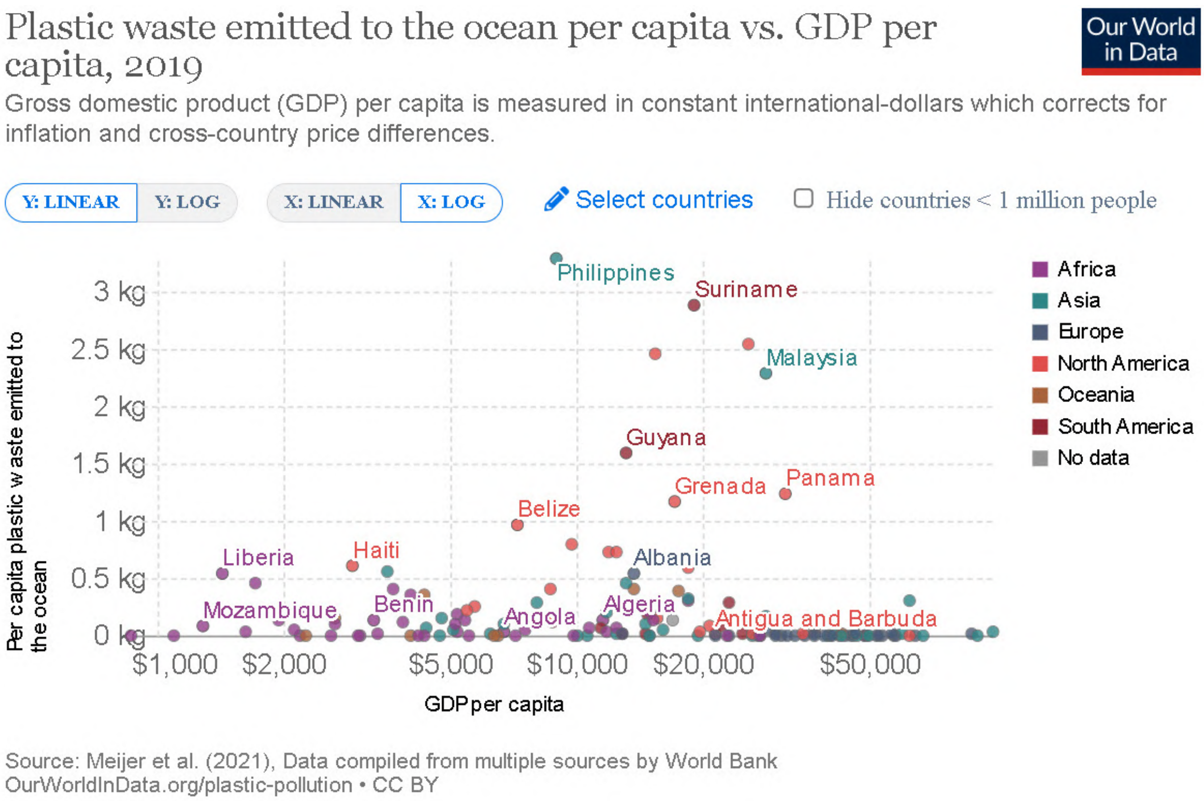

Figure 1. Plastic waste emitted to the ocean per capita vs. GDP per capita, 2019 [17, 18].

The situation is deteriorated by the fact that producers pursue only their own interests, caring for profit, forcing consumers to buy more goods and get rid of old things, throwing them in landfills. There they lie for many years, poisoning everything around. Over time, more developed countries realized that it is not possible to build landfills of different types of waste (figure 2). It includes plastic on their territories. This caused transportation (so-called "waste migration") from developed countries to poor countries in Africa.

Such decision caused some damage to the inhabitants of cities and towns close to such landfills. Many settlements on the Atlantic coast migrated because it is impossible to live in such places. Waste may contain toxic substances, chemicals, heavy metals, which together with precipitation can enter water bodies through groundwater. The vast majority of this waste is plastic. It is decomposed over millions of years, releasing various harmful substances in the process. Plastic is incinerated to free space for new waste in most of these landfills. Its combustion releases heavy metals that deplete the ozone layer. In addition, combustion produces smoke, which can lead to life-threatening diseases and even death during breathing. Decay products of plastic is rised into the air and then fall back to the Earth's surface in the form of acid rain [16].

Impact of landfills is pollution of air, groundwater and surface water and soil itself by hazardous components of waste and their decomposition products. These hazards are significantly exacerbated in the case of fire at the storage site. Large-scale multifactor emergencies occupying significant areas of the landfill are particularly dangerous for the

Figure 2. Uncertified landfill on the territory of Ukraine.

environment. It should be noted that waste burning cause unpleasant odor and air pollution. Such illegal actions lead to release of toxic substances, including carbon monoxide, dioxins and other. In addition, combustion of solid waste releases ash residues into the atmosphere. They may contain toxic metals such as mercury, lead, chromium, cadmium, arsenic.

Landfills and especially SDW dumps are powerful centers of environmental pollution - like a biochemical reactor. In its thickness there is formation of significant amounts of toxic gases ("landfill gases") and liquid filtrate, breeding flies, development of pathogenic microorganisms (carriers of dysentery, hepatitis, tuberculosis, even typhus); landfills attract small rodents and birds. Landfills (especially natural) are prone to spontaneous combustion. During combustion large amount of harmful gases are emitted into the atmosphere. It includes hydrogen chloride (solid waste contains up to 10% of plastics, including chlorinated polymers) and others. It should also be noted that nature is damaged by emissions of so-called biogas, which contains carbon dioxide and methane and other compounds.

Another problem is groundwater pollution. Rainwater (meltwater) is "enriched" with various chemicals formed during the decomposition of waste by seeping through layers of buried waste. Such water with dissolved in it pollutants is called a filtrate. Particularly toxic filtrate is formed when it passes through untreated waste. Waste in landfill contains iron, mercury, zinc, lead and other metals from cans, batteries and other electrical appliances, organic residues, all flavored with dyes, pesticides and detergents, agents and other chemicals. Illiterate choice of burial sites and neglect of security means allows this toxic mixture to reach aquifers. Waste decreases in volume during decomposing and soil subsides. In the formed depressions water is accumulated. This activates formation of toxic filtrate. Burial site can turn into a swamp after certain period of time [10]. Figure 3 shows sources of waste and their impact on humans and the environment [19]. Figure 4 includes illustrations of landfills and wastewater treatment plants sources [20].

Spreading further along different trophic chains, various toxic substances formed at landfills cause degradation of biosystem (flora and fauna, aquatic organisms) and adversely affect human health (through water, air, food) [21, 22].

Figure 3. Possible source of solid waste and their impact on human and environment [19].

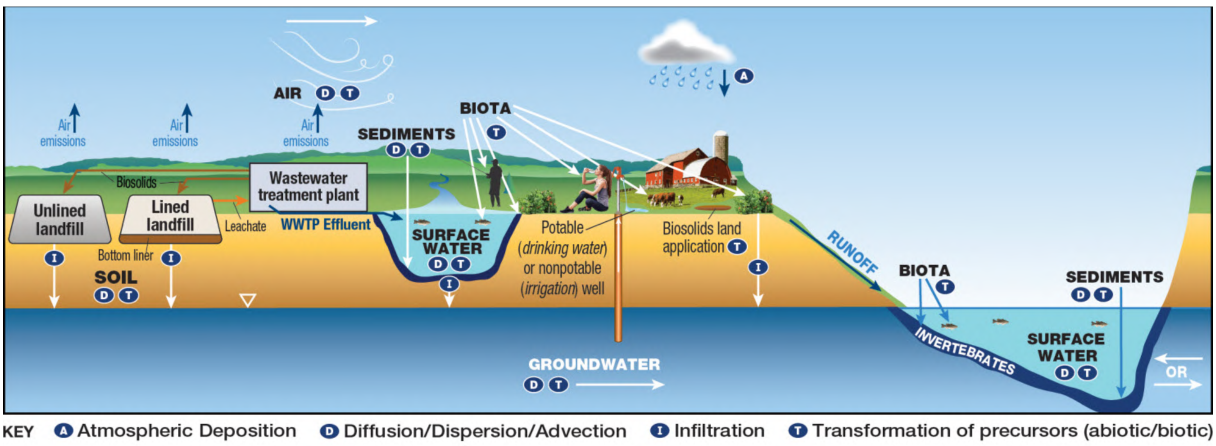

Figure 4. Conceptual site model for landfills and wastewater treatment plants [20].

5. The world experience of waste management

Figure 5 shows general management of global waste [23]. It is shown that open and closed landfills are dominated. Slightly smaller part is recycling and incineration. The smallest part is composting and anaerobic fermentation.

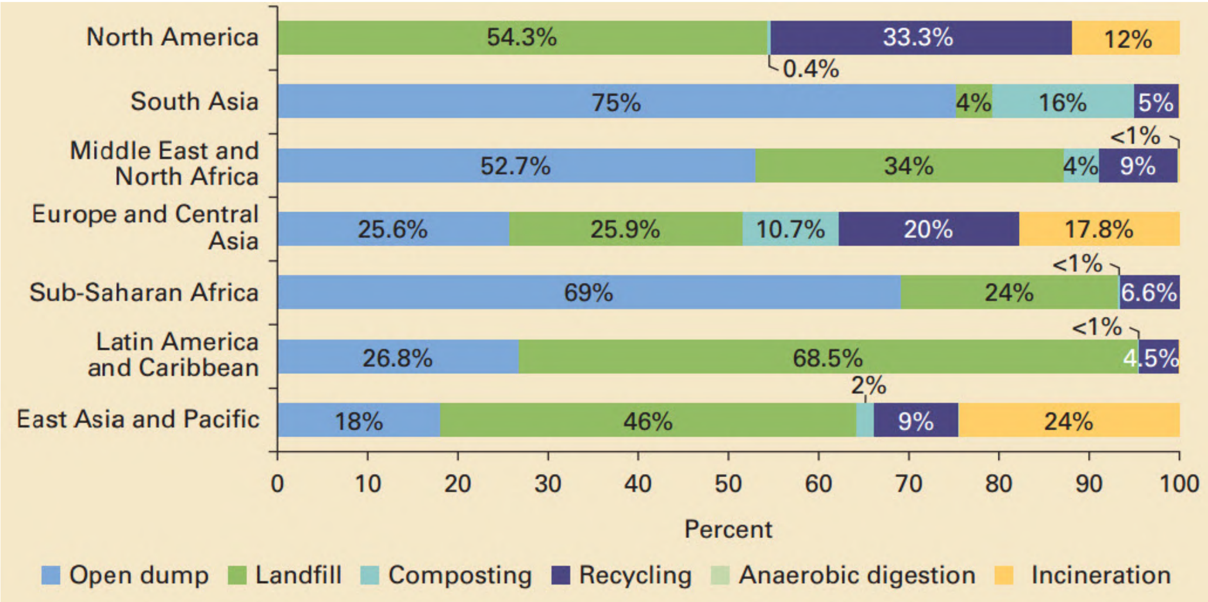

Figure 5. General management of global waste [23].

Governments in many parts of the world are looking for effective ways to manage waste, but the problem of environmental pollution still remains unresolved. European environmental policy is aimed at building specialized plants for processing of wide range of waste, including glass and plastic. Activities of such enterprises are very profitable from an economic point of view. About 80% of all waste coming for recycling finds “second life”. As a result, most economically developed countries are gradually abandoning solid waste landfills and switching to new methods of disposal that can improve the environment and receive additional funds and raw materials from recycling and energy [4].

The greatest attention is paid to the organizational and economic mechanism of waste management in developed countries. This is a comprehensive system of goals, incentives, functions, consisting of organizational and economic levers of waste management and implement the most effective policies at different hierarchical levels to balance environmental and economic interests of society and economic entities. In particular, Japan pays special attention to use of secondary raw materials. Japan uses administrative, financial and legislative levers to encourage producers to use secondary raw materials. The main areas of “recycling” in Japan are: disposal of waste as raw material for manufacture of raw materials, use of waste to obtain any marketable products, use for construction of dams, roads and embankments, fertilizers and biogas. Active introduction of the “recycling” system allowed to create new jobs, expand production, reduce production costs, reduce consumption of primary material and energy resources [4].

Sweden is currently the world leader in recycling. According to the Swedish waste management association Avfall Sverige, 99% of all household waste is recycled in Sweden. Almost half of the waste in the country is incinerated, but only after careful sorting. Plastic, paper, food waste go to the processing or production of biogas. Thus, 50.6% of household waste is recycled in the country for the second time, 48.6% is incinerated for energy production and only 0.8% goes to landfills [6].

Germany is considered to be one of the world leaders in waste recycling. In a typical German yard or house you can find at least 5 multi-colored waste containers (black - for unsorted waste, brown - for organic waste, blue - for paper, yellow - for packaging and plastic, green - for colored glass, green with a white stripe - for colorless). Every year, every resident of Germany receives by mail an information letter with a detailed description of the schedule of waste sorting services for the next year [4].

Therefore, Sweden, Germany, Switzerland, Austria and Japan can be called the world's leading waste recycling countries. These countries use waste recycling to heat buildings, generate electricity, make various household items, and so on.

6. Landfills of SDW in Ukraine

Ukraine is one of countries with the largest absolute volumes of waste generation and accumulation [4]. Ukraine generates about 10 tons of waste per capita per year, compared with 5.5 to 6 tons of waste per capita in the European Union according to the National Institute for Strategic Studies., Ukrainian volumes are of serious taking into account the extremely insufficient level of their utilization and disposal [24] compared to the indicators of waste accumulation in the European Union.

According to the Minister of Health of Ukraine Viktor Liashko in 2020 Ukraine generated 462 million tons of waste: 79.5% - waste from extractive industry, 6% - metallurgy, 2.5% - solid waste and 1.6% - agricultural waste. Solid waste is the most difficult to manage. 10 million tons of solid waste are generated annually in Ukraine. 79% of the population is covered by household waste removal services. 93% of waste is taken to landfills. Only 4% of waste goes to recycling. There are 33.000 unauthorized landfills in Ukraine [25].

According to the analytical portal "Slovo i dilo" [26], today in Ukraine there are officially 5,455 landfills and dumps with total area of over 8.5 thousand hectares. Such data are provided by the Ministry of Development of Communities and Territories of Ukraine. The largest city in the country Kyiv is served by only two official landfills - landfill №5, located in the village of Pidhirtsi of Obukhiv district of Kyiv region (area 63.7 hectares) and construction waste landfill № 6 on the street Pirogivsky Shlyakh, 94-96 (area 11.6 hectares). At the same time, Vinnytsia region has the largest number of landfills and dumps - 741, which on average occupy an area of 10-15 hectares. There are 675 landfills in Poltava oblast, 659 in Chernihiv oblast, and 608 landfills in Odesa oblast. The least official landfills are in Ivano-Frankivsk (17), Luhansk (18), Lviv (20), Cherkasy (21), Ternopil (31) and Khmelnytsky (35) regions [26]. Figure 6 presents map of landfills and dumps in Ukraine.

The main legal act regulating relations in the field of waste management in Ukraine is the Law of Ukraine "On Waste" dated 05.03.1998 № 187/98-VR. It stipulates that waste should be disposed. It is defined as any substances, materials and objects, formed in the process of production or consumption and goods (products) that completely or partially lost their consumer properties and do not have further use at the place of their formation or discovery and which their owner gets rid [27].

Ukraine committed to sort all waste by type of material and dividing it into reusable, landfill and hazardous from January 1, 2018. This is stated in Article 32 of the Law of Ukraine "On Waste" [27]. Relevant paragraph was added to this law in 2012. This item corresponds to two EU Directives - 1999/31/EC and 2008/98/EC. It regulates management of waste in European countries, provide clear sequence of actions to be taken with waste, classify waste, set strategic goal to reduce amount of waste taken out to landfills.

National Strategy for Waste Management in Ukraine until 2030 [28] was approved in order to reform and improve the waste management system. The Strategy defines main directions of state regulation in the field of waste management taking into account European approaches to waste management. Main goal of the Strategy is "to create favorable conditions for raising

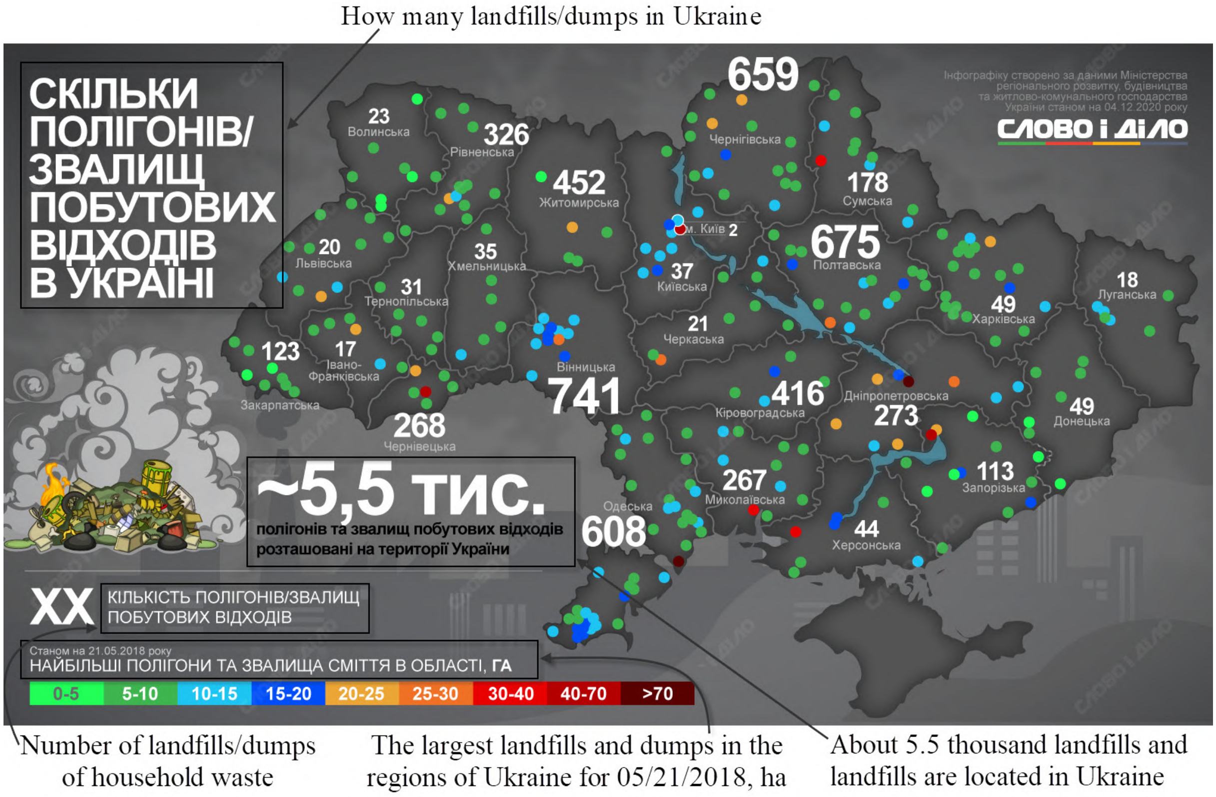

Figure 6. Map of landfills in Ukraine [26].

living standards by introducing systematic approach to waste management at the state and regional levels, reducing waste and increasing the amount of waste recycling, reuse". At the same time the National Waste Management Plan until 2030 was approved to implement the measures of this Strategy [29]. However, many points in these documents are grossly violated by both individuals and legal entities in practice.

Ban on the use of certain types of plastic bags in Ukraine is implemented through adoption of the Law of Ukraine "On Restrictions on Circulation of Plastic Bags in Ukraine" [30]. The article 2 of this Law prohibits distribution in retail, catering and provision of services of ultra-thin, thin and oxo-decomposable plastic bags (is not applied to biodegradable plastic bags and ultra-thin plastic bags used by retail outlets as primary packaging). These changes will start on March 9, 2022.

There are measures aimed at banning plastic bags encourage producers to produce biodegradable products, and producers of plastics in primary forms. They are aimed to produce biopolymers that compost and biodegrade as raw materials for the production of biodegradable products. Raw materials for the biopolymers production are various natural substitutes for plastic, for example: starch (potato, corn, etc.), bran cereals (oats, wheat, corn, etc.), algae extracts, grain waste (straw, corn leaves). However, limited use of natural raw materials for the biopolymers production is caused by their high cost compared to PET raw materials [31].

However, existing regulations on governing waste management are imperfect to create effective management system that meets challenges of times and European directives. Existing acts contain somewhat outdated definition of industrial and household waste, based on which it is impossible to establish management process.

Important aspect for SDW problem solving is adequate forecasting and modeling of waste generation. Publications [8, 9] describe different models and regression analysis, time series analysis. Certain indicators were used as initial variables: population, age, life expectancy in cities, total amount of solid waste, etc. Therefore, models of household waste generation are necessary for adequate planning of the management system and forecasting of environmental impact.

The study [9] shows that increase in solid waste is caused by increase in housing, growth in industrial production, retail and catering, increasing incomes. Methods of system dynamics were used to estimate volume of municipal solid waste. Simulation was performed using the AnyLogic 7 environment. Projected population and garbage generation by 2025 are presented. Simulation modeling of waste generation is performed. The model is not complex. It will be possible to add factors without changing its structure in the model. Each region suffers from difficulties related to environmental logistics of solid waste: changes in morphological composition (paper, polyethylene); getting into containers of hazardous and specific waste; minimum separate waste collection; low investment dynamism of the subjects of economic activity of ecological logistics of solid waste.

The Ministry of Environmental Protection and Natural Resources of Ukraine began in 2016 process of inventorying landfills in Ukraine. In particular, interactive map of landfills and dumps is developing. It has about 3,000 elements. Unfortunately, at the time of writing, there is no access to the developed interactive map of landfills and dumps in Ukraine, the site https://ecomapa.gov.ua/.

Important place in Ukraine in the process of waste disposal is occupied by incinerators. There were 5 incinerators in Ukraine at different times (Kyiv, Dnipro, Kharkiv, Rivne and today's occupied Sevastopol). Now only the "Energia" plant in Kyiv operates. Today, issue of chemical flue gas cleaning is acute at the enterprise. Similar problems are common to all incinerators. The products of waste combustion contain almost all elements of the periodic table, the most dangerous heavy metals, acids and sulfur dioxide. Modern technologies for flue gas cleaning can completely neutralize the negative effects of these substances [32].

In 2020, the Energia waste incineration plant in Kyiv (figure 7) began installing a chemical flue gas cleaning system. However, this is one permanent incinerator in Ukraine, which disposes only quarter of solid waste in Kyiv. This means that almost all other waste goes to landfills, and only small part of solid waste goes to waste collection points for processing.

Of course, environmental safety ensuring of incinerators and the introduction of modern methods of purification of exhausted gases significantly increase cost of construction of such plants. Such costs can be up to 50% in the structure of total cost of construction. The building cost of new plant for processing of 500 thousand tons of waste per year ranges from 300 to 400 million dollars. Concentrating such funds is extremely complicated task for the most local governments. Therefore, many of them are actively looking for investors to build incinerators [11].

Currently waste can be used to produce clean energy resources. It provides many potential benefits for sustainable development. Producing and using biogas implements closed economy idea. It brings benefits from reducing greenhouse gas emissions, improving waste management and improving resource efficiency. Energy security is one of the most pressing issues in different countries. Renewable energy became an integral part of the modern economy. Also, there was significant difference in the development in the construction of biogas plants compared with the development of other renewable energy sources. Waste is converted into product (biogas) and valuable organic fertilizer, closing the cycle from soil to harvest, to product, to waste and back to soil in the process of processing. Active government support for the development of biogas technologies is largely caused by increased greenhouse gas emissions and their devastating impact on the environment [33].

Figure 7. “Energia” Waste incineration plant, Kyiv, Ukraine.

Biogas extraction systems are installed at 26 landfills in Ukraine, and installations for production of electricity with a capacity of 30 MW are in operation according to expert estimations. The amount of utilized biogas in 2020 amounted to 64.0 million m^3 (50% methane). The amount of electricity produced in 2020 is 112.3 GWh. Example of Jenbacher generator at the landfill in Zhytomyr with a capacity of 1 MW is shown in figure 8 [34].

Figure 8. Jenbacher generator at the landfill in Zhytomyr with a capacity of 1 MW [34].

7. Measures to improve the environmental situation in Ukraine

Waste sorting by every citizen and processing of primary and secondary waste can significantly improve Ukraine’s environmental situation. It is borrowing of more developed countries experience. This turns waste into valuable resources: energy, fuel, household items and more.

Unfortunately, there is no waste management policy in Ukraine. This leads to loss of millions of tons of valuable materials each year. These wastes can be potentially put into circulation. Solid waste can contain up to 40% of valuable materials on average according to environmentalists. Potential secondary raw materials are spoiled and polluted and amount of valuable resources is reduced to 5-10% given that in Ukraine most waste is collected in "common" containers [11].

Waste sorting is one of the biggest problems for our country. People do not know how to properly separate waste and why. Meanwhile, proper disposal and sorting of waste can solve many environmental and financial problems. It is important to understand why sorting is needed in order to be motivated to separate waste for everyone. There are several good reasons why you should not put all your waste in one container and then send its contents to landfill. It is important to understand that all waste can be divided into safe and dangerous. Safe include: organic residuals, cardboard and paper, cellophane, garden waste - wood, leaves. These wastes do not poison water sources and soil, are not dangerous to humans, animals and plants when decomposed. Moreover, organic waste is beneficial because it is suitable for production of fertilizers and mulch. Hazardous waste is: batteries and accumulators, expired drugs and vaccines, paints and varnishes, car tires, polyethylene, mercury lamps, thermometers, etc. Hazardous waste is toxic and poisons land and water sources within radius of several tens of kilometers when getting to landfill with ordinary waste [4].

Also, waste sorting will significantly help to protect against harmful effects of chemicals because they will not end up in landfills. They will be disposed properly. Moreover, in every city, even a small one, there are collection points: waste paper, glass containers, scrap metal, plastic. Therefore, you can still earn a little by dividing waste and taking it to the collection point.

Waste is sent to processing plants from the collection point. They create secondary raw materials from them and then new products. This is very important because you do not need to extract resources again to create something new, but you can use existing ones [4].

We believe that one of the main indicators of the country's civilization is its attitude to problem of sorting and disposal of waste. Therefore, in our opinion, it is necessary to create conditions for the most convenient and automated approach to sorting, processing and reuse of various types of waste (figure 9).

Figure 9. Waste sorting.

The first thing to start is to form and develop environmental competence of each citizen. Ideally it is better to start with educating younger generation, instilling in children and young people the habit of sorting waste and awareness of their position as a conscious citizen of their country under auspices "I do for my clean and healthy future!".

Also, constant informing of population about environmental, economic and social consequences of the accumulation of industrial, household waste and ways to solve this problem is profitable. Thus, informing population (educational activities) is carried out by several groups of methods: through poster agitation, social advertising, conferences and events, environmental tours and more. At the same time, one of the main tasks for solving the issue of waste management is to encourage population to sort waste using financial levers and social advertising in the media.

At the state level measures should also be taken to encourage producers of polyethylene and polypropylene packaging materials to produce biodegradable products and producers of plastics in primary forms to produce biopolymers that are compostable and biodegradable as raw materials for biodegradable products. The raw materials for production of biopolymers are such natural substitutes for plastic as starch (potato, corn, etc.), bran of cereals (wheat, oats, corn, etc.), algae extracts, grain waste (straw, corn leaves). Limited use of natural raw materials for biopolymers production is due to their high cost compared to PET raw materials [35].

Today, Ukraine needs to revise principles of recycling at existing enterprises, as companies that use waste as an energy source cause great damage to the environment. However, it is necessary to spend a lot of money to make these businesses environmentally friendly.

8. Conclusions

Ukraine is one of the countries with the largest absolute volumes of waste generation and accumulation. According to the National Institute for Strategic Studies in Ukraine, about 10 tons of waste per capita is generated annually against 5.5 tons - 6 tons of waste per capita in the European Union.

Situation with landfills in Ukraine is uncontrolled. It is evidenced by illegal landfills. They constantly deteriorate environmental situation in Ukraine by their harmful chemical emissions. And there is only one working waste incineration plant "Energia" in Ukraine. It can not solve the problem of the whole country.

Landfills will remain the main way to accumulate solid waste for a long time. It is possible to reduce impact of various household wastes on the environment through:

- improvement of existing regulations and their implementation;
- forecasting of SDW amount and study of morphological composition due to changes in environmental and social factors that affect the morphological composition of waste is important;
- mathematical modeling of pollutants distribution in the components of the environment which are formed on the territory of landfills;
- control and register of landfills;
- relocation of landfills;
- sorting of solid household waste;
- construction of waste processing and incineration plants;
- informing of population about environmental, economic and social consequences of accumulation of industrial and household waste and ways to solve this problem;
- revision of waste recycling principles at existing enterprises;
- implementation of measures that will encourage producers of polyethylene and polypropylene packaging materials to produce biodegradable products, and producers of plastics in primary forms - to produce biopolymers that compost and biodegradable, etc;
- introduction of environmentally safe technologies of waste processing - biogas extraction systems and installations for electricity production;

- information policy and development of educational programs aimed at raising of public awareness of waste management.

Thus, uncontrolled dumping of waste into the environment is no longer acceptable in modern conditions. Even controlled landfilling and incineration of organic waste are no longer considered as optimal methods. Environmental standards are becoming stricter and aimed at recovering energy and organic residues.

It should be understood that if humanity does not start to improve environmental situation now then in a couple of decades we will get poisonous (unfit for drinking) water, land that can not produce organic fruit. These consequences will have very negative impact on life and health. In further research, attention should be paid to waste disposal in Ukraine and abroad.

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Human-centered management in polyergatic information systems. Multi-criteria distribution of functions between operators

To cite this article: E A Lavrov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012020

Human-centered management in polyergatic information systems. Multi-criteria distribution of functions between operators

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Abstract. The article considers the problem of human factor in complex polyergatic systems with a flow of applications for functions (problem solving) arising at random moments of time. The structure of a decision support system for the operator-manager, including subsystems of monitoring, forecasting and decision- making, is justified. The system of criteria relevant to solving the tasks of functions distribution was substantiated and its multi-criteria nature was shown. The technology of multi-criteria evaluation and choice of alternatives based on the methodology of hierarchical system analysis of problems and the method of analysis of hierarchies Thomas Saaty has been proposed. The decision-making system, which has been tested in the operation of control systems of various complex technical and production objects, has been implemented. The proposed method differs from the known approaches in that this method is aimed at prompt decision-making, as well as in that it uses a multi-criteria approach and both pragmatic and ergonomic criteria are used as criteria.

1. Introduction

The Fourth Industrial Revolution allowed the expansion of the widespread introduction of robots and automation [1–3] . The efficiency of agricultural and industrial production has significantly increased [4–6], educational technologies and means of access to information resources have changed dramatically [7–9]. However, unfortunately, in recent years the problem of the so-called "human factor" [10–12] has become increasingly apparent. This is associated not only with expectations of catastrophic consequences of the displacement of humans by robots and artificial intelligence, but also with the increase in tension of operators' work, stress, increase in the number of errors leading to catastrophic consequences, increase in cases of injuries and even deaths of people [13–15].

2. Statement of the task

Researchers of the "human factor" problems note a fundamental change [16–19] in the role of the human operator in automated systems (figure 1).

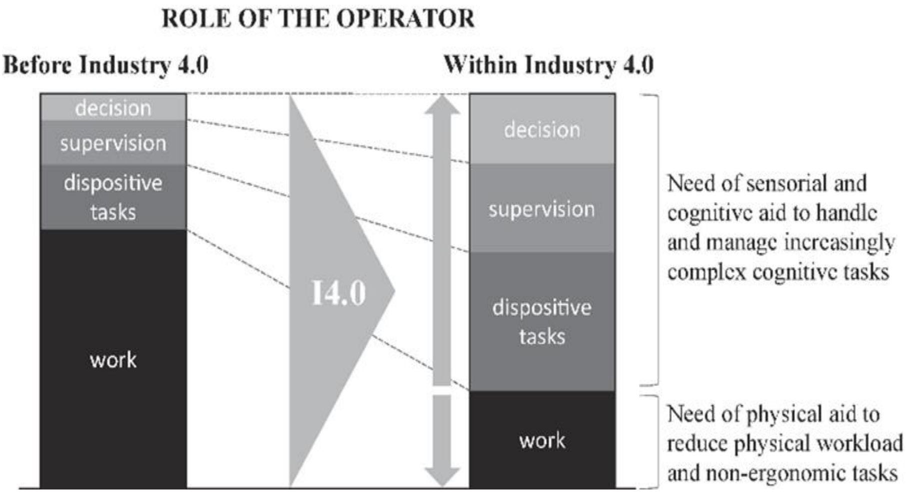

Figure 1. Changing the role of the human operator [18, 19].

The share of ergatic systems with the number of simultaneously working operators exceeding 1 (one operator) is increasing. Such systems are called "polyergatic" [20–24]. Executive operators work, as a rule, under the guidance of operator-managers and actively interact with each other. Operators work in a single information space under conditions of a random flow of tasks that need to be urgently solved [22–24], while for critical systems, the requirements for reliability (error-free and timely performance of functions) are significantly increasing [19, 23, 24]. In these circumstances, there is an increasing need to support the decision-making of operator-managers on the optimal operational choice of an operator (one or more), which is advisable to entrust the execution of the incoming request [18–21]. Methods for solving such problems in recent years have been proposed in a number of papers [21–26]. However, a common methodological drawback of these studies is orientation on one-criteria optimization (in most cases a problem of maximization of error-free execution probability is set) [23, 24, 27, 28], which does not allow to fully take into account the so-called "human factor" and use not only pragmatic criteria but also purely ergonomic criteria [29].

Statement of the problem. In connection with the described above problems we set a problem to develop an approach to rational distribution of functions with the use of both pragmatic and organizational and ergonomic criteria of optimization.

3. Results

The operator-manager should assign the execution of the request to the operator who will provide the maximum probability of error-free and timely execution, while taking into account many parameters and characteristics of the operator himself, as well as the conditions of his activity (characteristics of technical and software tools, exposure to harmful environmental factors, tensions, etc.) – figure 2. [28].

3.1. Analysis of indicators to be considered in solving the problem

The analysis of the problem situations of the activity of the operator-manager revealed two groups of indicators, which should be used to solve the problem of allocation of functions (see examples – table 1):

- Pragmatic (β, P, and economic gain (loss)).
- Characterizing operators' performance and working conditions (Ω_1-Ω_6).

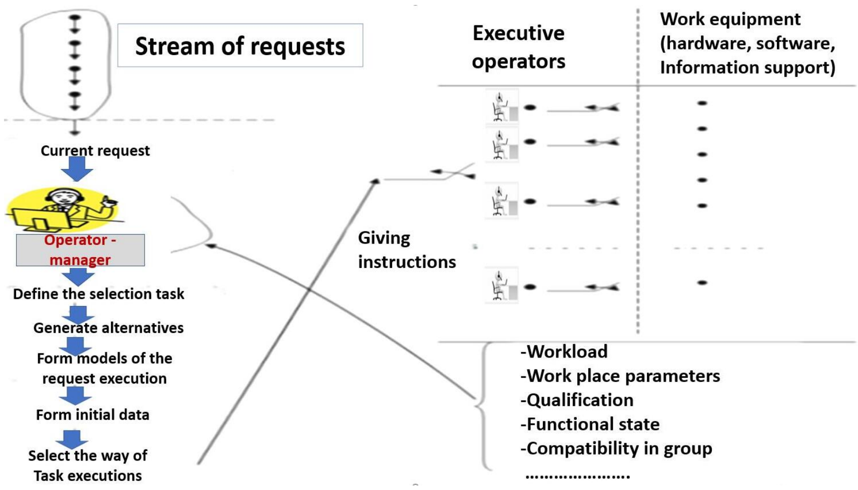

Figure 2. Demonstration of the problem situation of the operator-manager [28].

Table 1. Examples of indicators characterizing the quality of the option of fixing the function (fragment).

Indicator	**Ability to use as a criterion**	**Ability to use to form a restriction**
β – probability of error-free execution	In most cases (maximization)	+
P – likelihood of timely execution	In most cases (maximization)	+
Ω_1 – category of the current functional state (working capacity) of the operator (from 1 to 6)	Expedient (minimization)	+
Ω_2 – category of the predicted functional state (working capacity) of the operator after the function (from 1 to 6)	Expedient (minimization)	+
Ω_3 – severity category of working conditions (current) of the operator (from 1 to 6)	Expedient (minimization)	+
Ω_4 – category of the predicted severity of the operator's working conditions after performing the function (from 1 to 6)	Expedient (minimization)	+
Ω_5 – queue of requests for execution (current)	Expedient (minimization)	+
Ω_6 – queue of requests for execution (forecast at the time of completion of the request)	Expedient (minimization)	+

3.2. The task of selecting an operator to execute a request

Obviously, in the general case the problem is multi-criteria in nature and for the example considered (table 1) can be represented as follows (in the real activity of managers the number of target functions can be larger, some indicators can be used to form constraints):

$$\begin{cases} \beta(X) \to max; \\ P(X) \to max; \\ \Omega_1(X) \to min; \\ \Omega_2(X) \to min; \\ \Omega_3(X) \to min; \\ \Omega_4(X) \to min; \\ \Omega_5(X) \to min; \\ \Omega_6(X) \to min; \\ X \in X_0. \end{cases}$$

Here X is the vector characterizing the fixation of functions, X_0 is the set of admissible variants of the fixation of functions.

3.3. Developing principles for solving the problem

We have analyzed the decision-making process of operators-managers of complex automated control systems of critical type and identified the main requirements for a decision support system. Basic requirements (principles):

- Focusing on objective quantitative indicators.
- Monitoring of the current state of operators and the environment.
- Using prediction models of the environment, ergonomics, error-free and timely implementation of functions.
- Using activity models (such as "functional network" [30–33]) to predict the reliability performance and execution time of function.
- Use of ergonomic databases (statistical data bases of operators' errors and operations execution time with all influencing factors taken into account) to form the initial data about reliability and execution time of all functional elements of functional network.
- Enabling the operator-manager to formalize ideas about the importance of criteria in a particular problem situation.
- Providing a possibility for the operator-manager to formalize the degrees of "desirability" of the values of local indicators.
- Providing a possibility to form the integral quality assessments of function distribution options.
- Enabling convenient on-line decision-making with visualization of the results.

3.4. Development of the conceptual structure of the decision support system for the allocation of functions

Based on the developed principles and requirements for the decision support system, we can propose the following system structure, including a subsystem of monitoring the current states of operators and the working environment, a subsystem of forecasting the state of operators and the environment after the implementation of activities on the application, as well as a subsystem of forecasting the results of activities taking into account the individual characteristics of operators, their functional state and work environment parameters (figure 3) .

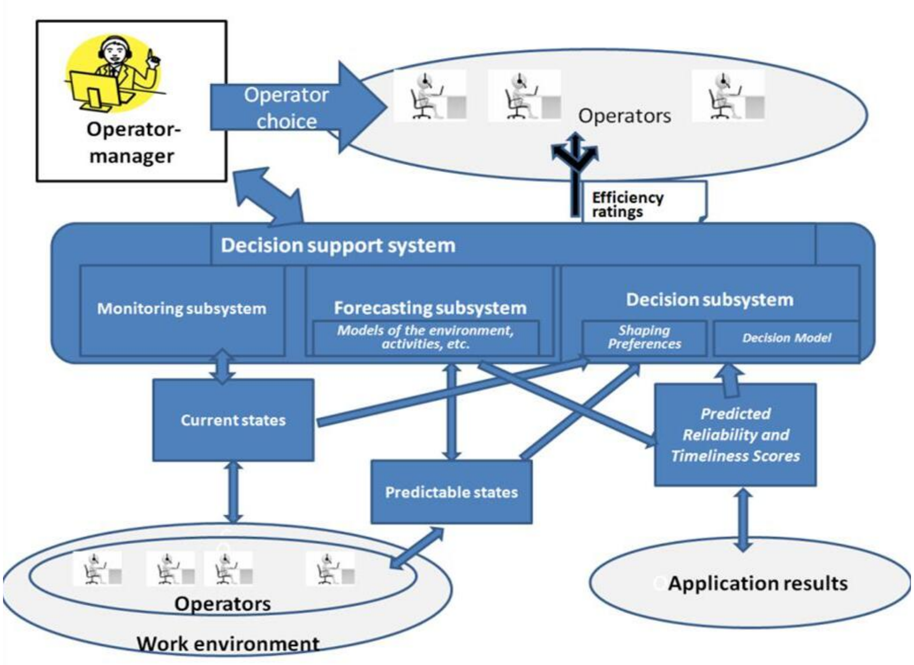

Figure 3. An enlargeds chematic diagram of the decision support system for the operator-manager.

3.5. Models for monitoring and forecasting

To monitor the functional state of operators we propose to use the method of keyboard handwriting analysis, consisting in the analysis of key press duration when entering the text of key phrases and solving the classification problem using neural networks, as well as using special manipulators of "mouse" type with built-in sensors for evaluation of cardiac system activity. We evaluate the difficulty of work according to the system of methods [30, 34] of complex accounting of all workplace parameters (physical, psycho-emotional, activity tension) developed by us. We use a 6-point scale for evaluating working conditions. To predict the error-freeness and implementation time of the activity algorithm, we use the method of describing this activity in the form of a functioning network (SF) and application of a library of computational dependencies for typical combinations of blocks [30–32]. The software package [23, 24, 27] developed by us allows to carry out such estimation automatically. An example of reducing the dimensionality of SF necessary to carry out calculations is shown in (figure 4).

3.6. Model for choosing the option of fixing requests

Based on the above substantive analysis of the problem, we can conclude that it is reasonable to apply the method of hierarchy analysis [35–40] for multicriteria evaluation of alternative variants of functions distribution. As applied to the task of ergonomic justification of the choice of variants of execution of applications, let us define the main stages of the solution of the problem:

- Structuring the problem in the form of a hierarchical structure with several levels: goals – criteria – alternatives (see the example for 3 operators in figure 5).
- Pairwise comparison of elements of each level (alternatives for each criterion and importance of criteria of quality of function distribution).

  When comparing the criteria, usually the decision support system asks the operator-head

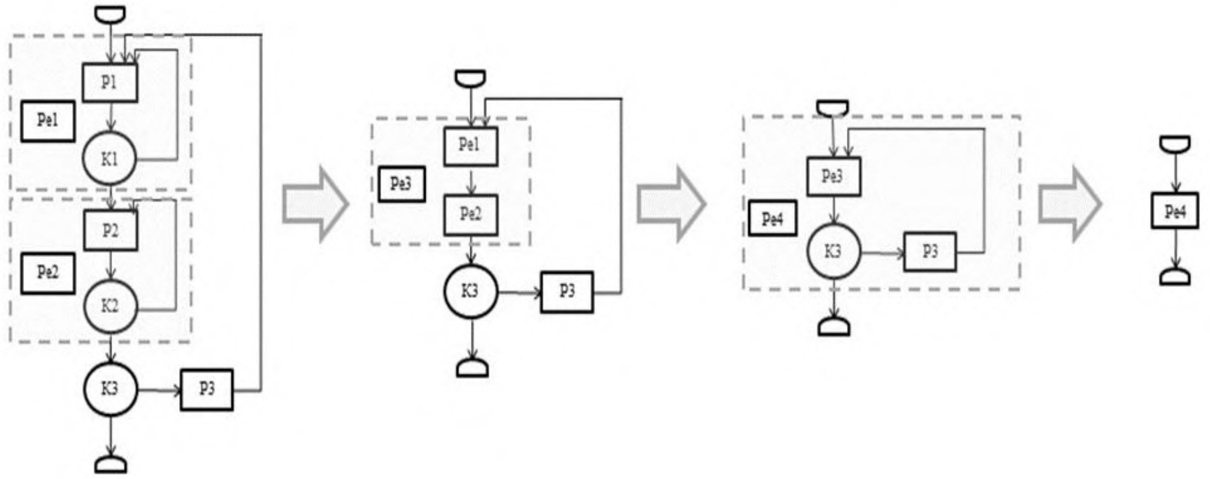

Figure 4. The principle of automatic reduction of the dimensionality of SF for the calculations of error-free and time of realization of activities (the identified typical blocks are replaced by an equivalent work operation with equivalent characteristics). The notations and calculation formulas are according to the generalized structural method of Anatoly Gubinsky [30–32].

which of the criteria is more important; when comparing the alternatives in relation to the criteria – which of the alternatives is more preferable. If element E_1 dominates over element E_2, the matrix cell corresponding to row E_1 and column E_2 is filled with an integer, and the cell corresponding to row E_2 and column E_1 is filled with the inverse of it. To establish the relative importance of the elements in the hierarchy, a scale of relationships is used. This scale allows the operator-manager to assign certain numbers to degrees of preference (table 2). Examples of evaluation of criteria importance under different approaches to decision making ("pragmatic" and "ergonomic") are shown in table 3 and table 4.

- Quantitative Evaluation of the Integral Indicator of Quality of Alternatives. Selection of the best alternative. (Examples of visualization of the results are shown in figure 6.)

To establish the relative importance of the elements in the hierarchy, a scale of relationships is used. This scale allows the operator-manager to assign certain numbers to degrees of preference (table 2).

Table 2. Examples of indicators characterizing the quality of the option of fixing the function.

Significance	Definition
1	Equal importance
3	Some predominance of the importance of one action over the other
5	Significant or strong relevance
7	Obvious or very strong significance
9	Absolute significance
2,4,6,8	Intermediate values between two adjacent judgments
Inverse values	$a_{ij} = 1/a_{ji}$

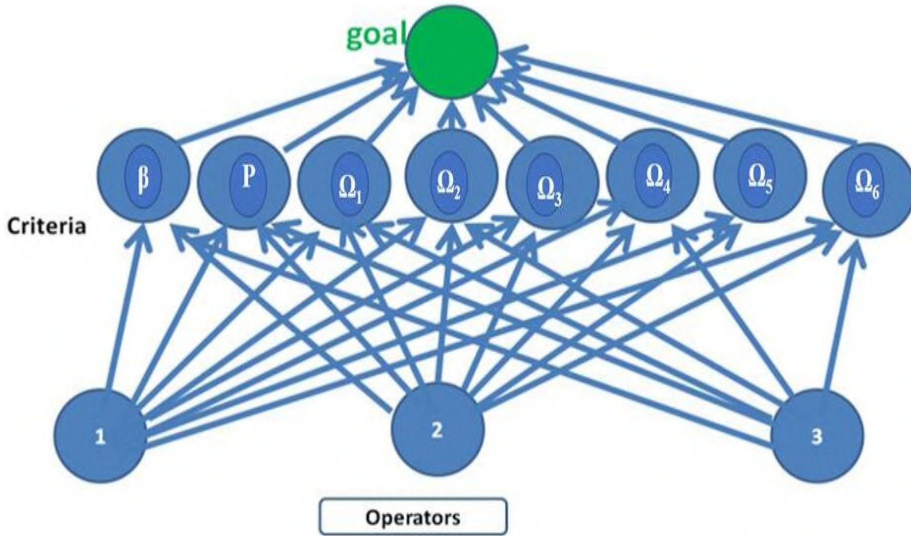

Figure 5. Hierarchical structure of the function allocation problem (for 3 operators – $Q_1 - Q_3$ and the system of criteria given in table 1).

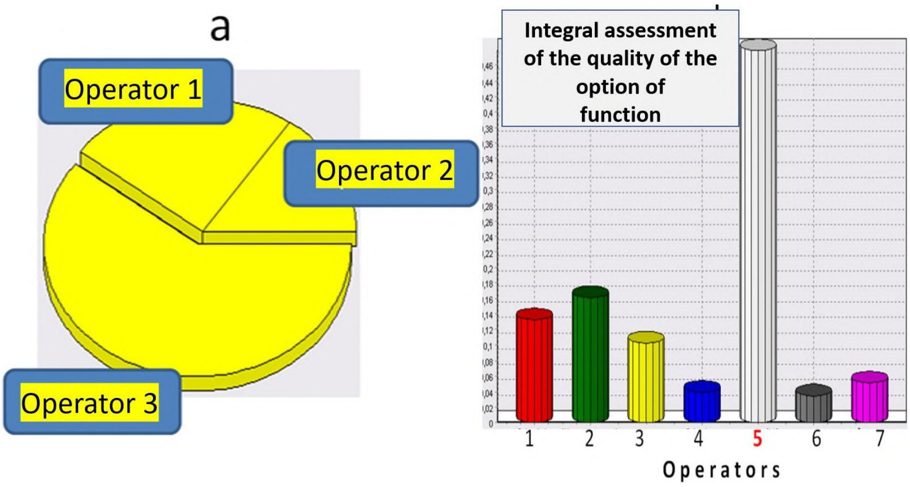

Figure 6. Examples of visualization of the results of solving the problem to fix operators in the control system of the main gas pipeline: a – 3 operators, b – 7 operators (prepared by the student Victor Koshara).

4. Testing

The results are used in pipeline control systems, e-learning and in banking and process control systems in mechanical engineering [28, 41–44].

5. Conclusion

In complex management systems, a single information space is usually occupied by an entire group of operators. In the context of a continuous flow of task orders, the operator-manager must make a quick decision about assigning the task to a specific operator and executor. Both pragmatic criteria and criteria related to ergonomics and the functional states of the operators are important in this process. Under these conditions, a decision can only be made if the

Table 3. Example of evaluation of comparative importance of criteria (Extreme approach "orientation on pragmatic indicators") with equal importance of indicators within the group.

	β	P	Ω_1	Ω_2	Ω_3	Ω_4	Ω_5	Ω_6
β	1	1	$^1/_9$	$^1/_9$	$^1/_9$	$^1/_9$	$^1/_9$	$^1/_9$
P	1	1	$^1/_9$	$^1/_9$	$^1/_9$	$^1/_9$	$^1/_9$	$^1/_9$
Ω_1	9	9	1	1	1	1	1	1
Ω_2	9	9	1	1	1	1	1	1
Ω_3	9	9	1	1	1	1	1	1
Ω_4	9	9	1	1	1	1	1	1
Ω_5	9	9	1	1	1	1	1	1
Ω_6	9	9	1	1	1	1	1	1

Table 4. Example of evaluation of comparative importance of criteria (Extreme approach "orientation on indicators characterizing working conditions and ergonomics" with equal importance of indicators within the group.

	β	P	Ω_1	Ω_2	Ω_3	Ω_4	Ω_5	Ω_6
β	1	1	9	9	9	9	9	9
P	1	1	9	9	9	9	9	9
Ω_1	$^1/_9$	$^1/_9$	1	1	1	1	1	1
Ω_2	$^1/_9$	$^1/_9$	1	1	1	1	1	1
Ω_3	$^1/_9$	$^1/_9$	1	1	1	1	1	1
Ω_4	$^1/_9$	$^1/_9$	1	1	1	1	1	1
Ω_5	$^1/_9$	$^1/_9$	1	1	1	1	1	1
Ω_6	$^1/_9$	$^1/_9$	1	1	1	1	1	1

manager is provided with a special decision-support system, including a monitoring, forecasting and decision-making system. The evaluation of alternative options is conveniently carried out on the basis of a systematic and hierarchical analysis of the problem and the use of the methodology of the hierarchy analysis method. The scientific novelty consists in the fact that, for the first time, the principles of decision-making support for the operator-manager have been substantiated and, in contrast to the existing single-criteria problems, the problem of multi-criteria evaluation of alternatives has been set and solved. The novelty of the results also lies in the fact that the method assumes objective quantitative indicators (including the forecast of error-free and timely execution, obtained on the basis of a model called "functional network"). Practical relevance: The method is materialized in the form of a decision-making support system that is convenient for managers of complex systems of managing critical objects.

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IOP Conference Series: Earth and Environmental Science

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To cite this article: T M Derkach and Ya V Shuhailo 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012021

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012021 doi:10.1088/1755-1315/1049/1/012021

Adapting engineering education to challenges of sustainable development

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Abstract. Textile and clothing industries generate a lot of waste at both production stages and in the process of wearing garments. Every inhabitant of developed countries annually wastes up to 30 kg of used but still suitable clothes, which decompose very slowly in natural conditions. The broadest possible implementation of textile waste processing technologies, such as downcycling and upcycling, is the key to ensuring the successful operation of the textile and clothing industries under conditions of sustainable development. The paper goal is to determine factors controlling students' upcycling behaviour to strengthen the educational components and meet sustainable development challenges for the garment industry. Based on interpersonal and planned behaviour models, 93 students of 1-6 years majoring in clothing technology, design and sectoral professional education were surveyed to understand their upcycling behaviour. The surveyed students are divided into similar-sized groups of optimists (practice upcycling more than once every three months) and pessimists (less than once a year). Upcycling behaviour was shown to correlate with intentions, which are, in turn, affected by social factors, attitude, and perceived behaviour control. Perceived habits and facilitating conditions have a relatively small impact. There is almost no difference between students of different years of study and specialities. Students' understanding of the benefits of upcycling is shallow and does not change with training years. Amid a highly-positive attitude towards upcycling, a low level of knowledge of the benefits and lack of progress with years indicate existing problems in developing upcycling behaviour in the learning process.

1. Introduction

In today's world economic system, two competing sectors coexist. They are linear economy and circular economy [1,2]. Since the Industrial Revolution, the linear economy model has dominated for centuries as the only available business model using available technologies. This model aimed at increasing industrial production, employment, urban development, living standards, profits and demand for all goods. Its main stages were the extraction of resources by industry (usually in unlimited quantities), production and distribution. Consumers used the products for some time (during the product's life) and then disposed of as waste in landfills or incineration. This model has a one-dimensional linear dimension, where the input of raw materials (stocks of which fall over time), and the output - waste, the amount of which is growing.

The concept of circular economy assumes and is based on the idea of the ability of the economic system to recover, which allows implementing the concept of sustainable development. The circular economy converts end-of-life goods into resources for other goods [1]. This transformation closes the so-called loops in industrial ecosystems and minimises waste. The main thing is that the economic logic in such a system has changed. Sufficiency replaces production. The new reasoning calls for the reuse of all that is possible, for recycling what cannot be reused, repairing what is broken, and restoring what cannot be repaired.

The implementation of the circular economy concept applies to virtually all areas of economic activity. Absolute priorities are energy-saving [3, 4] with the simultaneous development of renewable energy [5, 6]. The next set of challenges concerns the economic use of resources such as water [7, 8], forests and plants as a source of medicines and other substances [9, 10], the comprehensive implementation of green chemistry technologies [11, 12]. Last but not least, it is to solve the problems of utilisation and processing of waste from various industries and reduce industrial carbon emissions [13, 14]. A study of seven European countries showed that the transition to a circular economy would reduce greenhouse gas emissions in each country by 70% and increase its labour force by about 4%. The lowest possible carbon consumption will characterise the economies of these countries [1].

Strange as it may seem, the global fashion industry annually produces 4% of the world's waste [15]. Because clothing is a very symbolic product, often a sign of high social status, consumers want to buy clothing as often as possible [16]. In turn, the industry offers more and more inexpensive clothes and supports the variability of fashion trends. As a result, in developed countries, each consumer annually throws away up to 30 kg of used textiles [17]. Old clothes are more often thrown away not because they are worn out, but because they are outdated, and old clothes are getting faster and faster.

Modern materials from which clothes are made cannot decompose appropriately in the environment and eventually pollute the water. In addition, the textile and garment industries affect carbon emissions [18, 19]. Global greenhouse gas (GHG) emissions continue to rise due to high consumption. This fact becomes evident when comparing the dynamics of territorial emissions (i.e. industrial emissions in a given area) and consumer emissions. In the latter case, emissions from local production and goods and services imported into the area are considered. Consumer emissions are about twice as much as territorial emissions in industrialised countries. For example, the UK's territorial emissions between 1990 and 2009 showed a decrease of 27%, while GHG emissions based on UK consumption showed a 20% increase. Thus, the rapid increase in consumption, in this case, nullifies efforts to reduce carbon emissions from local industry.

As already mentioned, waste from the textile industry has a significant impact on waste generation. Therefore, changing consumer behaviour can significantly reduce waste and emissions across national borders. In turn, the textile industry has considerable potential for reducing waste and emissions in the case of transition to the principles of sustainable development and implementation of the circular economy model [18, 19]. Circular models and relevant practices help reduce the environmental impact of textile production, use and disposal. The resulting products are characterised by a high potential for energy and non-renewable resources savings. Eco-fashion textiles meet ecological and quality criteria suitable for processing and biological decomposition of the material. Thus, it reduces the volume of chemicals released into the ecosystem.

People of all ages and qualifications are central to circular economy models. Insufficient knowledge or fear of the unknown significantly slows down the spread of circular economics [1]. Therefore, it is necessary to promote the formation of new traits in human behaviour, such as, for example, the purchase of environmentally friendly products, processing, use less plastic packaging, energy-saving [18, 19]. Waste disposal can significantly reduce waste, energy consumption, and greenhouse gas emissions.

Widespread circular economy ideas are impossible without incorporating them into academic and professional communities. The intellectual forces of nations are scholars' knowledge, and expertise concentrated in universities [20]. In addition, the worldview of future generations is formed in universities. Therefore, to achieve the goals of sustainable development, it is necessary to bring the content of educational programs to the requirements of professional activity in the conditions of sustainable development [21–23].

Technologies studied in training a future engineer usually relate to specific stages of the product's so-called "life cycle". This technological "life cycle" starts with the stage of product design and engineering. This stage becomes crucial to ensure the sustainability of production. At this stage, the possibility of recycling the product after its use by the consumer is established.

Other technological stages that should be noted are cutting, product manufacturing, transferring the developed technology to production, product sales and stage of its use. The need for time is to design the possibility of reusing the product or adapting the product to another purpose, i.e. different ways of recycling. However, this stage is still often disregarded in the study of technology.

The need or order for specialists familiar with modern recycling technologies comes from employers. There is already a contradiction between the needs of employers and the existing competencies of graduates. It encourages changing the content of engineering training for future professionals.

In production, the transition is made from optimising individual stages of technology to the full understanding and optimisation of the technological chain throughout the product's life cycle. Accordingly, specialists who understand this and can work at all stages of the life cycle and predict the consequences of technological activities are in need. Today, there is a lack of such specialists, as no targeted training would take into account modern requirements. There are no specialists - there is no production, so modern technologies cannot be implemented.

Students who study in the training programs of engineering and pedagogical specialists in the clothing industry and specialise in textile technology or textile design must master the following competencies:

a) know the methods of effective organisation of work in compliance with environmental safety requirements;

b) be able to design and manufacture modern clothing for various purposes;

c) be able to organise the educational process in the relevant disciplines in sectoral educational institutions,

d) know the methods of optimising materials and reducing industrial waste.

All these knowledge and skills are formulated following the requirements of the linear economy. There is a lack of skills needed to succeed in the circular economy. In particular, there are no requirements for processing textile waste and producing textile products using secondary raw materials. Today, the critical competencies for working in the context of sustainable development of the textile and clothing industry have not yet been formulated.

A whole layer of knowledge about existing and promising approaches and technologies aimed at the optimal use of waste is ignored at all stages of production, utilisation and waste disposal. First of all, recycling and upcycling technologies should be mentioned. At the same time, there is a steady demand from employers for professionals with these technologies [24, 25]. The article aims to study the existing problems that hinder the formation of the necessary competencies of future technologists and designers of the clothing industry. Formulating ways to overcome these problems will contribute to the acquisition of knowledge and skills in the disposal of waste from the fashion industry and work in the business environment of the circular economy model.

2. Experimental

2.1. Survey methodology

A survey of students of the Faculties of Fashion Industry and Design of the Kyiv National University of Technology and Design (KNUTD) was conducted to determine personal motives and various aspects of attitudes towards processing wastes and raw materials. A total of 93 students in years 1-6 of bachelor's and master's degrees took part in the study.

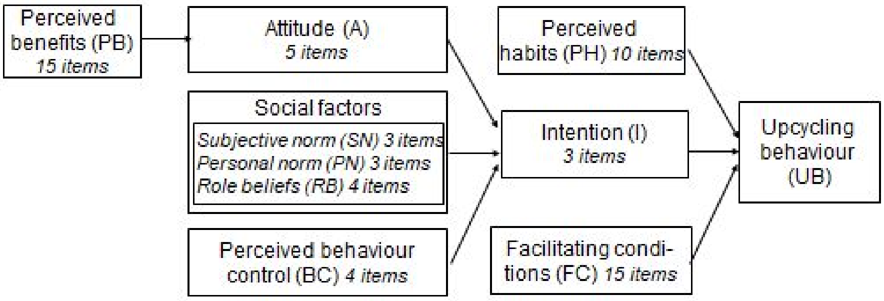

Figure 1. Combined model [28–30] of the Theory of Interpersonal Behaviour and the Theory of Planned Behaviour.

The materials used in the survey were developed according to the principles of the Theory of Interpersonal Behavior [26] and the Theory of Planned Behavior [27]. The combined model, which contains elements of both of the above, was developed in [28–30]. The combined model was used to study the behaviour of people in the UK who are actively involved in upcycling. According to [26, 27], several primary factors have been identified that should shape a person's attitude to waste recycling. These factors are indicated in the block diagram in figure 1.

The influence of each factor is estimated based on the answer to the different number of questions. The numbers of items are illustrated in figure 1. The questionnaire contained 62 questions on nine individual influencing factors in the scheme. A separate question was asked about personal experience in the scheme's upcycling frequency shown as upcycling behaviour (UB). The content of individual questions, if necessary, will be shown later in the text. The principles of the combined model and questionnaire used are described in more detail in [31, 32].

Eight of the nine factors have a direct impact either directly on the frequency of upcycling behaviour or intentions regarding upcycling (figure 1). Only the perceived benefits (PB) factor directly influences the attitude to upcycle (factor A) and does not directly influence upcycling behaviour (UB). However, this factor is shown in the scheme. Understanding the benefits helps to improve the argumentation of upcycling practices and can seriously affect attitudes toward upcycling.

A 7-point Likert scale [33] was used to quantify the responses to the seven factors in figure 1. A 7-point Likert scale ranges from one extreme to another, like "extremely likely" to "not at all likely." For six factors, the ranking included the following options: strongly disagree (1 point), disagree (2 points), somewhat disagree (3 points), either agree or disagree, i.e. not determined (4 points), slightly agree (5 points), agree (6 points), and strongly agree (7 points). For each of the five questions for the seventh factor (Attitude), the range from strongly disagree (1 point) to strongly agree (7 points) was substituted by other options, for example, unpleasant (1 point) - pleasant (7 points). As you can see, the scale remained unchanged.

The 7-point scale is the most accurate scale among other Likert scales; it is easy to use and better reflects the respondent's precise assessment. At the same time, as a shortcoming, it is known that previous questions may influence respondents' answers. According to the model in figure 1, certain factors influence respondents' upcycling behaviour (UB), which is assessed by the frequency of application of upcycling techniques. Respondents chose one of eight available answers that best describes their experience: never use upcycling (1 point), less than once a year (2 points), once a year (3 points), once every six months (4 points), once a quarter (5 points), once a month (6 points), once a month week (7 points), and more than once a week (8 points).

2.2. Statistical treatment
Statistical analysis of the results was performed using the statistical software package IBM SPSS version 21. Descriptive statistics were applied for the results' general descriptions, which calculate the mean and median values, standard deviations and standard errors (SE). The

significance threshold in all tests was $p < 0.05$.

Correlation analysis methods analysed the presence or absence of correlations between individual factors. As virtually all indicators are rank variables, Spearman's rank correlation coefficients were calculated in the correlation analysis.

Table 1. Cronbach's Alpha to test the reliability of a scale.

Factors	Number of items	Cronbach's Alpha
Perceived benefits (PB)	15	0.957
Attitude (A)	5	0.922
Subjective norm (SN)	3	0.643
Personal norm (PN)	3	0.814
Role beliefs (RB)	4	0.837
Social factors (all together)	10	0.863
Perceived behaviour control (BC)	4	0.891
Intention (I)	3	0.928
Perceived facilitating conditions (FC)	15	0.904
Perceived habits (PH)	10	0.813

As a preliminary step, the consistency of the survey questions and, accordingly, the reliability of the survey results were investigated. The Cronbach's Alpha test was used for this purpose. Cronbach's alpha measures internal consistency between elements in a group. The consistency between separate questions concerning the same factor is investigated in our case. Cronbach's alpha is a coefficient of reliability (or consistency) that indicates how closely a set of elements is linked as a group. The results are shown in table 1. For the factor of subjective norms (SN), Cronbach's Alpha value is close to 0.64. For all other factors, Cronbach's Alpha exceeds the value of 0.8. Acceptable internal consistency is suggested for the scale if Cronbach's Alpha varies between 0.6 and 0.79. A Cronbach's Alpha value above 0.8 indicates good reliability.

Fitting experimental distribution curves using nonlinear curves with the fitting parameters, function expression, constraints and determination coefficients R^2 was performed using the software package OriginLab, version 8.

3. Results

3.1. Descriptive statistics

Figure 2 gives the general impression of the obtained results. It illustrates the average scores for each factor. They are obtained by summing all the answers to all the questions and calculating the arithmetic mean. Abbreviated factor names were first described in figure 1. The 4-point ring in figure 2 corresponds to the boundary between negative and positive answers. The shaded area contains negative answers, i.e. those cases when the respondents' answers are dominated by disagreement (average score in the range from 1 to 4 points) with the given statement. The unshaded area with an interval of 4 to 7 points corresponds to positive answers.

As we can see, only three factors, namely A, I and BC, confidently confirm the positive attitude of the respondents. In the case of factor A, the average score of the respondents roughly corresponds to the answer "agree" or 6.05 ± 0.26 points. For the I factor, the average score is close to "somewhat agree" or 4.89 ± 0.35 points. For the BC factor, the average answer is intermediate, namely 5.59 ± 0.30 points.

For the other five factors, namely SN, PN, RB, PH, FC, the average scores are slightly above zero (4 points) and range from 4.17 to 4.54. According to the respondents, the influence of these factors does not reach even the weakest positive assessment of "somewhat agree". For another

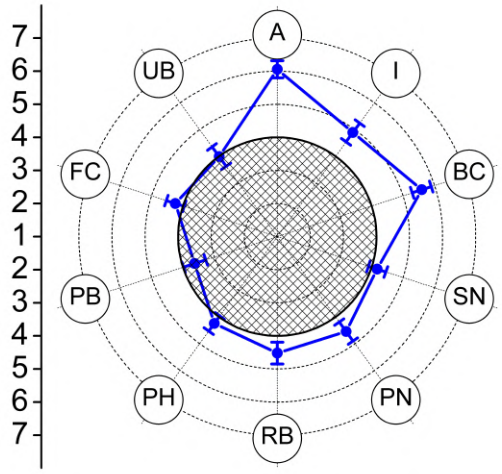

Figure 2. Average values of all factors in points. The shaded area, limited by a 4-points circle, separates disagreement (shaded) and agreement (unmarked) areas in answers.

factor, RV, the average response of the respondents was between uncertainty (4 points) and weak disagreement with the proposed statements. The average score for PB is 3.63 ± 0.35.

For UB, the average value was 3.99 ± 0.36. However, unlike other factors, a score of 4 does not mean a zero mark but corresponds to the frequency of upcycling once every six months. The obtained average value does not allow to draw any conclusions about the most common practice of upcycling. It does not contain information on the distribution of the number of respondents according to the frequency of upcycling. Accordingly, the average frequency can reflect the actual situation and be a superposition of indicators of several respondents who have entirely different attitudes to the frequency of upcycling. This issue will be discussed in detail in the following sections.

3.2. Correlations between influencing factors

As mentioned above, Spearman's Rank Order Correlation was calculated to study correlations between rank values. According to the scheme, the influence of various factors on upcycling behaviour (UB) is ultimately reduced to the impact of factors I, PH and FC (figure 1). Thus, it is necessary to investigate first the existing correlations between, on the one hand, the listed factors and, on the other hand, UB. The calculation results are given in table 2.

The highest level of correlation exists between all items of the I factor and HC. The correlation shows a very high significance level ($p < 0.01$) and can be attributed to the average strength of correlations when the coefficients vary r_S between 0.387 and 0.454.

The opposite picture is observed in the case of facilitating conditions (FC) when significant correlations are completely absent. In other words, the presence or absence of FC does not affect the upcycling behaviour of respondents.

The correlations between perceived habits (PH) and UB is not evident. On the one hand, no correlation is observed between the averages of PH and UB. On the other hand, there is a correlation between 9 out of 10 individual items of PH and UB. The strength of such correlations is relatively weak. The value of significant r_S ranges between 0.212 and 0.361. The significance level in different cases corresponds to the probabilities of 95% and 99%. The most probable reason for the lack of correlation between average PH and UB is the unrepresentative nature of UB values. As already mentioned, the nature of UB distribution by the number of respondents is far from normal. Accordingly, the average value poorly characterises the available sample. However, correlations between individual indicators will need to be considered in analysing the results obtained.

According to the above, the most critical factor is the factor of intentions. The I factor, in turn, is formed under the influence of factors A and BC and three social factors (figure 1). The

Table 2. Spearman's Rank Order Correlations between items of intension (I), perceived habits (PH), facilitating conditions (FC) against upcycling behaviour (UB).

Correlation between factors	I - UB	PH - UB	FC - UB
Number of significant correlations r_S among available item pairs	3 out of 3	9 out of 10	0 out of 15
The values of r_S between average factors' ranks	0.447**	-0.044	-0.071
Range of significant individual r_S	0.387**–0.454**	0.212*–0.361**	-
Range of all individual r_S	0.387**–0.454**	0.169–0.361**	-0.158–0.17
The items with max r_S	I1	PH7	-

** Correlation is significant at the 0.01 level (2-sided)
* Correlation is significant at the 0.05 level (2-sided)

results of calculations of correlation coefficients between individual and average values are given in table 3.

According to the results, significant correlations are present in all five pairs of factors. Moreover, the significance level of correlations between the average values in all cases exceeds 99%. The strength of the correlation consistently exceeds the value of $r_S > 0.4$. The average correlation coefficient for I and BC reaches 0.661. Thus, the factor of intention formation depends on all five factors, as shown in figure 1. At first glance, this dependence is slightly higher for factors A and BC and somewhat lower for social factors. However, a more detailed analysis is needed to clarify the role of individual factors, including individual component effects.

3.3. Bi-modal distribution for upcycling behaviour
Surveys indicate the presence of two modes in the behaviour of respondents regarding the frequency of use of upcycling and recycling techniques (figure 3).

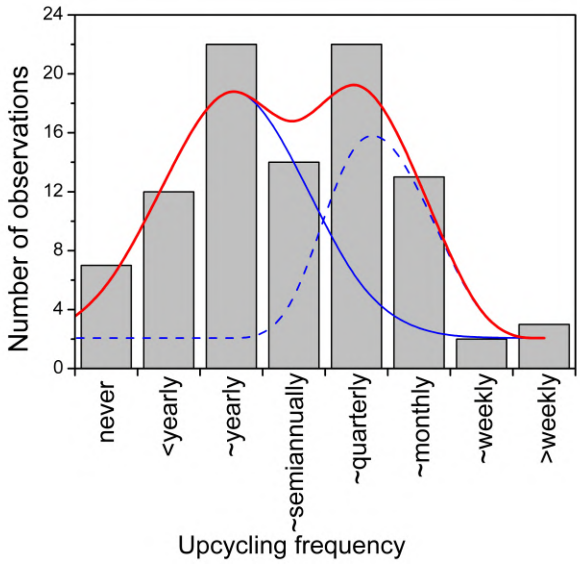

Figure 3. The number of observations as a function of the frequency of upcycling.

These modes divided the respondents almost in half. This distribution is a reasonably stable value that does not depend on external parameters, such as speciality, year of study, gender, etc. Accordingly, it is possible to assume that students at the beginning of their studies have permanent advantages (positive or negative attitude) over the practical application of recycling.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012021 doi:10.1088/1755-1315/1049/1/012021

Table 3. Spearman's Rank Order Correlations of the individual (I1-I3) and average (I) values of intension vs both individual and average ranks of attitude (A), perceived behaviour control (BC), subjective norm (SN), personal norm (PN) and role beliefs (RB).

Pair of factors	A(1-5) - I1	A(1-5) - I2	A(1-5) - I3	A(1-5) - I
Number of significant correlation pairs	5 out of 5	5 out of 5	5 out of 5	5 out of 5
Correlations r_S between average values	0.538**	0.506**	0.488**	0.549**
Range of significant r_S (the items with max r_S)	0.363**-0.549**(A5)	0.352**-0.559**(A5)	0.280**-0.491**(A5)	0.357**-0.567**(A5)
Pair of factors	BC(1-4) - I1	BC(1-4) - I2	BC(1-4) - I3	BC(1-4) - I
Number of significant correlation pairs	4 out of 4	4 out of 4	4 out of 4	4 out of 4
Correlations r_S between average values	0.666**	0.520**	0.584**	0.661**
Range of significant r_S (the items with max r_S)	0.289**-0.665**(BC3)	0.284**-0.580**(BC1)	0.254*-0.558**(BC3)	0.272**-0.634**(BC3)
Pair of factors	SN(1-3) - I1	SN(1-3) - I2	SN(1-3) - I3	SN(1-3) - I
Number of significant correlation pairs	3 out of 3	3 out of 3	3 out of 3	3 out of 3
Correlations r_S between average values	0.601**	0.559**	0.500**	0.591**
Range of significant r_S (the items with max r_S)	0.338**-0.520**(SN2)	0.411**-0.466**(SN1)	0.275**-0.482**(SN1)	0.361**-0.522**(SN1)
Pair of factors	PN(1-3) - I1	PN(1-3) - I2	PN(1-3) - I3	PN(1-3) - I
Number of significant correlation pairs	3 out of 3	3 out of 3	3 out of 3	3 out of 3
Correlations r_S between average values	0.484**	0.441**	0.406**	0.472**
Range of significant r_S (the items with max r_S)	0.265*-0.529**(PN3)	0.251*-0.495**(PN2)	0.233*-0.445**(PN3)	0.262*-0.501**(PN3)
Pair of factors	PB(1-4) - I1	PB(1-4) - I2	PB(1-4) - I3	PB(1-4) - I
Number of significant correlation pairs	4 out of 4	4 out of 4	4 out of 4	4 out of 4
Correlations r_S between average values	0.550**	0.591**	0.559**	0.600**
Range of significant r_S (the items with max r_S)	0.314**-0.521**(RB2)	0.396**-0.567**(RB2)	0.338**-0.526**(RB4)	0.363**-0.551**(RB2)

** Correlation is significant at the 0.01 level (2-sided)
* Correlation is significant at the 0.05 level (2-sided)

These advantages do not change during the learning process. As shown in figure 3, about half of the students resort to upcycling once a year or less, i.e. they do not actually have such a permanent habit. The other half does it once a quarter or more often. In this case, one can talk about the practice of applying upcycling. The approximate curve in figure 3 can be written as follows:

$$y = 1.58245 + \frac{39.91154}{2.01461\sqrt{\frac{\pi}{2}}} exp^{\left(-\frac{(x-3.14011)^2}{2.01461^2}\right)} + \frac{32.6833}{0.57042\sqrt{\frac{\pi}{2}}} exp^{\left(-\frac{(x-5.970266)^2}{0.57042^2}\right)} \tag{1}$$

At the same time, the nature of the identified bimodality is not entirely clear. Figure 4 illustrates the observation numbers as a function of the scored points. For most factors, there are no signs of bimodal behaviour. Some symptoms of such behaviour can be attributed to factors of role beliefs (RF), perceived benefits (PB), and partially facilitating conditions (FC). In some cases, the distributions tend to gradually increase from left to right, indicating that a favourable opinion to the factor impact prevails over the negative one. Other curves demonstrate close to the normal curves.

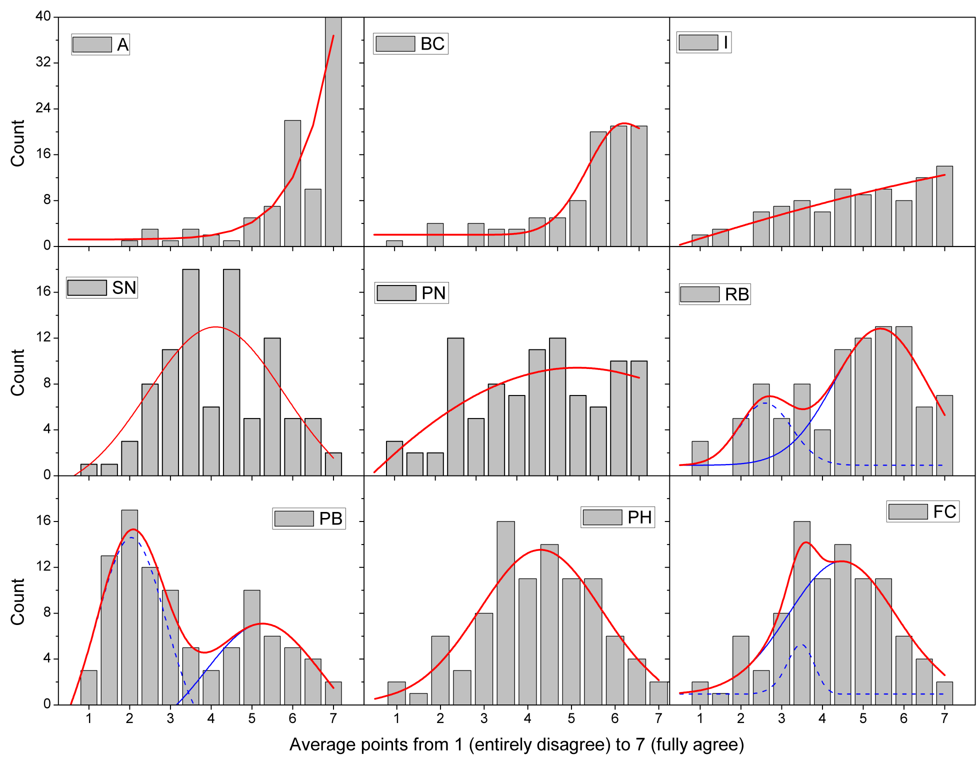

Figure 4. The number of counted observations as a function of the average number of points in responses related to attitude (A), behaviour control (BC), intention (I), subjective norm (SN), personal norm (PN), role beliefs (RF), perceived benefits (PB), perceived habits (PH) and facilitating conditions (FC).

However, the main practical conclusion is that the data obtained still do not provide sufficient grounds to identify the most influential factors that shape the respondents' behaviour concerning recycling techniques. Under such conditions, it seems logical to build additional simplified models that will be able to identify the most influential items and explain at least part of the sample.

4. Discussion

According to the results, future specialists are poorly versed in recycling technologies. They do not understand their importance and are not even interested. There are no significant changes over the years of study, which is an obvious disadvantage of the learning process used. Accordingly, the conditions for sustainable development of the industry will not be provided by relevant specialists in the coming years.

4.1. Accessing strengths of influencing factors

The results obtained during the study indicate a positive students' attitude towards upcycling practices. However, this positive attitude does not seem conscious and, perhaps, reflects general fashion trends rather than a mindful attitude. The lack of correlations with PBs and evident scepticism about possible benefits from upcycling activities are noteworthy. Then, it is not easy to expect that future teachers and engineers in the clothing industry who are not aware of the benefits of recycling (figure 2) will consciously use environmental standards in their professional work.

The results' analysis allows one to transform the primary scheme in figure 1, as the correlations between individual behavioural factors were not significant in some cases. On the contrary, statistically significant correlations were found for other factors. The updated diagram is shown in figure 5. The double arrow in the diagram illustrates correlations of the highest degree - at the level of 99% or $p < 0,01$. Single arrow - slightly weaker, but significant correlation (95% or $p < 0.05$). The dotted line in the arrow indicates no significant correlation.

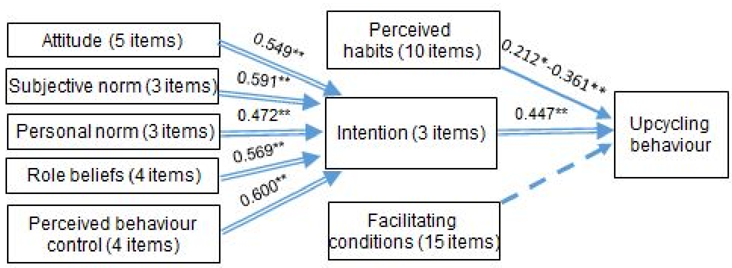

Figure 5. Combined model to explain upcycling behaviour with the values of average Spearman's Rank Order Correlations between factors.

As can be seen from figure 5, the formed intentions of students correlate well with upcycling behaviour. In contrast, available facilitating conditions (FC) to a greater extent and perceived habits (PH) to a lesser extent are not formative factors of upcycling. In turn, intentions are formed under the influence of all three factors shown on the scheme (A, BC and three social norms). Accordingly, the obtained data indicate a rather complex relationship between formative factors and upcycling behaviour. It is impossible to identify the most critical elements at this stage. To answer this question, one needs to make certain assumptions and develop on this basis further models, which will be implemented in the next section.

4.2. Regression model explaining upcycling behaviour

Upcycling behaviour is a complex function of many factors. These factors were grouped into nine groups, which combined the answers to 62 questions. The correlation of UB with FC and PB factors is minimal, while these correlations are significant for the other seven groups. However, due to the mentioned complex dependence on individual items, it is impossible to say which questions and answers give the most robust understanding of the respondents' upcycling behaviour.

Models and corresponding logistic regressions will be built to identify these critical items. The apparent disadvantage of logistics models is that they, due to simplicity, explain the behaviour of only part of the sample. On the other hand, the construction of logistics models can dramatically reduce the number of influencing factors. It can be achieved by involving a limited number of the most influential items in logistic regressions. Questions with the highest correlation coefficients are used as determinants in correlation analysis. Two questions with the highest correlations for factors A, SN, PN, RB and BC, three questions for factors I and PH were selected. FC and PB are not included in the analysis because of the absence of significant correlations with UB. All answers on a 7-point scale were recoded into binary nominal data for logistic regression. Points in the responses from 1 to 4 were converted into 0 points corresponding to a negative attitude to upcycling. Former 5 to 7 points converted to 1 point (positive attitude).

The parameters of intentions (I) and upcycling behaviour (UB) are accepted as indicators that illustrate the ability of respondents to use upcycling technologies. UB indicators were also translated into a binary system, where 0 (negative upcycling behaviour) was used instead of 1-4 points obtained in the answers, and 1 - instead of 5-8 points.

According to the significant correlations between individual factors found in the previous sections, logistic regressions were constructed for three different models (figure 6). Independent variables were introduced as a single block (enter method) in all three models.

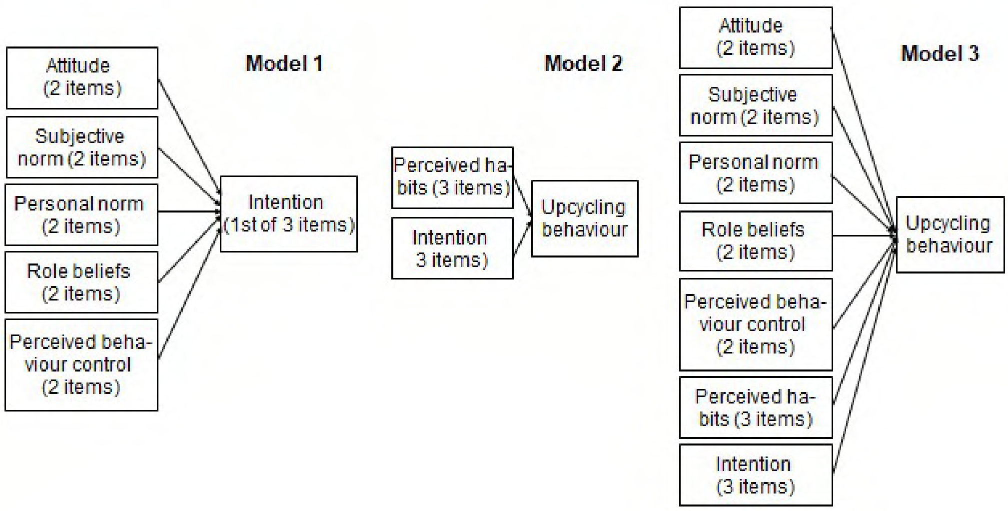

Figure 6. Three models to develop logistic regressions.

In the first model (table 4), factor I (more precisely I1) is a dependent variable and factors A, SN, PN, RB, and BC are influencing factors. This model explained the intentions' behaviour and contained ten items with the highest correlation coefficients among the five factors mentioned above as independent variables. The model was statistically significant (χ^2=65.085, df=10, $p < 0.000$). Therefore, the model can distinguish between respondents who intend and do not resort to upcycling. The model explained the variance of intentions from 49.6% (R^2 Cox & Snell) to 66.4% (R^2 Nagelkerke) and correctly classified 84.2% of cases.

One item to the factor BC (Upcycling things would be easy for me) has the largest contribution to the model with statistical significance p=0.005. The ratio of chances is 9.146. Therefore, respondents who said 'Upcycling things would be easy for me' intend to apply upcycling nine and half times more often than those who disagree with this statement. Another influential item (factor RB) is 'Upcycling fits my role in my family' (Exp(B)=5.317, p=0.024).

The second model focuses on the UB study (table 5). Three items of factors I and PH served are determinants. The model is statistically significant (χ^2=17.671, df=6, $p < 0.007$). It differentiates the respondents with frequent and rare upcycling practices. The model explained from 17.1% (R^2 Cox & Snell) to 23% (R^2 Nagelkerke) variances and correctly classified 67% of the variances.

Table 4. Logistic regression explaining likelihood of reporting relatively more probable upcycling intention by model 1.

Predictor	B	SE B	Wald's χ^2	df	p	Exp(B)
S11bin	0.937	1.263	0.551	1	0.458	2.553
S12bin	0.890	1.150	0.598	1	0.439	2.435
S22bin	1.370	0.994	1.900	1	0.168	3.937
S23bin	-0.202	0.937	0.046	1	0.829	0.817
S31bin	0.974	0.718	1.842	1	0.175	2.650
Upcycling fits my role in my family	1.671	0.738	5.125	1	0.024	5.317
A1bin	0.469	1.129	0.172	1	0.678	1.598
A5bin	-0.068	1.266	0.003	1	0.957	0.934
C1bin	1.036	0.978	1.122	1	0.289	2.817
Upcycling would be easy for me	2.213	0.780	8.043	1	0.005	9.146
Constant	-4.706	1.327	12.585	1	0.000	0.009
Tests		χ^2	df	p		
Omnibus tests of model coefficients		65.085	10	0.000		
Hosmer and Lemeshow test		7.618	7	0.368		
Model summary & classification						
Pseudo R^2 statistics		Cox&Snell	Nagelkerke			
		0.496	0.664			
Overall percentage correct		84.2%				

The third item belonging to factor I (I intend to upcycle things) produces the most significant impact. People who responded positively to this item were 4.466 times more likely to apply upcycling often (p=0.042). Model 2 is inferior to models 1 and 3 in predictive power, explaining only 67% of the sample.

The third model studies factors' effect on UB (table 6). Influencing factors were independent variables A (2 items), SN (2 items), PN (2 items), RB (2 items), BC (2 items), PH (3 items) and I (3 items).

The model is statistically significant (χ^2=27.371, df=16, p < 0.038). As model 2, model 3 differentiates respondents with rare and regular upcycling practices. The model explained from 25.3% (R^2 Cox & Snell) to 33.9% (R^2 Nagelkerke) variances and correctly classified 76.6% of variances. The most influential items (Upcycling things would be easy for me, and I intend to upcycle things) belong to factors BC and I, respectively. People who responded positively to the above items, in 4.361 (p=0.041) and 3.503 (p=0.122) times more often apply upcycling frequently.

The obtained results indicate the presence of certain shortcomings in the training of students, which can be reduced to the following.

First, students need to be taught to overcome the indifference threshold in their attitude to waste management in general and textile waste in particular. That graduates get used to, wanted and were able to coordinate their daily activities with the requirements of sustainable development of society.

Second, they must understand what benefits of sustainable development in society exist and what personal benefits they will have - ethical, social, economic, etc.

Third, it is clear that if students do not have upcycling skills, they do not want to do them. It is necessary to teach techniques that allow one to work in production without waste and provide

Table 5. Logistic regression explaining likelihood of reporting relatively more frequent upcycling by model 2.

Predictor	B	SE B	Wald's χ^2	df	p	Exp(B)
I1bin	0.433	0.803	0.291	1	0.590	1.542
I2bin	-0.081	0.888	0.008	1	0.927	0.922
I intend to upcycle things	1.497	0.735	4.141	1	0.042	4.466
H2bin	-0.421	0.550	0.585	1	0.444	0.656
H7bin	0.895	0.612	2.135	1	0.144	2.446
H8bin	-0.838	0.572	2.148	1	0.143	0.433
Constant	-1.508	0.494	9.302	1	0.002	0.221
Tests		χ^2	df	p		
Omnibus tests of model coefficients		17.671	6	0.007		
Hosmer and Lemeshow test		1.842	7	0.968		
Model summary & classification						
Pseudo R^2 statistics		Cox&Snell	Nagelkerke			
		0.171	0.230			
Overall percentage correct		67.0%				

knowledge on the organisation of the circular output.

The formation of key competencies of sustainable development for future specialists is not provided for in the recently approved educational standards of Ukraine. Meanwhile, demand from employers exists for specialists with waste management technologies at all stages of production, use and disposal of used products [34,35]. In today's conditions, the necessary skills and abilities are formed in students in fragments, during the study of individual disciplines, or in the process of their professional activities.

With the purposeful filling of education with ecological content and organisation of students' activities, which will promote the development of the features of a specialist in sustainable development, changes in the mentality of students can occur relatively quickly. At the same time, a fragmentary change in the content of academic disciplines is not enough. Mastering individual, unrelated modules do not provide an opportunity to look globally at a range of sustainable development issues. Therefore, achieving the desired effect requires significant changes in educational programs by introducing holistic disciplines. Such disciplines should be interdisciplinary in nature, which will allow not occasionally, but constantly to develop skills and knowledge of future specialists in sustainable development [36–38]. It is also evident that certain adjustments in their teaching should accompany the introduction of new disciplines. Student personalities and preferred learning styles [39, 40] should be taken into account, and pedagogical approaches that best meet the task of forming key competencies of sustainable development should be applied.

5. Conclusions

Sustainable development of the clothing industry involves introducing appropriate technologies. They will ensure consistent and optimal industrial waste administration at all stages of the product life cycle, from their design to the recycling of used items. Created technologies must be provided with qualified personnel who understand the importance of recycling technologies and have the necessary professional competencies.

The vast majority of students declare a positive attitude towards recycling or upcycling

Table 6. Logistic regression explaining likelihood of reporting relatively more frequent upcycling by model 3.

Predictor	B	SE B	Wald's χ^2	df	p	Exp(B)
S11bin	-0.911	0.870	1.097	1	0.295	0.402
S12bin	0.716	0.828	0.748	1	0.387	2.046
S22bin	-0.721	0.809	0.794	1	0.373	0.486
S23bin	0.676	0.802	0.710	1	0.399	1.967
S31bin	0.816	0.734	1.236	1	0.266	2.261
S32bin	-0.539	0.734	0.539	1	0.463	0.583
A1bin	1.098	0.890	1.522	1	0.217	2.997
A5bin	-0.853	1.108	0.592	1	0.441	0.426
C1bin	-1.472	0.906	2.640	1	0.104	0.230
Upcycling would be easy for me	1.473	0.721	4.167	1	0.041	4.361
I1bin	0.031	0.960	0.001	1	0.974	1.031
I2bin	0.849	1.093	0.604	1	0.437	2.337
I intend to upcycle things	1.254	0.810	2.397	1	0.122	3.503
H2bin	-0.807	0.627	1.656	1	0.198	0.446
H7bin	0.732	0.710	1.062	1	0.303	2.079
H8bin	-0.366	0.656	0.311	1	0.577	0.694
Constant	-1.706	0.754	5.119	1	0.024	0.182
Tests		χ^2	df	p		
Omnibus tests of model coefficients		27.371	16	0.038		
Hosmer and Lemeshow test		12.616	8	0.126		
Model summary & classification						
Pseudo R^2 statistics		Cox&Snell	Nagelkerke			
		0.253	0.339			
Overall percentage correct		76.6%				

technologies. However, this attitude is more theoretical and is often not supported by appropriate actions. The study showed that almost all students do not understand the benefits that can be provided by careful waste management - neither economic nor environmental nor the benefits at the level of consciousness.

In general, attitudes towards waste disposal or use upcycling practices remain almost unchanged throughout the years of study. In this regard, the ratio of undergraduate students does not differ from that of undergraduates. Therefore, training in existing curricula does not increase interest in the problem of waste recycling.

The distribution of students according to the frequency of application of upcycling techniques is bimodal. All respondents are roughly divided into those who practice them regularly (1-3 months or more) and those who use them sporadically (once a year or less).

Analysis of factors influencing the attitude of individuals to upcycling showed that the most influential is the factor of intentions, which, in turn, is formed under the influence of attitude factors, three social factors, and perceived behaviour control. A rather complex relationship exists between influential factors and upcycling behaviour.

The construction of logistic regressions allows identifying the most critical questions in the questionnaire. The answers to them allow predicting the intentions of upcycling and the frequency of upcycling for 70-80% of the sample. Only three items were among the most influential: Upcycling things would be easy for me; I intend to upcycle things, and Upcycling fits my role in my family.

6. Acknowledgement

The authors would like to thank Miss A Shpetna for her assistance in inquiring.

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Seafarers high quality training provision by means of VR technologies in the context of maritime transport sustainability

To cite this article: S A Voloshynov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012022

Seafarers high quality training provision by means of VR technologies in the context of maritime transport sustainability

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Abstract. The solution to a number of global problems nowadays depends on the nature of human interaction with the world's oceans. The constant growth in shipping operations requires ensuring the environmental safety of the planet and belongs to strategic targets of the environmental policy of IMO Convention (International Maritime Organization) in the context of sustainable development of the maritime industry. The aim of the study is the necessity to form ecological consciousness of future seafarers by means of educational VR technologies. The issue of the effective use of cloud computing and VR technologies is considered throughout the research. The definitions of simulation and distance educational technologies, their role in the formation of environmental competence of seafarers are revealed on the example of applying the "Safe Tank Cleaning Operation" course with the use of projected virtual reality simulator. According to the experiment's results the quality of environmental competence formation in experimental group is 88% and in control group - 82%. The research reflects modern approaches and describes a methodology for acquiring practical skills by means of VR simulation technologies. The authors have shown the effectiveness of practical skills mastering by using VR simulators in the process of forming the environmental competence of seafarers.

1. Introduction

As an important part of world trade, the maritime industry is responsible for ensuring environmentally friendly international shipping. This is one of the key ideas for the sustainable development of maritime transport, which is at the intersection of three factors: economic, environmental and social.

The goal of sustainable transport development is to maximize welfare and provide a reliable economic, social and environmental base for both present and future generations [1].

It is important to highlight the link between sustainable development and other important current processes in the economic, environmental and social spheres. Thus, efficient transport systems are an integral part of economic development of society, and represent a tool to reduce the negative impact of transport on the environment. Sustainable development is guided by the basic principle that a sustainable transport strategy is the result of the integration of broad instruments, ranging from infrastructure and management, technological improvements, social awareness, quality education, pricing and taxation [2].

The various modes of transport, maritime transport in particular, have a common interest in achieving the goals of sustainable development. The maritime transport system operates worldwide and it is important that generally accepted and broad international standards continue to be clearly followed. Thus, the International Maritime Organization (hereafter - IMO) is a specialized agency of the United Nations, responsible for establishing global standards of safety, security, promoting international shipping and preventing pollution from ships. IMO regulations cover the design, construction, operation, assembly and processing of ships, as well as the education of seafarers. The IMO regulatory framework covers all types of technical issues related to ship security and safety of life at sea, navigation efficiency, and the prevention and control of marine and air pollution from ships [3].

One third of all oil pollution in the world's oceans is caused by maritime transport. It is clear that tankers are the largest source of such pollution. That's why the main focus is on the safety of tankers, qualifications and competence of the crew in various procedures that can cause pollution.

Oil pollution from tankers comes from two main sources: various types of tanker accidents and routine tanker operations, such as cleaning the tanks, ballasting and other operational activities for periodic discharge of liquid overboard.

Thus, one of the urgent problems of the maritime transport system nowadays is the pollution of the sea with waste that poisons local waters with ballast materials emitted from ships. If we talk about cleaning procedures on tankers, the vessel must be provided with appropriate means for cleaning cargo spaces and moving dirty ballast (residual liquid after cleaning the tanks) from cargo tanks to the settling tank. Settling tank devices or combinations of settling tanks must have the capacity required to hold the waste waters, generated by flushing cargo spaces, oil residues and dirty ballast [4].

The ability of the ship's crew to implement successfully the treatment of bilge water reduces the amount of dirty waste. If the result of cargo tank cleaning is of poor quality, it must be repeated. This undoubtedly affects the time, labor, cost of chemicals for cleaning, equipment [5]. So, the issue of the seafarers' professional competence is directly related to the negative impact on the environment.

When it goes about solving key problems related to maritime transport, the focus is primarily on the technological development of cleaner, quieter and more cost-effective vessels or the application of the latest technologies to reduce emissions into the environment. The human factor is always overlooked, although it is the ship's team who is responsible for and controls most shipboard operations, such as ballast and cargo tanks cleaning, and human negligence is the most common cause of accidents, involving intentional marine pollution and deliberate violations of IMO legislations.

Very often the cause of marine pollution is the lack of both professional knowledge and skills of seafarers and environmental education in general. A common problem today is that a very small number of higher education establishments can provide maritime students with quality education with the involvement of modern digital technologies.

Sustainable maritime transport system requires properly trained and educated seafarers. Professional training and environmental education should be based primarily on such Conventions as the Safety of Life at Sea (hereafter – SOLAS), the Standards of Training, Certification, and Watchkeeping (hereafter - STCW), the International Convention for the Prevention of Pollution from Ships (hereafter - MARPOL), and include systematic training. Safety and environmental awareness should be a priority of modern society [3].

In our opinion, a thorough and comprehensive system of seafarers' training in higher education establishments is more effective than the system of penalties, in terms of motivation and proper use of cleaning technologies on board during tank cleaning procedures.

The aim of the study is the need to form the environmental awareness of future seafarers with the help of educational VR-technologies in order to find the best option for human interaction with the sea.

2. Theoretical basis

The problem of quality education ranks 4th among the key goals of sustainable development in 2015-2030 for Ukraine and the world. The focus is on ensuring better coordination of maritime education and training, including updating model courses and training methods to meet new technical requirements, as well as the development of distance, virtual and simulation training.

The need to create a new quality of education is reflected in construction of new pedagogical tools. The latters become global trends in the development of information technologies in education: open access and active involvement into the information society, development of distance and virtual reality training, continuous and life-long education, professional retraining [6].

Comprehensive thorough training of future seafarers can be achieved only through the students' acquisition of certain competencies in a cluster. This goal is realized through implementing the system of "blended learning", augmented and virtual reality, which integrate different types of learning activities: classroom learning, online learning, distance learning, deep learning, virtual learning, simulator learning and more [7].

Following K.Hew [8] and K.Buhaichuk [9], we interpret "blended learning" as a modern model of learning that combines traditional and online classes in the format of pair, group and individual work. The advantage of this model of learning is, firstly, in a deep emphasis on socialization and continuity of the learning process, which continues outside the classroom. Secondly, the involvement of modern information technology, which allows deep learning and active use of the Internet environment to solve educational problems.

Blended learning meets the systemic principles of open education: mobility of participants in the educational process, equal access to educational systems, provision of quality education, formation of structure and implementation of educational services [10]. At the same time, there is a need to introduce innovative teaching methods such as: transfer of traditional educational material to e-learning and increasing its concernment, the use of gamification, adaptive learning technologies, deep learning and digital learning technologies [11].

Innovative strategies of simulation and virtual learning are united by a common function – creating conditions for the transition to student-centered learning. If simulation technologies enable the formation of students' skills within educational establishments, then virtual technologies imitate the real environment and the conditions under which these skills are formed.

The main advantage of the implementation of simulation and VR technologies in the educational process is the creation of conditions for the development of critical thinking, the formation of affective and cognitive skills of students, safe demonstration of competencies with unlimited ability to work on mistakes.

Currently, the educational process at the Kherson State Maritime Academy (hereinafter - KSMA) is based on the system of blended learning (figure 1) and integrates:

1. traditional learning in classrooms on the basis of communicative and competency approach;
2. online learning in a digital educational environment that combines LMS Moodle (www.mdl.ksma.ks.ua);
3. virtual training in the laboratory of virtual reality;
4. simulation training on maritime simulators in specially equipped laboratories;
5. practical training on a ship.

As we can see, the core of the educational process in KSMA consists of traditional and electronic classes in the format of pair, group and individual work, due to which the professional

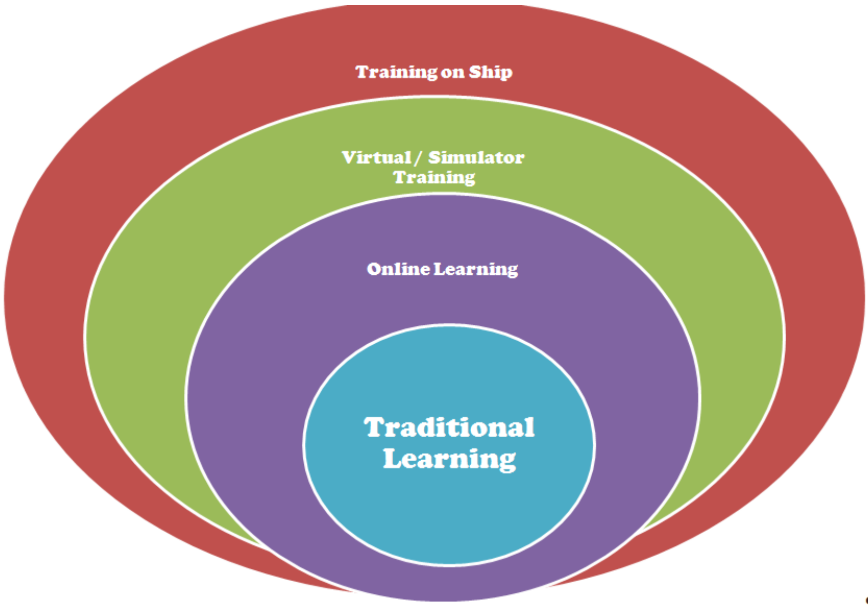

Figure 1. Scheme of educational process in KSMA.

competencies of students are formed. Practical trainings on virtual reality simulators allow you to master the algorithms of action and demonstrate the level of acquired competencies, improve practical skills and analyze mistakes before training on a real simulator and practice on a real ship.

In our opinion, the stage of training on virtual reality simulators is even more important, because practice itself can not ensure the development of skills and decision-making in various emergencies, as they may not occur [12].

The implementation of virtual and simulation methods in the educational process allows students to learn about the objects of their study and related concepts, interact with processes and understand what underlies the dynamic behavior of objects of their study [13]. Such an experience cannot be reproduced by traditional approaches only.

In addition, virtual and simulation technologies encourage students to learn actively, as virtual reality facilitates decision-making when interacting with virtual environments, enabling independent research, understanding of complex concepts, creating new experiences and learning during study [14].

Today, there is a wide range of virtual simulation technologies that differ only in the degree of immersion in the virtual environment [15]:

1. Cabin simulators, which are mainly used to reproduce and simulate a real closed object, such as a navigation bridge. The cab windows are replaced with computer displays that simulate movement and navigation, and it can be equipped with surround sound for greater realism.
2. Projected virtual reality simulator, which consists of a moving avatar that displays the user's movements in real time and is visualized on a wide screen.
3. Augmented reality simulator, which requires special glasses or a mobile device to visualize augmented objects superimposed on objects of the real environment.
4. Desktop virtual reality simulator, which simply requires a normal computer display. Interaction with the virtual world is limited by the capabilities of the computer, but does not require expensive hardware or software, being easy and effective to use.

Virtual and simulation training in KSMA includes cabin simulators and simulators of projected virtual reality for the training of future seafarers (figure 2).

Figure 2. VR simulators in KSMA.

Previously, there was no clear idea how to integrate effectively virtual reality technologies into the educational process, but now this practice is the most important and integral stage in the training of future maritime specialists at the KSMA. Its effectiveness is confirmed not only by the high level of students' preparation before starting practical training on a ship, but also by positive motivation, a sense of ideology, interest in gaining skills and experience. Thus, the use of simulation technologies has brought the practical skills of future maritime specialists to a new level without endangering the lives and health of people [12].

3. Results

In the context of environmental education, as one of the transport strategy tools to achieve sustainable development goals, KSMA has developed a course "Safe Tank Cleaning Operation" aimed at preventing violations of MARPOL regulations on cleaning tanks and proper treatment of contaminated ballast and sewage waters.

At the legislative level, the course is based on the IMO Model Course 1.03: Advanced Training for Chemical Tanker Cargo Operations [16], STCW Table A-V / 1-1-3 [17] (table 1), MARPOL (Annexes I, II, IV) [4] and focuses on the following objectives:

- raising awareness of using safe procedures when performing various operations on board tankers and other vessels;
- gaining experience in identifying operational problems and their solutions;
- improving the ability to promote a culture of security and protection of the marine environment.

According to the IMO Model Course 1.03 [16] the "Safe Tank Cleaning Operation" course content is based on the formation of the following competencies:

- contents of a tank cleaning plan for a chemical tanker;
- pre-cleaning checks prior commencing tank cleaning operations of tank cleaning;
- maximum allowed stripping quantity remaining on board after discharge for categories X, Y and Z substances, as per MARPOL;
- exemptions from mandatory prewashing requirements in accordance with MARPOL Annex II;

Table 1. Legislative basis of the course.

Competence(Table A-V/1-1-3 STCW Code)	Knowledge, understanding and proficiency	Topic (IMO Model course 1.03)	Knowledge, understanding and proficiency
Ability to safely perform and monitor all cargo operations	7.3 tank cleaning operations	Knowledge and understanding of chemical cargo related operations	7.3 tank cleaning operations / prewash operations
Monitor and control compliance with legislative requirements	Knowledge and understanding of relevant provisions of MARPOL and other relevant IMO instruments, industry guidelines and port regulations	Knowledge and understanding of relevant provisions of MARPOL and other relevant IMO instruments, industry guidelines and port regulations	Knowledge and understanding of relevant provisions of MARPOL and other relevant IMO instruments, industry guidelines and port regulations

- requirements for discharge to reception facilities and concentration of substance in the effluent discharge to shore;
- limitations on subsequent discharge of wash water into the sea;
- washing procedures for high-viscosity and low-viscosity substances;
- tank-cleaning procedures for water-reactive cargoes;
- requirements for special areas defined in MARPOL and implications for discharge of residues of noxious liquid substances;
- slop tank discharge restrictions and requirements;
- wall wash test requirements and procedures including factors leading to the contamination of wall wash samples;
- tank-washing operations with portable and fixed machines;
- knowledge of MARPOL Annexes I, II and IV which are particularly applicable to chemical tanker cargo procedures and control of operational discharges of residues of noxious liquid substances.

Methodologically the course is based on the principles of blended learning, combining the following types of students' educational activities:

1. lectures, practical and laboratory classes in the disciplines of "Ecology and Environmental Protection", "Prevention of Environmental Pollution", "Chemistry", "Maritime English", "Maritime Law" are aimed at forming the above mentioned competencies;
2. online classes in e-learning environment based on the LMS Moodle platform (figure 3). LMS Moodle has an electronic course "Safe Tank Cleaning Operation", which includes: description of professional competencies, lecture notes on all topics, didactic materials, additional videos and links to Internet resources (articles, blogs, youtube, wikipedia, etc.), test tasks to control the level of competencies within the summative and formative assessment;

3. practical training on a virtual reality simulator in the VR-laboratory, aimed at developing skills and demonstrating the level of competency "Proficiency in Wall Wash Test Requirements and Procedures". This is a complex operation that ensures the readiness of tanks to accept the next cargo and is an indicator of the tanks cleaning procedure effectiveness. In our opinion, it is logical that this operation was chosen to demonstrate the level of competence acquired on the VR simulator, as it is the final in the procedure of cleaning cargo tanks and its unqualified conduct can have far-reaching consequences for the ship and crew and marine ecology.

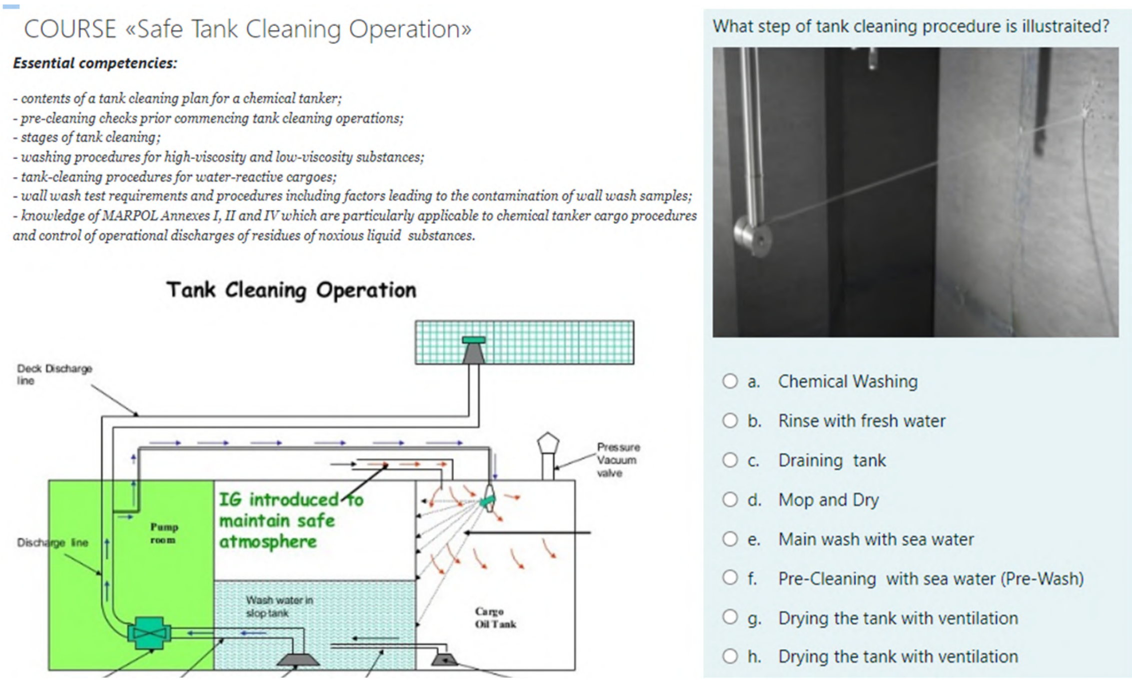

Figure 3. Course "Safe Tank Cleaning Operation" in LMS Moodle in KSMA.

Practical trainings on VR-simulators include two important stages, which differ in the target orientation: the current running and the final running. The current course running is aimed at mastering the skills acquired in blended learning, and includes the gradual completion of any operation on the ship in accordance with the commands. Such conditions of the virtual environment simulate the initial operation on the ship, when a cadet performs duties of an Ordinary Seaman, follows the commands of Bosun and makes the necessary decisions in accordance with the formed competencies (figure 4). The current course has an infinite number of attempts and is unlimited in time. This stage includes both direct commands ("Take bottom for samples", "Spill out the liquid", "Go to the forward bulkhead", etc.) and tips ("Avoid testing on wet or hot bulkheads"). The final course running is focused on demonstrating the level of acquired competency. The student's actions are limited in time, he/she acts without prompting, based on his/her own knowledge and skills.

The current and final operation "Wall Wash Test" on the VR-simulator in KSMA includes the following stages [18]: introduction and safety, familiarization with wall wash west equipment, choice of correct chemicals for wall wash test, familiarization with sample collection procedure, demonstration of test for presence of hydrocarbon, demonstration of test for presence of chlorides, demonstration of permanganate fade time test, demonstration of acid wash colour of aromatic hydrocarbons.

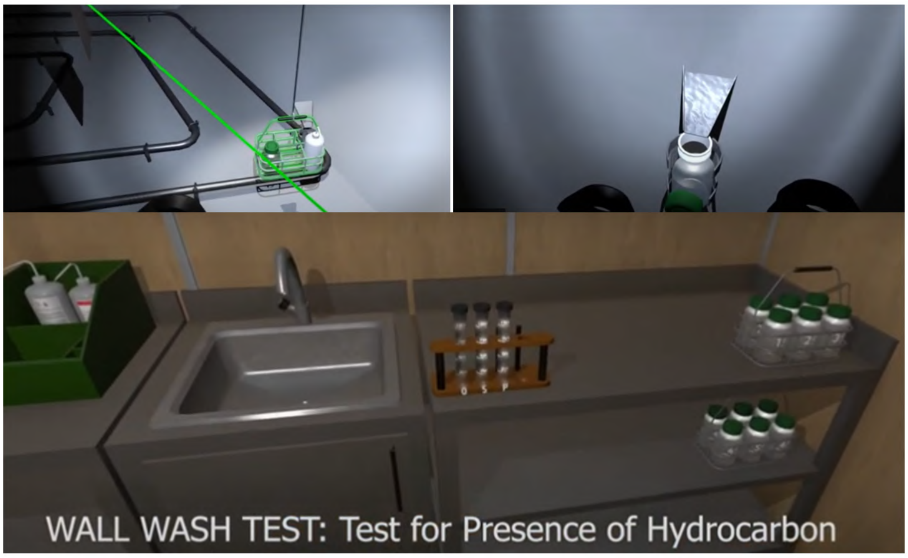

Figure 4. "Wall Wash Test" procedure in VR simulator in KSMA.

The effectiveness of the tank cleaning procedure is assessed by inspecting the walls, which includes applying the solvent to selected areas of the tank. The solvent is allowed to drain to the surface, and then it is collected in a clean bottle with a special funnel. After that the sample is analyzed and a series of studies is performed. They vary from the color of the sample, checking for the presence of suspended solids in a test tube. In addition, cadets perform tests for the presence of hydrocarbons, contamination and chlorides.

Involving online and simulation training allows to get fast feedback at both the current and final stage of training, ensures its continuity and is characterized by high interest of students.

Thus, the advantages of the course "Safe Tank Cleaning Operation" are the formation of professional competency of seafarers in effective cargo tanks cleaning on chemical tankers, environmental awareness and reduction of the risk of environmental pollution by ballast and sewage waters, and as a result – minimizing overtime costs due to re-cleaning operations, shortening downtime, saving energy, reducing water consumption and usage of substances for cleaning, which in turn has a positive effect on reducing marine pollution from ships.

In accordance with the aim of study it was conducted an experimental research of effectiveness of using our course Safe Tank Cleaning Operation. To solve these problems at different stages of experimental work, a set of research methods and techniques was used, including:

- empirical: questionnaires, surveys, testing, conversations with participants of the educational process, direct, observation of the process;
- comparison;
- method of expert assessments, etc.;
- methods of mathematical statistics for quantitative and qualitative analysis and verification of the results of experimental work by Pearson criteria ($\chi 2$), etc.

The research was conducted in KSMA with 197 students and 11 teachers. At the first stage we checked the students‘ level of knowledge and grouped them in two groups: experimental (96 students) and control (101 students). We used special questionnaire (check-list) to check residual knowledge of students on the basis of our course Safe Tank Cleaning Operation:

- contents of a tank cleaning plan for a chemical tanker;
- pre-cleaning checks prior commencing tank cleaning operations;
- stages of tank cleaning;
- maximum allowed stripping quantity remaining on board after discharge for categories X, Y and Z substances, as per MARPOL;
- exemptions from mandatory prewashing requirements in accordance with MARPOL Annex II;
- requirements for discharge to reception facilities and concentration of substance in the effluent discharge to shore;
- limitations on subsequent discharge of wash water into the sea;
- washing procedures for high-viscosity and low-viscosity substances;
- tank-cleaning procedures for water-reactive cargoes;
- requirements for special areas defined in MARPOL and implications for discharge of residues of noxious liquid substances;
- slop tank discharge restrictions and requirements;
- wall wash test requirements and procedures including factors leading to the contamination of wall wash samples;
- tank-washing operations with portable and fixed machines;
- knowledge of MARPOL Annexes I, II and IV which are particularly applicable to chemical tanker cargo procedures and control of operational discharges of residues of noxious liquid substances.

We tried to understand how students were ready to show and use their practical skills in real situations onboard the vessel – check the level of their competency formation. Because coming onboard a future seafarer should have practical skills and knowledge on how to conduct cleaning procedures environmental friendly.

The evaluation of each check-list was conducted with a help of 100 points assessment. After the analysis of students' evaluation, which showed 68% control group and 63% experimental group, we used Pearson criteria (χ^2) to check the deviation of statistical difference between control and experimental group. We calculated that χ^2 = 8,11, showing that two groups are statistically equal. After this stage we started presenting our course "Safe Tank Cleaning Operation (involving "Wall Wash Test" procedure on VR simulators) in the experimental group. Teachers also were invited to take part in this experiment. In control group the educational process was conducted according to the ordinary curriculum of KSMA.

In our course the main aim was to use practical skills as more as possible with the help of virtual reality training. In the end the students of control and experimental group were checked again using our check-list. The average point in the control group was 82% and in the experimental group was 88%. Also students in both groups fulfilled procedure "Wall Wash Test" on VR simulator. While the students of experimental group finished it in one day, students in control group finished the procedure in 3 days, because they had only theoretical knowledge and didn't know how to use their skills in real situation.

4. Conclusions

Cleaning the tanks is a complex procedure which requires a high level of seafarer's training. Coming onboard a future seafarer should have practical skills and knowledge on how to conduct tank cleaning procedures safely and environmental friendly. To achieve this aim in KSMA it was created a special electronic educational environment, based on blended learning and virtual technologies. We conducted a research, using the course "Safe Tank Cleaning Operation", within control and experimental groups on the basis of traditional lessons, LMS Moodle and VR training "Wall Wash Test". It was noticed that the average point in the control group was 82%, while in the experimental group - 88%. VR technologies helped to improve the transmission of educational content, as well as allowed students not only to see the content, but also to interact with it. Such electronic educational environment is a reliable way to significantly reduce negative impact of the maritime transport on ecological situation at sea and provide its sustainable development. The research reflects modern approaches and describes a methodology for acquiring practical skills by means of VR simulation technologies. The authors have shown the effectiveness of practical skills mastering by using VR simulators in the process of forming the environmental awareness of seafarers.

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Sustainability of biogas production: using of Shelford's law

To cite this article: Ye B Shapovalov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012023

Sustainability of biogas production: using of Shelford's law

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Abstract. The article is devoted to proposing a method of regulation of biogas installations dissemination using Shelford's law. It is based on the hypothesis that there is some optimal amount, and on both sides around it, the sustainability of the process will decrease because of biogas production that can affect ecosystems both positively and negatively. It declared that in different countries Shelford's law graph could be different due to differences in both natural and social conditions. It shows that nowadays some unsustainable experience is taking place (In the case of Germany, it is using useful recourses which have to be grown and in the case of Ukraine, these are low-efficiency technologies which can be harmful to the environment). It proposes approaches to provide more sustainable biogas production using modern technologies and strategic planning.

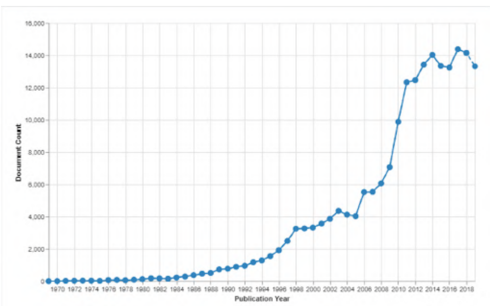
1. Introduction

Sustainable development declared in a huge number of strategic documents. It declares the development of sociality in a way to provide quality of life and environment not worse than nowadays. One of the urgent parts of it is the production of energy using alternative energy sources. The driving force behind the development and use of bioenergy is the Renewable Energy Directive (Directive 2009/28/EC) [1] adopted in April 2009 by the Council and the Parliament of the European Union. The aim of this act is, by 2020, for 20% of the EU's total energy consumption to be from renewable sources and for 10% of the energy used for transport be from renewable sources. A global strategy insisting on safety and sustainable aspects established in the Agenda "Energy 2020 - A Strategy for Competitive, Sustainable and Secure Energy" [2]. The main aspects of this Agenda are set high requirements for the development of safe technologies in an appropriate and effective regulatory context. In the document (2009/C 66 E/05) [3], the European Parliament underlines the importance of biogas as a renewable energy resource. The main document which underlines the importance of sustainable energy consumption in Ukraine is "Ukraine 2020". The main task of this document is to ensure energy security and transition to energy-efficient and energy-saving use and consumption of energy resources by using innovative technologies. According to the policy context, it highly prioritizes renewable energies, in ordinary those that could be produced locally and in a distributed manner, such as biogas. At the same time, the shift to renewable energy has to be safe, sustainable and secure. However, alternative energetics is not always defined by sustainability as it has not only a positive effect but also a negative one.

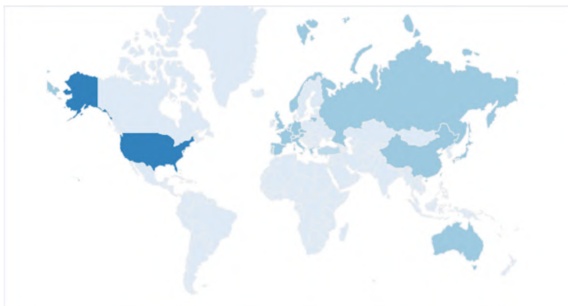
Therefore, it is necessary to consider these factors during the design and implementation of alternative sources. Usage of best-known approaches have proposed previously, but even they cannot provide sustainability without strategic planning and regulation. So, this article is related to proposed approaches to provide an implementation of different technologies (on the example of anaerobic digestion technologies) of implementation in conditions, which guarantee sustainability. It's worth to mention that the idea of sustainable biogas production has already been proposed by N. Bachmann [4]. However, it has not proposed to use strategical planning and its management to provide sustainability.

2. Technologies of sustainable biogas production

Anaerobic digestion researches are developing widely. Many world-known institutions work on this topic, that means that there are a wide variety of technologies developing today. Also, the amount of anaerobic digestion researches characterized by the tendency to growth (up to 14 000; figure 1). As you can see from figure 1 the number of researches in anaerobic digestion topic increased significantly from more than 100 in 1970 to more than 14,000 in 2018. The leading countries producing biogas equipment are Germany, China, USA, India, Japan, Great Britain and France. Among the world's leading manufacturers of biogas plants are GE Jenbacher (Germany), EnerGNedalo (Netherlands), Clarke Energy (Great Britain), Dalkia (France), Deutz (Germany), Caterpillar (USA), Guascor (Spain), Baxter Engineering (Australia), Hochreiter (Germany), Eneria (France), Zorg Biogas (Germany), Firm Green Energy (USA), Biotec (Belgium), and others.



(a)



(b)

Figure 1. Dynamics of documents related to biogas production to per year (a) and its worldwide spread (b).

Sustainable biogas production technologies are that technologies, which can provide biogas production from waste (not from useful products), and characterized by high performance of destruction, with obtaining of high quality of biogas and biofertilizer, being maximally environment-friendly. It this case both utilizing waste and obtaining useful products will be provided. However, waste can be more complicated for destruction. For example, some of previous studies have devoted to digestion of chicken manure which is characterized by a high content of ammonia which can inhibit the process [5, 6] and it is necessary to provide detailed biogas researches to solve this problem. Shift to the right side can be obtained by solving some issues of biogas production, such as more effective mixing [7–9], separated stages of the process [10, 11], an increase of the efficiency by addition of enzymes [12] or degradation of sewage sludge [13, 14]. Usage of some results of modelling will increase the efficiency of the process by determination of optimal parameters of the process. There have been successful attempts to provide modelling of wastewater treatment [15], modelling of two-stage anaerobic digestion [11], modelling of waste co-fermentation [16, 17] and anaerobic digestion during the sorption of ammonia [18]. It also seems perspective to combine biogas production with modern chemistry nanotechnologies to provide final purification [19–22] which proves great results of organic matter destruction and is characterized by high environment safely effect. Implementation of high-efficiency technologies is important, but it will lead to sustainability only in case of environmental management based on detailed research of the current state of biogas plants development [23,24] and strategies of developments generally [25].

3. The problem of sustainability of renewable and alternative energetic

All types of alternative renewable energy sources have some disadvantages. Solar, wind and wave energy resources defined by cycles of energy production, but, for consumption, those production cycles provide the problem of excess and deficit of energy at different times. Therefore, the issue of energy storage is relevant nowadays, that is why chemical technologies such as batteries or hydrogen production have been using. Moreover, potentially, it may cause disastrous changes in ecology in case of battery life output and placing it in landfills. It is certainly possible to provide recycling of the used batteries, but it will lead to additional expenses. In some classifications, nuclear energy and hydroelectricity have mentioned as sources of alternative energetics. There are some risks of explosion during the usage of atomic energy, which must need to consider during the design and implementation of nuclear reactors. Hydroelectric power plants have defined by changing internal hydro systems of ecosystems. This effect may cause natural disasters that are not common for the ecosystems and human-populated areas. However, those facts are well-known and have considered before the construction process. Anaerobic digestion of organic matter with biogas production is more complicated and curious in terms of sustainability. The process has defined by huge variabilities of parameters. Even its implementation can be related to different aims (for example, waste recycling, biogas production, fertilizers production or its combination) which will affect the sustainability of the technology. Shelford's law could be involved to define the state of sustainability of the number of renewable energy sources, considering their disadvantages. It is necessary to upgrade it by presenting the suitability of the human development on the oY axis and amount of the energy provided by alternative sources on the oX axis (see figure 2.

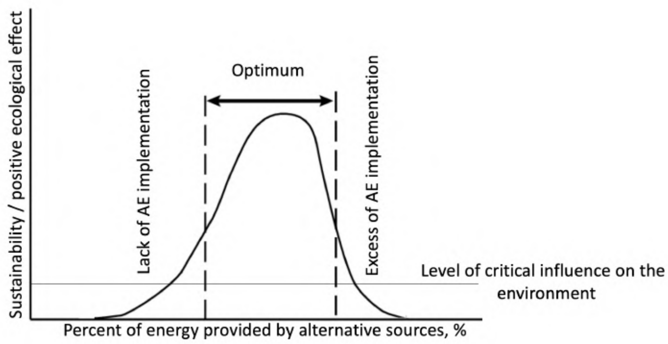


Figure 2. Shelford's law for the assessment for alternative energy (AE) development.

It is worth noting that the graph will change with the development of new sustainable technologies of alternative energetics. For example, solving the problems with energy production by solar or wind plants will shift to the right side of the graph.The same situation will be related to other AE fields. For example, optimization [26] and intensification [18, 27] of the anaerobic treatment will led to increase in biogas yeild and in turn to increase of economic attractiveness. The example of changing of Shelford's law graph after designing of new technologies have presented in figure 3.

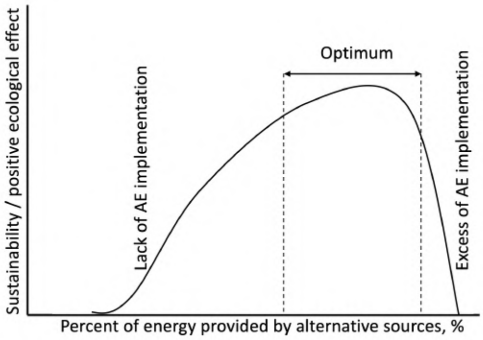


Figure 3. The example of changing of Shelford's law graph after designing of new technologies.

As shown on the graph, we suppose that all parameters of the sustainability interpreted in the graph will change (character of the graph, peaks, zone of the optimum) after designing new technologies. It indicates, that one of the main principles of the EU – using the best-known practices, is very important to provide a sustainable future for Europe and the whole world. For each country, the graph will be different based on the individual country characteristics. All factors of sustainability (economic, social and ecological) will affect the graph character, peaks, and optimum zone. For example, in countries with developed economies, the salary of the people and energy costs will be higher, compared to countries with developing economics that affects the attractiveness of alternative technologies implementation. Otherwise, it is necessary to provide the development of energetic infrastructure for countries with developing economies. Also, in equatorial countries, summary of solar radiation will be much higher than in countries with a moderate climate. Social aspects such as population density will affect sustainability too. For example, it will be not sustainable if, in countries with high population density (for example India), residential buildings will be demolishing in favour of solar energy stations that need significant areas for implementation. Maybe there are some more urgent social problems such as lack of water for food. Therefore, for example, it is possible to interpret Shelford's law graph to estimate the sustainable level of solar station implementation for some equatorial and temperate climate zones, both economically developed (figure 3).

Therefore, humanity generally and each country must find that the optimum level of implementation of alternative source and provide strategical planning according to this level and further regulation by economic instruments.

4. Shelford's law as tool to provide sustainability

Shelford's law of tolerance, was proposed by American zoologist Victor Ernest Shelford in 1911, that states that the presence and success of an organism depends on the degree of compliance with a set of conditions. The absence or failure of an organism can be controlled by a qualitative or quantitative deficiency or excess, or by any of several factors that may approach the tolerance limit for that organism. Each individual or population is a subject to environmental changes that create a minimum and maximum capacity to cope with any complex environmental factors. The

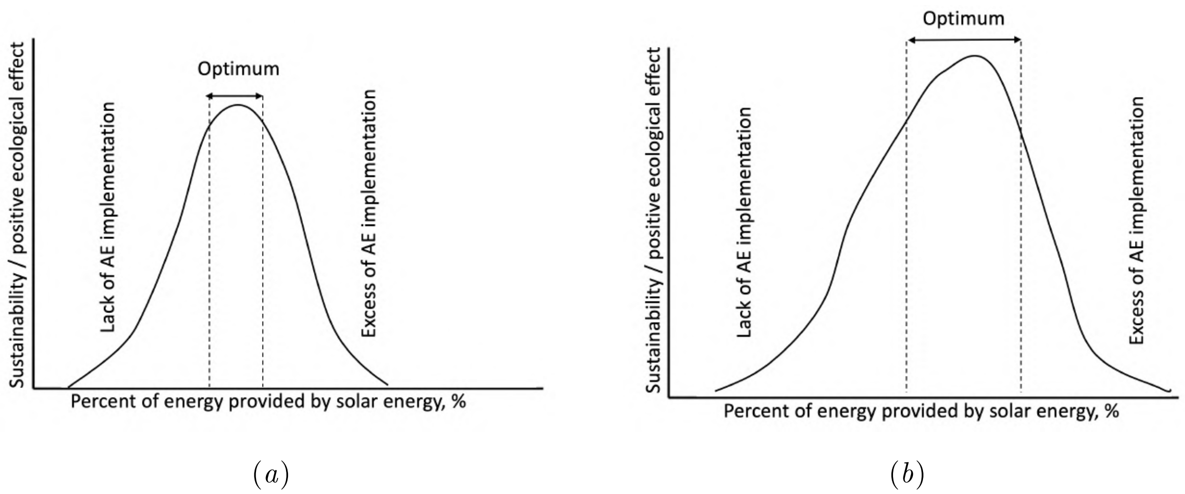


Figure 4. Interpretation of Shelford's law graph to estimate the sustainable level of solar station implementation for some temperate (a) and equatorial (b) climate zones, both economically developed.

range in which it occurs from minimum to maximum means the limit of the body's tolerance, and if all known factors are actually within a specific range of certain organisms, but it still fails, it is important to consider additional factors in the relationship with other organisms Livestock Application: In agriculture, using Shelford's Law, the animal feeding rate is calculated. This law is applied in a protected area, considering not only the optimal feeding rates but also the conditions that should be in protected areas. In microbiology, the optimal composition of the nutrient medium for microorganisms calculated, as well as the conditions of the cultivated area by this law. In zoology and ecology as a whole: Law used to predict zones where this or that creature will migrate, as well as to predict and calculate the area of residence.

5. Economics as the main instrument of regulation of the technology's implementation quantity

Similar to sustainability, it is possible to interpret Shelford's law to predict the level of development of alternative sources (including biogas production). In this case, it is possible to present a graph with oX axis that can predict the level of alternative sources of energy dissemination and oY axis presenting economical alternativeness. The real-life business process will provide an implementation of energy generation from alternative sources in the amount, which will be most economically attractive. In this case, it is possible to provide regulation of dissemination of alternative sources of energy using changes in economic attractiveness. For example, it is possible to ensure a green tariff for biogas, and it will provide a shift of the graph to the right. Therefore, it is possible to analyse the graph and find probabilities of dissemination of provided energy by alternative sources (%; low and high). Using Shelford's law with economic instruments as a control method of dissemination of the technologies is presented in figure 4. The efficiency of the proposed method has proved by finding a correlation between energy costs and dissemination of biogas plants in Ukraine and the EU. According to the Report from the Commission to the European Parliament, the European Economic and Social Committee and the Committee of the Regions on European Commission [28] and Report of European Biogas Association (on the Biomethane Biogas Report) [29], the number of biogas plants in the countries with higher electricity costs (where it is more attractive to produce it) is also higher. However, it is just one of the examples, and it is necessary to prove this hypothesis additionally.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012023 doi:10.1088/1755-1315/1049/1/012023

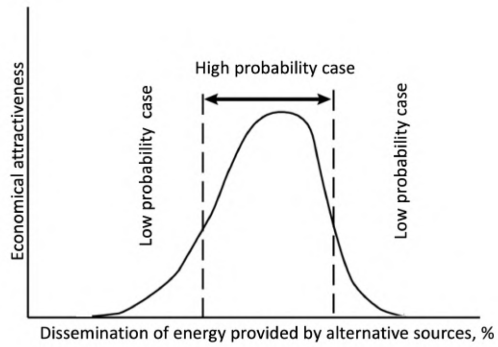
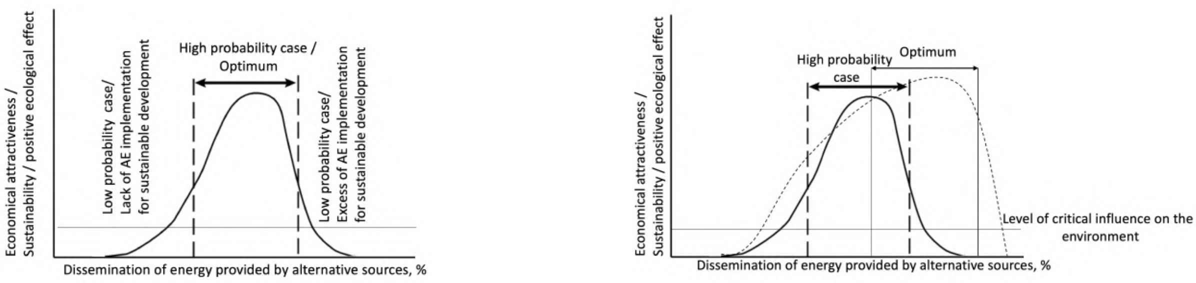


Figure 5. Using Shelford's law with economic instruments as a control method of dissemination of the technologies.

In such terms, those types of graphs (figure 4 and figure 1,figure 2,figure 3) are similar, and it is possible to use them to provide sustainable development. Therefore, representing both sustainability and probability of dissemination of provided energy by alternative sources in one graph will show consistency with an existing strategy to sustainable development. Examples of sustainable (a) and unsustainable (b) development programs have presented in figure 5.



(a) (b)

Figure 6. Examples of sustainable (a) and unsustainable (b) development programs.

Therefore, it can be interpreted as the probability of technology dissimilation (P)

$$P = f(\sum Fp - \sum Fn) \tag{1}$$

Where:
P is the probability of technology dissimilation
F_p positive factors
F_n; as subtraction - negative factors
It seems relevant to interpret Shelford's law for sustainability as a mathematic formula. It is possible to use equation type:

$$y = -x^2 + c, \tag{2}$$

where:
c will be equal to 100 (% of sustainability; it's always 100 in the sustainability units, but it will be variable in actual dissemination unit, for example, per cent of biogas installation

dissemination; according to figure 3). In this case, "y" will be used as prognoses level of biogas plants dissemination, and "x" will be used as:

$$\sum Fp - \sum Fn \tag{3}$$

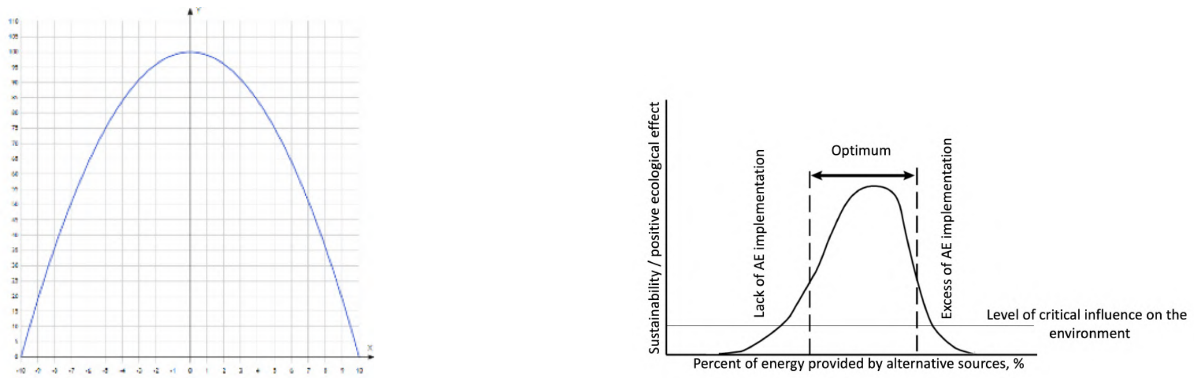
which interpreted as

$$xp^2 - xn^2 \tag{4}$$

In this case, x_p^2 and x_n^2 are real factors, which affect biogas technology dissemination positively and negatively, respectively, and can process with simple mathematical operations (addition, subtraction). Therefore, the general view of the proposed function will be the following:

$$y = -(x_p^2 - x_n^2) + 100 \tag{5}$$

Where
x_p^2 – quadratic representation of $\sum Fp$;
x_n^2– quadratic representation of $\sum Fn$;
100 – represents 100% of replacing traditional energy with alternative (in the case when nothing hinders development). Proposed formula (a) and its comparison with typical Shelford's law interpreting have presented in figure 6.



(a) (b)

Figure 7. General view of the proposed function (a) and its comparison with typical Shelford's law interpreting (b).

Of course, the proposed equation is not perfect, has some disadvantages, and it will be more relevant to use a polynomial equation, but it will be worse to provide manipulation with dissemination. Therefore, it is possible to affect both XP and XN by providing an implementation of legislation, and in case they are balanced and equal to zero, it will be possible to obtain maximum sustainability. In this way, the equitation has presented in the following form:

$$y = -(\sum Fp - \sum Fn) + 100 = 0 + 100 = 100 \tag{6}$$

6. Factors that affect the sustainability of biogas production

Today, biogas production is a very variable and complex technology in terms of economics. It defined with: needs of energy (for heating and mixing), water consumption, waste purchasing (in some cases), that vary a lot in different countries and therefore may or may not stimulate the provision of biogas technologies, operating costs, capital costs, including development of technical documentation (significantly depends on the level of salaries in the country) and a profitable component. Equally important is the state of the legislative framework related to biogas technologies implementation, including strategic documents. It means that governance politics in the field can stimulate the spread of anaerobic digestion of organic waste by providing some programs including regulation of the cost of both raw materials and products, as well as provision of economically attractive programs of financing anaerobic digestion technologies in implementation programs. Nowadays, one of the problems of sustainable biogas production is the usage of biofertilizers produced by anaerobic installations. Biofertilizer, defined by higher efficiency compared to other types of fertilizers (including compost and mineral fertilizers) as well as by higher profit compared to biogas produced during anaerobic digestion, cannot be realized. It means, that this is a useful substance that isn‘t used nowadays either in Ukraine or worldwide and even provides negative changes for the environment. It is going on because of the lack of full-scale field experiments on the usage of this fertilizer. However, in scientific publications, the high potential of increasing of growing productivity of different agrarian cultures is shown. However, this is not enough to convince agrarians to use it. This fertilizer is stored in lagoons and pollutes air (by emissions), grounds (by itself) and waters (by dissemination in groundwater). The dissemination effect may be very significant as it is necessary to provide waste dilution up to 10 times which leads to an increase in the amount of produced biogas effluent (biofertilizer). The Law of Ukraine on Waste prohibits biogas plant construction without effluent utilizing. However, in the practice of Ukraine, this law is not considered, and biogas settings constructed without systems of effluent utilizing and have stored in lagoons.

7. Experience of unsustainable biogas production

As shown previously, there is a dependency between the number of biogas plants and the price of energy. It means that it seems perspective to analyse the state and sustainability of the branch in Germany, where both cost of energy (140 €/MW) [28] and the number of biogas plants (more than 11 000) [29] are the highest. Nowadays, this amount will be increased, in both EU member states and Ukraine. Generally, in Germany, anaerobic digestion technologies usage is widely developed. However, the main substrate is not waste, but plants that need to be grown [30]. It means that the full cycle of technology provides plants growth in the fields and their further use for the production of biogas. The fields that can be used to grow food, are used to produce biogas; it can also lead to degradation of the fields. In economic terms, it foresees an increase in operational costs. Therefore, this is not the most sustainable approach of biogas production, but it has provided due to the high cost of energy, which means high economic attractiveness. Biogas production from waste (generated by the food industry) can be more perspective. However, some technologies, even in this case, can be non-sustainable. For example, in Ukraine, where gas prices are significantly lower than in Germany, this approach is more common than the growing of plants (there are no notes about this technology in the industrial scale) and enterprises use anaerobic digestion not only for biogas production but also for waste utilizing. However, those technologies sometimes are still not effective in the environmental. There are few biogas installations, which provide dilution of waste up to 10 times and its storage (for example Oriellider, Dnipro), badly affecting the environment. Therefore, today it is necessary to provide anaerobic treatment of organic waste (not plants) with high economic and ecological efficiency to provide sustainability. However, now modern technologies are implemented not quickly, and nowadays there are not a wide variety of examples of industrial installations working on hard, disposing of anaerobic digestion substrates, which are characterized by high ecological and economic effect.

8. Conclusions

The use of Shelford's law to provide an assessment of project sustainability is proposed. The proposed approach considers a lot of factors, including ecological, economic and social. Economics as an instrument to provide regulation of dissemination of technologies to provide sustainability, and the experience of both sustainable and unsustainable biogas production is described. We have described the problem of sustainability of renewable and alternative energy and assessed potential ways of risks decreasing. The practical aspects of using the proposed model of Shelford's law to reach sustainability of alternative energy sources dissemination are shown in examples of effect on Shelford's law graph providing of new technologies and effect of nature factors on the graph. Also, it is proposed to use economics to reach sustainability related to alternative energy source usage. To provide it, it is proposed to change the factors that affect the economic attractiveness of providing such technologies by private enterprises and then the amount that will be the most probably implemented will correspond to sustain optimum. The cases of both, effective usage of economics and ineffective ones are shown and described. The basic formula that can be used to provide a practical approach of Shelford's law usage related to alternative energy dissemination is described, but it is required to be optimized in further works. To prove the relevance of usage of the proposed model, the factors that affect sustainability and causes of instability of biogas production are described.

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Seeds on a parachute: the technology of greening

To cite this article: A V Zdeshchyts and V M Zdeshchyts 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012024

Seeds on a parachute: the technology of greening

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Abstract. To strengthen the sides of tailing dams and stockpiles, it growing forests from trees, shrubs and plant grass. Due to the difficult topography of the terrain, greening technologies require new ideas and material support. The objective of the research is to develop a technology for sowing large areas of plants with seeds from the air. In order to sow large areas with plants, it proposed to scatter seeds (grains) from a height onto hard-to-reach slopes, attached to a parachute system of a special design. Thousands of swarms of miniature capsules with seeds lifted by the drone and released by it at a given height will be scattered by the wind over large cultivated areas. The capsule filled with grain, fertilizer, humus and a compartment with water (gel). The parachute system is a three-dimensional paper platform that allows the capsule attached to it to fall smoothly and slowly. The hooked plumage of the platform provides its reliable grip on the ground. The platform is also soaked with seed nutrients before launch. Analytical, computational and experimental studies have confirmed the highly efficient aerodynamic properties of the developed parachute systems. 3D flying platforms demonstrated controlled rotation kinematics (18 rad/s) and low final speeds of 1.6-1.9 m/s .

1. Introduction

To strengthen the sides of tailing dams and stockpiles, it growing forests from trees, shrubs and plant grass. Forests regulate and retard surface runoff, and prevent the washing away of soil growing on the slopes. It prevent the formation of landslides. Not least is the protection of cities from dust. Not only tailings are gathering dust, but also dams and access roads. All this requires a universal landscaping technology.

Due to the difficult topography of the terrain in Kryvyi Rih iron ore basin, the process of greening is especially laborious. It is extremely difficult to tie together an aggressive and hard environment with tender green sprouts. In addition, an average of 55 mm of precipitation per month falls in the Kryvyi Rih region, which is clearly not enough for the successful germination and further stable development of the plant sprout.

The stockpiles are planted with greenery using different technologies at Kryvyi Rih mining and processing plants. For example, a special cultural liquid was used for the reclamation of the dump slopes at Ingulets GZK [1]. Using hydraulic monitors, a mixture of rapeseeds, cereals and useful substances (nitrogen, potassium, phosphorus, organic polymers) is applied to the dumps. At the end of 2020, the technology was already applied on a plot of more than fifty hectares. As reported, plants sprouted all over the surface. Although it is clear that it is impossible to cover the surface of the slopes with this method. How much the landscaping of one square meter of the slope costs is also not reported, but, obviously, this is an expensive technology.

The slopes of the Northern GZK tailing dump covered with silt, moistened, sown with herbaceous plants to reduce dusting [2]. It is clear that it is also not realistic to process all dusty surfaces in this way. The same gloomy picture is observed at other mining and processing plants.

Therefore, the goal of our research is to develop a technology for sowing plants with seeds over large areas, using a natural assistant - the wind and modern technology - drones.

2. Analysis of actual research

Irish company BioCarbon Engineering uses drone to restore mangrove forest in Myanmar [3]. Figure 1 shows the technology of planting capsules with plants.

Figure 1. UAV-assisted forest planting technology.

As you can see, the capsules fall on the loosened soil. Watering is carried out after planting the seeds, that is, the exact coordinates of the capsules are required, the processing of a large array of data, and so on. It is difficult to apply this technology to rocks on slopes, although it is progressive in itself. Currently, the drone developed by the company can carry 150 seed capsules at a time.

Drones from the American company DroneSeed shoot seeds into the ground at a speed of 800 seeds per hour [4].

AirSeed Technologies plants up to 40,000 tree seedlings a day [5]. The unique advantages boost the growth rates of developing seedlings by delivering necessary elements directly to the root systems of the germinated seeds. The data collected is used to drive accurate flight plans that not only fly the drones, but also trigger the carbon seed pod and carbon pellet delivery systems at predefined GPS coordinates.

Thus, drone-landscaping technologies are evolving.

3. Object and methods of research

The object of our research is the development of a technology for sowing a mining surface with plant seeds using wind and drones. The work is theoretical and applied. Methodologically, the research based on the well-known laws of mechanics, aerodynamics and conservation of energy.

Its main scientific and practical results obtained with the use of video and photo recording, digital technologies for processing the results of numerous experiments.

In order to sow large areas with grain and grass crops, it proposed to scatter seeds (grains) from a height onto hard-to-reach slopes, attached to a parachute system of a special design. Thousands of swarms of miniature capsules with seeds lifted by the drone and released by it at a given height will be scattered by the wind over large cultivated areas.

Also, miniature wireless electronic sensor devices can be let out together with a swarm of seeds on the same parachute systems, which will create a system for monitoring the environment and tracking the growth of trees and shrubs [6].

4. Results

The shape of the flying platform was determined by us based on the analysis of the results of works devoted to the creation of large swarms of miniature wireless electronic devices [7, 8] for environmental monitoring [9], population monitoring [10], registration of the presence of diseases in the crowd [11] and other applications requiring coverage of large areas. In addition, the results of works studying the scattering of seeds by wind [12], as well as modern methods of mechanical assembly of three-dimensional structures [13–15], were studied. The optimal design of a 3D flying platform is shown in figure 2.

Figure 2. Photo of the parachute system with the seed capsule.

The capsule in the center of the platform is filled with grain, fertilizer, humus and a compartment with water (gel). The parachute system is a three-dimensional paper platform that provides the capsule attached to it with a smooth, slow fall due to wings optimized for this purpose. It is the long fall time of the platform that provides a large spread of seeds released by the drone in one place and picked up by the wind. The hooked plumage of the platform provides its reliable grip on the ground. The platform is also soaked with seed nutrients before launch. Instead of a paper platform, other environmental materials that have the property of absorbing moisture from the air (moisture-retaining substances) can also be used. The dimensions of the parachute system correlate with the size and weight of the transported seeds.

The average annual wind speed at a height of 10 meters in the Kryvyi Rih basin is 4.2 m/s. As you know, wind speed increases with height according to a power law. The exponent k is determined by the structure of the underlying surface. For cities with tall buildings $k \approx 0.4$. Obviously, for a sown mountainous area, the exponent of k will be of the same order. Therefore, in our calculations, $k = 0.4$ and the dependence of the speed on the wind was taken equal to:

$$v_1 = v_0 * (H_1/H_0)^{0.4}, \tag{1}$$

$v_0 = 4.2$ m/s - wind velocity at height $H_0 = 10$ m above the earth's surface.

The final choice of the design of the flying platform shown in figure 2 is due to preliminary optimization of parachute system parameters. For this purpose, an analytical model was developed for three-dimensional falling aircraft with rotation, and their aerodynamic behavior was considered. The final vertical velocity v_{max} and the angular velocity ω_{max} were chosen as the key parameters that describe the behavior of aircraft during a fall in a stable flight state. They significantly depend both on the properties of the air (air density ρ, dynamic viscosity μ, etc.) and platform geometry (three-dimensional configuration, tilt angle, their number, area, and so on). The rotation velocity of the platform is proportional to the ratio of the final fall velocity to the radius of the platform. Thus, the maximum vertical fall velocity of the platform is decisive in the calculations. The performed calculations showed that the maximum vertical velocity of the platform fall is determined by the formula:

$$v_{max} = \left[\frac{2}{\rho G}\left(\rho_{mat} g d\sqrt{\eta} + \frac{P}{\pi r^2\sqrt{\eta}}\right)\right]^{1/2}, \tag{2}$$

where ρ - the air density, G - the coefficient that takes into account the drag and lift force of a rotating blade aerodynamic profile, d - the blade thickness, η - the platform area fill factor, P - the seed weight.

In situ experiments were carried out to determine the actual vertical velocity v_2 of winged platforms fall. The vertical velocity of 3D platforms in our experiments was the value $v_2 = 1.6$ - 1.9 m/s, which is safe for seeds. The relations between the weight of the cargo P [mN] with the platform and the final velocity of the falling platform ∅ 40 mm was determined by empirical formula (figure 3):

$$v = -0.3P^2 + 1.36P + 0.17, [m/s] \tag{3}$$

The influence of the porosity of the platform material on the final velocity of its fall was also studied. The advantage of porous materials is a significant reduction in the weight of the platform. As it turned out in experiments, the limiting rate of fall decreases k times with increasing porosity p according to a linear law:

$$k = \frac{p}{3}. \tag{4}$$

The maximum radius of the covered area depending on the height of the seed discharge (figure 4) is determined by the formula:

$$R = 1.67 * \frac{H_1^{1.4}}{v_2}. \tag{5}$$

In the general case, the radius of the area covered by the seeds is affected by the properties of the air: air density, dynamic air viscosity, and so on. The effect of air temperature on the final velocity of fall - within 20%.

Another no less important parameter that affects the size of the seed coverage area is the drone's payload. The carrying capacity of heavy quadcopters starts from 5 kg. The payload of the DJI Matrice 600 is about 15 kg. Therefore, to calculate the maximum radius of a circle covered with seeds by a drone at a time, it is necessary to set the carrying capacity of the drone,

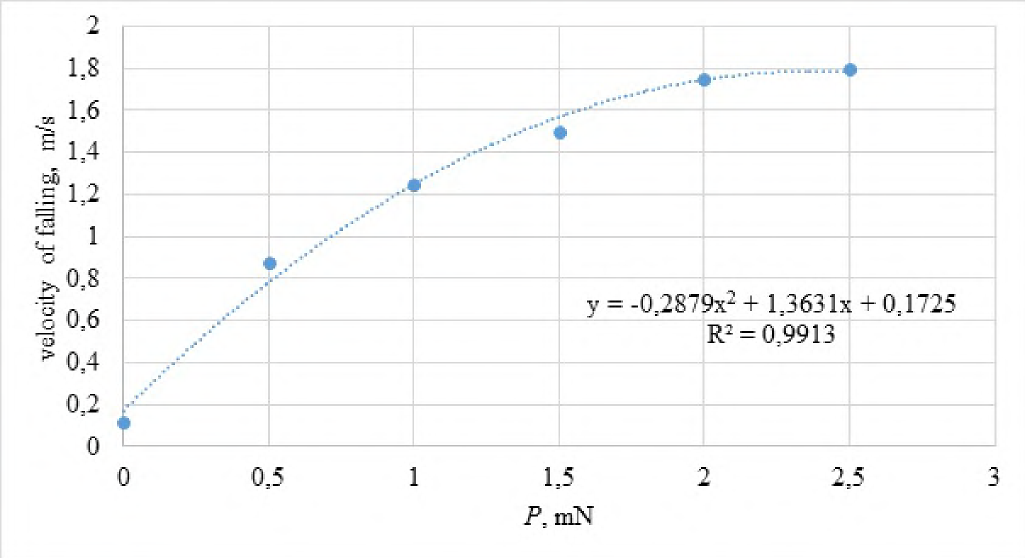

Figure 3. The relations between the weight of the cargo P [mN] with the platform and the final velocity of the falling platform ∅40 mm.

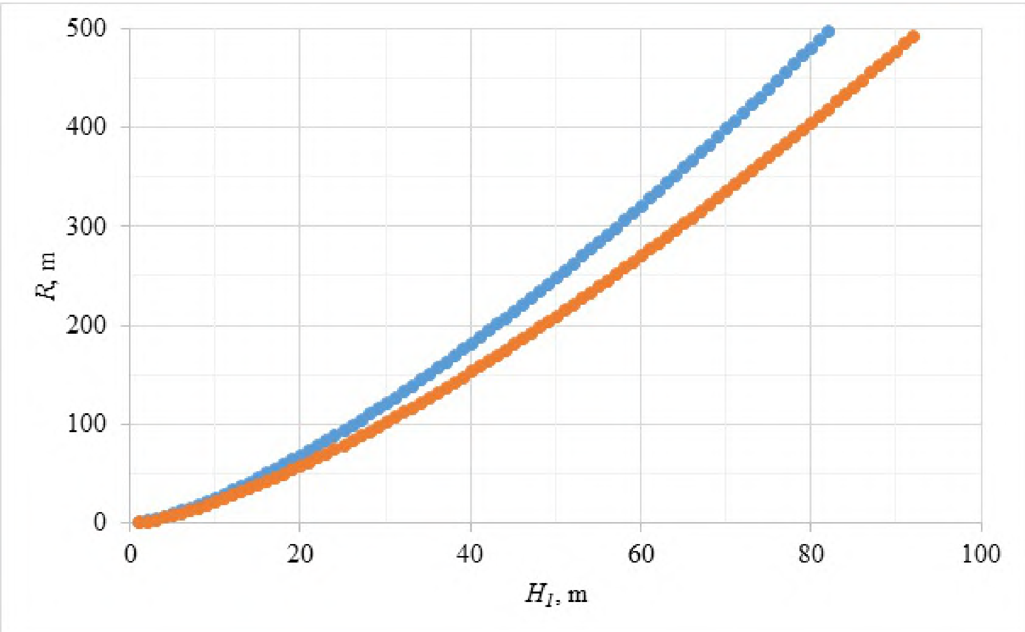

Figure 4. The dependence of the covered area radius on the height of the seed discharge: blue color – v=1.6 m/s, red color – v=1.9 m/s.

the mass of the seed, the mass of the flying platform, the number of grains per one m^2. So, with a load capacity of 5 kg, a grain mass of 40mg, a coverage grid - a square with a side of 1m, the coverage radius will be 300 m. The height of seed discharge without a platform in this case is 60 meters. When placing seeds in a grid with a side of 0.5 m, the coverage radius will be 150m and the seeds must be dropped from a height of 40 meters.

Thus, the criteria for the successful operation of a sowing drone are defined. The technology of greening includes five stages:

1. Creation of a 3-D map of the area by photographing areas subject to reclamation with drone cameras.
2. After analyzing the topography of the terrain data, creating a seeding plan that best fits the landscape.
3. Drones are equipped with tubes that contain flying platforms with capsules that include germinated seeds and hydrogel.
4. Drones fly at a calculated height above the ground. Following the landing pattern, they release biodegradable seed capsules over the slope, located on flying platforms.
5. After planting the seed, the drones perform low-level flights, photographing seedlings to assess the health of shoots and seedlings.

5. Conclusions

Thus, the main result of the study is evidence that the combination of drones with miniature parachute three-dimensional (3D) systems provides a solution to an important environmental problem, namely, sowing the slopes of tailing dams and stockpiles with plant seeds.

The main parameters for the optimal distribution of seed capsules under the effect of wind was determined. The designs of load-bearing platforms was studied, their shape was determined, which ensures controlled flight in the natural environment. Analytical, computational and experimental studies have confirmed the highly efficient aerodynamic properties of the developed parachute systems. 3D flying platforms demonstrated controlled rotation kinematics (18 rad/s) and low final speeds of 1.6-1.9 m/s. The aim of the work achieved using the proposed concept of gardening hard-to-reach places using drones, wind, and microcapsules with seeds on a flying 3D platform.

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To cite this article: V Morkun *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012025

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012025 doi:10.1088/1755-1315/1049/1/012025

Formation of the separation characteristic of ore material thickening based on the model predictive control method

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Abstract. The aim of the investigation is to form an optimal separation characteristic of beneficiation processes on the basis on operational information on time-varying of their parameters exemplified by the process of thickening ore raw materials. Methods of research. In the research work, the following methods are used: analysis of scientific research and practical experience; statistics methods and the probability theory for estimation of experiment results; methods of analytical synthesis and numerical simulation; methods of model predictive control for developing control algorithms of the thickening process; numerical simulation methods for synthesizing and analyzing a mathematical model. The scientific novelty of the investigation is in finding optimal values of the control horizon and the prediction horizon in terms of quality control for a single-channel system of model predictive control of ore raw material thickening. Practical significance involves development of methods and software for determining the control horizon and the prediction horizon values of the single-channel system of model predictive control of the process of ore raw material thickening that are optimal from the point of view of quality control, this enabling optimization of separation characteristics of ore raw material thickening. Results To form a separation characteristic of the process of ore raw material thickening based on model predictive control for the single-channel control system of the thickening process, satisfactory control results are achieved by setting the control horizon equal to one interval. For this value, the quadratic control error does not exceed 0.1452-0.1474. A further increase in the prediction horizon is not feasible since it does not allow significant reduction of the quadratic control error. At the same time, the value of 3-5 intervals is sufficient for prediction horizons. These values are determined by an increase in computational complexity of prediction by 10-20 intervals, which causes a slight decrease in the quadratic control error.

1. The problem and its connection with scientific and practical tasks

Optimization of the technological line of ore beneficiation requires determination of a resulting separation characteristic with the operating point within the optimal separation limit. Yet, in flows of raw materials of the ore processing line, significantly different varieties of raw ore as for their mineralogical, physical, chemical and mechanical characteristics can be processed at different stages [1–3].

Ore processing plants involve such multistage technological processes to prepare ore for subsequent separation as crushing and grinding [4, 5]. The main goal of these operations is in releasing useful ore aggregates and reduce the size of mineral grains to 0.1 mm or less to separate particles of different minerals. The size of inclusions of the useful component in some cases exceeds several classes of particles by its size used to assess particle size distribution of beneficiation products at ore beneficiation plants [6, 7]: "+3", "-3 + 1", "-1 + 0.5", "-0, 5 + 0.25", "-0.25 + 0.125", "-0.125 + 0.071", "-0.071 + 0.056", "-0.056 + 0.044", "-0.044 + 0".

Therefore, it is necessary to study calculation parameters of separation characteristics of technological processes of ore processing, in particular ore raw material thickening, based on operational information about dynamics of their parameters.

2. Analysis of researches and publications

According to the research results [4, 8, 9] for quantitative evaluation of mineral products besides distribution of mineral particles in fractions with varied physical properties ξ, it is advisable to use the index of distribution of useful components. Indices and also allow quantitative evaluation of ore materials. To quantify efficiency of technological units, it is proposed to use separation characteristics which determine the degree of mineral fractions release ϵ into final products of ore processing. The releasing of useful components from initial raw ore mass and moving them into the final product becomes possible due to differences in physical properties ξ of a given useful component. The action of physical forces in the working zones of ore processing units separates particles of raw ore in such way: certain physical properties ($\xi > \xi_p$) of some part of ore particles causes them to move in the different way than other part of ore particles with other physical properties ($\xi < \xi_p$).

A separation characteristic is a continuous function that determines a dependence of release of elementary fractions $[\xi, \xi + \Delta\xi]$ into the concentrate on the physical property ξ [4, 9]. The perfect separation characteristic is noted for a step-like appearance with a jump at a point ξ_p. This point corresponds to the elementary fraction, which is half released into the concentrate, half – into tailings. Real technological units have an imperfect separation characteristic with some inclination $\tan\alpha = d\kappa(\xi)/d\xi$ at the working point, which corresponds to the separation boundary $\xi - \xi_p$. The value of the useful component content β in it correlates with the physical property ξ of each mineral particle: β increases with increasing ξ (or vice versa).

In [10], flocculation of iron ore tailings in a thickener (thickener) at the ore beneficiation plant is investigated. There are obtained dependencies of flocculation efficiency (sediment volume, settling rate, turbidity) on dosage of flocculant. The disadvantage is in that operational control of thickening becomes more complicated as a result of the chemical agents usage.

The research [11] proved that the sediment flow and also the depth of the sediment layer caused increasing residence time for particles in the thickening process. Simultaneously, the disadvantage here is operational control methods for characteristics of ore particles that the work does not suggest.

The research results of ultrafine particles slurry dehydration with the solid phase are presented in [12]. Presented results does not consider formation of control actions directly during the ore processing to increase thickening quality indices.

The research [13] applies methods of calculating fluid dynamics to improving quantity and quality indices of thickening process. In the research a model for balancing the number of particles was used. It is noted that simulation of the feed source enables forecasting solid particle flows and fluids, yet sufficiently accurate results are not provided. Therefore, the authors apply a model for balancing the number of particles. The research results of the balance between hydrodynamic and physicochemical requirements for flocculation are described. There are presented some basic conclusions on optimization of the feed channel design and potential application of the obtained results to controlling the thickener. That's why further research in area of information support of the control system is required.

The research [14] proves that when concentrating a flocculant solution, there appears significant differences in concentration of sands with and without displacement. In the process of the proposed dependencies implementation to control methods of ore thickening must be taken into account the differences in mineral's varieties characteristics.

Methods of cleaning of technological water, used in iron ore processing was proposed in [15]. According to this approach usage of chemical methods of cleaning in thickening process was proposed.

The research [16] suggests neural network approach for creation of the model of ore processing plant. In this case additional investigation in the field of information support is required. Results of flocculation characteristics research is proposed in [17]. According to this approach usage of chemical methods in thickening process was proposed.

The research [18] considers the influence of ultrasonic radiation characteristics on final concentration of thickener sands and flocculation processes in this unit. It is established that ultrasound is able to significantly improve concentration of overflow, while its frequency and capacity are the most important factors. The research [19] investigates into slurry treatment by means of ultrasound and its influence on electrochemical and flocculation designated to increase efficiency of precipitation processes.

3. Problem statement

The results of the analysis of scientific research and practical developments have shown that application of the ultrasonic methods to thickening in developing a method of automated control of ore raw material thickening requires additional research.

This research is aimed at developing a method of automated control of ore raw material thickening to optimize a separation characteristic of this technological process when concentrating several mineral-technological varieties of ore based on the model predictive control method.

4. Presentation of materials and results

An example of comparing the useful component content in a certain grain-size class to the yield of this class distributed along the technological line of beneficiation provided on figure 1. The results of testing the technological line are obtained under the supervision of professor Oliynyk [20, 21].

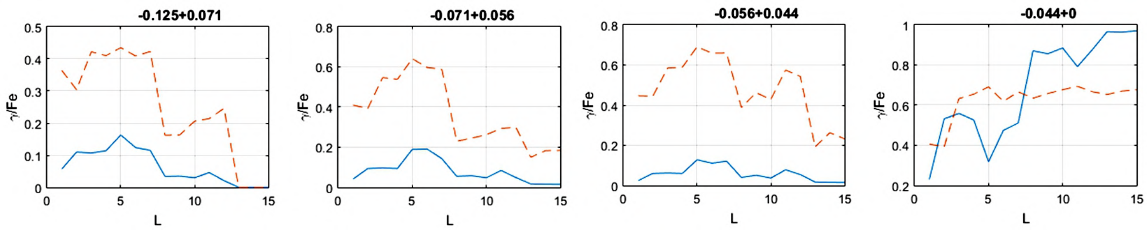


Figure 1. Useful component content in the grain-size class and the yield of this class distributed along the technological line.

The final fractions are released by dividing the total range $[\xi_{min}, \xi_{max}]$ of changes in the physical property ξ of ore particles by a certain number of fractions [4, 22]. The solid fraction in the concentrate is equal to the ratio of the solid yield of a given fraction in the concentrate and the initial material .

$$\bar{\epsilon}_{ik} = \frac{P_{i\,k}}{P_{i\,in}} = \frac{Q_k \bar{\gamma}_{i\,k}}{Q_{in} \bar{\gamma}_{i\,in}} = \frac{Q_k \gamma_{i\,k}(\xi_i)\Delta\xi_i}{Q_{in} \gamma_{i\,in}(\xi_i)\Delta\xi_i} \tag{1}$$

where Q_k, Q_{in} is the yield of solids in the concentrate and initial materials respectively, t/h; $\bar{\gamma}_{i\,k}$, $\bar{\gamma}_{i\,in}$ is the yield of the fraction in the concentrate and the initial material respectively; $\gamma_{i\,k}(\xi_i)$, $\gamma_{i\,in}(\xi_i)$ is distribution of solids in fractions in the concentrate and the initial material respectively. Application of this formula to each fraction allows obtaining a set of released fractions. When the condition $\Delta\xi_i \to 0$, $n \to \infty$ is fulfilled, the mentioned set becomes a continuous function, i.e. the separation characteristic [4].

The values of separation points of the first sizing stage calculated by formula (1) and the data of experimental studies [20, 21] are presented in table 1.

Table 1. Results of calculating the separation characteristic of the first sizing stage.

Grain-size class, mm	Input fraction yield, %	Output fraction yield	Fraction size	Separation characteristic
-1+0.5	23.40	1.50	0.500	0.0000
-0.5+0.25	19.10	8.00	0.250	0.0000
-0.25+0.125	8.90	10.90	0.125	0.0224
-0.125+0.071	5.70	11.00	0.054	0.1461
-0.071+0.056	4.10	9.40	0.015	0.4272
-0.056+0.044	2.40	6.00	0.012	0.6731
-0.044+0	23.00	53.20	0.044	0.7997
Total	100.00	100.00	-	-

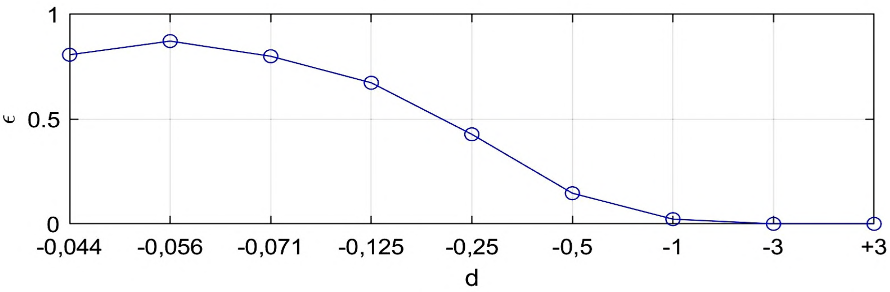
On figure 2 it is shown separation characteristics of sizing units of the technological line at the ore beneficiation plant.

Numerical values of separation characteristics are given in table 2.

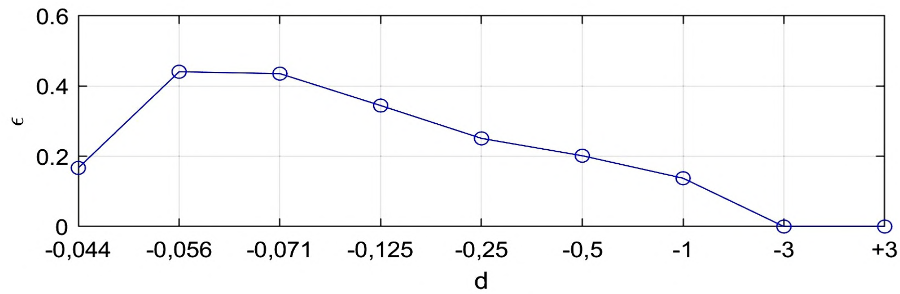
Table 2. Results of calculating separation characteristics of sizing units.

Grain-size class, mm	Classifier 1 (overflow)	Classifier 2 (sands)	Thickener 1 (sands)	Classifier 3 (overflow)	Thickener 2 (sands)
+3	0.0000	0.0000	0.0000	0.0000	0.0000
-3+1	0.0000	0.0000	0.0000	0.0000	0.0000
-1+0.5	0.0224	0.1376	0.0000	0.0000	0.0000
-0.5+0.25	0.1461	0.2016	0.0000	0.0000	0.0000
-0.25+0.125	0.4272	0.2510	0.0000	0.0000	0.0000
-0.125+0.071	0.6731	0.3445	0.9171	0.0000	0.0000
-0.071+0.056	0.7997	0.4354	0.9395	0.1154	0.8846
-0.056+0.044	0.8720	0.4408	0.9892	0.1306	0.8846
-0.044+0	0.8068	0.1669	0.8756	0.3594	0.9379

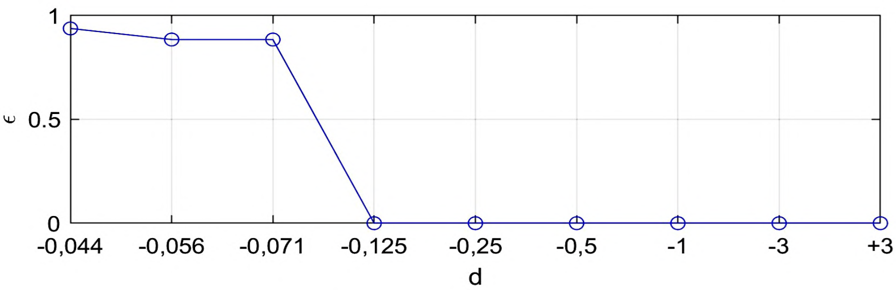
To apply separation characteristics of technological units to controlling beneficiation processes, it is necessary to approximate them. Basic results of approximation are presented in table 3.



(a)



(b)



(c)

Figure 2. Separation characteristics of sizing units of the technological line at the ore beneficiation plant: classifier overflow (a), classifier sands (b), thickener sands (c).

Parametric models (table 3) are evaluated by the following indicators. The sum of squares due to error (SSE) is calculated by the formula [23]:

$$SSE = \sum_{i=1}^{n} w_i (y_i - \hat{y}_i)^2. \tag{2}$$

The closer to 0 the value obtained is, the smaller the value of the random error component is, this indicating high accuracy of the model. The multiple coefficient of determination (R-Square) indicates what fraction of result dispersion is caused by the influence of independent variables. This indicator is determined as a ratio of the sum of regression squares (SRS) and the total sum of squares (TSS). SRS and TSS are determined as follows [23]:

Table 3. Results of approximating separation characteristics of sizing units.

Function	Number of coefficients	SSE	R-square	Adjusted R-square	RMSE
Gaussian	3	0.01177	0.9897	0.9863	0.04429
Linear	3	0.09543	0.9169	0.8892	0.1261
Polynomial	2	0.1013	0.9118	0.8992	0.1203
Polynomial	3	0.1012	0.9118	0.8824	0.1299
Power	2	0.4844	0.578	0.5177	0.2631
Power	3	0.09881	0.9139	0.8852	0.1283

$$SSR = \sum_{i=1}^{n} w_i(\hat{y}_i - \bar{y})^2, SST = \sum_{i=1}^{n} w_i(y_i - \bar{y})^2. \quad (3)$$

At the same time, these indicators are related by the ratio $TSS = SRS + SSE$. The multiple determination coefficient (R-Square) is defined as follows [23]:

$$R - Square = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \quad (4)$$

The value obtained is in the range from 0 to 1. The closer the value obtained to 1, the greater dispersion fraction is taken into account by the model. The Adjusted R-Square is used to ensure correctness of the models with different number of factors, so that the number of fixed variables (factors) does not affect the results [24].

A radial thickener is a low cylindrical tank (3.6m–4.2 m) with a conical bottom and an annular chute for draining the clarified slurry [25]. A truss is installed in the tank with the rakes fixed for continuous mixing of settled materials to the unloading opening at the bottom of the conical part of the tank. The truss makes 0.01-0.3 revolutions per minute. The feed slurry is continuously supplied to the middle of the thickener tank through the recessed feeder. The clarified fluid is poured through the threshold into the annular chute and removed through a special pipeline to the tailings or used as circulating water. The thickened slurry formed from sediments is removed through the discharge openings and pumped out. The main input signal – a controlled value for automatic stabilization of the thickener – is the density of the thickener overflow slurry (or initial concentration), and the density of the overflow slurry (or initial concentration) is the main signal to optimize the unit [25, 26]. Main disturbances of the process are changes in concentration and volume of the feed slurry. Changes in the valve opening of the overflow of the thickened slurry at the output from the thickener and coagulant consumption are control actions.

The control of the thickening process is formed using the method of model predictive control (MPC). The MPC controller uses the following mathematical model [27, 28]:

$$\begin{aligned} x_p(k+1) &= A_p x_p(k) + BS_i u_p(k) \\ y_p(k) &= {S_0}^{-1} C x_p(k) + {S_0}^{-1} DS_i u_p(k) \end{aligned} \quad (5)$$

where S_i, S_0, So are the diagonal matrix of input and output scale factors in technical units, x_p is the state vector, u_p is the vector of dimensionless values of control coefficients, y_p is the vector of dimensionless values of the controlled object output. When synthesizing model predictive control, the controller solves an optimization problem at each control interval. The result of the solution is the values of controlled variables to be applied to the object in the next control interval.

The formation of model predictive control of the thickening process by the channel "area of the overflow valve opening - initial concentration" is depicted on figure 3.

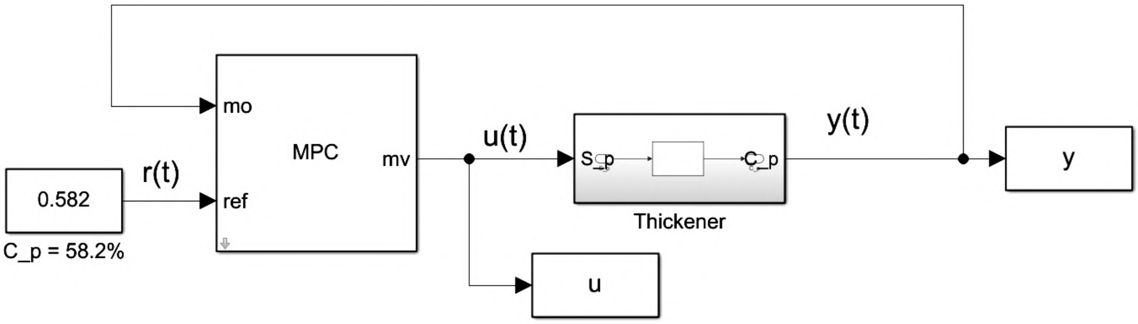


Figure 3. System of forming model predictive control over thickening.

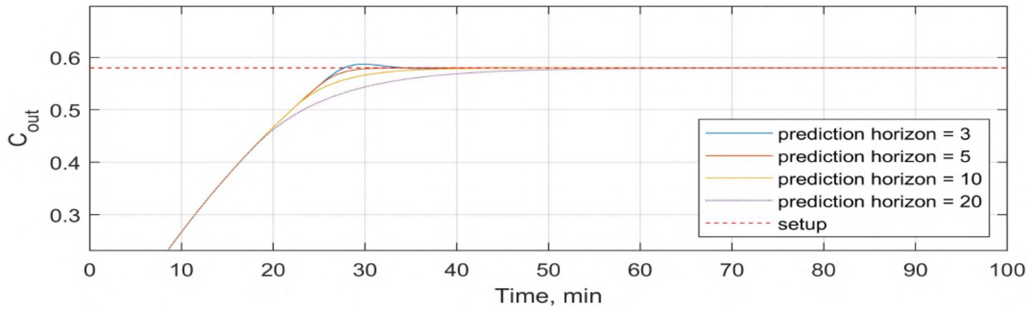
On the basis of this model predictive control scheme (figure 3), the influence of values of the control horizon and the prediction horizon on control quality of the ore thickening process is investigated. The duration of the control interval is assumed to be equal to 1 min. The simulation results for different control and prediction horizons are presented in figure 4. The research methodology enables the fixed control horizon (1, 2 and 5 intervals) and different values of the prediction horizon set (3, 5, 10 and 20 intervals).

Total results of calculating control quality indicators of iron ore thickening at the set values of the control horizon and the prediction horizon are presented in table 4.

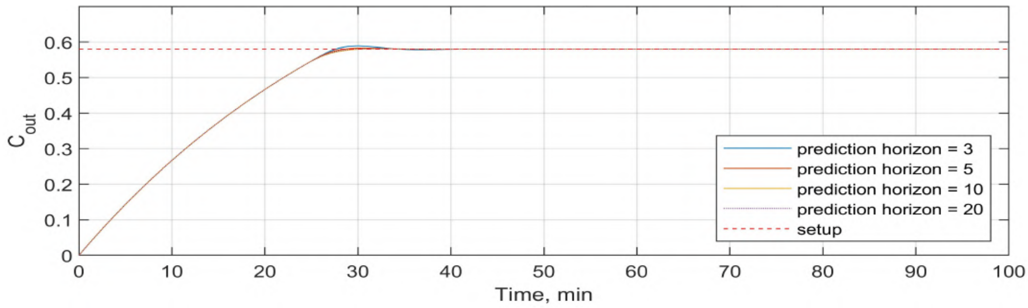
Table 4. Control quality indies for iron ore raw material thickening.

Control horizon	Prediction horizon	Overcontrol	Mean error	Quadratic error
1	3	1.2349	-0.0715	0.1474
1	5	0.005	-0.072	0.1472
1	10	0.0001	-0.0733	0.1467
1	20	0.0016	-0.0778	0.1452
2	3	1.6074	-0.0715	0.1475
2	5	0.5218	-0.0717	0.1473
2	10	0.1553	-0.0719	0.1473
2	20	0.2301	-0.0718	0.1473
5	3	1.6558	-0.0715	0.1475
5	5	0.9032	-0.0716	0.1474
5	10	0.8679	-0.0716	0.1474
5	20	0.7708	-0.0716	0.1474

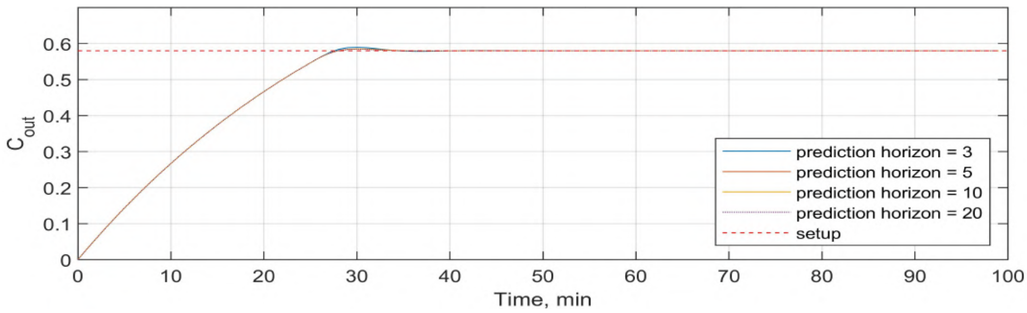
The obtained results allow concluding that when forming model predictive control for a single-channel control system of the thickening process (figure 3), the control horizon equal to 1 interval is sufficient. For this value, the quadratic error varies within 0.1452-0.1474. Further increase in the prediction horizon does not significantly reduce the quadratic control error. Yet, the value of 3-5 intervals will be sufficient for the prediction horizon as increased computational complexity of prediction by 10-20 intervals leads to a slight decrease in the quadratic control error.



(a)



(b)



(c)

Figure 4. Output variable for different control and prediction horizons: 1 step prediction horizon (a); 2 steps prediction horizon (b); 5 steps prediction horizon (c).

5. Conclusions and further research

To form the separation characteristic of the ore raw material thickening process based on the model predictive control method for a single-channel control system, satisfactory control results are provided by setting the control horizon equal to 1 interval with the prediction horizon of 3-5 intervals. Further research is aimed at studying the possibility of controlling the thickening process as a multidimensional object with variable parameters considering, in particular changes in characteristics of mineral and technological varieties of processed iron ore.

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Substantiating arched support made of composite materials (carbon fiber-reinforced plastic) for mine workings in coal mines

To cite this article: V I Bondarenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012026

Substantiating arched support made of composite materials (carbon fiber-reinforced plastic) for mine workings in coal mines

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Abstract. This paper studies a new composite materials based on carbon fiber-reinforced plastic, which is planned to be used for supporting the preparatory workings when mining the coal at depths of more than 1000 meters. The composite material made of carbon fiber-reinforced plastic has sufficient lt high physical-mechanical properties, which are even higher than that of low-alloy steel used as the main material for supporting in coal mines. The purpose of the research is to substantiate the model of support (arched three-link) and determine its rational parameters. The calculation of the stress-strain state around mine working, using the support made of composite materials, has been perfomed based on the method of finished elements in the Solid Works software product. In addition, a model of the support for coal mines has been developed on a 3D-printer. This made it possible to conduct additional research on the interaction of the support with the rock mass. Using the Solid Works software, a detailed modeling of the composite supporting system has become possible. The stress-strain state of the rock mass has revealed that support can be used to improve the strength characteristics and prevent uneven pressure distribution around mine workings. A support made of composite materials contributes to the introduction of resource-saving technologies in the mining industry.

1. Introduction

In the 20th century, the coal-mining industry is still one of the most important sectors of the world economy in many countries. At present [1], [2], the importance of coal decreases, mainly due to its negative impact on the enviroment and the change over to alternative energy sources. However, its use in the energy sector is several times cheaper than natural gas. This allows coal companies to increase production during periods of rising oil prices and leads to an increase in the cost of coal. The implementation of new technologies in the field of processing and use of coal has made it a relatively eco-friendly source of energy.

Long-term macroeconomic indicators show that the world is ready to completely abandon the coal economy. While some countries are phasing out the use of the thermal coal, sales and production may decline in the future, but global demand [3] will remain stable. For example, the current coal share in global energy production is approximately 40 percent.

From the data in figure 1, it can be concluded that the coal-mining industry is a dynamically developing industry [4]. Stable demand is provided by high consumption at the world‘s energy

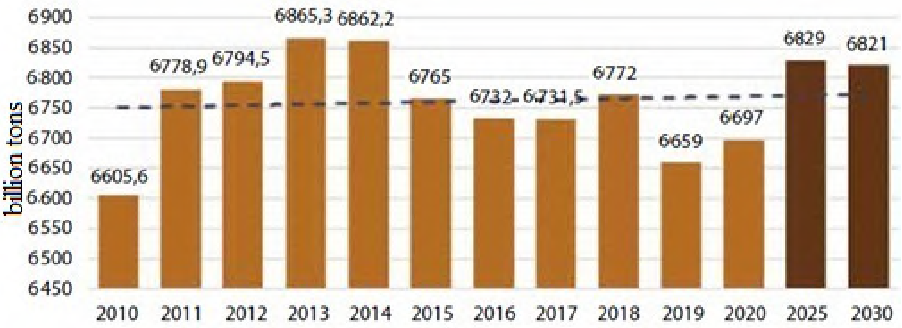

Figure 1. Global bituminous coal consumption dynamics from 2010 to 2030.

enterprises. According to experts, with the current of consumption, the world's coal reserves will be enough for about 230 years (natural gas – for 60 years, oil – for 40 years). This indicates the prospects of coal as an energy resourse.

In modern conditions of influence of decarbonization trends [5], [6], [7], [8], [9], significant attention is still paid to mining of minerals, especially in the context of deteriorating mining-geological conditions [10], [11], [12], which corresponds to the scientific needs of the world economy. There is also a gradual shift from metallic materials to composite plastics, which is conditioned by the greater lightness and plasicity of the latter.

Analyzing the trends in coal-mining industry development in Ukraine [13], it should be noted that rather difficult mining conditions, which are constantly becoming more complicated, are a serious problem in mining the reserves (figure 2). It is with an increase in the depth of mining operations that the mining-geological conditions worsen and the need to ensure the stability of mine workings increases. In Ukraine, the average depth of more than 600 meters and 15 percent – more than 1000 meters. The increase in the depth of mining over the past 30 years on average in Ukraine 505 meters, or 16.8 meters per year.

Figure 2. Deformation of fastening elements in the mine workings at deep mines.

Proceeding from this, a scientific-technical problem immediately arises – the development of support from composite materials for mine working of coal mines located on ultra deep horizons, especially where a sharp deterioration in mining geological conditions is observed. The support structure should not only be light weight due to the use of composite materials, but also meet all the requirements of strength and stability. The implementation of innovative materials is not only actively developing, but also meets certain goals and objectives. These include: strength, elasticity, resource saving, enviromental friendliness and durability. Innovative materials have a namber of properties suitable for fastening of mine workings. However, as indicated by research on the physical-mechanical properties [14], [15], it is better to use carbon fiber-reinforced plastic (CFRP) as a fastening material for the coal-mining industry, since it has high bending strength (1190 MPa) and a low density (1500 kg/m^3), as well as ultimate tensile strength (1400 MPa), etc. An analylis of the physical-mechanical properties of composite materials [16] confrims that CFRP is light weight (5 times ligher than metal), resistant to mechanical stresses, flexible, and can be made of any geometric shape. One of the problems for using the carbon fiber-reinforced plastic [17], [18] is its high cost. Having analyzed the global trend in the market of composite materials, dependence has been constructed (figure 3) that shows that in about 5 – 10 years the material cost will be equal to that of metal.

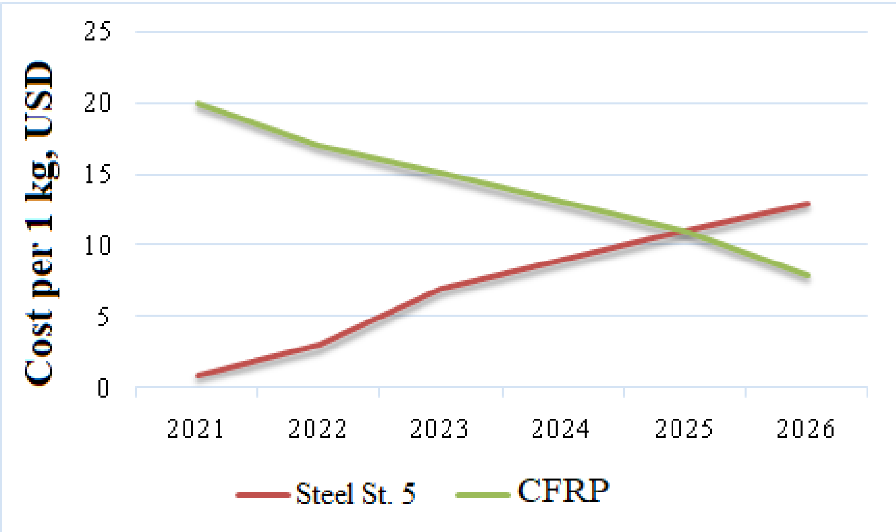

Figure 3. Dynamics of changes in the cost of steel and CFRP for the next years.

The only way to reduce the cost of CFRP is to improve the process of automating the CFRP production, which will reduse the material cost and help to be competitive in the market for innovative and metallic materials.

Horizons with increased nonuniform pressure, developed by coal mines, are an integral part of mining operations. With an increase in the depth of mining, the costs of conducting and maintaning preparatory mine workings, the share of which in the cost of coal reaches 30 – 45 percent, increase significantly. For the fastening of mine workings, mainly arch supports from a special SCP profile (90 – 95 percent) are used, the specific metal consumption of which has doubled and amounts to 600 – 1000 kg per meter run. However, annually, the average length of repaired mine workings reaches 43 – 57 percent, and fully refasted mine workings – 12 – 25 percent of the volume of maintained mine workings [19].

The process of developing a technology for fastening a mining area [20], [21], [22], [23] is a very difficult task, which is aimed not only at preventing the rock mass deformation, but also at controlling the negative phenomena: water inflows, heaving of bottom rocks and others.

The purpose of our research is mathematical modeling of a rock mass with a support from CFRP in real mining-geological conditions, analysis of the obtained stress-strain state and substantiation of recommendations for the possible use of innovative fastening elements.

2. Problem statement and solution

The development is based on the task of improving the arch support, in which, by implementing new structural elements and their interconnection, the possibility of damping is achieved by changing the interaction of the cap board with the frame prop stays, there by making the structure light weight, reducing stresses around the fastening contour, especially in difficult mining-geological conditions. Due to this technical solution, the labor intensity of the work perfomed is reduced, which acceleratest the time of technological work, as well as the safety of miners. The model of an arch yielding support (figure 4) made of composite materials for coal mines on ultra-deep horizons (developed Tsivka, Bondarenko, Kovalevska, and Sheka, 2021) includes cap board connected by yielding nodes with prop stays of the same profile. The yielding nodes are made in the form of arod-shaped cylinderfilled with a plastic material, with the possibility of moving frame cap boardin vertical plane, as well as damping the support.

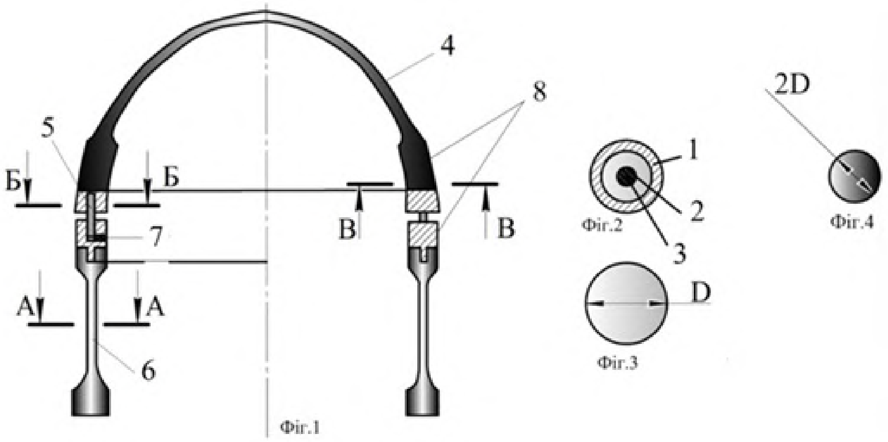

Figure 4. Model of an arch yielding support of replaceable profile from CFRP: 1 – metal, 2 – carbon fiber-reinforced plastic (CFRP), 3 – plastic material, 4 – replaceable profile capboard, 5 – metal rod-shaped piston, 6 – replaceable profile prop stay, 7 – orifice hole, 8 – yielding node.

The yielding property of a structure begins to occur in difficult mining-geological conditions. The frame cap board with a built-in metal rod subsides, after which the plastic material flows and exits through the orifice hole. The arch support begins to work in a yielding mode under conditions of significantly high stresses. There is a possibility of a plastic material leaking through the orifice opening, when the structure begins to dampen, and the metal rod is lowered along the frame prop stay. This is accompanied by a more uniform distribution of stresses along the entire support contour, which, together with the replaceable profile factor, helps to reduce the negative phenomena of rock pressure manifestations.

The presented model can ensure the stability of mine workings by means of more uniform stress distibution around the support contour, as well as to increase the loadbearing capacity of structure due to variable section with a significant reducion in the special profile weight by 5-6 times. At the same time, the labor intensity of perfomed work is reduced and the miners work safety is increased.

With the help of computer modeling in the Solid Works software product, a support made of composite materials and a laminal isotropis mass have been modeled in detail for the conditions of PFSC Mine Administration “Pokrovske” (figure 5). In addition, to substantiate it, the intensity of stresses in the “mss-composite support” system has been studied. The model has a number of limitations, such as: the depth of mining the extraction working, as well as its orientation relative to the coal seam; structure of rock layers and their physical-mechanical characteristics; typical section of mine working, as well as structural and technological characteristics of the composite support.

Despite the limited size of the border rock zone, it is in it that the main geomechanical processes occur, which ultimately affect the stability of mine working. These include the formation of de-stress zones in the rocks of the roof and bottom of mine working, as well as zones of increased rock pressure (IRP) in the sides. In these areas, zones of the limiting state of the rock are formed (stages of weakening and loosening in the complete deformation diagram), which make a decisive contribution to the formation of loads on the support.

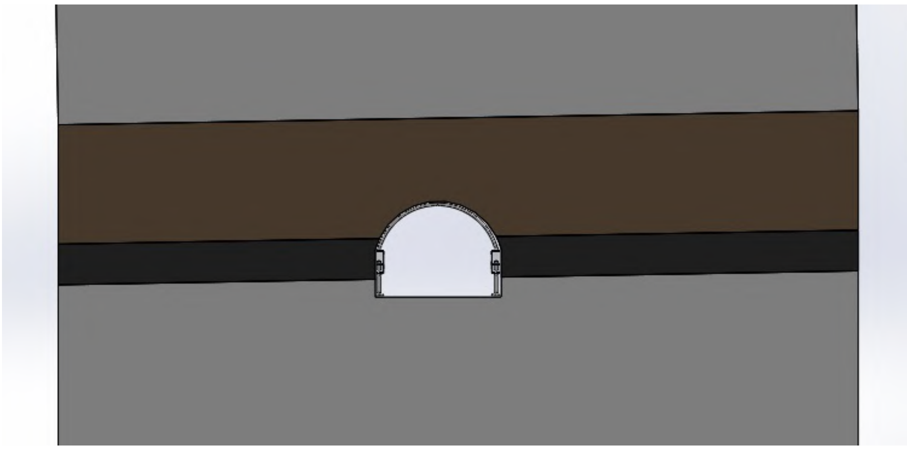

Figure 5. Composite support in a laminal isotropic rock mass according to the conditions of PJSC Mine Administration "Pokrovske"

The analysis of the strain-stress state of the rock mass under the action of horizontal and vertical stresses depends on the Poisson's ratio of each rock layer, set in the Solid Works program when determining the number of parameters and mechanical characteristics of rocks. The loads of 27.5 MPa are applied, calculated by the formula:

$$\sigma = \gamma H \tag{1}$$

where H – the depth of mining (1100 m).

One of the most important characteristics that determine the stress distribution in the rock mass is the lateral pressure coefficient. With changing the load, the values of the coefficients also change. As the load increases, the coefficient also increases, and only in a certain load interval it remains constant. The lateral pressure coefficient is calculated by the Dinnik formula for the model:

$$\lambda_{el} = \frac{v}{1-v} \tag{2}$$

where v – is the Poisson's ratio of the required rock.

The vertical component (vertical intensity) at a specified depth is determined by the weighted average rock density, while the horizontal component (horizontal intensity) is proportional to geostatic pressure and is determined by the formula:

$$\sigma_x = \lambda_{el} \gamma H \tag{3}$$

Analysis of horizontal stress (figure 6) for the border mass presents the following information. To begin with, such a range of stress values has been set from -18 MPa for compressive stresses and up to +7 MPa for tensile stresses.

According to the research results, it can be seen that compressive stresses arise in the mine working side rocks within the range of -3 – 0.5 MPa. When examining the upper and lower layers of the coal seam with a Poisson‘s ratio of 0.21, it can also be concluded that there are compressive stresses in the side rocks.

Analyzing the mine working immediate roof, represented by siltstone, it is possible to observe tensile stresses. In the central part, tensile stresses act in the range from 2.0 to 3.5 MPa. The immediate roof destruction in the mine working can occur in an area that is approximately 2.1 m wide and about 1 m high.

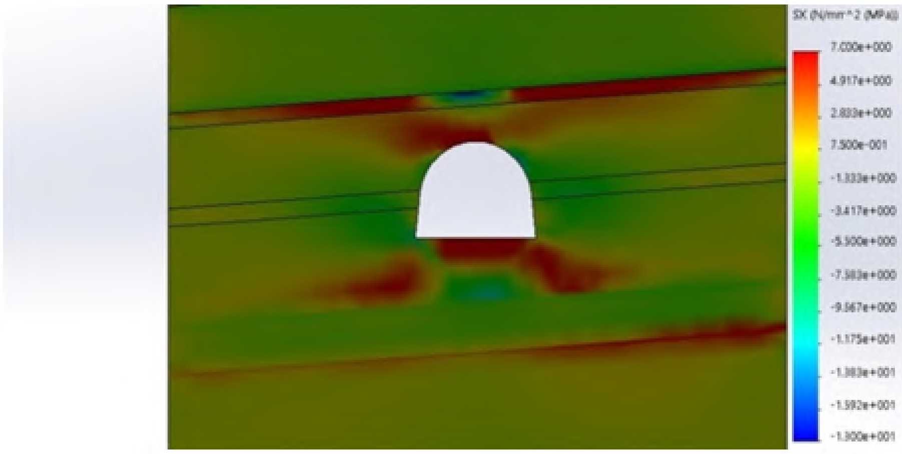

Figure 6. Curve of horizontal stresses for rock outcropping.

Taking into account the entire roof area, tensile stresses from +1 to +3.5 MPa act there. When examining the mine working bottom, the tensile zone has a smaller width than the width of the mine working and is approximately 3 m and a depth of 1.5 m. Tensile stresses in this area range from 2.5 to 4 MPa. There is also a zone of de-stressing in the lower part of the mine working, taking into account the coefficient of destruction and water-cut of the coal seam. Stronger tensile loads are observed in the right corner of the mine working than in the left corner, and this part of the right corner is about 3 m wide and 2 m deep. There are also de-stressing zones in both sides of the mine working bottom. This area is about 5 m wide and 3 m deep with a stress range from +1 to +2 MPa. Due to tensile stresses, heaving of rocks is expected in the mine working bottom.

The zone of two tensile stresses occurs above the coal seam 4 m wide and 4 m high, and below the coal seam there is a zone 5 m wide and 3 m deep. As far as the side rocks have a high degree of destruction and water saturation, but the coal seam has a high strength, according to the action of compressive stresses, destruction does not occur.

The analysis of the reduced stresses for the border rocks of the in-seam working in block №11, PJSC Mine Administration "Pokrovske", shows the following results. Under the coal seam, there is a significant area of rocks that are exposed to compression (figure 7). This area is approximately 3.5 m wide and 4 m deep. Stress range is 6.5 – 9.5 MPa. Rock heaving and increased stresses in the mine working bottom are possible, caused by rock dinting. Increased stresses occur in the corners of mine working, ranging from 27 MPa to 30 MPa. In these places, compression of rocks is possible.

Analysis of the distribution field of horizontal stresses in the frame support (figure 8) shows the following results. A range of -50 MPa for compressive stresses and up to +50 MPa for tensile stresses has been set for the frame support.

The peculiarities of the stress field in the composite support are as follows. Quite large

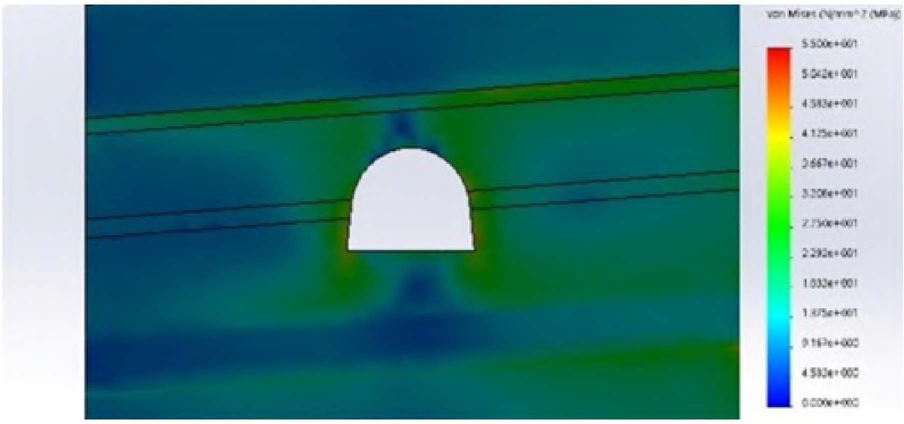

Figure 7. Curve of stress intensity for rock outcropping.

compressive stresses 34 – 40 MPa act in the cap board, the most destressed is the yielding joist, where compressive stresses 5 – 10 MPa act, as it should be when it comes into action. Tensile stresses practically do not act in the lower parts of the prop stays, while relatively large tensile stresses act in the middle part of the prop stays, approximately 45 – 50 MPa.

Taking into account the stress intensity, it has been determined in the SSS analysis of the composite support that the stress ranges from 0 MPa to +300 MPa (figure 9). Stresses 50 – 70 MPa act in the central part of the composite support cap board, and the other part is almost destressed. This indicates a relatively uniformly low-loaded cap board. Quite small loads 5 – 15 MPa act in the yielding nodes, which is caused by a completely new technology of the yielding mode. The frame prop stays are the most loaded, where the strongest stresses 80 – 110 MPa act.

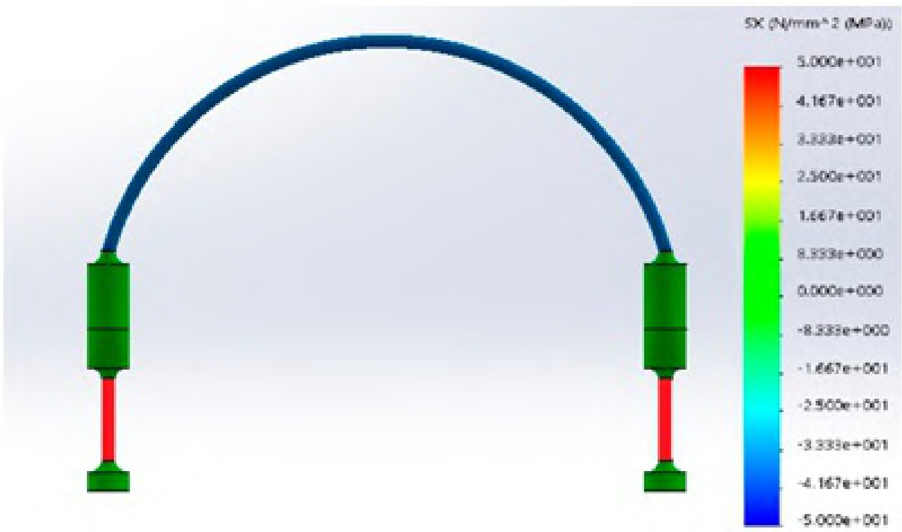

Figure 8. Curve of horizontal stresses in composite support.

The development of large depths of mining, especially in difficult mining- geological conditions with unstable rocks, requires a reassessment of the requirements for the role of support characteristic. It should be noted that in the studies [24], [25], [26], the maximum permissible stresses are considered to be 100 – 150 MPa, which generally corresponds to typical mining-geological conditions and the existing development of means for fastening the mine workings. Under these conditions, the structure is stable, slightly deformed, operates in a yielding mode, and the mine working is able to perform its operational functions. Moreover, at great depths, the stress intensity can increase up to 200 – 250 MPa, and more will be inexpedient.

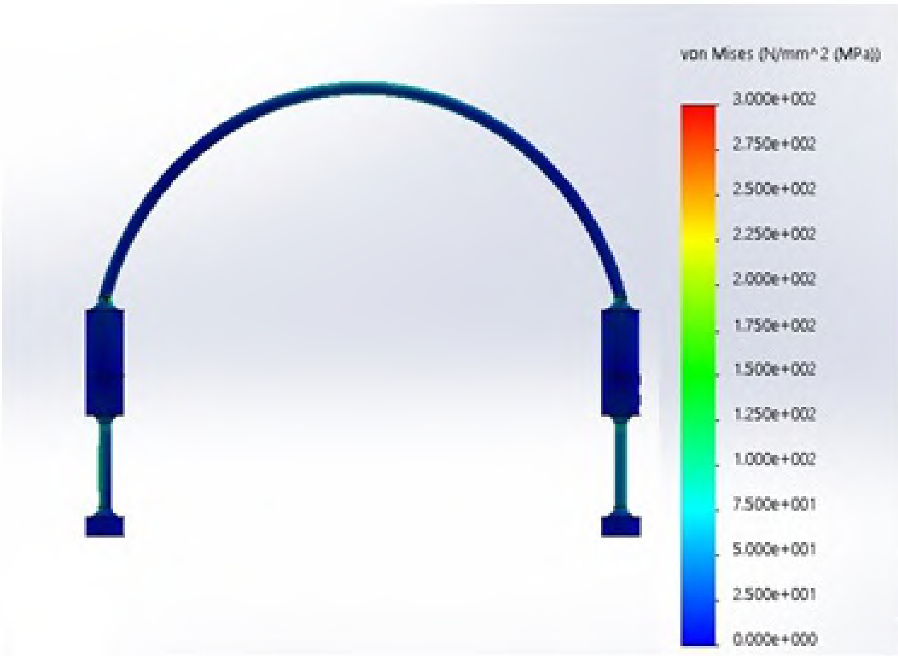

Figure 9. Analysis of reduced stresses in composite support.

According to the quality factor, the parameters of the distribution components of stress deformations correspond to the existing representation of the rock mass deformation processes around the mine working [27], [28], [29]. The results obtained do not contradict numerous geomechanical studies in this area [30], [31], [32], [33], [34], [35]. This confirms the correspondence of the model to the real conditions of mining operations in coal mines.

What is more, in the last decade, 3D-printing technologies [36], [37], [38] have become widespread, with the help of which it is possible to create different models. In the studies [39], [40], [41] the three-dimensional printing process is called Rapid Prototyping. Thus, 3D-printing is a method that makes possible to obtain a layer- by-layer physical object from a mathematical model developed in a special CAD system. Technologies of 3D-printing are widely used in many fields, such as medicine (creation of artificial implants, etc.), in machine-building industry, in instrument-making industry, in energy, motor vehicle industry, etc. [42], [43], [44], [45].

Based on this, the following rather relevant scientific and technical task arises – the development of a model for coal mine support made of CFRP using a 3D printer. This makes it possible to conduct additional research on the support resistance. The manufacturing material is a special carbon thread for 3D printers, and the process of creating a support structure is shown in figure 10. This makes it possible to test and study the composite support for compressive and tensile stresses in the laboratory (figure 11).

Under laboratory conditions, an equivalent stress of 8 KPa is set on the press, which indicates the following results. In the frame prop stays, the tensile stresses of approximately 0.3 – 0.5 KPa act, and in the frame cap board, on the contrary, compressive stresses 0.1 – 0.4 KPa act.

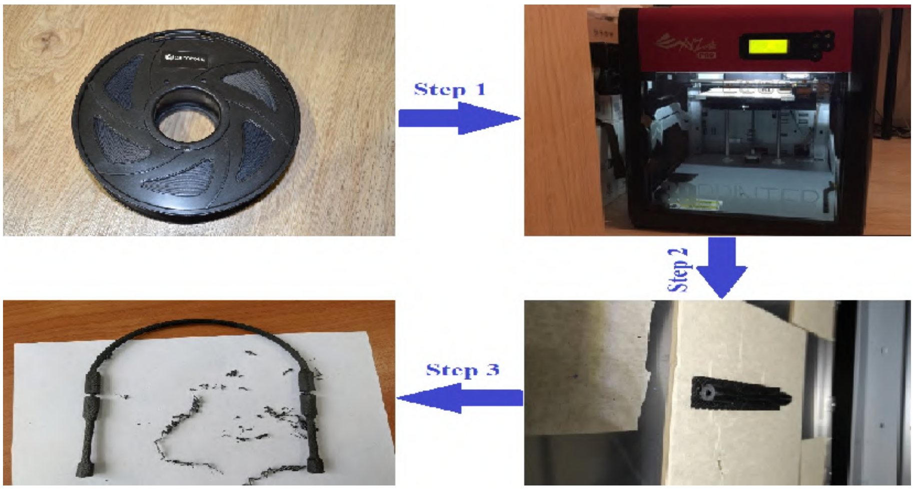

Figure 10. A step-by-step process for creating a composite support on a 3D-printer.

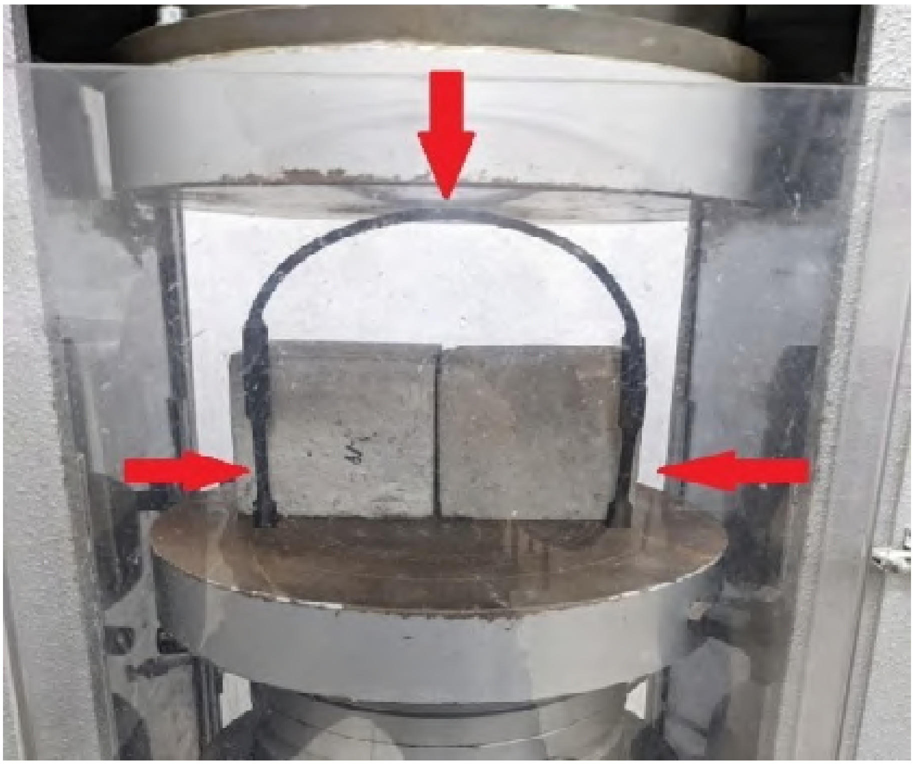

Figure 11. Conducting of laboratory tests on composite support for tensile and compressive stresses.

Moreover, the frame prop stays begin to deform, but in general, the composite support remains stable, as can be seen from figure 11. This makes it possible to compare the results of computer modeling and laboratory tests.

3. Conclusions

The new structure is called a "composite support". The innovative development idea is to move from the traditional SCP profile to a round section, as well as to move from a yielding joist to a yielding node. With the help of computer modeling, a laminal rock mass has been developed, as well as a computational experiment has been performed. The study of SSS analysis of the composite support has revealed that the stress intensity in the frame structure of the support is not more than 110 MPa. Insignificant compressive stresses act in the frame cap board, and tensile stresses act in the prop stays. This indicates the support operation in a yielding mode even in difficult mining-geological conditions with significant manifestations of nonuniform rock pressure.

A composite support model, developed on a 3D-printer, makes it possible to study the structure using a press in the laboratory. The convergence of the results has been confirmed during computer modeling. The implementation of composite support in the mine workings will not only improve the state of drifting workings, but also strengthen the rock mass and improve the working conditions of miners.

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Research of amber extraction technology by vibroclassifier

To cite this article: V Ya Korniyenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012027

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012027 doi:10.1088/1755-1315/1049/1/012027

Research of amber extraction technology by vibroclassifier

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Abstract. The article presents basic information about the method of hydromechanical extraction of amber from amber-containing rocks, water-sludge scheme and classification scheme. The constructive scheme of the vibroclassifier is also presented, which is based on the principle of using the influence – vibration and bubbling of the suspension by air bubbles. Studies of the separation process and distribution of fractions in multidisperse liquid on a vibroclassifier of complex action were performed. The obtained theoretical and graphical dependences allowed to establish changes in the parameters of the velocity of sand and amber particles in the bath of the vibroclassifier on the size of fractions and density of the suspension, focusing on the size of amber up to $5mm$. At the same time, the problem of determining the dependence of the transition coefficient from the rate of free to the rate of compressed deposition on the density of the suspension and the size of the fractions was solved. Dependencies have been established that have a theoretical justification for the physical process and that describe the experimental data on the Rayleigh curve.

1. Investigation of the process of separation and distribution of fractions in a multidisperse liquid by a vibroclassifier of complex action

Developed devices based on mechanical spiral classifiers have been proposed for amber mining in Ukrainian Polissya deposits, which differ from known devices by the use of additional influences – vibration and bubbling of the suspension by air bubbles, for example, vibroclassifier, shown in figure 1 [1, 2].

Perforated tubes for bubbling the suspension with small air bubbles are placed in the vibrating classifier inside the chute, a device for creating vibrations is installed under the bottom, additional water is supplied (1) [3]. Small particles of sand, clay and amber get into the lower part of the bath, where with the help of a device with paddle grips (2), through the drain threshold, are discharged into the receiving chute of the drain (3). The sands are picked up in a spiral and unloaded at the top of the classifier (4) [4].

To determine the size of the fractions carried into the drain, you must first determine the speed of free movement of the sand fractions and amber, then compressed air, and then determine

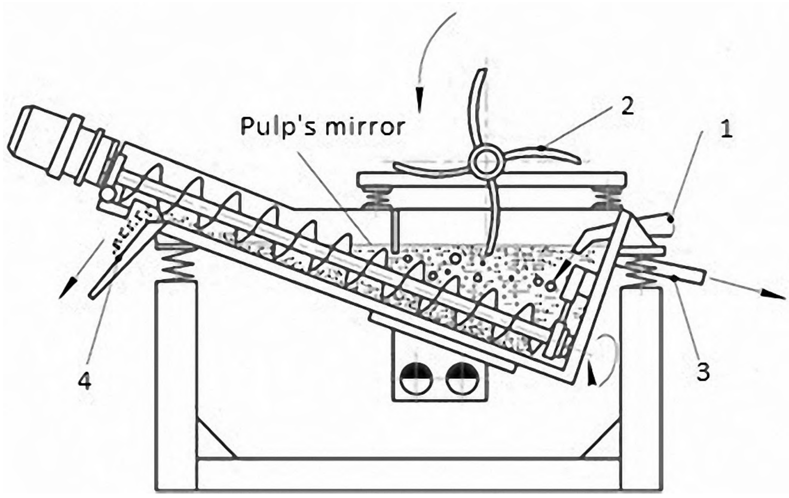

Figure 1. Vibroclassifier of complex action for amber extraction: 1 – additional (circulating) water; 2 – device with paddle grippers for moving floating fractions; 3 – unloading chute for floating amber fractions; 4 – unloading sands.

the degree of additional factors influence – vibration and bubbling [5, 6].

To predict the course of this process in optimal conditions, it is important to have, if possible, a simple analytical apparatus to quantify its features [4, 7].

The vibrating classifier is fed by amber-bearing rocks of the Klesiv deposit with host rocks, consisting of small and medium-sized sand fractions with a small amount of clay.

The rocks are mixed with water and fed into the bath of the vibrating classifier. According to the water-sludge scheme (figure 2), the density of the sand-clay suspension (pulp) in the bath is $1565g/l$ or $\approx 1.6g/cm^3$.

The average content of amber in rocks $19\ldots21g/t$. The density of amber is $1.05\ldots1.24g/cm^3$. Since the density of amber is less than the density of the suspension, then for amber we calculate not the deposition rate, but the rate of ascent [8, 9]. In the calculations we take $\rho_a = 1.24g/cm^3$, which will determine the lower limit of the rate of amber ascent, as fractions with lower density emerge faster.

The main host rock is sand, so for the solid phase of the suspension we take the density of sand $\rho_s = 2.65g/cm^3$. The conditional size (diameter) of the fractions is the arithmetic mean diameter of two adjacent sieves.

The process of separation and distribution of fractions in the bath of the classifier is very complex (figure 3).

To perform a theoretical analysis, we assume that the pulp, which consists mainly of a mixture of sand different sizes with water, is a multidisperse, unstructured Newtonian fluid. To calculate the rate of free fractions deposition in such a suspension, we use the Rayleigh diagram (dependence of the fractions deposition coefficient on the Reynolds number), which we approximate and distinguish several areas: laminar, initial, middle, end of transition and turbulent. Each area is interpolated by its dependence and calculation formula [10, 11].

The choice of the formula for calculating the rate of free deposition was performed not by the Reynolds criterion $R_e = (Vd)/\nu$, as it includes indeterminate values – velocity and diameter of parts, but by our dimensionless criterion A, which is converted by the first parameter P. Lyashchenko, only then adjust the results of the calculation in accordance with the Reynolds criterion (R_e):

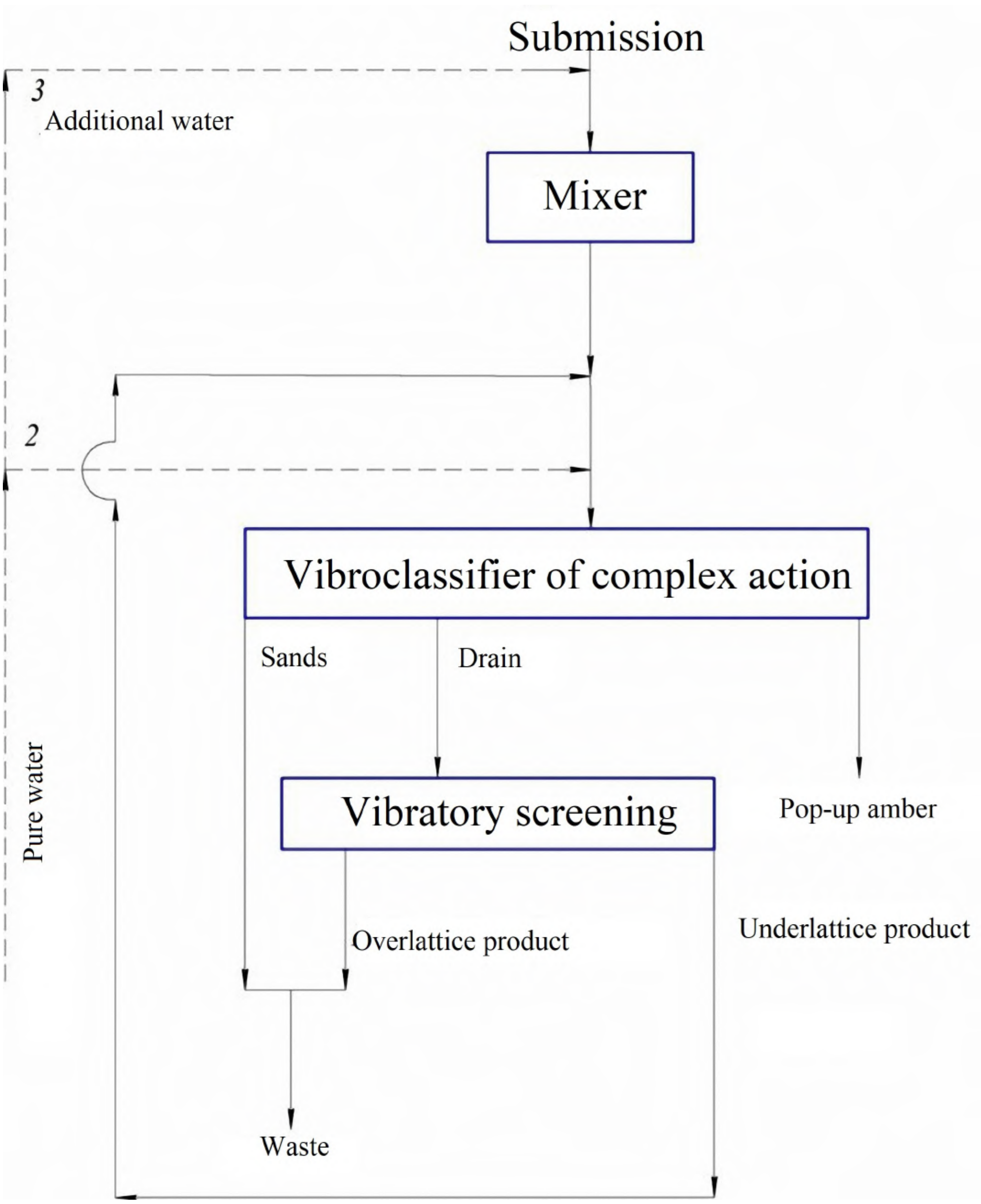

Figure 2. Water-sludge scheme.

$$A = \frac{\pi d^3 g \Delta}{6\nu^2} \tag{1}$$

where

$$\Delta = \frac{\rho_1 - \rho_2}{\rho_2} \tag{2}$$

where d – diameter of fractions, cm; g – acceleration of free fall, $981 cm/s^2$; ρ_1, ρ_2 – density of solid medium and pulp, respectively, g/cm^3; ν – kinematic viscosity of the pulp, cm^2/s.

According to the value of A in table 1 we choose the formula for calculating the rate of free fractions deposition in the liquid.

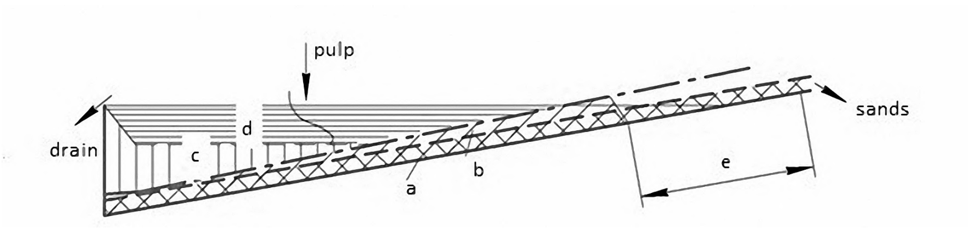

Figure 3. Classification scheme: a – plane of large fractions; b – zone of sands movement before unloading; c – zone of stratification; d – zone of horizontal water flow; e – area of sands dehydration.

Table 1. Formulas for calculating the rate of free deposition of fractions in the liquid depending on criterion A.

№	Criterion A	Area on the Rayleigh curve / author of the formula	The rate of free precipitation of fractions
1	From 0 to 5.25	Laminar / Stokes	$V = 54.481d^2\nu^{-1}\Delta$
2	From 5.25 to 720	The beginning of the transition area	$V = 23.6d^{3/2}\nu^{-2/3}\Delta^{5/6}$
3	From 720 to 23000	Middle / Alain	$V = 24.3d\nu^{-1/3}\Delta^{2/3}$
4	From 23000 to $1.4 \cdot 10^6$	The end of the transition area	$V = 37.2d^{2/3}\nu^{-1/9}\Delta^{5/9}$
5	From $1.4 \cdot 10^6$ to $1.7 \cdot 10^9$	Turbulent / Newton-Rittinger	$V = 57.5d^{1/2}\Delta^{1/2}$

V – cm/s.

Among the formulas of table 1 only the first and fifth have a theoretical justification adequate to the physical process, others – describe the experimental data on the Rayleigh curve. All these formulas, as well as formula (1), includes the kinematic viscosity of the pulp ν, the value of which must be determined.

2. Calculation of the sand fractions free deposition rate and amber ascent

The choice of formula for calculating the speed of free movement of individual fractions in dense pulps is determined according to criterion A, then specified according to criterion R_e (table 1).

The choice of formula depends on both the size of the fractions and the density of the pulp, as illustrated in table 2, 3 in which criterion A is calculated at a pulp density $\rho_c = 1.4g/cm^3$, and $\rho_c = 1.6g/cm^3$, respectively $\nu = 0.021cm^2/s$ and $\nu = 0.036cm^2/s$, $\rho_a = 1.24g/cm^3$. In formula (1) for A, the value of Δ for amber is negative, so in the calculations we take the modulus Δ and determine not the deposition rate but the ascent rate [11].

According to the table 2, 3 Stokes' formula describes the movement of small fractions, Alain – large, but in most cases it is necessary to use the formula (2) table 1, for the beginning of the transition region (from laminar to turbulent), for which $A = 5.25 \ldots 720$, $R_e = 0.5 \ldots 30$. Each formula for velocity is applied to a certain range of fractional sizes, this is illustrated in figure 4. Modern computer capabilities allow for the dependencies of figure 4, as well as similar, with a different density of the suspension, to obtain simpler interpolation formulas than the formulas

Table 2. Criterion A for different pulp density and size of fractions, $\rho_c = 1.4g/cm^3$.

d, mm	A, sand	A, amber
2	8315*	1064*
1.5	3508*	449
1	1039*	133
0.5	130	16.6
0.3	28	5.25

* – Alain speed formula, ** – Stokes speed formula; others - the end of the transition area (table 1)

Table 3. Criterion A for different pulp density and size of fractions, $\rho_c = 1.6g/cm^3$.

d, mm	A, sand	A, amber
2	2080*	720
1.5	877*	301
1	260	89
0.5	17	11
0.3	7.0	2.4**

* – Alain speed formula, ** – Stokes speed formula; others - the end of the transition area (table 1)

given in table 1.

According to figure 5, the dependence of the amber free ascent rate on the density of the suspension is extreme.

It increases with increasing density, reaches a maximum at $1.5 \ldots 1.6g/cm^3$ and then tends to decrease, while the rate of deposition of sand decreases linearly throughout the studied density range. This feature is found for free deposition of fractions, but if this trend continues with limited deposition, it can be concluded about the rational density range, where the rate of amber ascent. Note the Newton-Rittinter formula (table 1), which is used in the turbulent region at R_e more 3000 and A more $1.4 \cdot 10^6$. In equation (1) we set A=$1.4 \cdot 10^6$, and in turn setting a different density of the suspension and its corresponding viscosity, for each density we determine the limiting size d. Then d is adjusted to meet the condition $R_e = 3000$.

3. Conclusions

In this work, the dependences of the velocity of sand and amber particles in the vibroclassifier bath on the size of fractions and the density of the suspension were established, emphasizing the size of amber up to $5mm$. Also solved the problem of determining the dependence of the transition coefficient from the rate of free to the rate of compressed deposition on the density of the suspension and the size of the fractions.

Therefore, it is seen that for sand of the same size with increasing pulp density, the deposition rate decreases, and vice versa. For amber, the rate of ascent is higher for a higher density of the

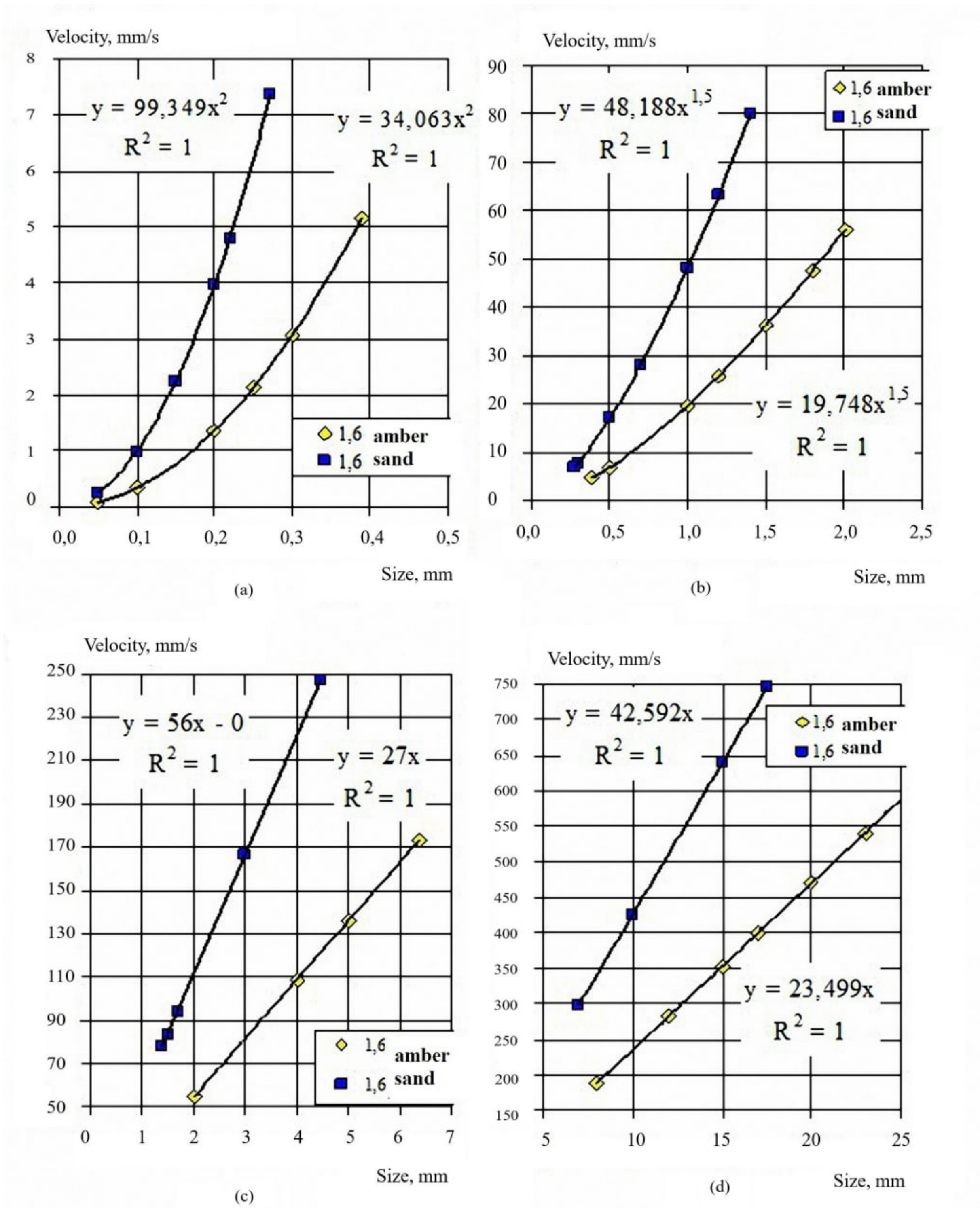

Figure 4. Dependences of the rate of free deposition of sand and amber ascent on the size of the fractions at a pulp density of $1600 g/l$: (a) according to Stokes; (b) the beginning of the transition area; (c) according to Alain; (d) end of the transition area.

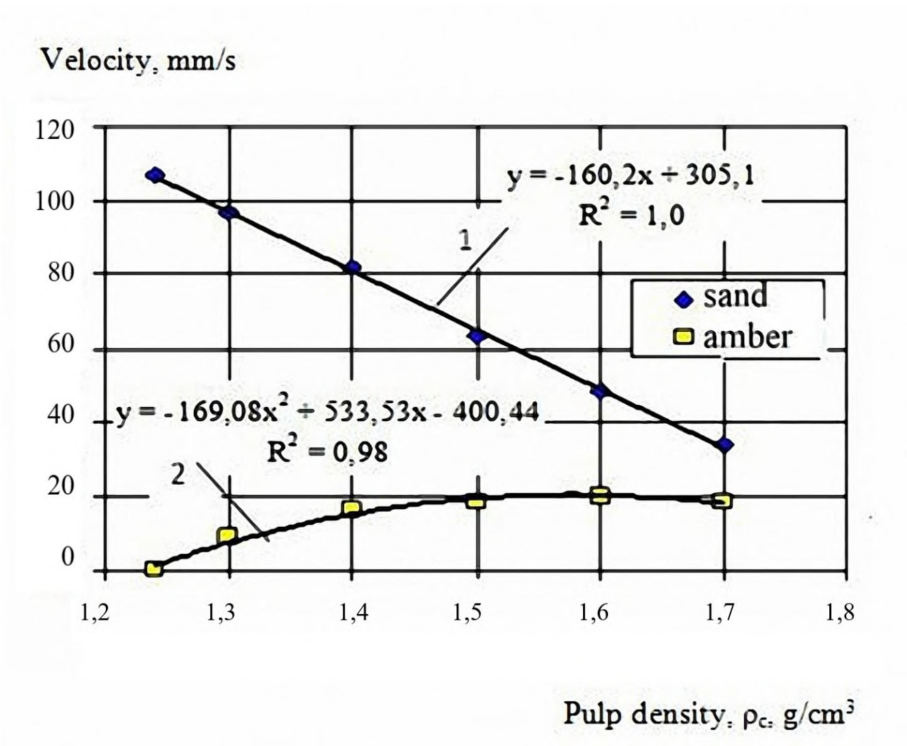

Figure 5. Dependences of the sand fractions free deposition rate (1) and the ascent of amber (2) with a size of 1 mm from the density of the pulp.

medium, but here the difference in density does not significantly affect the speed as for sand.

The calculation performed in the program Excel allowed to obtain a description of the large fractions motion by Newton-Rittinter: at a density of suspension $\rho_c = 1.5\ g/cm^3$ starting with amber size $23mm$ and above, at $\rho_c = 1.6 g/cm^3$ – starting from $25.7mm$, for $\rho_c = 1.7 g/cm^3$ – starting from $30mm$.

Acknowledgments
This work would have been impossible without the support and assistance in conducting experiments provided by the National University of Water Management and Nature Management, Rector Moshynsky V. S. and LTD Klesiv aggregates quarry Technobud.

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A reliability indicator based on assessment entropy of mining building and structure elements

To cite this article: D V Brovko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012028

A reliability indicator based on assessment entropy of mining building and structure elements

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Abstract. The quality reconstruction of the mine industrial facilities is the maximum possible elimination of the identified defects. Assess the suitability of the object for further operation or reconstruction based on the inspection results of a building or structure as actual values of the controlled parameters. Provide the science-based methodology for diagnosing the technical state, assessing the reliability and physical wear for mining buildings and structures by using the probabilistic and statistical methods. A retrospective analysis of the results of surveys, collection, processing and generalization of information on states (diagnoses) and characteristic defects (diagnostic features), based on the probabilistic-statistical apparatus of technical diagnostics and elements of information theory. An assessment of state and reliability, physical wear of structures of all levels. The Kulbak-Leibler distance as a key indicator in the method of estimating the "survivability of the element" provides for the probability distribution of the tensile strength. Developed methods of using technical diagnostics based on probabilistic statistical methods – the Bayes method, statistical solutions - including the concepts of theory information. When performing a probabilistic analysis of the technical condition of all elements, the numerical solution showed the effectiveness of the proposed diagnostic methodology. The innovative method is to analyze and assess the reliability of mine facilities using a mathematical modeling to determine the probabilistic characteristics of defects in structural elements. The analysis method in the survey allows for determining the technical state of the object, the set of further measures, effective planning the operating and restoring costs.

1. Problem statement

The high-quality reconstruction of the mine industrial facilities implies the maximum available identification of existing defects. A survey of surface objects stands for determining their technical condition. The survey findings as actual values of controlled parameters enable to assess the suitability of an object for further operation, reconstruction or to find the need for restoration, strengthening, and repair of structural elements. This task reflects the utmost importance, since undetected defects can cause structural failures during the operation of mine industrial facilities.

2. Unsolved aspects of the problem

Updated scientific and production methods for determining the actual state of structural elements (SE) of mine surface objects are based on standard concepts. Developing new ways to comprehensively determine the actual state of surface objects prolongs their safe operation.

3. Analysis of the recent research

To address the above challenges for determining the technical state, reliability and wear of structural elements and building, as well as to upgrade the current normative references in a survey, it is proposed for the first time to use the mathematical mechanism of technical diagnostics based on probabilistic-statistical methods with including information theory elements in the diagnostic procedure. The Bayes method is one of the main statistical methods of technical diagnostics used in research. It was further developed by I. A. Birger, A. Zelner for complex technical systems [1, 2]. I. A. Birger notes in his works that the technical diagnostics is aimed at increasing the reliability and service life of systems and should be considered as one of the main sections of the general theory of reliability. Thus, the technical state and its key feature - reliability, reliability and its important section - technical diagnostics, technical diagnostics and survey of the technical state should be links of one process that ensures normal up-to-date functioning of buildings and structures. The links in this "chain" must be inseparable, in aggregate and interconnected. The scientists V.V. Bolotin, S.L. Butorin, B.A. Garagash, A.P. Kudzis, O.V. Luzhyn, V.D. Raiser, A.R. Rzhanitsyn, A.G. Roitman, N.N. Skladnev, V.S. Utkin, S.G. Shulman, G.S. Shulman considered the reliability of building structures based on probabilistic approaches [3–14]. Also, the foreign scientists G. Augusti, A. Baratta, F. Kashiati, made significant progress with the theory of reliability [15]. This paper depicts a fairly detailed use of a probabilistic-statistical approach to detect the technical state of building systems and their elements within mathematical methods of technical diagnostics, as well as material on estimating their reliability parameters.

4. Previously unsolved part of the general problem

The technical condition of structural elements of buildings and structures is assessed by comparing the maximum limits (calculated or standard) and actual values of strength, stability, deformability and operational characteristics of structures. When designing surface objects, the operational characteristics are not set up. The physical wear of structural elements and the object is not modeled. In the design phase of the building, it is almost impossible to forecast the future reliable operation costs.

5. Objectives of the article

A retrospective analysis of the previous examinations to collect, process and summarize information on states (diagnoses) and characteristic defects (diagnostic signs), and develop the methods based on the probabilistic-statistical apparatus of technical diagnostics and elements of information theory. This allows for assessing state, reliability, and physical wear of all structures at all levels.

6. Presentation of the main research

When operating the surface complex of the mines of the Kryvyi Rih iron ore basin, a number of accidents and disasters were caused by the structural destruction of mining buildings. A number of external factors and underground mining may cause the destruction of structures. All mining structures are located close to the zone of rock shifting, which sometimes might damage the structural integrity of buildings. The mines of Kryvbas have used mining with massive ore collapse and overlying rocks so far, which resulted in damaging the integrity of the rock mass [16, 17]. Thus, the foundations of mining structures were partially destroyed. Transiting to chamber mining systems [18, 19] increased the active zone of rock shifting from 60 to 75 degrees and significantly decreased harmful impact of underground mining on mining structures. The following structures on the surface- high tower headframes, trestle bridges connecting buildings, steel headframes, loading bunkers, processing plants, administrative and household plants of modern architecture- characterize primarily the architectural and construction design of modern mining enterprises. Most of the mine structures have a service life over 30-40 years under significant physical wear. The structures in the limit state endanger the life and health of the technical personnel of the mine. The current regulatory methods for determining the technical state of structures are general guidelines and do not sufficiently consider the actual operation of these structures. It is very difficult, and sometimes impossible, to promptly identify emergency conditions by technical operation services and the engineering staff of specialized organizations, since the centers of physical wear of structures are in hard-to-reach places. Kryvyi Rih National University systematically carries out technical diagnostics, strengthening and reconstruction of building structures of mining objects [19]. To date, we have diagnostic data for seven major enterprises: ShidGZK, NothernGZK, KZhRK, SUKHA BALKA, CentralGZK, PivdenGZK, InGZK. We present the graphs of the development of the defects intensity to consider the current situation of the objects under study. The empirical values of the defects of headframe elements and overhead buildings over time are presented in (figure 1).

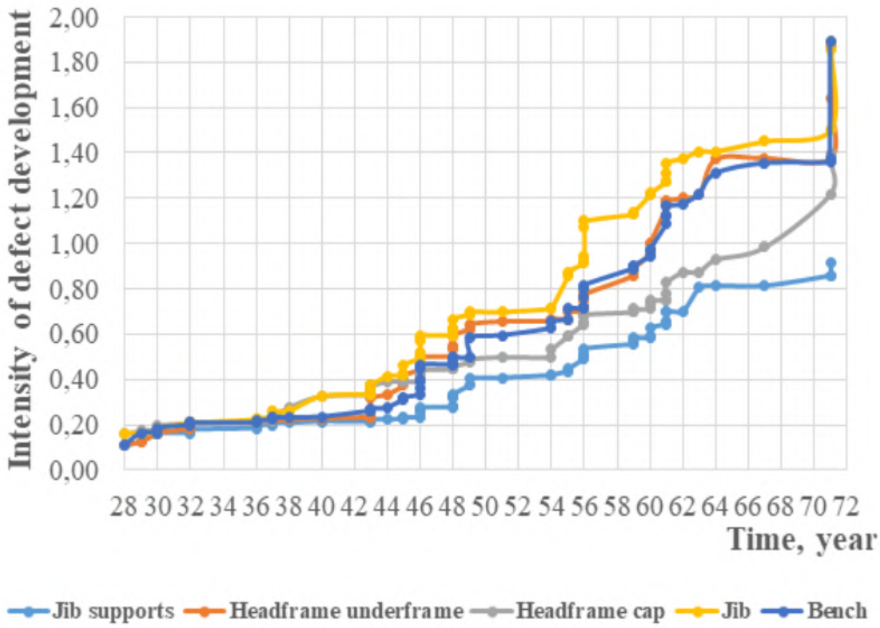

Figure 1. Corrosion processes in the elements of headframes and mine buildings over time.

For 35-38 years, we observe a uniform development of defects in all elements, without progress jumping. Further, up to the 57th year of operation, the structural defects are jumping in the main elements. After 60 years, we see a sharp increase. To establish the main regularities of physical wear, the methods are as follows: the factor analysis as sequential two-sided classifications identifies characteristic operational damage and zoning of structures [20]; the statistical methods for processing diagnostic data determine the conditional rates of corrosion and abrasive wear of elements of metal structures [20]; the accelerated laboratory tests determine corrosion rates at characteristic points [21,22]; the method of analyzing the elastoplastic system destruction assess the impact of operational damage [23]. The failure of even one element can have drastic consequences for complex systems. Therefore, the primary task is to select the best design and mechanical parameters of the system in view of cost, reliability, weight and volume. Hence, assessment of the elements reliability is required at the design stage. The reliability calculations are based on the fact that each element has a certain strength in relation to loads. The design method including the safety and the capacity factor does not show the probability of element failure. In addition, the same safety factor can vary the probability of failure widely. Using a safety factor is justified only when its value is set on extensive experience in using elements similar to the mentioned above. Besides, design parameters are often random variables, which are completely ignored by conventional design methods. The usual deterministic approach to design is not satisfactory in terms of reliability analysis. Another design method is therefore required that would consider the probabilistic nature of the design parameters and assess the reliability of the elements at the design stage. Here, all design parameters are specified, which determine the stress and strength distributions. If both distributions are defined, then the probability of failure-free operation of the element can be calculated (figure 2).

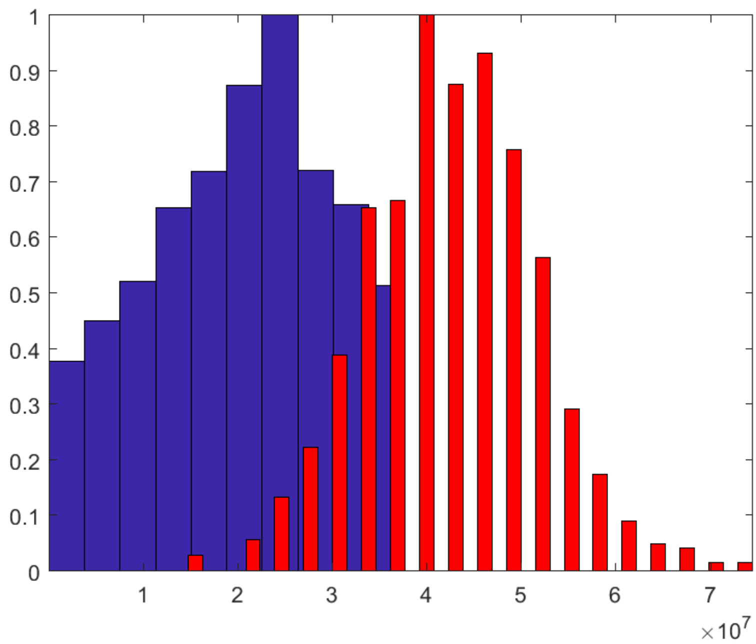

Figure 2. Statistical distributions of the probability density of the tensile strength of steel (blue histogram), and the actual distribution of stresses in the rods (red histogram).

Here, the measure of reliability is the probability that the maximum stress arising under the action of the load will not exceed the bearing capacity (strength) of the element, then:

$$H = P\left(R > S\right). \tag{1}$$

where H is the reliability; P is the probability of the event; R is the bearing capacity; S is the effective maximum stress. More generally,

$$P\left(R > S\right) = \int_{-\infty}^{\infty} f(S)\left[\int_{-\infty}^{\infty} f(R)dR\right] dS \tag{2}$$

Using this expression, we can also calculate the probability of failure-free operation of the element in various combinations of the distribution laws of the bearing capacity and load. That is, in normal distribution of load and bearing capacity, the probability of failure-free operation is defined as,

$$P\left(R > S\right) = \frac{1}{2} + \varPhi\left(\frac{m_R - m_S}{\sqrt{\sigma_S^2 + \sigma_R^2}}\right) \tag{3}$$

Where $\Phi\left(\right)$, is the normalized Laplace function; m_R and m_S are the mathematical expectations of R and S; σ_R and σ_S are the standard deviation of R and S. In real, the bearing capacity and durability of the element depend on the geometric dimensions, material characteristics and external factors. The geometric parameters are deterministic values, the characteristics of the material are random variables with given distribution laws, the intensity of external factors is mostly stochastic, which makes it impossible to define them both theoretically and empirically. Thereby, we reasonably replace the random processes with slices of one-dimensional random variables. It follows that the reliability system is based on statistical methods operating with the distribution function parameters, which describe both the stress state of structural elements and the change in time (figure 3).

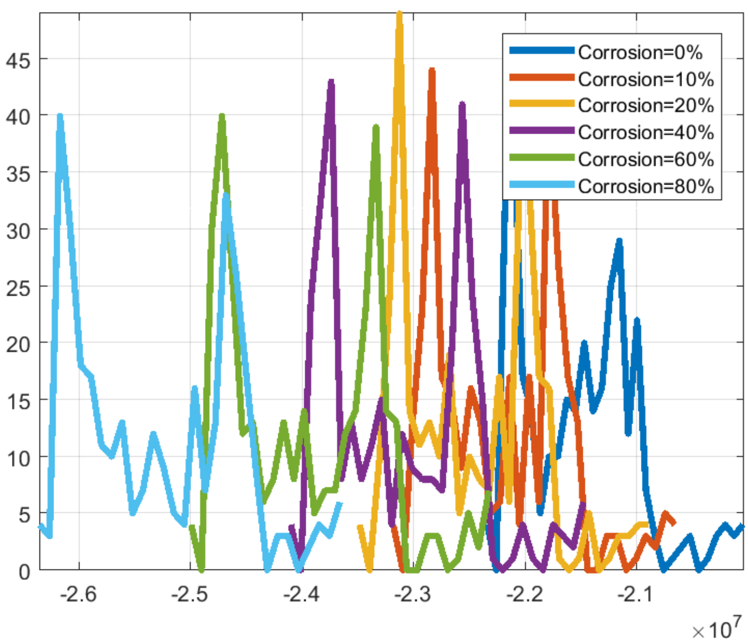

Figure 3. Stresses distribution in the nodes of the tower headframe elements at the 54th marks of the Yubileyny mine and stress changes depending on the corrosion.

The indicator (3) allows to substantiate the quantitative relations between the decrease in the "bearing capacity" of structures elements and the "states" of construction objects. In practice, this reduces the objectivity of assessing the actual state of operated buildings and structures and runs the risk of an emergency. Therefore, using the risk theory in our research helps significantly improve the reliability of buildings and structures in operation. We use the Kullback-Leibler distance to assess the "survivability of the element" considering the risk and a priori given values of the ultimate strength distribution. The Kullback-Leibler Distance (divergence) (D_{KL}) or relative entropy $H\left(P\|Q\right)$ is a non-negative functional, which is an asymmetric measure of the distance from each other of two probability distributions on the common space of elementary events, is defined as,

$$D\left(K\|Q\right) = \sum_{i=1}^{n} p_i \frac{p_i}{q_i} \tag{4}$$

The Kullback–Leibler divergence is a non-dimensional value, regardless of the dimension of the initial random variables. This is due to the fact that the identified law forms of stress distribution in the SE change both in height and design. We established that the form of the law degrades over time under corrosion, mechanical wear and the accumulation of other damage. Therefore, to estimate the residual resource of the system and its constituent elements, it is preferable to use estimation methods that are not sensitive to the distribution law, namely, to use non-parametric indicators such as the Kullback-Leibler divergence (D_{KL}), which is more preferable than the Bayes method. In the study, we calculated the values of the Kullback-Leibler divergence. Our goal is to assess the "survivability" of structural elements table 1.

Table 1. Dependence (D_{KL}) on corrosion.

Corrosion, %	Kullback-Leibler Divergence (D_{KL})
0	14.03
20	8.659
40	4.616
60	1.885
80	0.468

From the table 1, the Kullback-Leibler divergence is inversely related to the value of the SE corrosive wear. Thus, the maximum parameter ($D_{KL} = 14.03$) corresponds to the calculated (design) value, while the minimum parameter ($D_{KL} = 0.468$) refers to the SE emergency state. A graphical representation of the change in the Kullback-Leibler distance under the corrosion processes in the elements is shown in (figure 4).

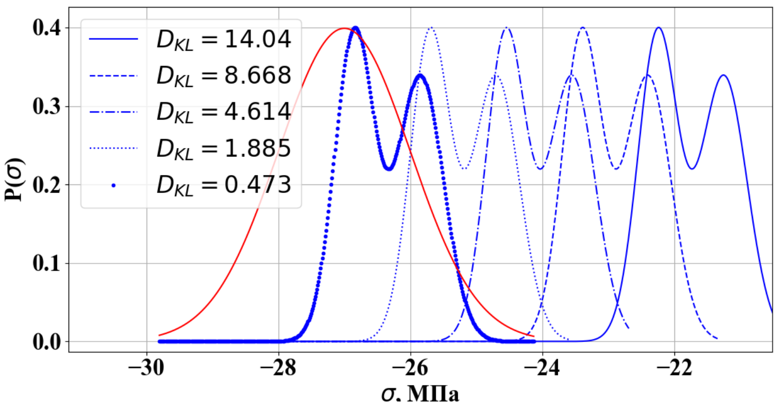

Figure 4. Change in the Kullback-Leibler divergence under the corrosion processes.

This is because the law of stress distribution in the elements shifts towards the law of ultimate strength distribution. The above graphs depict theoretical probability distribution densities corresponding to the selected model samples (in red is ultimate strength, corresponds to the density of normal distribution; in blue is stress distribution in the structural elements; the distribution density of the "complex" law is set in the first-staged algorithm). This reduces the distance between the laws of distributions and decreases the residual tensile strength of both the element and the system.

7. Conclusions and direction of further research

In determining an accurate technical state, reliability and wear of structures and structural elements, for the first time we developed the theoretical apparatus of technical diagnostics based on probabilistic-statistical methods- the Bayes method, methods of statistical solutions-including the concepts of theory information. When performing a probabilistic analysis of the technical state of all elements, the results of a numerical solution confirmed the general possibility of the proposed diagnostic methods. We proposed an analysis algorithm without a strict binding to a specific distribution law. Also, we calculated the Kullback-Leibler divergence in order to assess the "survivability" of structural elements. To sum up, with an increase of corrosion, the value D_{KL} decreases and shows the wear of the elements, while the maximum value corresponds to the calculated (design) value and the maximum reliability of both structural elements and the entire system.

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The mining and geometrical methodology for estimating of mineral deposits

To cite this article: S Pysmennyi *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012029

The mining and geometrical methodology for estimating of mineral deposits

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Abstract. Ensuring the correct development of the deposit is a priority production task, which is based on a scientifically grounded assessment of the geometrical characteristics of the mineral deposit and a clear understanding of the nature and quantity of the deposit’s re-serves. Aim of the study is a geological and industrial assessment of a mineral deposit, which provides for the correct determination of the quantity and quality of explored reserves, requires the collection and processing of such material, which would be sufficient to draw up a technically correct and economically feasible project for the development of the deposit. The research methodology consists in mining and geometrical modeling and monitoring of subsoil based on progressive and classical methods and techniques for geometrization of the array of minerals and host rocks. This includes a set of measures aimed at collecting and evaluating the initial information, assessing its accuracy, mathematical processing and determining the optimal and most effective methods for solving the problem of geometrization of the field. The results allow us to practically solve the problems of mining operations related to the assessment of reserves of mineral deposits, their genesis, the nature of occurrence, quality, the possibility of sorting, forecasting and industrial development. An effective set of methods has been developed based on the statistical assessment of mineral deposits, as well as the use of the latest geoinformation systems, which provide the possibility of high-quality and accurate calculation and assessment of mineral deposits.

1. Introduction

Of particular importance for ore deposits is the geometrization of the quality and physical and chemical properties of rocks and minerals, which is one of the most important tasks of a mining enterprise. [1–5]. The graphic-analytical method allows you to establish the distribution of the content and create a spatial model of the deposit in order to determine the relationship between the components [6–9]. The development of a deposit requires significant costs, and their effectiveness directly depends on the completeness and quality of information about deposits, their composition, the presence of minerals and, directly, mineral reserves. [10–14]. These problems can be solved on the basis of a set of studies aimed at geometrization, statistical evaluation of the deposit, and modeling and monitoring of its shape, properties and volumes [15–19].

Geometry and subsoil modeling [20–23] is based on information about geological, geochemical, geomechanical and other properties of the deposit that characterize various features and indicators (structure, properties, state) of the mountain massif and sources of georesources [24–27], which are modeled geometrically, including topographic surfaces and different types of projections [28–30]. Geometrization is the methodological basis of subsoil geometry. The complex of geometrization methods consists of collecting and completing the source information obtained during exploration, surveying, testing, geophysical and special research [31–33]; systematization, pre-processing and evaluation of the accuracy of information using variation statistics, the theory of random functions, finite differences; mathematical and geometric modeling and evaluation of model accuracy; using the model to solve problems of exploration and industrial development [34–36], as well as determining the geological and genetic composition of the deposit [37–40].

2. Purpose

The aim of the study is a geological and industrial assessment of a mineral deposit, which provides for the correct determination of the quantity and quality of explored reserves, requires the collection and processing of such material, which would be sufficient to draw up a technically correct and economically feasible project for the development of the deposit.

The task of geometrization of the mineral deposit is to obtain information about the deposits and its systematization in order to further its practical application and solve the problems of mining. One of the applications of geometrization is the estimation of mineral reserves [41–45]. This necessitates the creation of a set of methods [46–49] that will allow to perform with maximum efficiency the calculation of reserves of the mining enterprise.

3. Methods

Geometrization for the purpose of calculating mineral reserves can be carried out using geoinformation systems.

Consider the K-Mine geoinformation system. K-Mine contains a large number of routines to perform these calculations. The module allows you to perform calculations of volumes by different methods (the method of horizontal plans, the method of cross-sections, a modified method of cross-sections using triangulation networks and the like).

When calculating the volume by the method of areas and the average height perform the calculation of the volume of the area of the base, as well as the average height of the excavated layer, set by the user. When calculating the control of the volumes between the excavation and the embankment, the averaging of the height is performed over the entire area.

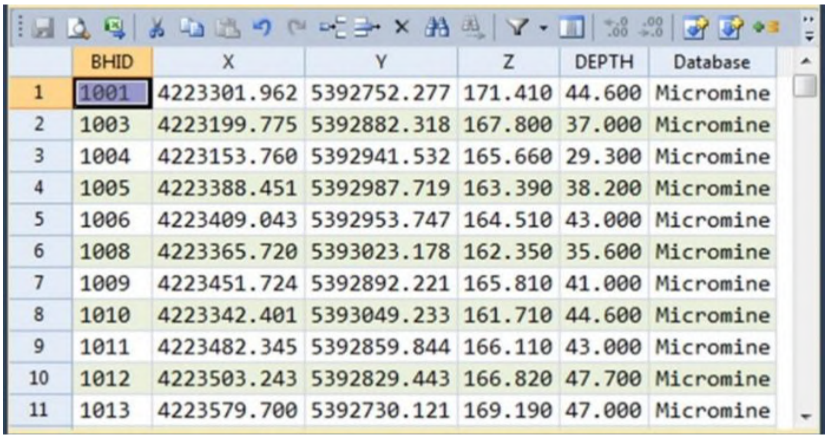
The calculation of volumes by the method of vertical sections is used to calculate the volumes of complex block figures, consisting of objects of different types, which can be located in several different layers, ledges and have a complex profile of the section. The peculiarity of the calculation of volumes in this way in K-Mine is that at the initial stage the construction of two triangulation surfaces for the new and old positions of the ledge, which have as a dividing line the calculation contour.

Triangulation surfaces are built on the basis of data of all objects included in each category of layers. Next, on the triangulation surfaces is the operation of their intersection with the vertical planes and determine the contours of the figures describing these sections. In the future, the solution of the problem is reduced to the solution of the standard problem of calculating volumes by the method of cross sections. Thus the package of the reporting documentation on a settlement figure is formed and all necessary constructions (construction of sections and their numbering) are carried out. The report contains a calculation table with indicators for calculating the area for each section, as well as a graphical representation of each section at a given scale.

After closing the editor before printing, the objects (frames, section lines and their numbers) on which the report was formed are deleted in the working area of the screen. Thus, K-Mine allows you to quickly assess the volume of mining operations in the design and modeling of mining operations.

Consider the microMine geoinformation system. As an example of deposit geometry, we take the results of calculating the balance reserves of ilmenite Birzuliv deposit in the program. The calculation of ilmenite reserves in the Birzuliv deposit was performed using the MicroMine system using the block modeling method, which is one of the most modern and objective methods of estimating the resources and reserves of minerals used worldwide.

A project based on the Birzuliv deposit database has been created to calculate stocks in the MicroMine environment. It consists of two files: Collar.dat (figure 1, figure 2), which contains information on wells and Assay.dat (figure 3), which contains information on samples.



	BHID	X	Y	Z	DEPTH	Database
1	1001	4223301.962	5392752.277	171.410	44.600	Micromine
2	1003	4223199.775	5392882.318	167.800	37.000	Micromine
3	1004	4223153.760	5392941.532	165.660	29.300	Micromine
4	1005	4223388.451	5392987.719	163.390	38.200	Micromine
5	1006	4223409.043	5392953.747	164.510	43.000	Micromine
6	1008	4223365.720	5393023.178	162.350	35.600	Micromine
7	1009	4223451.724	5392892.221	165.810	41.000	Micromine
8	1010	4223342.401	5393049.233	161.710	44.600	Micromine
9	1011	4223482.345	5392859.844	166.110	43.000	Micromine
10	1012	4223503.243	5392829.443	166.820	47.700	Micromine
11	1013	4223579.700	5392730.121	169.190	47.000	Micromine

Figure 1. The structure of the file Collar.dat database Birzuliv deposit.

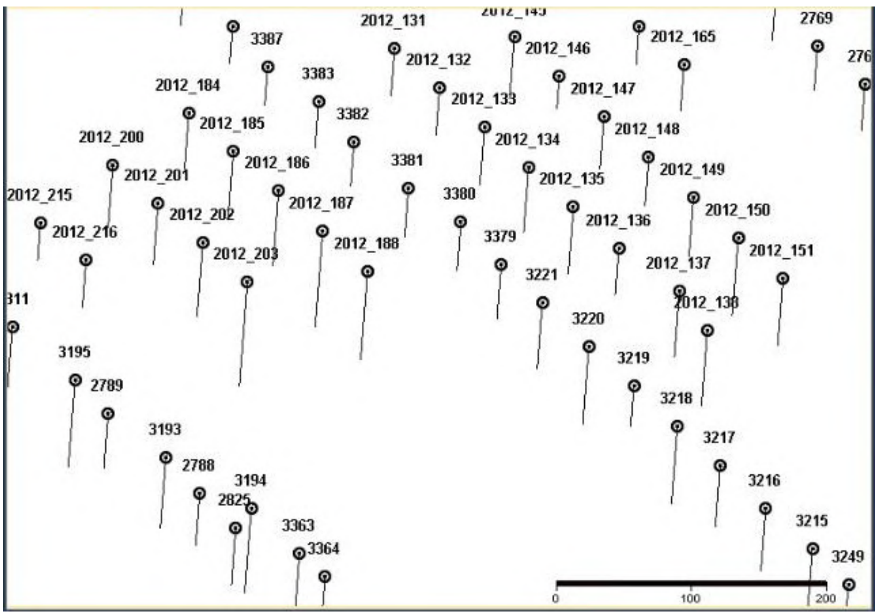


Figure 2. 3D-visualization of wells drilled at the Birzuliv deposit, according to information from the file Collar.dat.

	BHID	X	Y	Z	FROM	TO	Length	Weathering crust	Drilling	Lithcode	SG	ILMwt%	ILMkgm3
1	1	4223429.910	5393057.140	139.150	2.400	4.500	2.100	sand	own	1	1.710	2.270	38.800
2	3	4223473.900	5393079.540	140.000	2.300	3.500	1.200	sand	own	1	1.710	2.100	35.900
3	3	4223473.900	5393079.540	138.650	3.500	5.000	1.500	sand	own	1	1.710	2.210	37.800
4	3	4223473.900	5393079.540	137.100	5.000	6.600	1.600	sand	own	1	1.710	1.960	33.500
5	4	4223482.880	5393063.940	140.850	1.400	2.900	1.500	sand	own	1	1.710	3.700	63.300
6	4	4223482.880	5393063.940	139.100	2.900	4.900	2.000	sand	own	1	1.710	2.810	48.000
7	5	4223557.520	5393017.760	140.850	0.300	1.000	0.700	sand	own	1	1.710	1.730	29.580
8	5	4223557.520	5393017.760	139.600	1.000	2.800	1.800	sand	own	1	1.710	2.510	42.920
9	5	4223557.520	5393017.760	137.800	2.800	4.600	1.800	sand	own	1	1.710	2.320	39.670
10	5	4223557.520	5393017.760	136.000	4.600	6.400	1.800	sand	own	1	1.710	3.390	57.970
11	5	4223557.520	5393017.760	134.350	6.400	7.900	1.500	sand	own	1	1.710	9.980	170.660
12	5	4223557.520	5393017.760	132.550	7.900	10.000	2.100	sand	own	1	1.710	22.640	387.140

Figure 3. The structure of the file Assay.dat database Birzuliv deposit.

In addition, included graphic materials of the preliminary calculation of reserves, namely: the plan of calculation of reserves by the coordinate reference (figure 4). Due to this, if necessary, the results obtained in the process can be easily compared by overlapping and comparing.

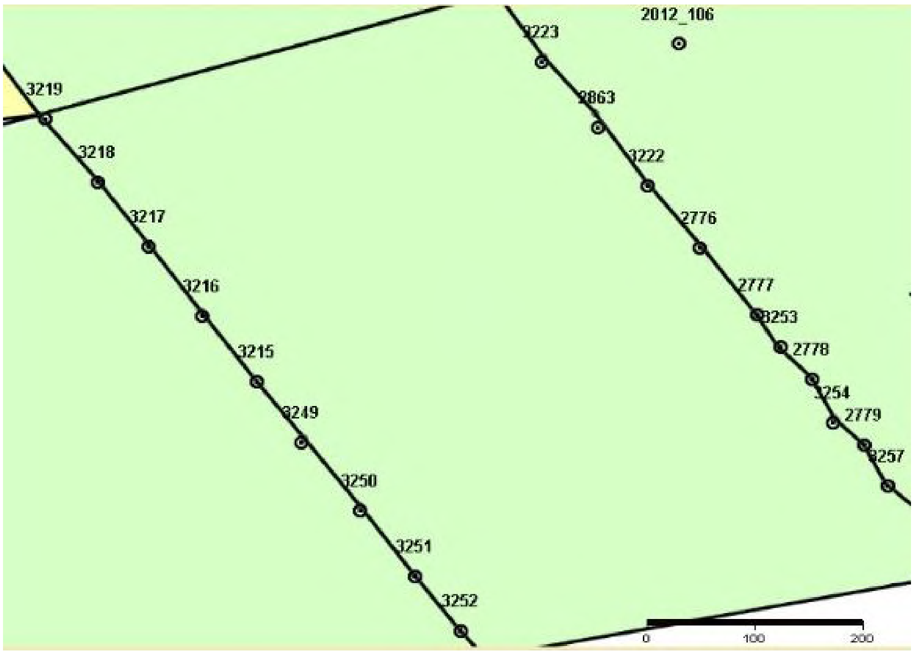


Figure 4. Plan for calculating reserves and wells extracted from the database in the MicroMine environment.

4. Results and discussion

At the first stage of work with the database, a statistical analysis of the distribution of values of ilmenite content of Birzuliv deposit was performed. The distribution in the samples is estimated as bimodal lognormal (figure 5). The bimodal distribution of a component in the geological sense is usually explained by two different geological processes (or two different stages of one process). In the case of the Birzuliv deposit, it seems that first an ore stratum was formed with the primary distribution of ilmenite in it, and then the ore component was redistributed within the stratum, most likely under the influence of gravitational factors. This is evidenced by the increased values of ilmenite content in the lower part of the thickness (closer to the sole is the roof of the weathering crust).

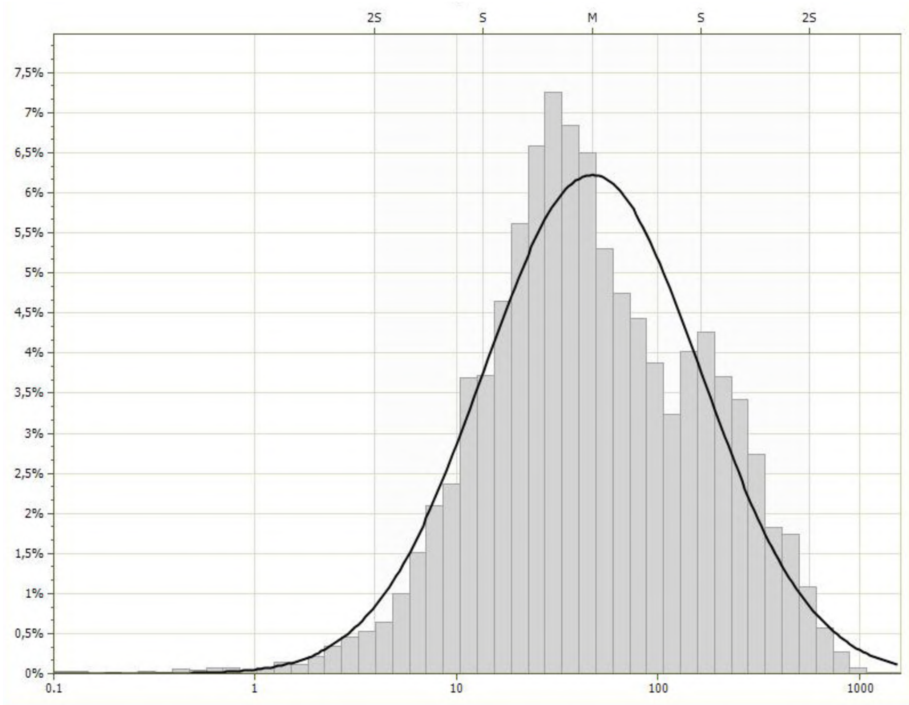


Figure 5. Histogram of distribution of ilmenite contents in samples by Birzuliv deposit (scale is a natural logarithm constructed in MicroMine environment).

The results of "logarithmic statistics" are used for the lognormically distributed value, namely: Ln mean (x)–$4,018$, Ln standard deviation (σ)–$1,327$. According to the "three sigma" rule, all values of a normally distributed random variable lie within $x \pm 3\sigma$ (for the lognormal distribution, the same applies to the logarithms of these quantities). To sample the results of mineralogical analysis of sands of the Birzuliv deposit, the maximum values of ilmenite content should not exceed:

$$exp(4,018 + 3 \times 1,327) = exp(7,999) = 2977,98.$$

Thus, we can conclude that among the values of the original sample for the Birzuliv deposit there are no ones that do not obey the laws of a certain distribution. Based on the performed calculations, it was decided not to exclude the maximum values of ilmenite contents when calculating reserves. Further, based on the test results (ASSAY.dat), composites (combined intervals) were created according to the ilmenite content in separate samples according to economically justified conditions. In addition, the concept of metro percentage (product of the content of the useful component and the capacity of the ore layer) was used, which was 20 kg/m$^3\times$m. The metro percentage is used to account for intervals with a relatively low content of a useful component with a large deposit thickness, or with a low deposit thickness with a very high content of a useful component. With the use of composites on each of the sections outlined the roof and sole of the mineral deposit (figure 6, figure 7).

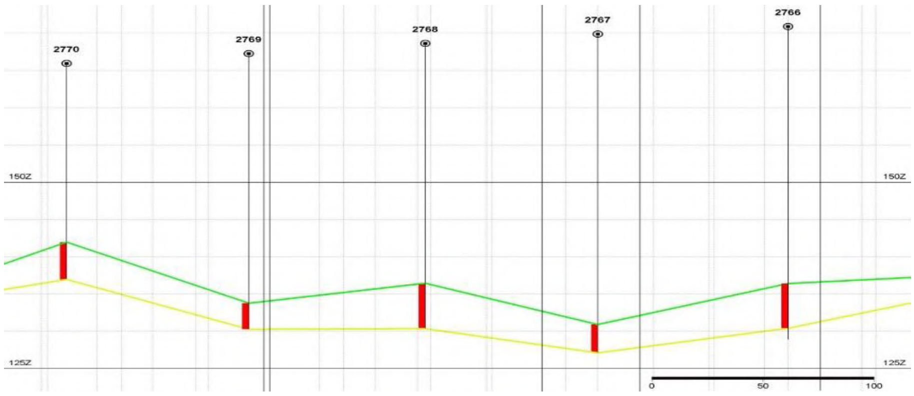


Figure 6. Roof and sole of the mineral, contoured in section using composites (combined intervals).

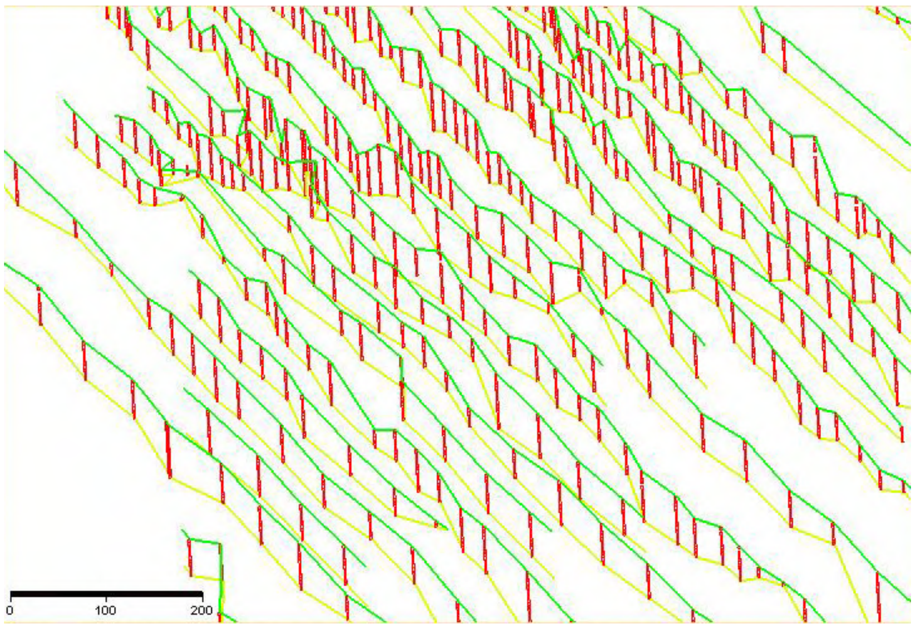


Figure 7. Roof and sole of the mineral, contoured by sections using composites (combined intervals).

Using the function to create digital models of surfaces, roof contours and soles of the sections are combined into two surfaces: the roof surface and the sole surface. In the future, they turn into a framework that limits the mineral on all sides (figure 8).

The framework does not include the area of off-balance sheet stocks (limited by the balance-off-balance limit using the polyline line trimming function). An empty block model is created within the obtained framework. The shape of the elementary (single) block of the block model is determined by the shape of the placer (ore thickness). The Birzuliv deposit is characterized by low capacity compared to the area of distribution. According to the available materials, there is no obvious elongated shape in the plan in any of the directions. Therefore, the most optimal shape with a ratio of length, width and power 10×10×1 m. The size of the elementary (single) block (subblock) of the block model is determined taking into account two main factors. First, there is no need to make a single unit less than the selected mining technology provides

Figure 8. Framework bounding the ore stratum of the Birzuliv deposit.

selective mining. Secondly, the unit block must be small enough to accurately describe the configuration of the ore thickness surfaces. The size of single blocks of 10×10×1 m and sub-blocks of 2×2×0.2 m was chosen for the block model of the Birzuliv deposit. The created model is "filled" with interpolated values of ilmenite content by the method of inverse distances using the 3D-estimation of blocks function (figure 9). The interpolation occurs in several stages, each of which corresponds to a certain category of reserves (B, C1, C2). One of the important parameters of interpolation is the size of the "search" ellipse, they increase from the highest category of reserves to the lowest and are based on the reasonable parameters of a drilling network (100×40 m, 200×60 m, 400×80 m, respectively).

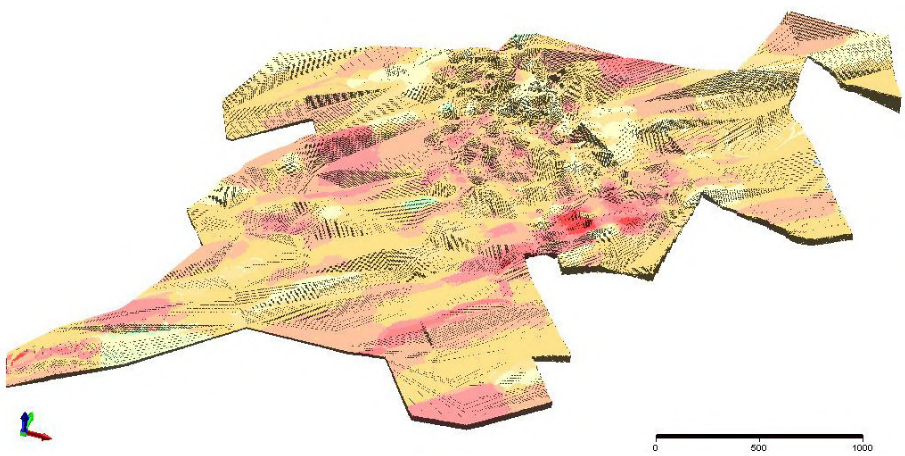


Figure 9. Block model of the Birzuliv deposit (color shows the content of ilmenite, which increases from green to red).

To delineate the reserves of different classes and categories, closed contours were created that limit the areas of different degrees of study (figure 10).

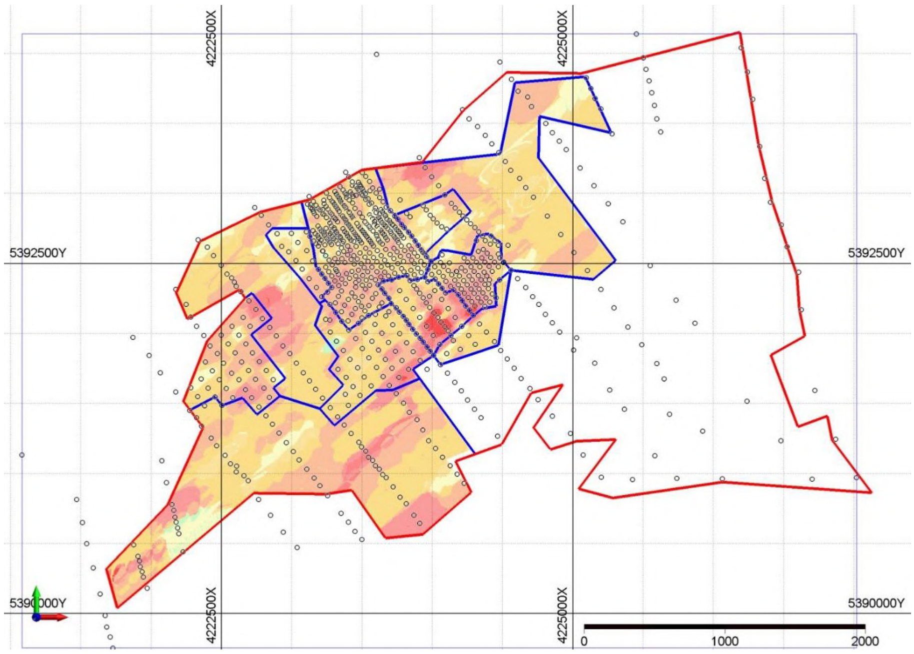


Figure 10. Distribution of the area of the Birzuliv deposit by classes (categories) of reserves.

5. Conclusions

As a result, a block model of the deposit was obtained, which reflects the distribution of ilmenite. It should be noted that the model allows not only to more accurately estimate reserves and other parameters of the deposit, but also to quickly decide on the direction of extraction work depending on the market situation of ilmenite concentrate or other factors. By assigning category contour indices to each of the blocks, all stocks of the block model were divided into corresponding classes (categories). As a result of creating a report on the block model, the distribution of ilmenite reserves was obtained. The total amount of balance reserves (B+C1+C2) of ilmenite of the Birzuliv deposit amounted to 4526 thousand tons. The error in calculating inventories was 8.3%. The solution of the actual scientific and technical problem of geometrization of the reserves of the mining enterprise, aimed at ensuring the process of mining production, was shown. The set of considered methods is practically applicable, and the researches directed on its improvement are very perspective.

Acknowledgments

The work was supported by the Ministry of Education and Science of Ukraine within the framework of the state scientific topics “Determination of regularities of the stress-strain state of rocks disturbed by workings with the purpose of developing resource-saving ore mining technologies” (State registration 0115U003179).

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Mathematical modeling of processes of technogenic deposits development

To cite this article: V I Golik *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012030

Mathematical modeling of processes of technogenic deposits development

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Abstract. The article aims to substantiate the tendency to solve the problem of the mineral and raw material base of non-ferrous metals due to the involvement of technogenic origin in substandard metal-containing raw materials. Critical analysis and systematization of new information on the current state of the mineral and raw materials base of non-ferrous metals and the environmental problems of mining associated with it. New data on the recovery and loss of metals in the process of ore dressing are presented. It is shown that the total value of metals in waste is comparable to the value of potential mineral resources in the bowels. The problems of the use of mining waste should be solved in a single package with environmental problems by creating a single technological cycle for the extraction and processing of industrial minerals of industrial waste, the use of which can make the development of industrial deposits economically viable. The practical significance of the work lies in the possibility of using best practices for non-ferrous metallurgy enterprises that are searching for ways to survive in the conditions of the establishment of market relations.

1. Introduction

In the context of increasing demand for non-ferrous metals, the issues of strengthening the state of the mineral resource base due to the involvement of substandard metal-containing raw materials of technogenic origin are of particular relevance [1, 2]. Studies on this topic use information about the current state of the issue and use the methods of analysis and systematization of new information for proof. The scientific novelty of research on this topic consists of considering the issue of involving the production of substandard metal-containing raw materials of technogenic origin simultaneously with environmental issues. Studies on this topic indicate the need to use best practices for non-ferrous metallurgy enterprises in the context of market relations with partial exhaustion of available deposits.

2. Materials and methods

The provision of basic sectors of the economy with reserves of the main types of minerals seems satisfactory, but recently the urgency of the problem of the mineral and raw materials base of non-ferrous metals has been increasing [3]. In the developed industrial countries of the world, the level of use of industrial waste reaches 70-80%, while in Ukraine and neighbouring countries it does not exceed 12-15%. In the USA, for example, 20% of all aluminium, 33% of iron, 50% of lead and zinc, and 44% of copper are obtained from industrial waste [4]. A similar trend in the use of secondary resources is observed in Canada, Great Britain, South Africa, Spain and other countries. For example:

- In the state of Montana (USA), the Mandiski mine dumps annually produce 2 tons of Au and 4 tons of Ag with a gold content of 0.84 g/t and silver of 2.8 g/t;
- In the state of Michigan (USA), 60% copper recovery has been achieved from the beneficiation of tailings containing 0.3% Cu;
- In South Africa, from the dumps of gold recovery plants with a gold content of 0.53 g/t and uranium - 40 g/t, 3.5 tons of gold and 696 tons of uranium per year are obtained with a productivity of 50,000 tons/day.

The development and creation of an information retrieval system for the processing and integrated use of mineral raw materials from technogenic deposits is a cardinal step towards a waste-free technology. In the Kryvyi Rih iron ore basin, according to various estimates, dumps contain up to 13 billion tons of overburden, and tailings contain up to 6 billion tons of waste from the enrichment of low-grade iron ore. In recent years, the possibility of using the mineral mass accumulated in dumps and tailings of the Kryvyi Rih basin has been increasingly studied. Obviously, the lack of methods for assessing man-made deposits adopted at the state level hinders their commissioning [5,6]. Currently, about 25 billion tons of solid waste alone has been accumulated on the territory of Ukraine.

These wastes negatively affect natural landscapes and environmental conditions, occupying an area of about 150 thousand hectares of fertile land and worsening the human environment. Technogenic deposits lead to the exclusion from economic circulation of large areas of land occupied by production waste. In addition, there is destruction or a decrease in the quality of land due to dust drifts from dumps and tailings [4]. The problem of industrial waste disposal is of paramount importance. An important circumstance is that the cost of commercial products from industrial waste is 5-15 times less than from traditionally mined ores from mineral deposits. The tendency to develop technogenic reserves is growing, which is becoming the main, and sometimes the only supplier of raw materials. The amount of non-recoverable metals is characterized by (figure 1).

The extraction rate of the main minerals is 65-78%, and associated elements in the extraction of non-ferrous metals – 10-30%. Elements such as In, Ga, Tl, Bi, Hg are almost entirely lost in the flotation tailings. Losses of other metals are characterized by (figure 2). In the copper sub-sector about 220 million tons of tailings have been accumulated, in which the copper content (0.34-0.37%) is close to the condition (0.35-0.50%). Sulfur accounts for 30-50% of the cost of tailings of ores beneficiation, precious metals – 25-45%, copper – 10-20%, and zinc – 10-15%.

The beneficiation tailings of copper-nickel ores contain industrial concentrations of platinum, gold, and silver, which are already available to modern processing technologies. When tungsten-molybdenum ores are enriched, up to 60% copper, up to 81% bismuth, up to 62% tantalum, gold, silver, and other elements are not extracted. The metal content exceeds 0.04% with the condition during production >0.1% WO3 (Tungsten trioxide).

Using new processing technologies, substandard ore dumps are a technogenic deposit suitable for mining at a lower cost than when mining metals from primary ore. In the tungsten - molybdenum sub-sector, the flotation and flotation-gravity concentration tailings contain about 400 thousand tons of molybdenum and more than 100,000.0 tons of tungsten. The metal reserves in the processing waste are equivalent to the reserves of new deposits (figure 3).

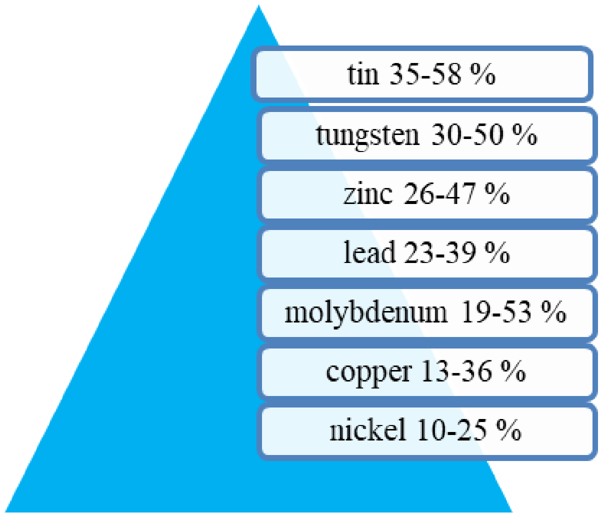

Figure 1. Average and maximum values of the fraction of unrecovered components relative to their amount in the initial ore, %.

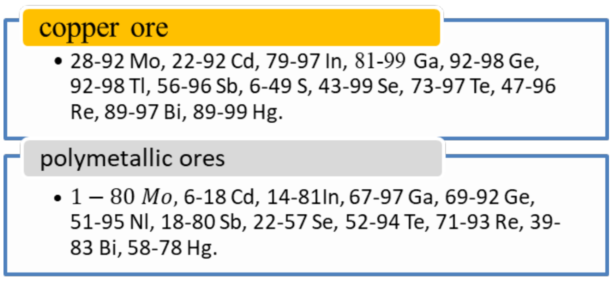

Figure 2. Loss of metals during flotation.

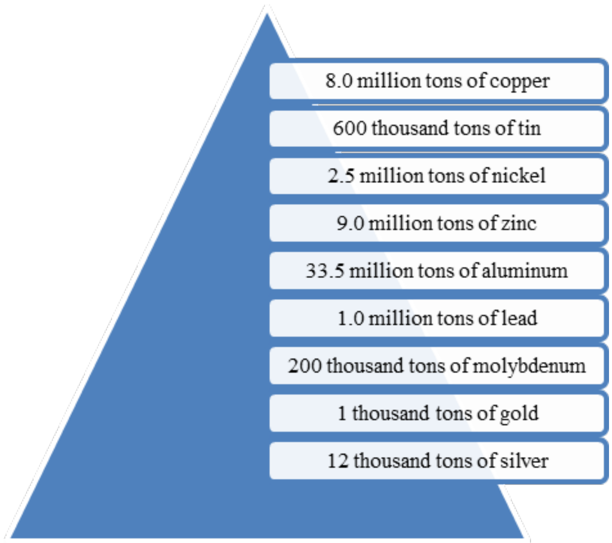

Figure 3. Non-ferrous metal reserves in processing waste.

3. Results and discussion

The total value of metals in waste according to the indicative estimate is comparable to the value of potential resources of mineral resources in the subsoil and which is several times higher than the value of known reserves in the subsoil, which are not yet used [7–10]. In most cases, mineral waste is used as raw material for the construction industry (no more than 10%). In technologically developed countries, more than 40% of copper, 35% of gold, and a significant amount of other metals are obtained from waste materials using new technologies, for example, leaching [11, 12].

The problems of the use of mining waste should be addressed along with environmental problems. The negative impact of tailings storage facilities on the environment is manifested in the territory, which is 10 times larger than the area occupied by the waste itself. The use of reserves of technogenic deposits is favored by the fact that they are located in habitable areas on the surface of the earth and are crushed, which sharply reduces the cost of obtaining metals. The insufficiency of the undertaken environmental measures is evident from the fact that large areas of land are occupied by waste production of 4th and 5th hazard classes. The environmental impact of waste is regional and global. Soil horizons are enriched by ore components of dumps, in which they are not isolated from water systems and affect the adjacent area.

In this situation, the prospects for reducing the negative impact on the environment are associated with the creation of a single technological cycle for the extraction and processing of minerals of technogenic waste: "ore processing - waste storage - utilization". With the use of new technologies, the development of technogenic deposits can become economically viable production. The main contradictions in the processes of production activity and waste generation of industrial enterprises can be resolved by utilizing technogenic and substandard mineral raw materials in the cycle of integrated development of non-ferrous metal deposits (figure 4).

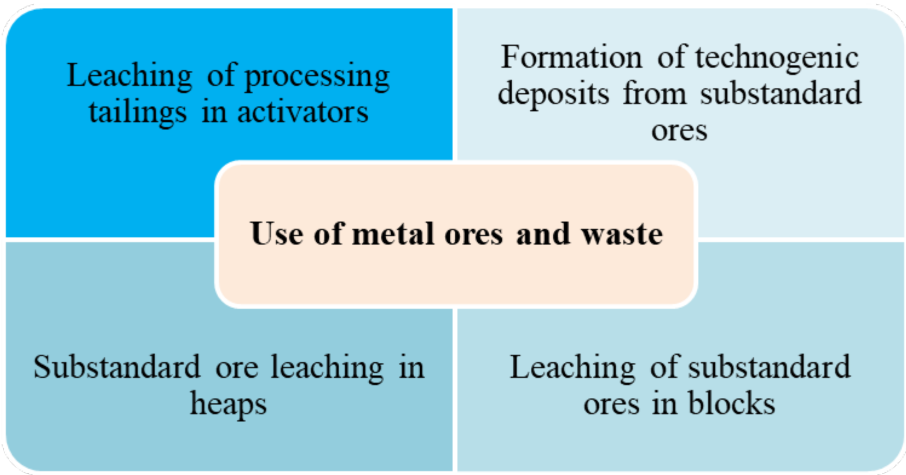

Figure 4. Model for utilization of technogenic and substandard mineral raw materials.

The unified model of leaching takes into account the type of metal leaching, the methods of metal production types of leachable metals. Accounting is carried out with the help of variable "n", that is, each species corresponds to its number:

- $n = 1$ – traditional metal leaching in agitators;
- $n = 2$ – tails activated in the disintegrator are leached in the agitator;
- $n = 3$ – leaching of tailings in the disintegrator combined with activation.

Different metal mining options are taken into account using a variable “m”:

- $m = 1$ – extraction of metals from the balance tailings of coal preparation;
- $m = 2$ – extraction of metals from off-balance tailings of coal preparation.

Accounting for extraction of different metals is taken into account using a variable “p”:

- $p = 1$ – corresponds to the zinc leaching model;
- $p = 2$ – corresponds to the leaching model of lead;
- $p = n$ – corresponds to the leaching model of another metal.

Calculations of regression models are performed in Maple 9.5. Based on the performed calculations, a unified mathematical model of the process of metal extraction from tailings is built. For all values of the variables n, m, p, the studied regression model has the same linear structure concerning the coefficients α_k and is a polynomial of the second degree concerning variables X_1, X_2, X_3, X_4 therefore, the general model has the form [12]:

$$\begin{aligned}\varepsilon = \varepsilon(n;m;p) = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_4 \cdot X_4 + a_5 \cdot X_1^2 + \\ + a_6 \cdot X_2^2 + a_7 \cdot X_3^2 + a_8 \cdot X_4^2 + a_9 \cdot X_1 \cdot X_2 + a_{10} \cdot X_1 \cdot X_3 + \\ + a_{11} \cdot X_1 \cdot X_4 + a_{12} \cdot X_2 \cdot X_3 + a_{13} \cdot X_2 \cdot X_4 + a_{14} \cdot X_3 \cdot X_4,\end{aligned} \tag{1}$$

where $a_k = a_k(n;m;p);\ k = 0, 1, ...14;\ n = 1, 2, 3;\ m = 1, 2;\ p = 1, 2.$

Expression $\varepsilon = \varepsilon(n;m;p)$ defined through expressions for $\varepsilon(1;m;p), \varepsilon(2;m;p), \varepsilon(3;m;p)$ using the Lagrange interpolation polynomial:

$$\begin{aligned}\varepsilon(n;m;p) = \frac{(n-2)(n-3)}{2}\varepsilon(1;m;p) + (n-1) \times (n-3) \times \\ \times \varepsilon(2;m;p) - \frac{(n-1)(n-2)}{2}\varepsilon(3;m;p).\end{aligned} \tag{2}$$

Similarly, $\varepsilon = \varepsilon(n;m;p)$ expressed through functions $\varepsilon(n;1;p), \varepsilon(n;2;p)$ by the formula:

$$\varepsilon(n;m;p) = -(m-2)\varepsilon(n;1;p) + (m-1)\varepsilon(n;2;p). \tag{3}$$

Respectively $\varepsilon = \varepsilon(n;m;p)$ expressed through functions $\varepsilon(n;m;1), \varepsilon(n;m;2)$ by the formula:

$$\varepsilon(n;m;p) = -(p-2)\varepsilon(n;m;1) + (p-1)\varepsilon(n;m;2). \tag{4}$$

Combining formulas 3 and 4, we obtain the dependence $\varepsilon = \varepsilon(n;m;p)$ from functions $\varepsilon(n;1;1), \varepsilon(n;1;2), \varepsilon(n;2;1), \varepsilon(n;2;2)$:

$$\begin{aligned}\varepsilon(n;m;p) = (m-2)(p-2)\varepsilon(n;1;1) - (m-2) \times (p-1) \times \varepsilon(n;1;2) - \\ -(m-1)(p-2)\varepsilon(n;2;1) + (m-1)(p-1)\varepsilon(n;2;2).\end{aligned} \tag{5}$$

By substitution of $\varepsilon(1;m;p), \varepsilon(2;m;p), \varepsilon(3;m;p)$ we obtain:

$$\begin{aligned}&\varepsilon(n;m;p) = \frac{(n-2)(n-3)}{2}[(m-2)(p-2)\varepsilon(1;1;1) - \\ &-(m-2)(p-1)\varepsilon(1;1;2) - (m-1)(p-2)\varepsilon(1;2;1) + \\ &+(m-1)(p-1)\varepsilon(1;2;2)] - (n-1)(n-3) \times \\ &\times [(m-2)(p-2)\varepsilon(2;1;1) - (m-2)(p-1)\varepsilon \times \\ &\times (2;1;2) - (m-1)(p-2) \times \varepsilon(2;2;1) + (m-1) \times \\ &\times (p-1)\varepsilon(2;2;2)] + \frac{(n-1)(n-2)}{2}[(m-2)(p-2) \times \\ &\times \varepsilon(3;1;1) - (m-2)(p-1)\varepsilon(3;1;2) - (m-1)(p-2) \times \\ &\times \varepsilon(3;2;1) + (m-1)(p-1)\varepsilon(3;2;2)].\end{aligned} \tag{6}$$

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012030 doi:10.1088/1755-1315/1049/1/012030

Expressions for $\varepsilon\left(n;m;p\right)$ at specific values n,m,p are determined from regression dependencies describing leaching processes. Zinc recovery regression equation for tailing leaching $(n=1;\ m\ =\ 1;\ p=1)$:

$$\begin{aligned}\varepsilon\left(1;1;1\right) &= 39.02+5.51X_1-11.09X_2+5.6X_3+1.43X_4+\\ &+3.58{X_1}^2+6.48{X_2}^2-9.39{X_3}^2-9.38{X_4}^2-2.61X_1X_2-\\ &-0.62X_1X_3-1.86X_1X_4-3.0X_2X_3-1.48X_2X_4+1.41X_3X_4,\end{aligned}\tag{7}$$

where X_1, X_2, X_3, X_4 – leaching indicators associated with the parameters (active class yield 0.08; chemical composition of the tailings; metal content in solution, mg/l; leaching time, h; metal recovery in solution, %):

$$X_1=\frac{C_{H_2SO_4}-6}{4};X_2=\frac{C_{NaCl}-90}{70};X_3=\frac{(L:S)-7}{3};X_4=\frac{t-0.625}{0.375};X_5=\frac{f-125}{75}.\tag{8}$$

Zinc recovery regression equation for tailing leaching $(n=1;\ m=2;\ p=1)$:

$$\begin{aligned}\varepsilon\left(1;2;2\right) &= 39.35\ +6.76X_1-18.88X_2-0.62X_4-\ 11.6{X_1}^2+\\ &+7.19{X_2}^2+2.03{X_4}^2-2.84X_1X_2-1.39X_1X_3-0.89X_1X_4-\\ &-2.04X_2X_3+X_2X_4-2.45X_3X_4.\end{aligned}\tag{9}$$

Lead recovery regression equation for tail agitation leaching $(n=1;\ m=2;\ p=2)$:

$$\begin{aligned}\varepsilon\left(1;2;1\right) &= 42.43+16.8X_2+2.68X_3+0.93X_4-3.89{X_1}^2-19.31{X_2}^2+\\ &+2.36{X_4}^2+2.12X_1X_2-0.9X_1X_4+1.73X_2X_3+1.04X_3X_4.\end{aligned}\tag{10}$$

Zinc recovery regression equation for leaching of activated tailings outside the disintegrator $(n=2;\ m\ =\ 2;\ p\ =\ 1)$:

$$\begin{aligned}\varepsilon(2;2;1) &= 36.37+9.96X_1-11.56X_2+1.07X_3-6.53{X_1}^2+\\ &+5.63{X_2}^2-1.00{X_3}^2-3.95{X_5}^2-1.21X_1X_2-5.79X_1X_3-\\ &-4.16X_2X_3-0.74X_2X_4-1.15X_3X_5.\end{aligned}\tag{11}$$

Lead recovery regression equation for leaching activated tailings outside the disintegrator $(n=2;\ m=2;\ p\ =\ 2)$:

$$\begin{aligned}\varepsilon\left(2;2;2\right) &= 29.91+1.1X_1+10.63X_2+6.15X_3+2.09X_5-\\ &-2.41{X_1}^2-26.29{X_2}^2+3.84{X_3}^2+9.25{X_5}^2+1.21X_1X_2-\\ &-0.72X_1X_3+3.21X_1X_5+4.81X_2X_3+1.08X_2X_5-1.00X_3X_5.\end{aligned}\tag{12}$$

Zinc recovery regression equations for leaching tailings in a disintegrator $(n=3;\ m=2;\ p=1)$:

$$\begin{aligned}\varepsilon\left(3;2;1\right) &= 32.15+11.4X_1-14.04X_2+0.68X_3+1.85X_5-\\ &-2.90{X_1}^2+9.25{X_2}^2-2.53{X_4}^2-0.39X_1X_2-1.95X_1X_3+\\ &+1.32X_1X_5+1.47X_2X_3+4.84X_2X_5+3.61X_3X_5.\end{aligned}\tag{13}$$

Lead recovery regression equations for tail leaching in a disintegrator $(n=3;\ m=2;\ p=2)$:

$$\begin{aligned}\varepsilon\left(3;2;2\right) &= 39.44-1.17X_1+16.76X_2+1.28X_3-0.55X_4-\\ &-5.64{X_1}^2-14.81{X_2}^2-0.86{X_3}^2-4.09X_1X_3-1.42X_1X_4-\\ &-0.42X_2X_3-1.00X_2X_4-0.82X_3X_4.\end{aligned}\tag{14}$$

For each specific process and metal, a single model will be a regression dependence. This single model of metal recovery during leaching is implemented in Maple 9.5, Matlab, Mathcad, etc. During the experiments, the most and least intense impact of all factors, i.e., two series, in one of which the values of all factors were taken as maximum (MAX), and in the second as minimal (MIN). Agitation leaching of crushed materials (AKX). Agitation leaching of materials pre-activated in the dry state (AAX). Leaching of materials at the moment of activation with solutions in a disintegrator (APX). Agitation leaching of materials subjected to activation in a disintegrator together with leaching solutions (PAX). Leaching of materials during activation with their repeated passage together with leaching solutions through a disintegrator (AMX) [13,14] (table 1).

The basis for determining the function between the function and independent factors is the multiple regression method implemented in Statistica 6.0. In the case of a one-factor dependence, the desired function is a one-dimensional surface in two-dimensional space - i.e., the line defined by equation $Y = a + a_1X$. According to this, the variable Y can be represented as a function of the constant (a), and the slope coefficient (a_1) multiplied by the value of the variable X.

In the case of multiple regression (when multiple predictors are used), the regression surface cannot be displayed in two-dimensional space, but the calculations are practically unchanged. A linear equation describes multiple regression:

$$Y \ = a + a_1X_1 + a_2X_2 + \ \ldots \ + a_kX_k. \tag{15}$$

where k - number of predictors. Regression coefficients ($a_1 \ldots a_k$) represent the independent contributions of each independent variable to the prediction of the dependent variable.

Table 1. The results of the experiment.

Factor values	Designation of the experiments				
	AKX	AAX	PAX	APX	AMX
Min	0.03	0.02	0.03	0.02	0.03
Max	4.75	8.50	4.00	10.00	32.75

The regression surface expresses the best-predicted value of the dependent variable (Y) for the given values of the independent variables (X). Since the task of linear regression procedures is to fit the surface, which is a linear function of the variables X, in accordance with the observed variable Y, the residual values of the observed points can be used to develop the criterion of "best fit". According to the Fisher criterion, hypothetical dependencies at a significance level of 5% are accepted as plausible. Dependencies are sought to take into account linear, quadratic effects and their interactions in the form of a regression equation:

$$\begin{aligned}\varepsilon_{Pb} &= a + a_1X_1 - a_2X_2 + a_3X_3 + a_4X_4 + a_5{X_1}^2 + a_6{X_2}^2 + a_7{X_3}^2 + \\ &+ a_8{X_4}^2 + a_9X_1X_2 + a_{10}X_1X_3 + a_{11}X_1X_4 + a_{12}X_2X_3 + a_{13}X_2X_4 + a_{14}X_3X_4,\end{aligned} \tag{16}$$

where X_1 – dimensionless coefficient characterizing the content H_2SO_4; X_2 - dimensionless coefficient characterizing the content NaCl; X_3 - dimensionless coefficient characterizing the ratio liquid (L) / solid (S); X_4 – dimensionless coefficient characterizing the duration of leaching (t), hours.

The parameters of the regression equation for the agitation leaching of enrichment tailings activated in the disintegrator with tailings reagents (AAX) are summarized in (table 2). The parameters of the regression equation for the leaching of materials at the time of activation with solutions in the disintegrator (APX) are summarized in (table 3). Tables 2 and 3 differ in leaching medium.

Table 2. Regression equation parameters of tailings agitation leaching activated in the disintegrator (PAX).

Regression; R-sqr.=0.93246; Corrected 0,8274. Residual SS=0.5964995						
	Regr.	St. error	$t(9)$	p	-95,%	+95,%
Average/bias	3.11279	0.369727	8.41917	0.000015	2.27641	3.949171
(1)H_2SO_4(L)	0.48611	0.182041	2.67034	0.025608	0.07431	0.897916
H_2SO_4(Q)	-0.25279	0.485916	-0.52024	0.615452	-1.35201	0.846427
(2)NaCl(L)	1.60122	0.182041	8.79595	0.000010	1.18942	2.013027
NaCl(Q)	-1.54879	0.485916	-3.18736	0.011053	-2.64801	-0.449573
(3)L/S(L)	0.49794	0.182041	2.73534	0.023022	0.08614	0.909749
L/S(Q)	0.24071	0.485916	0.49537	0.632208	-0.85851	1.339927
(4)t(L)	-0.11233	0.182041	-0.61708	0.552473	-0.52414	0.299472
t(Q)	0.30121	0.485916	0.61988	0.550708	-0.79801	1.400427
1L on 2L	0.61713	0.193083	3.19616	0.010898	0.18034	1.053910
1L on 3L	-0.27638	0.193083	-1.43138	0.186117	-0.71316	0.160410
1L on 4L	0.26162	0.193083	1.35498	0.208453	-0.17516	0.698410
2L on 3L	0.26463	0.193083	1.37052	0.203733	-0.17216	0.701410
2L on 4L	-0.12688	0.193083	-0.65710	0.527561	-0.56366	0.309910
3L on 4L	0.05312	0.193083	0.27514	0.789421	-0.38366	0.489910

Table 3. Parameters of the regression leaching equation in the disintegrator.

Regression; R-sqr.=0.94838; Corrected 0.86808. Residual SS=19.81881						
	Regr.	St. error	$t(9)$	p	-95,%	+95,%
Average/bias	26.8206	2.131152	12.58503	0.000001	21.9996	31.64163
(1)H_2SO_4(L)	-0.7969	1.049307	-0.75944	0.467012	-3.1706	1.57681
H_2SO_4(Q)	-3.8676	2.800883	-1.38086	0.200643	-10.2037	2.46841
(2)NaCl(L)	11.4013	1.049307	10.86559	0.000002	9.0276	13.77503
NaCl(Q)	-10.1006	2.800883	-3.60623	0.005693	-16.4367	-3.76459
(3)L/S(L)	0.8705	1.049307	0.82960	0.428222	-1.5032	3.24420
L/S(Q)	-0.5861	2.800883	-0.20926	0.838902	-6.9222	5.74991
(4)t(L)	-0.3759	1.049307	-0.35823	0.728433	-2.7496	1.99781
t(Q)	0.0974	2.800883	0.03477	0.973025	-6.2387	6.43341
1L on 2L	0.0769	1.112958	0.06907	0.946442	-2.4408	2.59456
1L on 3L	-2.7786	1.112958	-2.49661	0.034051	-5.2963	-0.26094
1L on 4L	-0.9663	1.112958	-0.86818	0.407848	-3.4839	1.55144
2L on 3L	-0.2886	1.112958	-0.25933	0.801214	-2.8063	2.22906
2L on 4L	-0.6833	1.112958	-0.61390	0.554476	-3.2009	1.83444
3L on 4L	-0.5597	1.112958	-0.50294	0.627084	-3.0774	1.95794

The consumer of secondary processing waste may be the most material-intensive construction industry. Hundreds of millions of tons of raw materials are produced annually in the world for the production of building materials. The volume of waste generated is commensurate with the demand for the building materials industry for mineral raw materials. However, no more than 10% of the waste is currently used.

The involvement of technogenic deposits in the economy allows us to solve the problems of the mineral resource complex and the environment simultaneously. It reduces the costs of prospecting and exploring new deposits, frees up wasteland, and eliminates sources of environmental pollution. The study results of the development trends of the mineral resource base coincide with the results of studies of experts [15–34].

4. Conclusions

The problems of using mining wastes are inextricably connected with environmental problems. They can only be solved by creating a single complex for the extraction and processing of minerals of technogenic origin, which allows the development of technogenic deposits to be economically attractive. The parameters of the leaching of metals from tailings can be determined from the proposed model. A universal mathematical model that describes extracting non-ferrous metals from raw materials of technogenic deposits, considering the impact of various mechanochemical factors on it is proposed. Specific parameters for the extraction of metals from processing tailings can be directly determined from the proposed model, which makes it possible to select the optimal scheme of the technological process and evaluate its technical and economic indicators at the design stage.

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To cite this article: A V Pavlychenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012031

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012031 doi:10.1088/1755-1315/1049/1/012031

Problematics of the issues concerning development of energy-saving and environmentally efficient technologies of well construction

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Abstract. Specialists of Dnipro University of Technology are among the leading researchers involved in studying the specifics of implementation and functioning of rational and energy-efficient schemes of organization of circulation processes while well drilling and operating. In particular, we have carried out thorough and comprehensive studies of physicochemical phenomena used while creating, preparing, and using the washing fluids. The purpose of the paper is to study and generalize the approaches to designing the parameters of hydraulic well washing programme under complicated geological and technical conditions, analysis of the factors of its correction basing on substantiation of analytical and research regularities of well circulation processes, and optimization of a component and quantitative composition of drill cleaning agents, which are aimed at the most efficient intensification of the bottomhole breaking processes. The development and implementation of a progressive complex hydraulic washing programme for wells under construction are analyzed involving modern methods of analytical analysis and experimental studies. The drilling circulation processes in a well were modelled in terms of experimental wells involving a drill rig UKB-4P and corresponding auxiliary tools and equipment.

1. Introduction

Such a hard-formulated and multifunctional problem as development and implementation of rational schemes of hydraulic cleaning programme of wells under construction is possible to be solved only basing on integration of the data concerning physicochemical properties of rock mass and the parameters of technological well sinking cycle – rotation frequency of a rock-breaking tool in terms of acting axial load (with the available or nonavailable dynamic component) and the amount of drill mud (special disperse system), circulating within the bottomhole interval, that does not contain any environmentally sensitive reagents [1]. The muds in general and drilling washing fluids in particular are meant as such homogeneous systems that consist of two or more substances being in a molecular-disperse state and having no division surface between the components. According to the fundamentals of physical chemistry [2], solutions are characterized by concentration – amount of the substance, dissolved in the specified volume of mud, which is defined in weight contents, weight parts, and moles of the dissolved substance. The solution process is not a simple distribution of molecules or ions of one substance among the molecules or ions of the other; in most cases, it is connected with different interactions of physical and chemical nature.

Rock breaking of the bottomhole using special tools is one of the main operations in the production cycle of constructing different-purpose wells [3]. Surface-active substances (SAS), being the components of working media (drilling washing fluids), influence both deformation and breaking of solid bodies mostly at the boundaries of sharp (dead) ends of the developing fractures. Within that body areas, adsorption influence of a working medium results in the changes in surface energy per one unit of surface and stipulates certain changes in strength properties of a solid body (P.A. Rehbinder effect) [4]. The greatest adsorption effect is observed when new surfaces, formed in the process of breaking, had time to be covered with adsorption layers.

Along with the effect of rock strength reduction, the substances added to the composition of a working medium (washing fluids) can and must perform another equally important function – improvement of lubricating action. In the process of friction, two main lubricating functions can be singled out: ability to form strong films on the surfaces of friction materials and interaction of friction pairs with the surface layers with the resulting changes in their structure and properties. These lubricating functions influence considerably the friction coefficient, wear, and boundary value of pressure and sliding rate, in terms of which inadmissible processes of vibration growth and rock-breaking tool destruction take place. Normal development of a drilling process requires elimination of slurry particles from the bottomhole, their further removing from the bottomhole zone and transporting either to the surface or to the special slurry collectors mounted at the bottom part of a drilling assembly. Insufficient well cleaning results in slurry accumulation, complicated drilling processes, and possible well accidents. Due to that, only bottomhole cleaning from the drilled-out rock and its taking to the day surface account for 70 percent of all energy consumed for well construction. The efficiency of well cleaning depends on such factors as size and shape of slurry particles, velocity of an upward flow and its motion conditions, and technological parameters of drilling washing fluids [5].

Thus, the represented brief description of current situation in terms of well construction technology and equipment demonstrates that the search for possible ways for improving efficiency and reducing capital capacity of drilling operations, i.e. their essential cycle – hydraulic cleaning programme, is rather a topical problem, which solution will help the oil-and-gas industry follow the road of sustainable innovative development.

2. Analysis of recent studies and publications and singling out of previously unsolved parts of a general problem

A process of well sinking is accompanied by continuous slurry generation (the rock broken by a rock-breaking tool). Drilling efficiency, especially in terms of complicated mining and geological conditions, depends greatly on proper cleaning of both the well bottomhole and the drill mud itself from slurry. Numerous scientific and practical papers deal with this problem; the papers consider the factors of determining the required velocity of an upward stream that provides removal of the drilled-out particles [6]; the latter gains special importance while performing operations for well shaft preparation for lowering a casing pipe and its further cementing.

It should be noted that the problematics of well cleaning from slurry depends considerably on a set of factors with the following most important ones: physical properties of washing and special process fluids; modes of their flow along the shaft; geometry of some generalized circulation channel determined by the design ratio of the well shaft elements and the drill column itself.

Arranging the measures for intensification of the slurry transportation processes, based on different physicochemical effects, may be rather an efficient method to improve the conditions for implementing a hydraulic programme of well cleaning from the rock breaking products.

In case of impact and percussive-rotary drilling, rock is broken on the bottomhole as a result of mechanical action of cutters or teeth of a rock-breaking tool. In this context, a breaking process means separation of certain particles from the rock mass by cutting, grinding, squeezing, spalling or crushing. The separated rock particles remain on the bottomhole or on the cutter blade, preventing the breaking of the next layer and resulting in the accelerated wear of a rock-breaking tool. A stream of cleaning agent is aimed at timely removal and transportation of the broken particles from the well bottomhole. In case of incomplete or untimely removal of the separated rock particles, they are subjected to secondary crushing; as a result, they complicate further effective rock breaking with the following considerable reduction in mechanical drilling rate and accelerated wear of a rock-breaking tool [7].

Great attention is paid to the analysis and formalization of the cleaning processes of well bottomhole and shaft while drilling. However, the indicated problem is far from its complex and logical solution, which is confirmed by the available numerous research and analytical works dealing with this problem and by the existing significant contradictions in the conclusions by competent authors. That is why our consideration of possible ways for further improvement of bottomhole washing while well drilling is of great practical and theoretical interest [8].

First of all, it should be noted that solution of this problem involves complicated tasks of deeper understanding of the role of different factors in the efficiency of implementing technological means for the well bottomhole and shaft cleaning [9].

Up to now, the regularities of movement as well as conditions of washing and removing functions of, generally, a cleaning agent within the bottomhole zone while drilling with different types of rock-breaking tools, have not been studied yet. Consequently, it is natural that a problem of possible design of modern advanced washing units of a rock-breaking tool has not been also solved yet [10].

One should also consider the regularities of slurry formation and its granulometric composition while drilling out the rocks, being dissimilar in their physicomechanical properties, with the help of tools of different types in terms of varying drilling conditions, taking into account the fact that nowadays we have accumulated rather considerable but unsystematized amount of data on the development of rock-breaking processes.

The influence of properties of a drilling washing fluid on a granulometric composition of breaking products should be analyzed in more detail, paying attention to the features of well manifestation of washing and removing capacities of a fluid flow.

The causes of such negative phenomena as slurry adhesion with the resulting packing have not been studied completely so far.

Deeper analysis of the effect of different factors of well washing processes on the technical and economic indices of a rock-breaking tool is of significant practical and theoretical interest [11].

It is necessary to consider thoroughly the issues concerning regulation of rheological properties of a drilling cleaning agent to increase its removing capacity; in its turn, that will allow decreasing the required rational supply of drilling washing pumps.

The improvement of a washing process is also connected with the possibility of solving a problem of washing fluid pressure decrease on the well bottomhole with the simultaneous support of technologically required pressure in the annular space of the well shaft [12].

According to some researchers, during the operation of a modern rock-breaking tool, the well bottomhole always has the excess volume of slurry, which removal will help increase the mechanical drilling velocity by at least 30-50 percent even in terms of preserved constant axial load and rotational frequency.

Critical analysis of the available data makes it possible to outline general tendencies in the main scientific and practical papers in terms of modernization of the conditions for implementing effective hydraulic programmes of well cleaning from the rock breaking products: development of the grounds for design and functioning of the necessary circulation equipment; complex physico-mathematical modelling and numerical studies of the processes of transportation of rheologically complicated substances (washing and process fluids); determining the features of changes in fluid flow modes relative to integral characteristic of the surface shape of well shaft walls; development of methodological and practical recommendations concerning the application of technical and technological solutions and innovative operations to provide reliable use of special equipment and methods of performing the corresponding operations while well drilling under the specified conditions.

Basing on the aforementioned, the following conclusions can be made. Study of the specifics of slurry particle motion within the annular space of a well under construction and development of a methodology for calculating optimal consumption of a washing fluid taking into account all key factors affecting the washing mode while well drilling, are rather topical and have significant scientific and practical value.

3. Statement of the main research material

Methodological hydraulic calculations of a circulation process are performed for determining the required characteristics of a drill pump (compressor) as well as substantiated selection of its type, being in the best compliance with the calculated values, and the necessary number of pumps [13].

The hydraulic calculations involve also the following important technological parameters: intensity of the cleaning agent supply; mode of the agent flow depending on the movement velocity; hydraulic (aerodynamic) fluid motion resistances in terms of specific areas, total hydraulic (aerodynamic) resistances.

A technological process of washing should be designed and implemented for reaching the best technical and economic drilling indices and the overall well construction performances. In this context, main attention should be paid to being stick to key technological functions and limitations.

At any drilling type, dimension of slurry particles is characterized by a wide range: from several microns up to centimetres. To evaluate the possibility of slurry transportation by the cleaning agent flow, average size of particles, which make up the main share of generated slurry along with the smaller fractions, is usually taken. However, certain particles on the bottomhole may be more than the average size by 3-5 times. The latter circumstance transforms into such a necessary additional factor of a hydraulic programme process: while rising above the bottomhole, large particles of the broken rock are subjected to the action of a rotating drilling assembly; they are crushed and then transported by the cleaning agent flow to the surface [14].

The average slurry size depends, first of all, on the design of a rock-breaking tool. The particle size is greater while drilling in fissured and grained rocks, in case of impacting action of a tool, while drilling with considerable axial load and minor rotational frequency. Table 1 represents analytical and practical data concerning granulometric composition of the breaking products obtained as a result of studies carried out at the Department of Oil-and-Gas Engineering and Drilling of Dnipro University of Technology (DUT) and production enterprises of the corresponding area.

A slurry shape influences significantly a value of the raising force generated by the flow. Depending on the structure of rocks being drilled out and a breaking method, there can be great variety of particle shapes. The most often particle shapes are grained ones including round and irregular samples.

In terms of flow velocity equal to critical V_{cr}, the average-sized slurry particles are only retained in a suspended state without their removing to the surface. Slurry transportation requires that the flow velocity V_n will be more than the critical one; moreover, the particles will move with velocity, being equal to the difference of the indicated flow velocities:

$$C = V_n - V_{cr}. \tag{1}$$

Table 1. Typical sizes of slurry particles while drilling with different rock-breaking tools (according to the DUT data).

Type of a rock-breaking tool	Averaged sizes of slurry particles, Range of distribution of typical sizes		
	(average)	(typical)	(maximum)
Roller bits of an oil range	5.0	0.4-12.0	20 and more
Roller bits of a geological-prospecting range	3.0	0.2-4.0	10.0 and more
Diamond crowns	0.2	0.01-0.25	up to 3.0
Hard-alloy crowns	0.4	0.1-0.5	up to 5.0

A value of particle velocity transportation is selected according to the drilling conditions. It should be sufficient for preventing slurry accumulation in a well. It should be the greater, the higher the drilling velocity and well depth are.

It is commonly supposed that quantitative criteria of well cleaning is a volumetric concentration of slurry particles in flow $X = V_{BSH}/V_{KP}$ (V_{BSH} – volume of slurry within the annular space of a well, V_{KP} - volume of annular space of a well) that should not exceed 0.05 of a relative unit, i.e. increasing density of the upward flow due to the added slurry is considered to be admissible up to the values of 20-30 kg/m^3.

Drilling practice uses another criterion as well. In this context, it is possible to determine the required velocity of slurry transportation for specific conditions according to the following formula

$$C = \frac{F_v V_m (\rho - \rho_p)}{F_{kn}(\rho_{pv} - \rho_p)}, \tag{2}$$

where F_v is bottomhole area of the well under construction; V_m is mechanical velocity of drilling; F_{kn} is area of the annular space of a well; ρ is density of the broken rock particles; ρ_p is density of the drilling washing fluid; ρ_{pv} is density of the upward flow of the fluid with added slurry.

In terms of the most typical conditions of well drilling, a value of minimum velocity of slurry particle transportation is usually within the range of 0.02-0.2 m/s. Under such conditions, the transportation velocity will be as follows:

$$C = \frac{F_v V_m}{F_{kp} X}. \tag{3}$$

Practical necessary rate of particle transportation while using gaseous agents is 0.1-0.4 m/s.

Nowadays, the practice of constructing different-purpose wells applies the following criteria for determining minimum consumption of washing fluid: magnitude of the upward flow velocity;

specific consumption per 1 cm of the rock-breaking tool diameter, concrete values of consumption for each type and size of a rock-breaking tool as well as properties of the rocks being drilled.

To organize effective and unambiguous study of the well washing conditions, specialists of the Oil-and-Gas Engineering and Drilling Department of DUT have developed a special research stand of aerohydrodynamic flows with principally new design, functioning mechanism, and control and measuring support that makes it possible to do the following: to analyze in the simplified form the local quantitative parameters of multiphase slurry-enriched flow under conditions being maximally close to the real ones with the addition of impurities simulating the rock mass breaking products; to enhance the capacities of experimental methods of slurry accumulation diagnostics; to model physicochemical interactions of the flow with the well shaft walls and generally within the cleaning agent volume. All that helps create the conditions for reliable development as well as testing and correction of technological characteristics of special drilling washing fluids that will be the guarantee for eliminating complications and accidents due to improper cleaning.

The stand for studying aerohydrodynamic flows consists of a closed case, with the connected main pipelines with a manometer and a loss meter, and the research devices mounted in it. The stand case is cylindrical; it is made from transparent plastic. The input unit “manometer – loss meter – anemometer”, to control the enriched flows within the well shaft, is mounted within the lower cylindrical part the case. A parametric unit, for which positioning can be performed, is mounted within the middle part of the case. On one side, this parametric unit consists of videorecorder; on the other side, it has thermoanemometer and turbine loss meter. Besides, the upper cylindrical part of the case is equipped with the material dosing unit.

In terms of the proposed scheme, one can measure 2D or 3D fields of velocities of a working flow in the effective volume.

Performance of the aerohydrodynamic stand for engineering studies of the well cleaning process was tested by numerous experiments.

The stand can be used for modelling the conditions of bottomhole and well shaft cleaning, under conditions being maximally close to the real ones, which helps obtain quite reliable local quantitative hydroaerodynamic characteristics of multiphase flows of circulating agents formed by the operation of drilling tool effectors. It also allows studying slurry accumulation processes with wide variations of technological parameters of a cleaning cycle in case of problematic areas.

The recommended upward flow velocities are taken more than enough for the well cleaning conditions. The estimated calculations and immediate laboratory and stand-based studies show that in case of diamond drilling the upward flow velocity being 0.12-0.15 m/s can be enough; in case of hard-alloy drilling, that is 0.15-0.2 m/s; and while drilling with roller bits of oil and geological-prospecting range, the value is 0.3-0.4 m/s.

Analysis of the recommendations taking into account the typical sizes of annular space for wells demonstrates that the minimum consumption of washing fluid should be selected at well diameter being up to 100 mm – in terms of specific consumption per 1 cm of the rock-breaking tool diameter; and if well diameter is more than 100 mm – in terms of the required upward flow velocity (Table 2).

Table 2 represents minimum and maximum values of specific consumptions. Rational consumption of a washing fluid is selected taking into consideration the properties of drilled rocks within the indicated range. The consumptions gain their maximum values while drilling in stable abrasive rocks giving great amount of slurry as well as at additional slurry falling from the well walls.

Field studies of a well cleaning process were carried out in terms of special drill rig (figure 1) located within the training drill field of the Oil-and Gas Engineering and Drilling Department of DUT. The stand includes: drill plunger pump $NB3-120/40$ (1), loss meter $EMR-2$ (2), well model (3), drill collar (4), drill pipes (5), suction and injection pipelines (6) and (7), drill

Table 2. Estimated values of the indices of a hydraulic well washing programme (according to the DUT data).

Type of a rock-breaking tool	Specific consumption of a washing fluid, (l/min)cm	Upward flow velocity, m/s
Roller bits (under normal drilling conditions)	7-15	0.3
Diamond crowns and bits	3-8	0.12
Hard-alloy crowns	5-10	0.15

rig (8), tank for cleaning agent sampling (9), ditch system (10), collector (11).

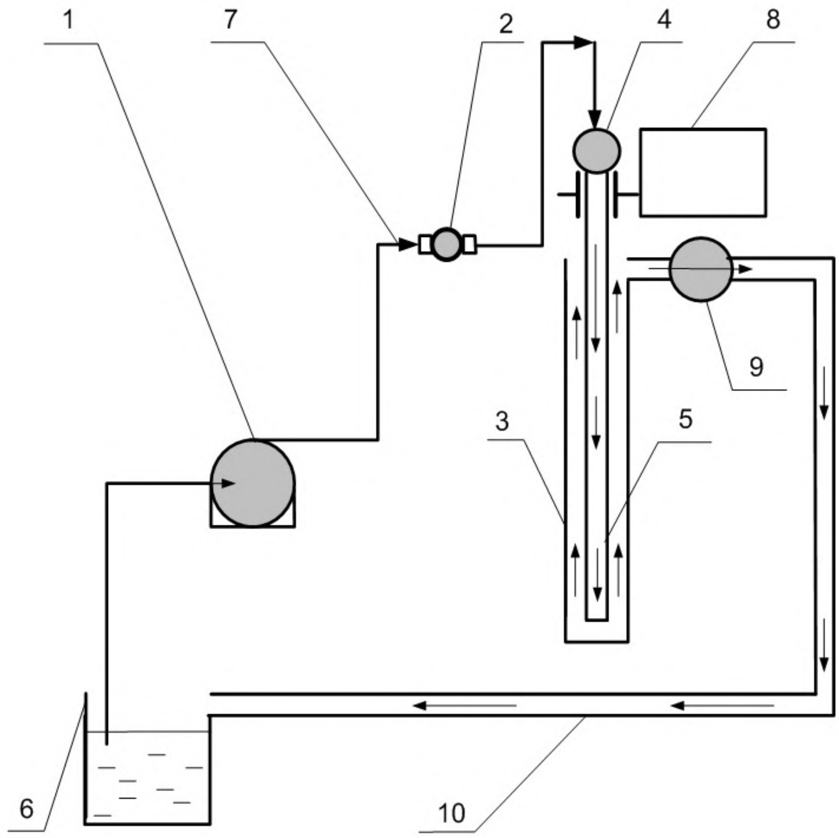

Figure 1. Scheme of the well under consideration.

The first stage involves the following: the calculated amount of tracer material (slurry) is put into the well model; in its shape, the tracer material is similar to the natural slurry with different fractions being peculiar for each drilling type. Washing fluid is supplied by a pump into the well model. While studying, the velocity of tracer particles and the time required for complete cleaning of the well bottomhole are determined. Photographing is used to identify distribution of the well shaft particles. The influence of the value of washing fluid consumption and its properties on proper cleaning of the well bottomhole is estimated according to the time of tracer's carrying out to the surface. The second stage involves determination of factual required time for the complete tracer's carrying out to the surface at the specified frequency of tool drill string rotation as well as technological properties of a washing fluid and its consumption.

In case of rotary drilling, the following rates of upward flows in the annular space are recommended: 0.6-0.8 m/s while drilling with a normal-density mud; 0.4-0.6 m/s while drilling with a weighted mud; up to 1.2 m/s while drilling in clay rocks; and 0.3-1.0 m/s while drilling upper intervals of wells. When drilling wells with the use of bottomhole motors, the cleaning agent consumption is determined by characteristics of the applied device. Generally, if drilling involves turbodrill, the amount of washing fluid supplied on the bottomhole is not enough for its effective cleaning from the broken rock. That is connected with the fact that up to 10 percent of the drill mud and up to 20 percent of technical water leak, not reaching the bottomhole, due to nontight connecting parts of turbodrills. In case of electric drilling, the consumption may be 0.035-0.05 $l/(\text{s}\cdot cm^2)$; and while drilling with hydraulic screw bottomhole motors, it is not more than 0.07 $l/(s\cdot cm^2)$.

If there is air drilling, selection of rational air consumption is calculated taking into account the same factors as the ones while well washing. Contrary to the washing, the upper limit of rational air consumption is seen less clearly and usually determined by the compressor productivity. Minimum required consumption of compressed air is taken from the conditions of slurry transportation along the well shaft. In practice, increase in mechanical drilling velocity is determined along with the growing air consumption and when the required velocity of an upward flow is reached owing to the improved well cleaning. Having reached certain air consumption value, further growth of drilling velocity terminates. Optimal value of air consumption is defined by the condition of well cleaning; it depends on the rock-breaking tool type, composition of drilled rocks, and available water inflows. It is determined by the research methods. In terms of minor values of annular section area, selection of air consumption only according to the upward flow velocity results in the obtaining of erroneously low results. Table 3 shows guide values of specific air consumption per 1 cm of the rock-breaking tool diameter.

Table 3. Guide values of the indices of aerodynamic programme of well cleaning (according to the DUT data).

Typical drilling type	Specific air consumption, m^3/min per 1 cm of the rock-breaking tool diameter	Possible upward flow velocities in different annular sections, m/s
Bit drilling	0.7-1.0	14-100
Diamond drilling	0.4-0.5	10-50
Hard-alloy drilling	0.5-0.7	10-75

Contrary to washing, rational consumption of compressed air depends on the well depth. If the depth is considerable, then the compressed air consumption should go up to compensate the reducing velocity of flow in the bottomhole zone due to the growing pressure in this zone. It is recommended to increase consumption for the first 600 m of depth with further increasing by 10 percent within the following 600 m. Certain increase in the compressed air consumption is recommended in case of water inflows in a well.

In most considered cases, the compressed air consumption coincides with the compressor productivity, which is within the range of 6-9 m^3/min. This productivity is enough for blowing wells with the diameters up to 100 mm. In terms of large well diameters, it is suggested either to use two compressors in parallel or to use special highly productive compressors.

Great number of papers is devoted to the study of such practically important problem as motion of broken rock particles within the rotating upward flow. The majority of those papers are experimental. Almost all those studies are similar in the fact that while analyzing the particle motion in a flow, a problem of particle distribution within the annular space is not examined though this problem is of great practical significance – the knowledge of regularities of slurry particle motion in a flow makes it possible to identify and prevent possible shaft contamination with the resulting seizure of drill pipes and formation of packing on them.

The following types of flow modes can be identified in the flow rotating together with the drill string: 1) laminar; 2) laminar with vortexes; 3) purely turbulent; 4) turbulent with vortexes. All these flow modes can be represented while well washing [15].

According to the previously indicated conditions, the particle moving in the dense fluid flow is affected by transversal forces stipulated by the difference between velocities on the particle boundaries during flow rotation $F_n^{'}$, on the one hand, and the difference between the velocities of axial flow F_n, on the other hand. In first approximation one may consider that the mentioned two forces are added geometrically, and the motion is determined by the resulting force. Besides, the particles rotating together with the fluid appeared to be under the effect of centrifugal force [16]. In terms of steady motion, angular velocity of particle rotation u_r is approximately equal to the angular velocity of fluid rotation with angular velocity ω.

In this context, if in case when annular space is formed by drill pipes with radius R_1 and well walls with radius R_2 and average distance between the well axis and conditional centre of the transported slurry particle is equal to some variable value R, the law of linear velocity distribution in the annular space in terms of normal section is described by expression

$$u_r = \frac{\omega}{(\frac{R_2}{R_1})^2 - 1} \times \frac{R_2^2 - r^2}{r}. \tag{4}$$

Force $F_n^{'}$ aims for particle replacing into the area with large u_r, i.e. taking the particle closer to a rotating drill pipe. This force demonstrates the largest value near the wall of a rotating pipe; the smallest value is seen near the well wall.

The process of drill string rotation in a visco-plastic fluid also involves migration of particles to the well walls; moreover, the more intensive the migration is, the more deviations of the properties of visco-plastic fluid are, compared to the properties of the viscous one [17]. The lower velocity of the particle falling is and the larger well diameter is, the slower transverse motion of the particle is. In all cases, the velocity of particle migration to the well walls increases along with the growing rotation velocity.

When a washing fluid moves within the well shaft, a slurry particle located on its surface experiences the washing action of the fluid flow moving in parallel to the bottomhole. In this context, the following variants of particle separation from the bottomhole are possible (figure 2).

Motion of the washing fluid immediately on the well bottomhole is characterized by one or another degree of flow turbulence, which value is determined by the value of Reynolds criterion

$$Re = \frac{U d_e \rho_p}{\mu}, \tag{5}$$

where U is flow velocity on the bottomhole, m/s; d_e is equivalent flow diameter, m; ρ_p is density of a washing fluid, kg/m^3; μ is dynamic viscosity of a fluid, $Pa{\cdot}s$.

While drilling, a boundary layer is formed on the bottomhole, in which either laminar (characterized by parabolic distribution of velocities) or turbulent (characterized by flattened distribution of velocities) mode can be at low velocities of washing fluid motion; though, irrespective of the motion mode within the boundary layer, a laminar sublayer is formed, influencing considerably the motion conditions of the broken rock particles [18]. Thickness

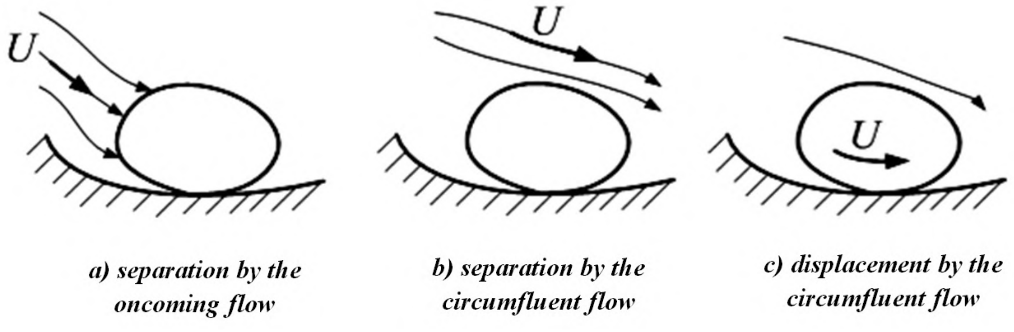

Figure 2. Review of possible separation patterns of the broken rock particles from the bottomhole.

of the laminar sublayer depends on the washing fluid density and velocity of the fluid motion. Thickness of a laminar sublayer as well as motion velocity in it is proposed to be determined by the following formulas

$$h_L = a\frac{v}{U_{ser}} \tag{6}$$

and

$$U_u = by\frac{U_{ser}^2}{v}, \tag{7}$$

where h_L is thickness of a laminar sublayer, m; v is kinematic viscosity of the fluid, m^2/s; U_{ser} is average velocity of the fluid within the bottomhole zone, m/s; U_u is velocity of the fluid motion within the laminar sublayer at distance y from the bottomhole, m/s; a and b are coefficients that depend on the coefficient of hydraulic resistance, the washing fluid density, and other factors.

Therefore, the following conclusion can be drawn. Some rock particles formed under the influence of a rock-breaking tool are affected by the boundary layer action while others enter the zones of laminar sublayer action (figure 3). As a result, a part of slurry is not removed by the washing fluid flow; that results in further crushing of this slurry and increased wear of a rock-breaking tool.

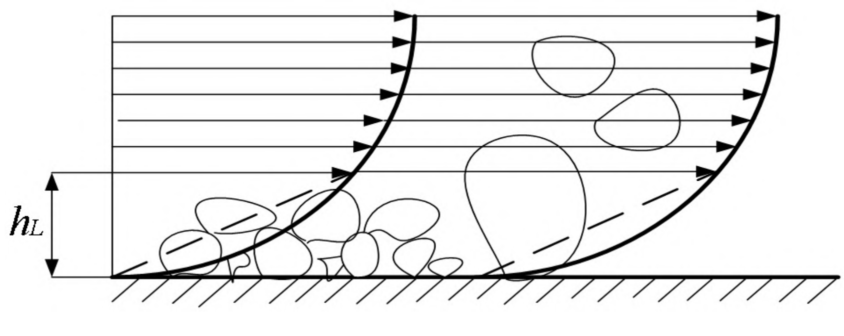

Figure 3. Guided profile of velocities within the bottomhole zone of the well under construction.

It is not hard to see that according to (6) and (7) the two-time growing velocity of fluid motion within the bottomhole zone results in two-time decrease in the laminar layer thickness and four-time increase in the fluid motion velocity within itself.

A turbulent state of a washing fluid within the bottomhole zone is the main factor of the well cleaning efficiency. Intensity of the flow turbulence on the bottomhole is determined mostly by the viscous properties of a washing fluid. Along with the growing density of a washing fluid, a level of turbulence decreases; thus, the conditions of well cleaning deteriorates.

In terms of roller bit drilling, a washing fluid pumped through the bottomhole zone has relative function: it catches the slurry suspended within this zone and removes it into the annular space. It can be assumed that this fluid moves around a bit in the form of vortex flow. The removing capacity of the vortex flow is higher, the greater the value of its velocity vortex is. At this vortex intensity, the value of its velocity is in reverse proportion to the area of cross section of a vortex flow f_v. As for the bottomhole zone, the cross-section area of the vortex flow is the cross-section area of the annular space between the bit and well wall. This area is not similar throughout the bit height.

The measuring results help state that the roller bits have maximum f_v at the level being from the bottomhole at the distance that is approximately equal to the projection of the bit roller diameter on the vertical axis; it is somehow more than f_v near the bit base, i.e. near the bottomhole (figure 4).

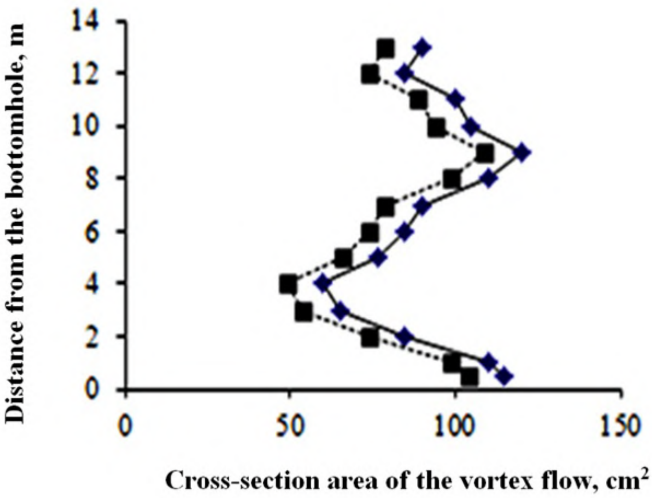

Figure 4. Averaged values of the cross-section area of the annular space between the bit and well wall throughout the bit height.

Minimum values of the cross section area of a vortex flow are observed on the shirttails, and it is lower than the maximum values by almost 2 times. Thus, at the level corresponding to the upper position of the peripheral roller cutter teeth, the velocity vortex has its minimum value. Therefore, there are conditions for slurry accumulation here.

Well drilling in sedimentary rocks is accompanied by the formation of different complications. The most often problem is seizures – unexpected accidents in a well characterized by partial or complete stopping of a drilling tool, metal tubing or geophysical (hydrogeological) devices and facilities. Seizures are the most complicated and labour-consuming accidents in drilling. There are three main types of seizures: 1) of drill strings; 2) of tubing; 3) of rock-breaking tools and rotatable drill pipes.

Table 4 shows concrete recommendations as for selection of effective washing systems for constructing wells in soft sedimentary rocks.

While studying the effect of washing fluids on the argillaceous rock swelling by the specialists of the Oil-and-Gas Engineering and Drilling Department of DUT, a swelling degree K was used

Table 4. Guide values of the indices of aerodynamic programme of well cleaning (according to the DUT data).

Complication	Typical rock	Recommended cleaning agents
Falls, washouts	Sand	Clay and chalk fluids with increased amount of solid phase, weighted fluids
Falls, swellings, plastic flow, washouts	Clay loam, clay, sand-clay soil	Inhibited clay fluids, chalk sapropel fluids
Falls, rock sloughing, minor swelling, plastic flow, washouts	Clay slate	Inhibited clay and chalk fluids with lowered filter loss. In some cases, clay fluids
Falls, rock sloughing, minor washouts, rock inrushes	Sandy shale	Clay and chalk fluids. Fluids based on drilled-out rocks, silicate-humic, polymer, combined

to characterize this process (this value includes such notions as volume of swelling fluid V_p and volume of dry clay particles V_o) being equal to the ratio of totals of volumes V_p+V_o; it shows by how many times the volume of dry particles increases.

$$K = \frac{\rho a}{m} + tg(\beta - 1), \tag{8}$$

where ρ is density of dry clay; m is mass of the specified sample; β is coefficient indicating the share of the porous space volume that fits in the swollen sample; a is coefficient depending on the clay properties and value β.

Since clay swelling was studied in washing fluids containing different substances, distilled water was taken as the reference fluid. The swelling process was analyzed in terms of the most active sedimentary rock – montmorillonite with the interpretation of the obtained results for other argillaceous rocks.

In terms of clay rocks available in the well section, their capacity for swelling determines complexity of the well shaft construction [19]. Clays containing montmorillonite are called bentonite clays. While swelling, they can increase in volume by 14 times. The current drilling practice proves that use of clay fluids allows in most cases preventing possible complications in the well shaft due to manifestation of different physicochemical properties of sedimentary rocks and, in our case, clays. Along with that, efficiency of clay fluid application can be maximum only in terms of drill mud conditioning that means physical and chemical processing of a disperse medium.

Even without any chemical processing, bentonite clays help prepare muds being better as for stability and other parameters. Kaolin clays dissolve badly in water. Stability of kaolin solutions is rather insignificant. Illite minerals give a solution being intermediate in its quality.

While preparing clay muds, one should control their main technological parameters (Table 5).

Preparation of clay mud involves additional clay dispersion [20]. A degree of clay particle dispersion depends of the grinding intensity, physicochemical and mineralogical clay composition. Montmorillonites have the highest dispersion while kaolin clays have the lowest one. In case of bentonite, a fraction of more than 1 mcm in per cent in weight is about 15 percent; for kaolinite, it is 60 percent; less than 50 mcm for bentonites - about 40 percent, and kaolinite does not produce such a fraction.

Table 5. Types and parameters of some types of clay-based washing fluids (according to the DUT data).

Type of washing fluid, mud	Main technological parameters				
	Density ρ, kg/m^3	Funnel viscosity T, s	Filtration loss B, $cm^3/30\ min$	Shearing stress (dynamic), Pa	Shearing stress (static), Pa
Normal clayey	1070-1130	20-24	20-30	17-20	7.4-13
Normal clayey with increased amount of clay	1150-1200	25-30	25-35	18-20	8-14
Improved clayey	1060-1100	19-23	12-15	19-21	8.2-15
Slightly clayey polymer-bentonite	1040-1060	16-33	3-12	2-4	1-3
Weighted with barium sulfate clayey	1600-1900	25-60	5-6	17-25	17-24
Fluid on the basis of drilled-out clay rocks, unprocessed	1020-1050	16-20	25-30	8-12	2.5-6

4. Conclusions

Basing on thorough study of literature sources and in-depth analysis of the industrial and laboratory data, the most significant factors for increasing the drilling operation quality have been identified; that also has helped determine the main directions of complex improvement of well technologies, i.e. in designing rational hydraulic programme of well washing. The features of circulation processes while well drilling as well as their physicochemical aspects have been considered comprehensively and successively. The following problems have been studied: influence of the parameters of a cleaning agent on the bottomhole processes of rock breaking; interconnection between the physicochemical characteristics of breaking products and circulation processes on the bottomhole and in the well shaft; features of the schemes of cleaning agent circulation connected with the variety of geological and technical factors.

It is necessary to continue experimental and theoretical studies of the features of implementing the principles of improved hydraulic programme of well washing that rely on the basic technologies of effect on the bottomhole and walls of the well under construction, while applying rational compositions of washing fluids. Further studies should involve identification and substantiation of the optimal technical and technological solutions with maximum consideration of specific mining and geological conditions of the deposits being developed.

Acknowledgments

The research is carried out by Dnipro University of Technology (Ukraine) and Caspian University (Kazakhstan) and Yessenov University (Kazakhstan). We express our gratitude to our colleagues who provided us with the required information and helped considerably complete the research.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012031 doi:10.1088/1755-1315/1049/1/012031

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Application of new constructive solutions of high buildings' zero cycle during building in difficult engineering and geological conditions

To cite this article: R A Timchenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012032

Application of new constructive solutions of high buildings' zero cycle during building in difficult engineering and geological conditions

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Abstract. Recently, there has been a significant reduction in the number of favorable areas for construction of buildings and structures, which leads to the need to build various facilities in special conditions, so in areas with difficult engineering-geological and mining-geological conditions of construction, which are deteriorating due to natural and man-made factors. It is necessary to assess the possibility of deformation of structures located on foundations with possible uneven deformation in the practice of design and operation. Only with reliable and accurate determination of the stress-strain state of foundation structures and soil mass the service life of buildings and structures can be predicted. Calculations performed with the help of PLAXIS and LIRA programs allowed to analyze the stress-strain state of the soil mass and the stability of the foundations with the same soil base (layer thickness and physical and mechanical properties), loads and boundary conditions: Option I – ordinary solid monolithic reinforced concrete foundation slab; Option II – proposed a solid monolithic reinforced concrete slab with a system of cross beams of different stiffness (patent № 13794). The validity of the theoretical forecast of the behavior of the foundation structure, which interacts with the unevenly deformed base, can not be obtained on the basis of the regulatory framework. The possibility of using a foundation with a system of cross beams of different stiffness in order to increase the reliable operation of high-rise buildings was experimentally and theoretically proved.

1. The problem and its connection with scientific and practical tasks

The thickness of the foundation slab depends on the applied load, the nature of its transmission and the physical and mechanical characteristics of the base soils. Problems of ensuring the reliable operation of "zero cycle" structures, such as groundwork, foundations and aboveground parts of high-rise buildings occupy a special place in their design and construction [1]. The uniqueness of the construction of the foundations of high-rise buildings shows that there is a need for scientific support of design and construction by specialized geotechnical organizations [2].

The choice of construction of the foundation of a high-rise building should be based on technical and economic analysis and is determined by the structural behaviour of the building,

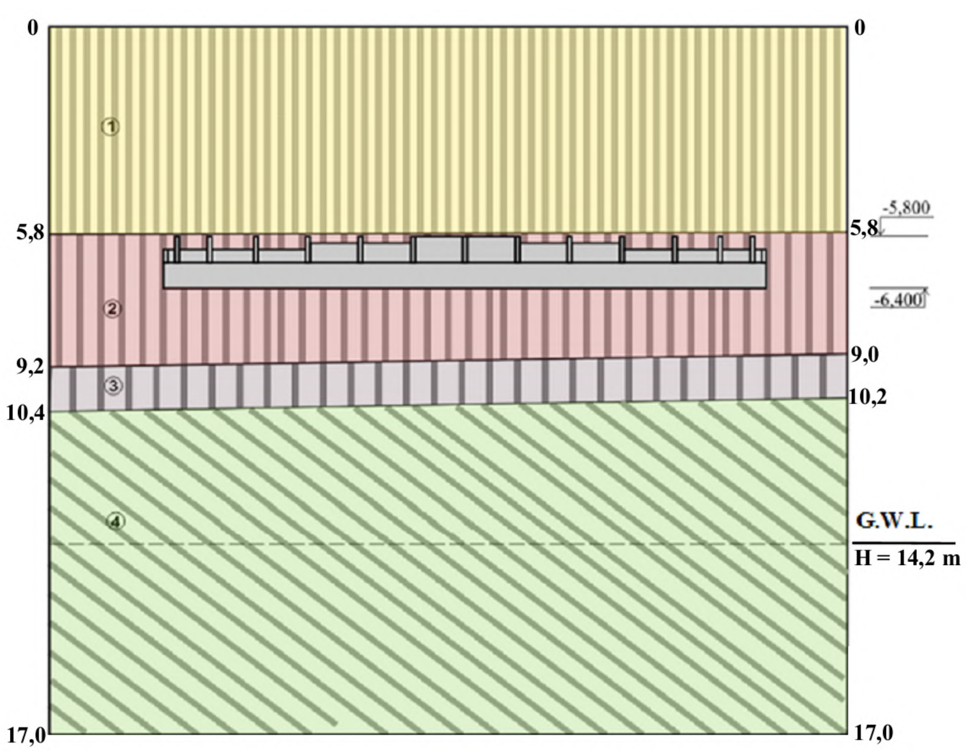
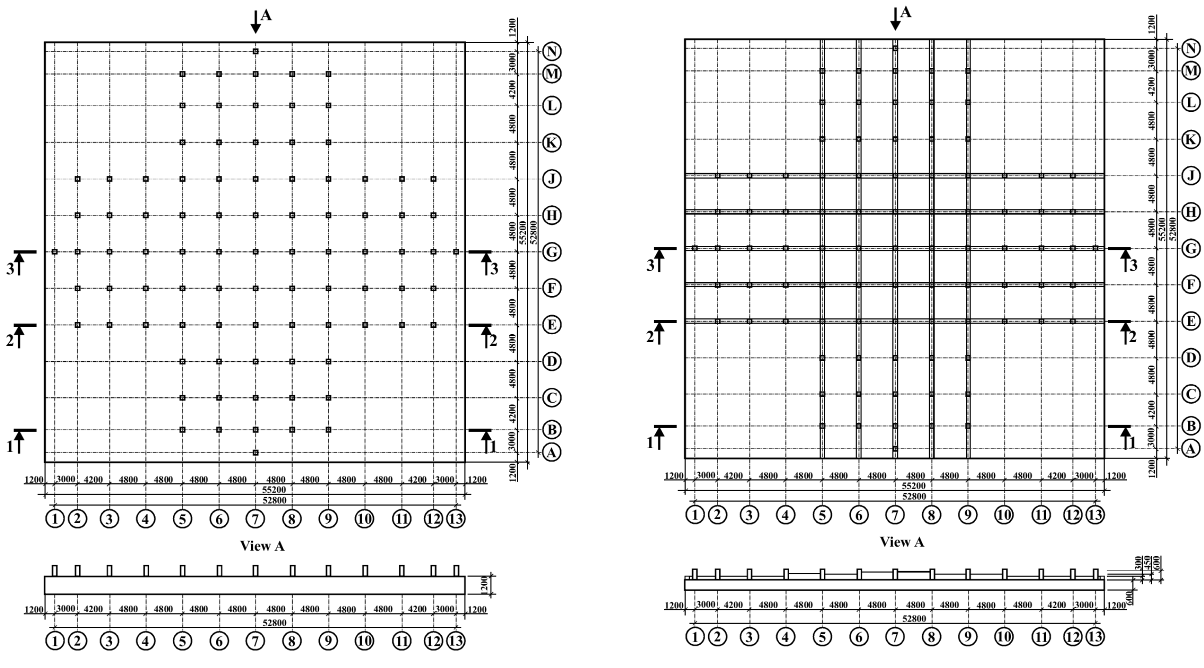


Figure 1. Engineering and geological section.



(*a*) (*b*)

Figure 2. Plan and type A I option (a) and II option (b) foundations.

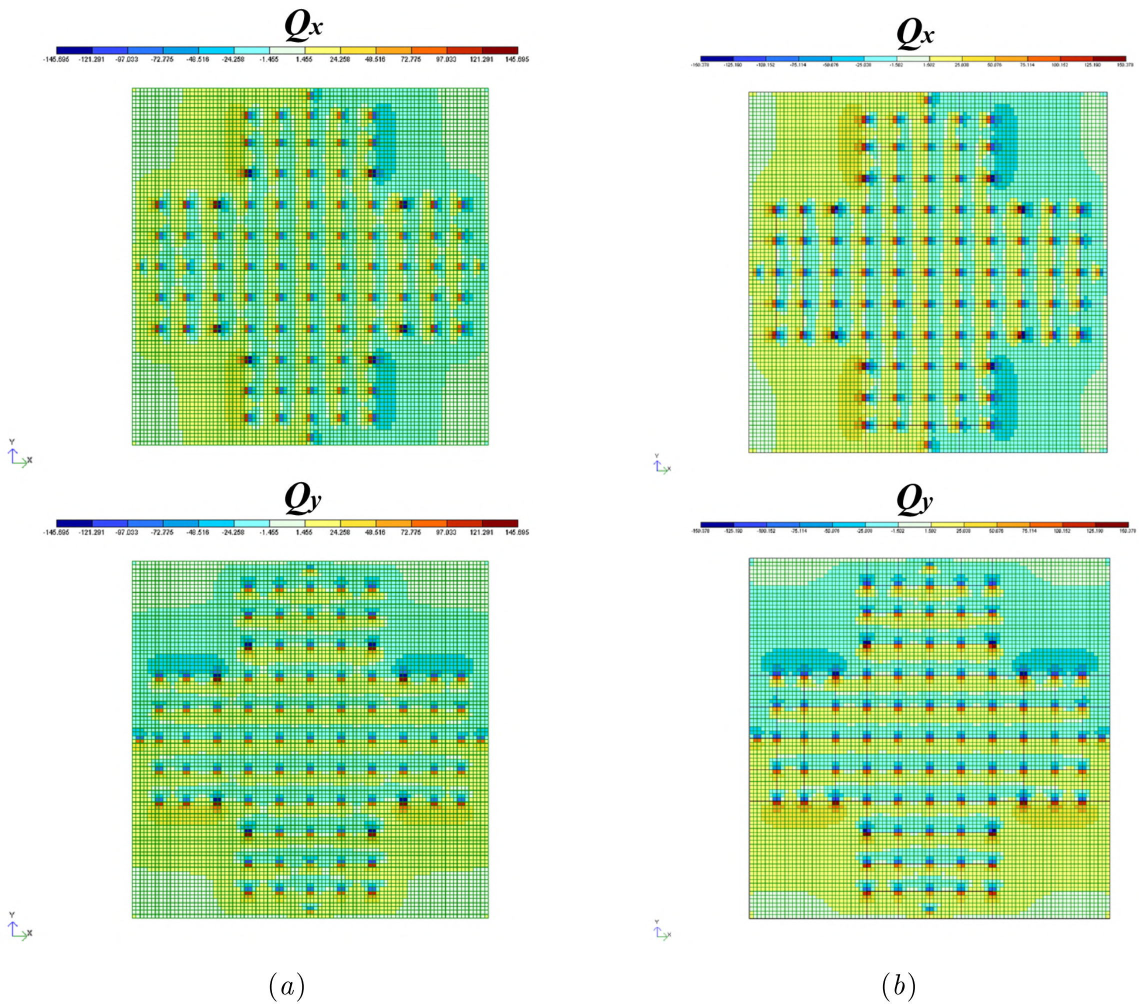


Figure 3. A mosaic of effort Q_x, Q_y, I option (a) and II option foundations.

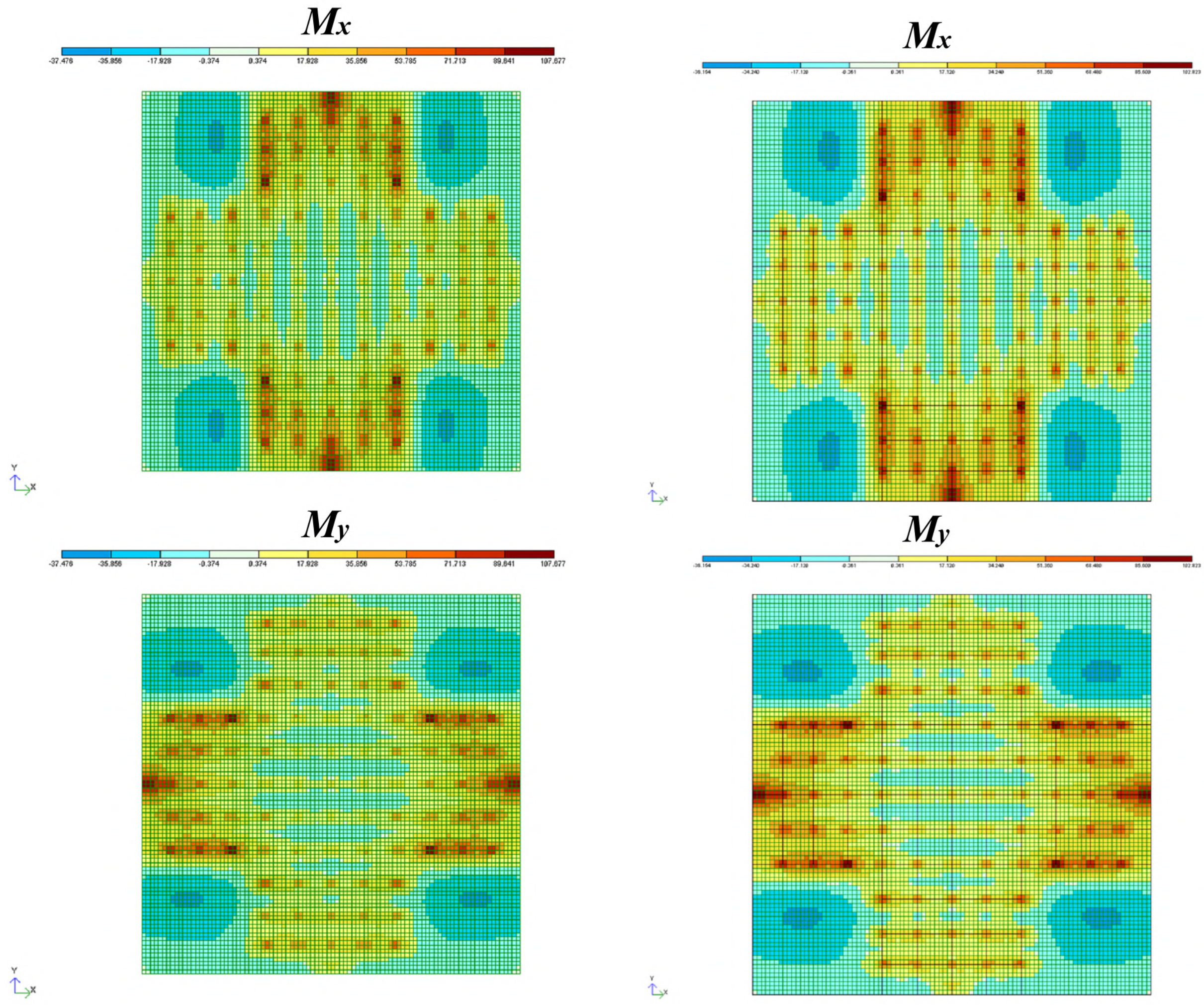
soil properties, loads transferred by the building to the foundation, interaction of the building with the soil and surrounding buildings [3].

The territory of Kryvyi Rih is characterized by complex soil construction conditions, where the initial subsidence is very uneven and other deformation soil processes are possible, regardless of the weight of the building, which can suddenly start at any time during the life of buildings. Therefore, in difficult conditions, the high risk and the unpredictability of deformation processes in the foundation soil are much higher than in normal conditions.

2. Analysis of studies and publications

The design of zero-cycle structures in difficult engineering and geological conditions requires improvement of the regulatory framework, modern methods for determining the physical and mechanical characteristics of the underlying foundations, new calculation programs that take into account physical and geometric nonlinearity [4–10].

Today, among the existing types of foundations for high-rise engineering structures, a significant percentage is occupied by raft foundations for work in special conditions, which are characterized, firstly, by deteriorating engineering and geological conditions, and, secondly, by processes with subsidence of foundations caused by natural and man-made conditions of urban



(a) (b)

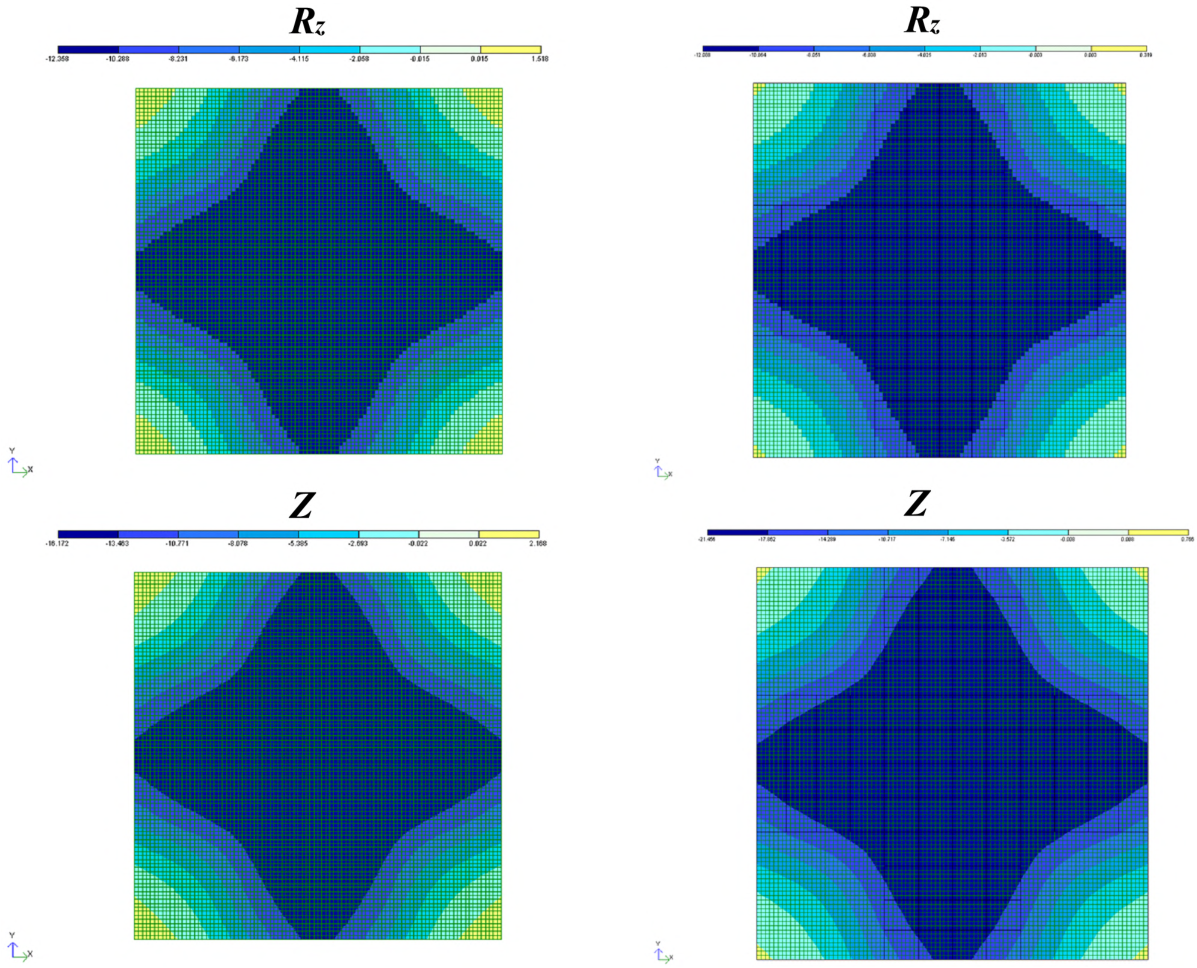
Figure 4. A mosaic of effort M_x, M_y I option (a) and II option foundations.

areas. Therefore, special foundation structures are needed that can work in such conditions.

When considering the "groundwork – foundation" system, emphasis is placed on the specifics of the properties of reinforced concrete or on the features of the soil foundation. However, the inaccuracy of calculation schemes, shortcomings in the assessment of soil base characteristics and in the behavior of buildings and structures during exploitation lead to the fact that these structures are subject to significant deformations (cracks in structures, shearing and torsional) and go out of service [11–14].

Analysis of existing work on the behaviour of foundation slabs that interact with unevenly deforming foundations shows that there is still no generally accepted method of calculation that allows to take into account the features of deformation of reinforced concrete and soil (under complex load) deformation of the base during the operation of buildings and structures [5–7].

Extensive theoretical and experimental studies of slab foundations by domestic and foreign scientists have led to the development of methods and the creation of calculation programs that allow to study the simultaneous behavior of the foundation with the base [1–5, 11–14].



(a) (b)

Figure 5. A mosaic of effort R_z, and isopoles of displacements Z I option (a) and II option foundations.

3. Formulation of the problem

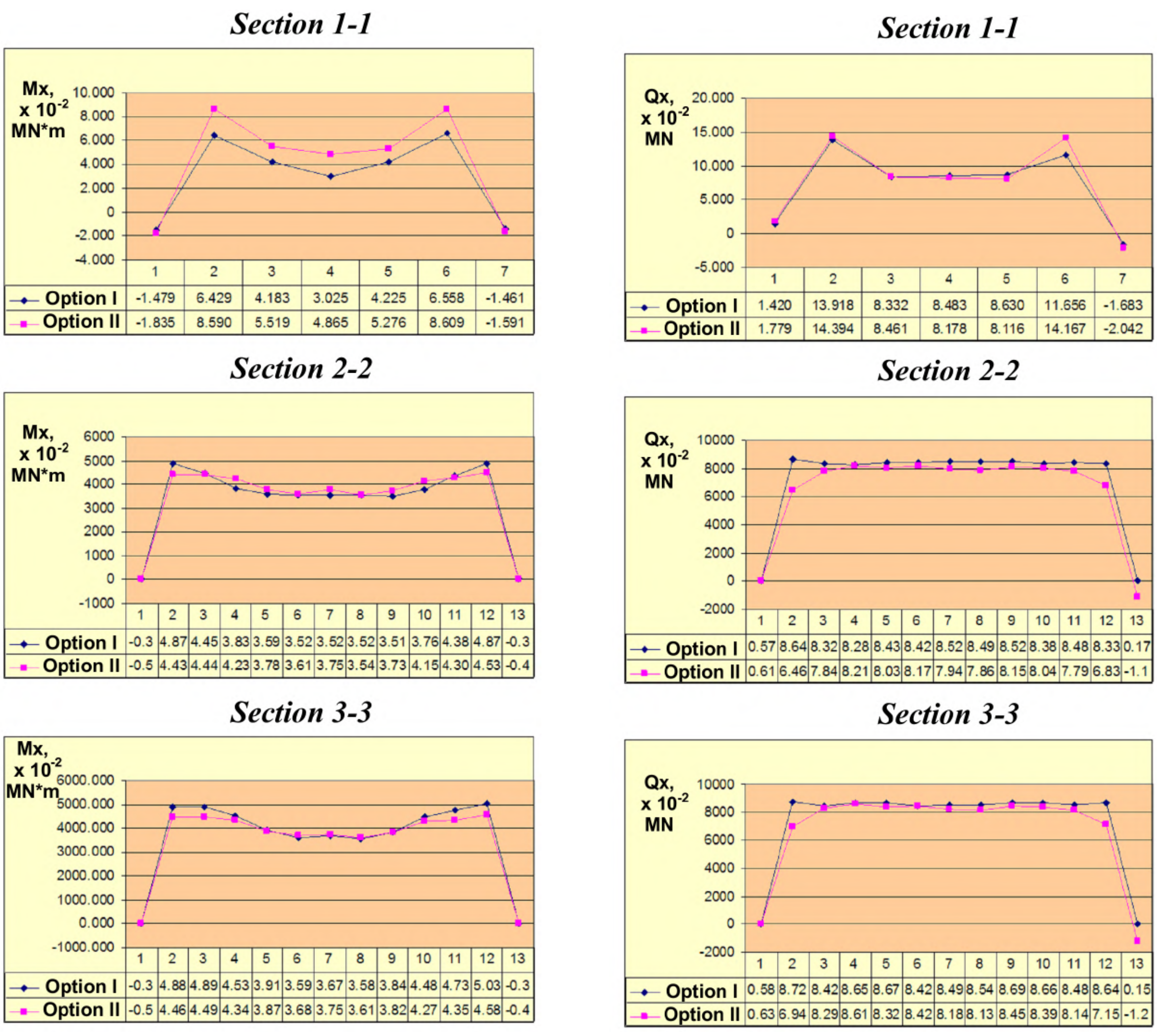
The *aim of the study* is to solve the problem of choosing an effective zero-cycle design that has increased load-bearing capacity and allows the safe design of multi-storey buildings in special conditions.

The *object of research* is the application of new design solutions of zero-cycle buildings as a modern approach to engineering protection in construction under special conditions.

The *subject of research* is the elastic-deformed state of the system "groundwork – foundation".

To achieve this goal the following *tasks* were solved:

- constructive calculations of two variants of foundations for high-rise buildings were carried out;
- step-by-step modeling of joint work of variants of foundation constructions of high-rise buildings with soil base was performed;
- the development of uneven deformations and the change of the elastically deformed state of the system "groundwork – foundation" under the influence of adverse physical and mechanical processes;



(a) (b)

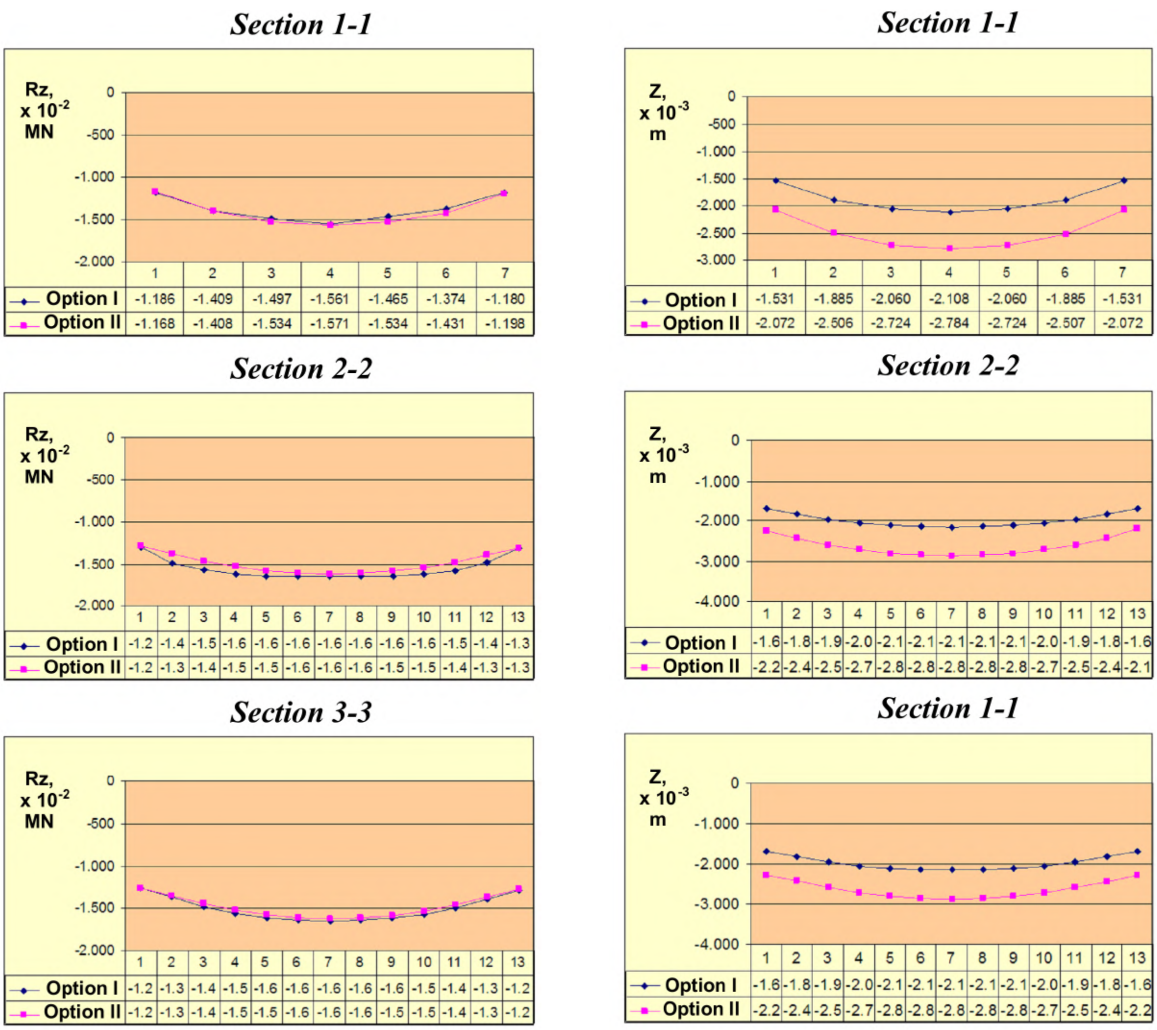
Figure 6. Comparison of the results of the calculation of M_x (a) and Q_x (b) 1 option and 2 option foundations.

- the choice of the design method of the zero cycle allowing safe design of high-rise buildings in special construction conditions is substantiated.

4. Presentation of material and results

The results of engineering and geological surveys are necessary for a reasonable choice of types and sizes of foundations and load-bearing structures of underground parts of a high-rise building. They should contain data taking into account the forecast of changes in engineering-geological and hydrogeological conditions and the possible development of harmful processes during the construction and operation of the facility, and also necessary data to assess the impact on the system "basis – foundation" of adverse physical and mechanical processes (figure 1).

The characteristics of soils of natural composition, as well as artificial origin, should be determined, as a rule, on the basis of their direct study in the field or laboratory conditions, taking into account possible changes in soil moisture during construction and operation.



(a) (b)

Figure 7. Comparison of the results of the calculation of R_z (a) and Z (b) 1 option and 2 option foundations.

The values of soil characteristics are given as follows:

- normative – γ^n, ϕ^n, c^n ;
- to calculate the design of the base for the first group of limit states – γ_I, ϕ_I, c_I;
- the same, for the second group of boundary conditions – γ_{II}, ϕ_{II}, c_{II}.

A comparison of the usual solid monolithic reinforced concrete raft foundation – I option (figure 2), with the proposed solid monolithic reinforced concrete slab with a system of crossed beams of different stiffness – II option (figure 2). Structural dimensions: length $L = 55.2$ m; width $B = 55.2$ m; in the axes: 52.8 m in both directions, the depth of the foundation – 6.4 m, the height of the foundation slab – 1.2 m (option I), from 0.6 to 1.2 m (option II). The foundation is designed for construction on a site with a relief value of the design pressure on the base under the sole $R_0 = 0.2$ MPa.

LIRA software package is a multifunctional software package for calculation, research and design of structures for various purposes [15, 16].

The calculations of the foundations under the raft for the most unfavorable combination of loads were performed, the results of which are given in figure 3, 4, 5.

The analysis of the obtained results of step-by-step modeling of zero-cycle structures shows the possibility of using both option I and option II of the foundation – the maximum subsidence of all models are within acceptable limits according to current regulations [8–10] and are shown in the figure 6, 7.

At the same time, the obtained research results indicate better quantitative results of the II variant of the foundation. Thus, at the stages of modeling with relatively identical total deformations in a conventional slab foundation (option I) there are larger vertical deformation displacements compared to version II of the foundation.

The obtained results are explained by the fact that the increase in the flexibility of the slab due to the inclusion of truncated beams of different stiffness and, accordingly, some increase in displacement contributes to a more uniform redistribution of stresses in the structure and some reduction of contact forces in the soil. The principle of "flexibility" used in this case is a more effective solution of the considered options and gives preference to the proposed option II over the typical option I of the foundation.

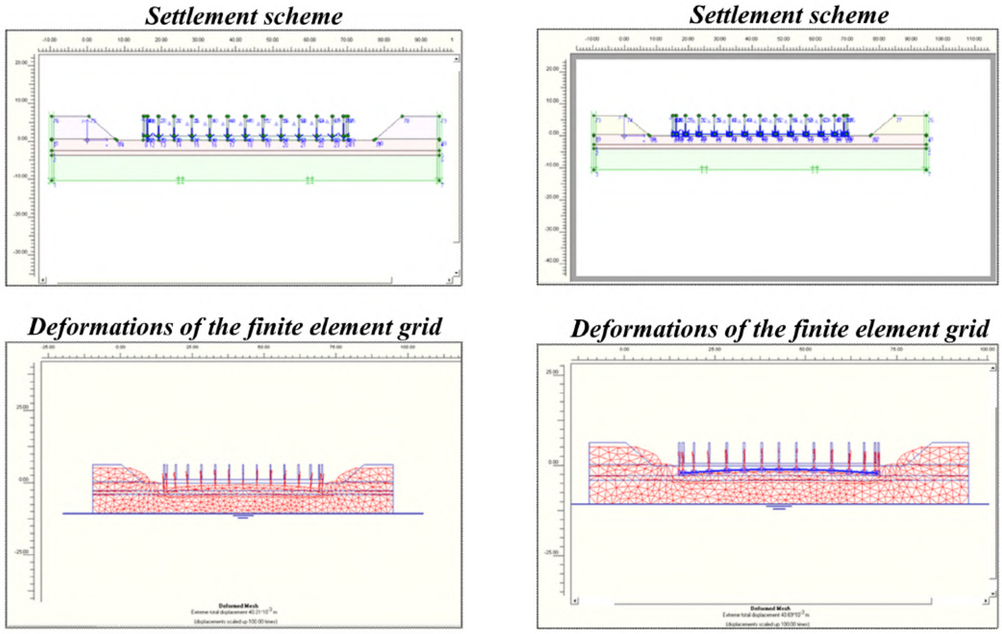
The authors propose an improved design solution for slab foundations for the design of high-rise buildings in special conditions [17]. The developed method of estimating the stress-strain state of the "soil – foundation" system under possible load combinations taking into account special design conditions takes into account complex engineering and geological conditions of construction – in forged areas and foundations composed of compressible soils. These stages of modeling were performed in order to monitor the behavior of the foundations (I and II options) in adverse working conditions.

Step-by-step modeling of joint interaction of the foundation structure is carried out on a 12-storey residential building with a ground base with the help of the Plaxis software package. This modeling involves determining the elastic-deformed state of the system, taking into account the technological aspects of the construction of the zero cycle of the building – from the device of the slab foundation to its operation [18, 19].

As a result of a detailed analysis of the technology of foundation construction, six calculation schemes (models) of changing the behavior of the foundation slab in accordance with the soil base during the construction of the zero cycle of the building were obtained. Each of the obtained models corresponds to a certain stage::

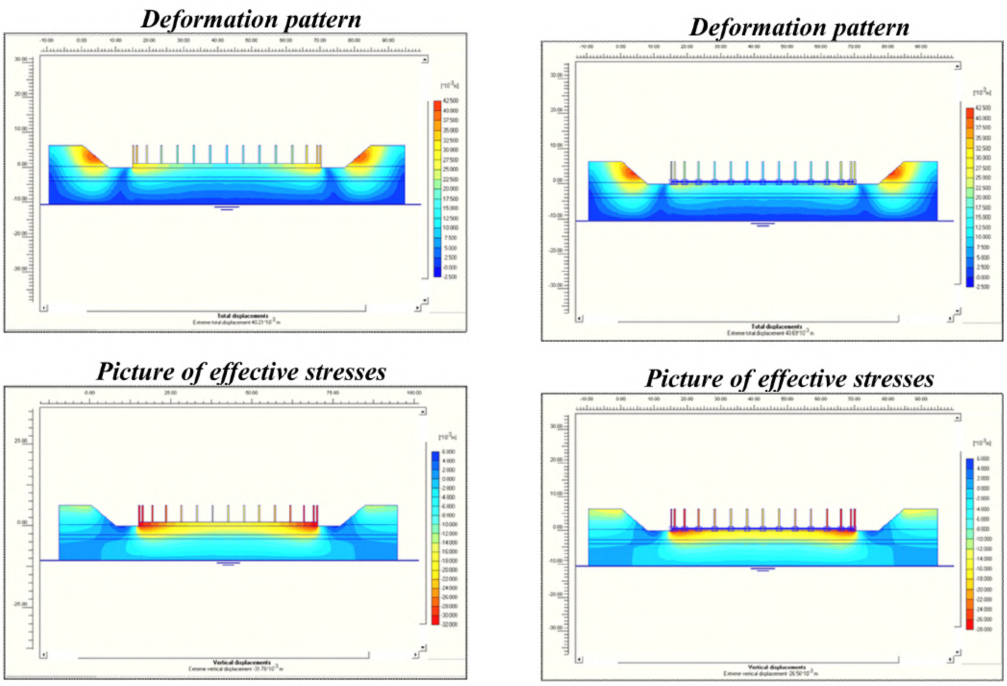
- stage 1 – the foundation on the project mark;
- stage 2 – backfill (reverse) with compacted soil;
- stage 3 – passing of deformations of the 1st ledge 13.8 m long under the foundation (1/4 of the foundation length);
- stage 4 – passing of deformations of the 2nd ledge 27.6 m long under the foundation (1/2 of the foundation length);
- stage 5 – passing of deformations of the 3rd ledge 41.4 m long under the foundation (3/4 of the foundation length).

The situation was simulated taking into account the deformations on the 1st, 2nd, 3rd ledges (modeling stages № 3 – 5). The developed method of assessing the elastic-deformed state of the system "soil – foundation" under possible combinations of loads, taking into account special design conditions considering complex engineering and geological conditions of construction – in forged areas and foundations composed of compressible soils. These stages of modeling were



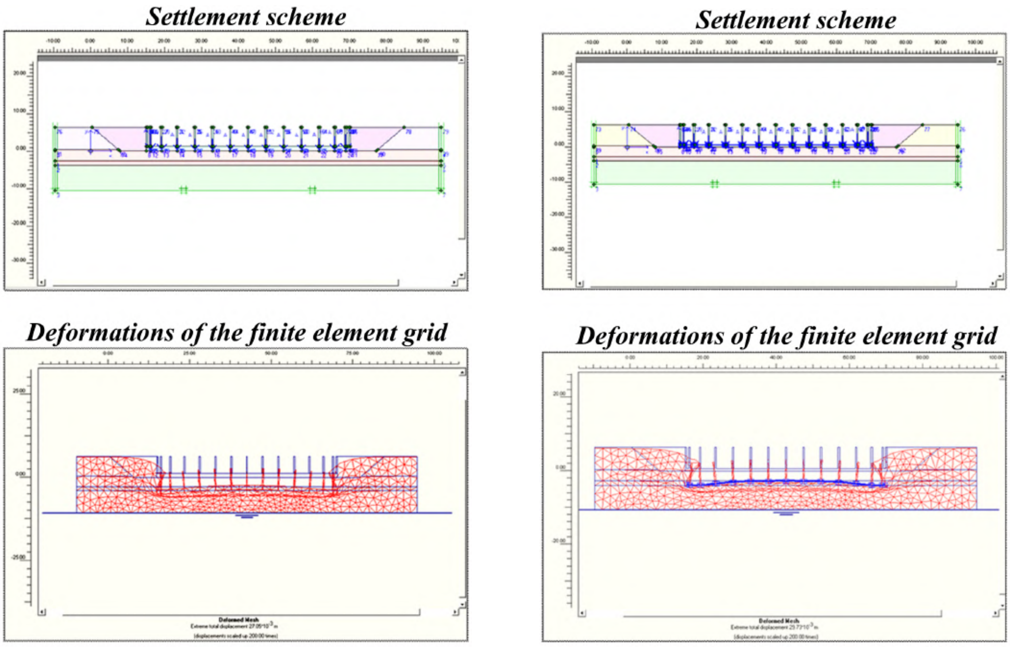
(a) (b)

Figure 8. 1st stage of modeling I option (a) and II option (b) of foundations.



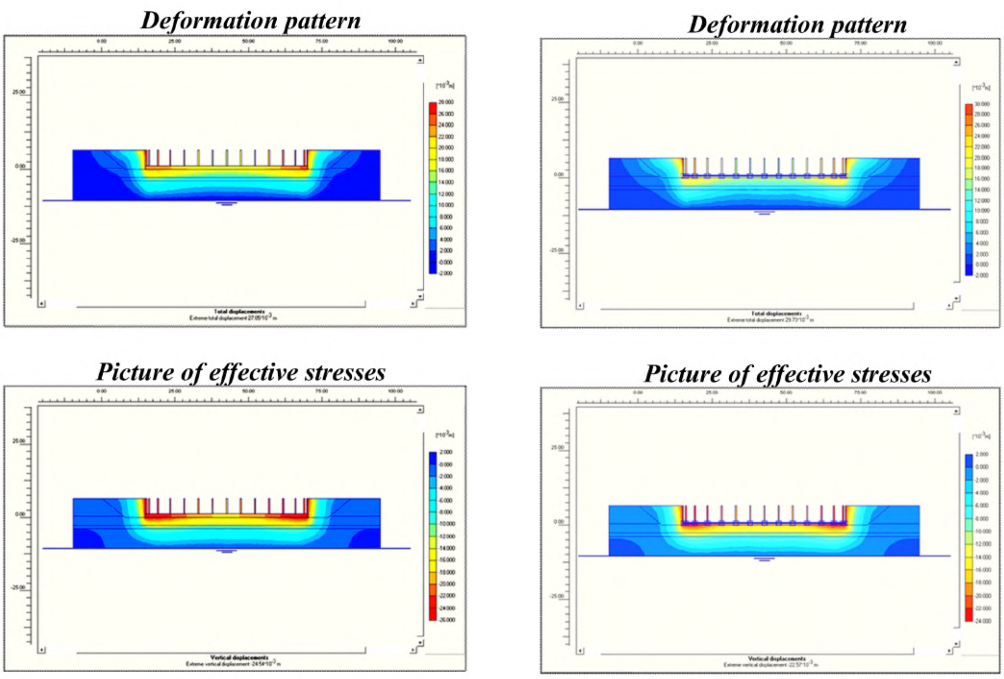
(a) (b)

Figure 9. 1st stage of modeling I option (a) and II option (b) of foundations.



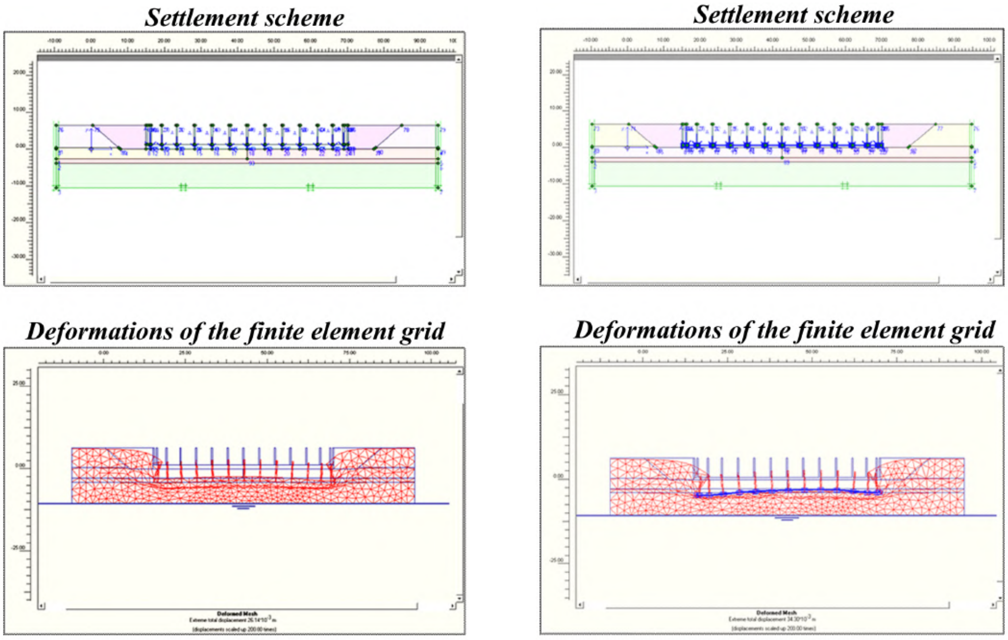
(a) (b)

Figure 10. 3rd stage of modeling I option (a) and II option (b) of foundations.



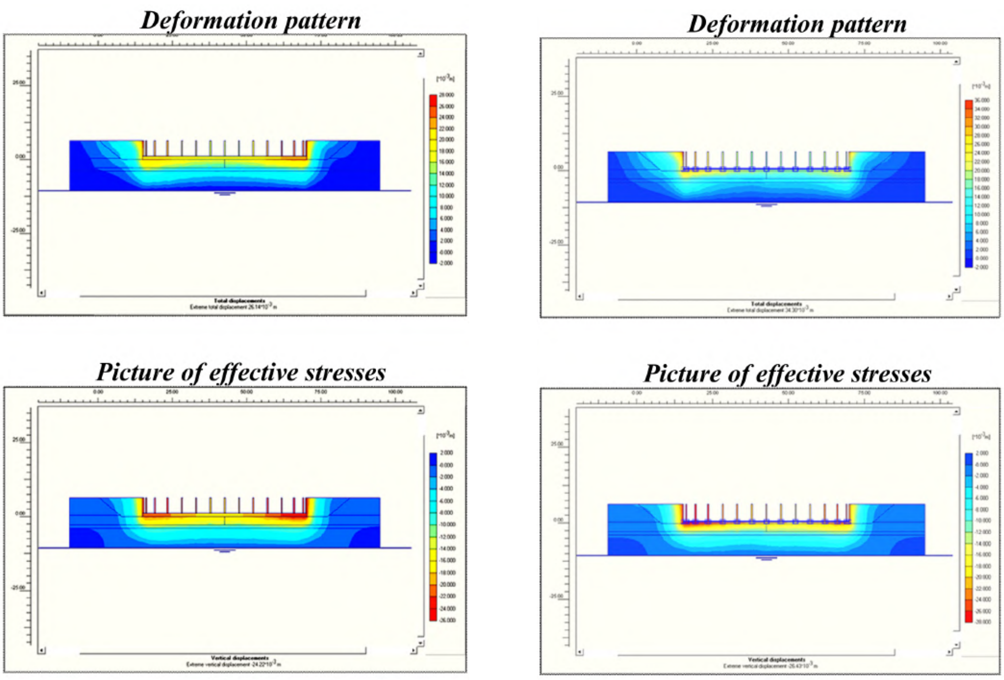
(a) (b)

Figure 11. 3rd stage of modeling I option (a) and II option (b) of foundations.



(a) (b)

Figure 12. 5th stage of modeling I option (a) and II option (b) of foundations.

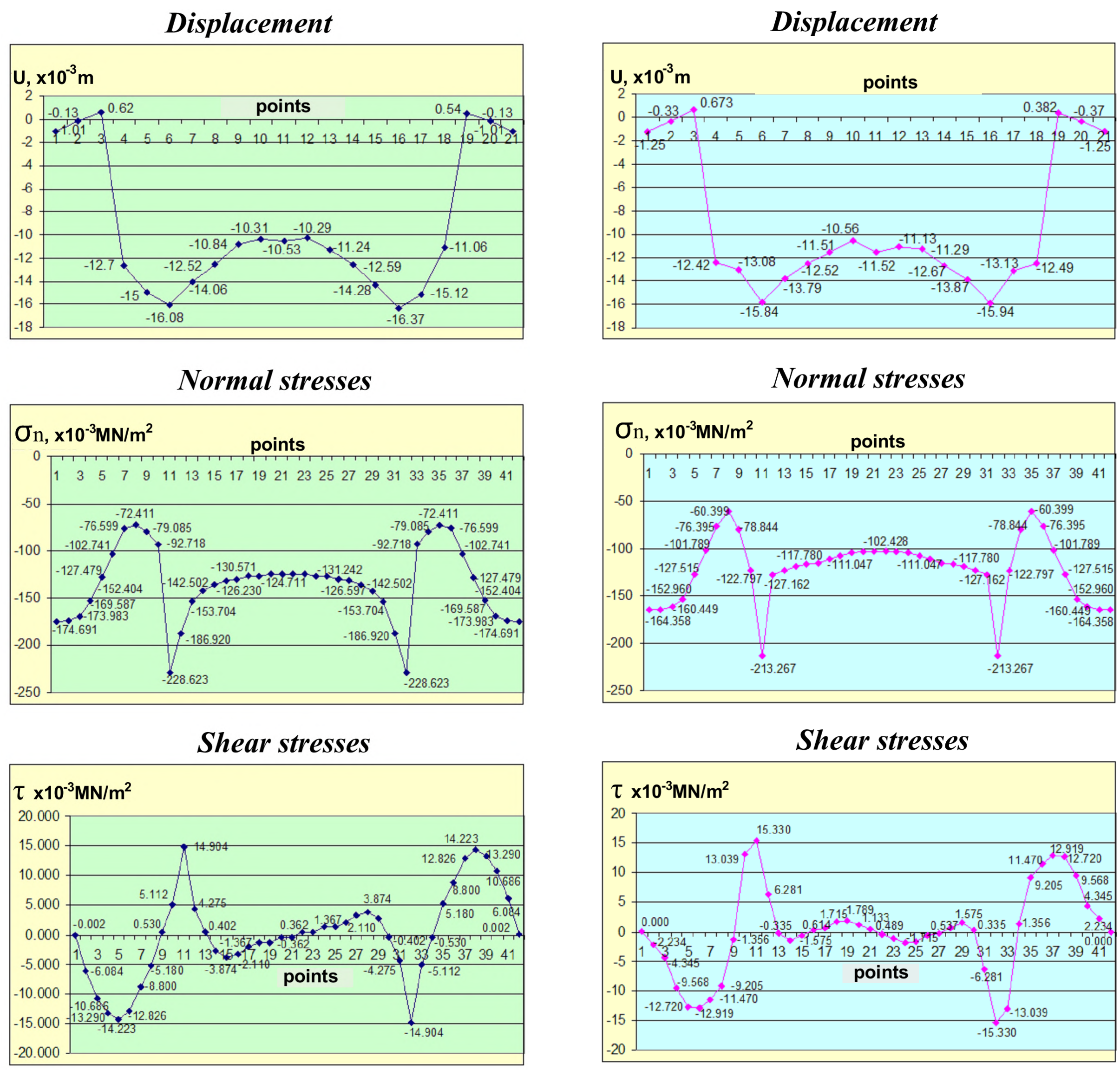


(a) (b)

Figure 13. 5th stage of modeling I option (a) and II option (b) of foundations.

performed in order to monitor the behavior of the foundation (I and II options) in adverse conditions during exploitation (figure 8, 9, 10, 11, 12, 13).

The simulation results for I and II option of joint work of the foundation structure with the soil base are are shown in the figure 14, 15, 16.

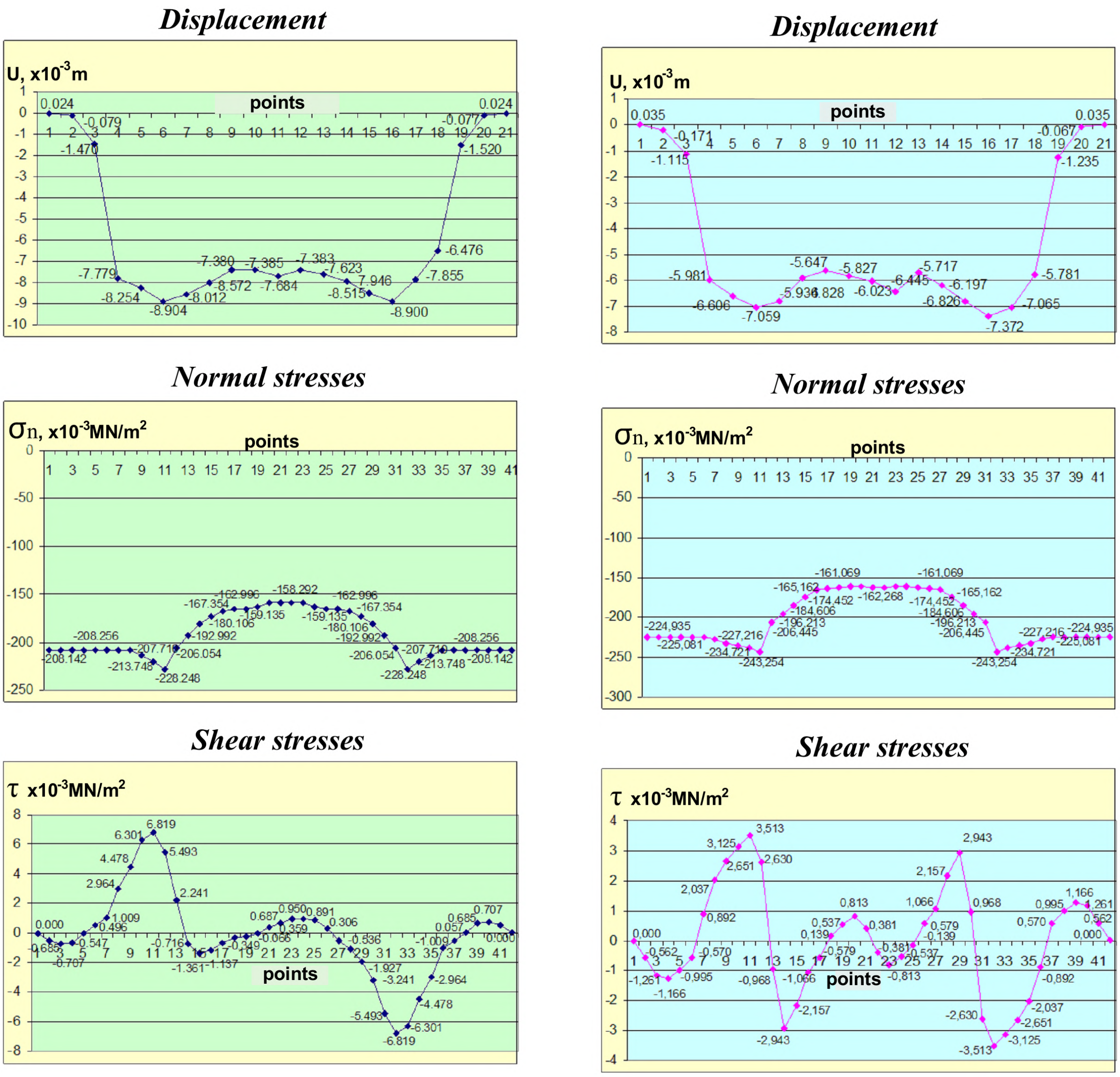


(a) (b)

Figure 14. Graphs of the results of the 1st stage of modeling of I option (a) and II option (b) of foundations.

The analysis of the obtained results of step-by-step modeling of zero-cycle structures shows the possibility of using both option I and option II of the foundation – the maximum subsidence of all models are within acceptable limits according to current regulations.

At the same time, the obtained research results indicate better quantitative results of the II variant of the foundation. Thus, at 1-3 stages of modeling with relatively identical total deformations in the usual slab foundation (option I) there are larger vertical deformation



(*a*) (*b*)

Figure 15. Graphs of the results of the 3rd stage of modeling of I option (a) and II option (b) of foundations.

displacements, compared to the II version of the foundation. The stresses during the operation of the option II of the foundation are much lower compared to the option I (according to the graphs):

– at the 1st stage of modeling the maximum stresses (I option) – 0.228623 MN/m^2;
– at the 1st stage of modeling the maximum stresses (II option) – 0.213267 MN/m^2;
– at the 3rd stage of modeling the maximum stresses (I option) – 0.218836 MN/m^2;
– at the 3rd stage of modeling the maximum stresses (II option) – 0.211886 MN/m^2;
– at the 5th stage of modeling the maximum stresses (I option) – 0.228248 MN/m^2;
– at the 5th stage of modeling the maximum stresses (II option) – 0.228248 MN/m^2.

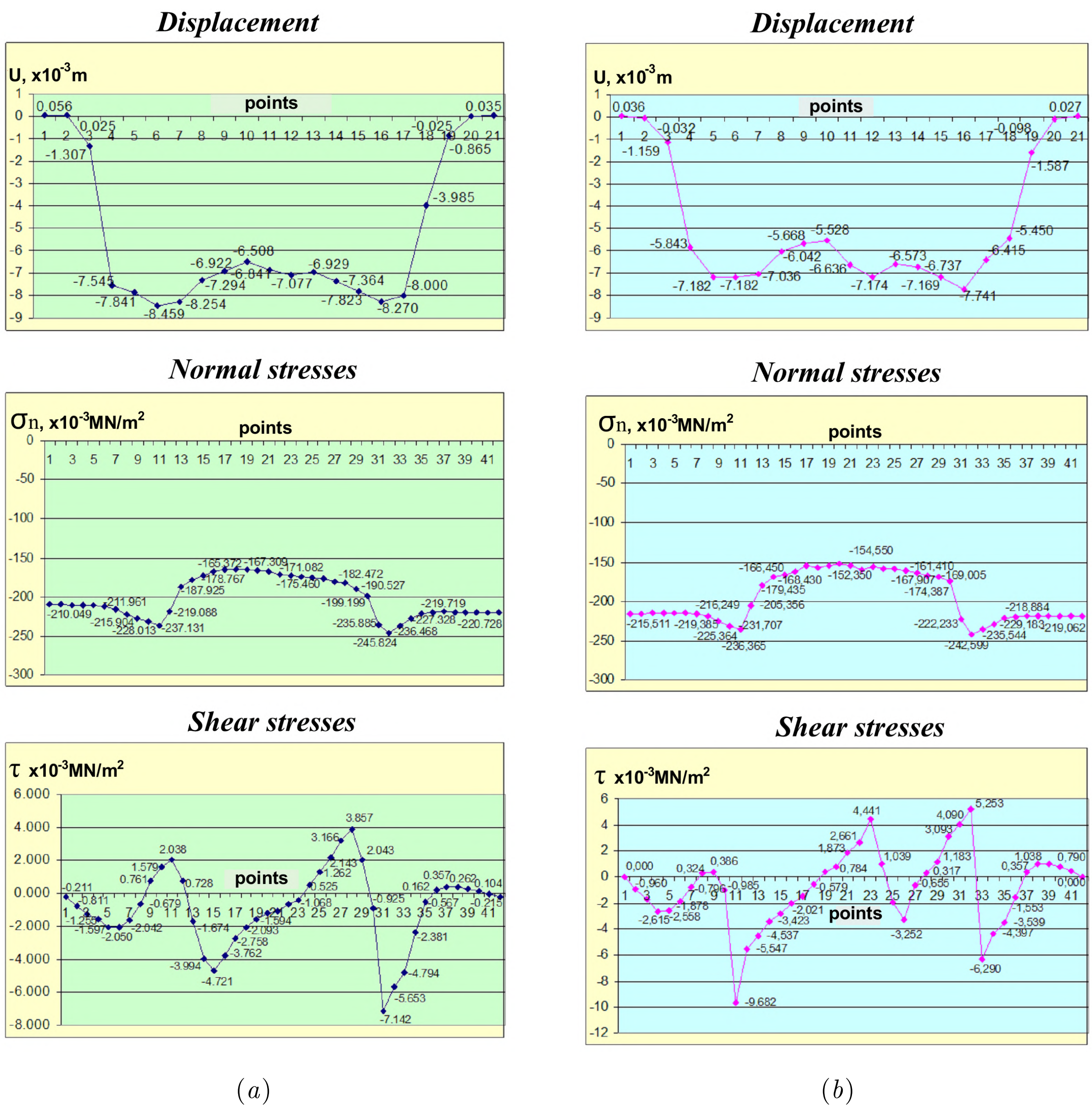


Figure 16. Graphs of the results of the 5th stage of modeling of I option (a) and II option (b) of foundations.

The obtained results can be explained as follows: the flexibility of the slab increases due to the inclusion in the structure of the system of crossed beams of different stiffness and accordingly some increase in displacement contributes to a more uniform redistribution of stresses in the structure and some reduction of contact forces in the soil thickness – that is, to improve the interoperability of the “groundwork – foundation” system.

It should also be noted that the design of the proposed version of the foundation (option II) with a system of intersecting beams of different stiffness, rigidly fixed in the plate, provides the perception of step-like deformations of the base (sealing), which occur as a result of adverse physical and geological processes in the forged areas. This is evidenced by the results of 3-5 stages of modeling – the second version of the foundation has less subsidence and the resulting effort. That is, in special design conditions, when the design of the zero cycle is subject to additional influences and deformations, the proposed design of the foundation has an advantage in the work.

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Building stone resources of Dnipropetrovsk region

To cite this article: N B Panteleeva *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012033

Building stone resources of Dnipropetrovsk region

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Abstract. The article deals with the analysis of building stone resources of Dnipropetrovsk region that are used and can be used in order to provide construction needs. Dnipropetrovsk region is one of the most economically developed Ukrainian regions due to mineral and raw material resources being located on its territory. A part of regional mineral raw extraction comes up to almost 50% of mineral deposit balance reserves and the provision exceeds three times the national rate. Crystalline Pre-Cambrian rocks of East European platform fundament as gneiss, granites, quartzites, migmatites, granodiorites, amphibolites and sedimentary apron rocks – malmrocks – are natural construction material in the region. 42 building stone deposits are located on the territory of the region among them 19 deposits are developed also refer to big and middle and 24 are not developed. The biggest amount of developed deposits is located in the Dnipro, Kryvyi Rih, Kamianske and Nikopol districts. Building stone extraction is equal to approximately 14% from national quantity. Deposit exploitation is performed by commercial structures and state corporation enterprises. The conclusions are made about the ways of expanding capacities of building stone extraction due to complex iron ore deposit development and the opportunity of building stone reserve increase in the region.

1. Problem setting

Comparing to other Ukrainian regions Dnipropetrovsk region owns thick mineral and raw material base the significant part of which has complex forming character. Almost 50% of all Ukrainian mineral resource reserves are situated on the territory of the region including building stones. Pit gravel, gravel and granitic subsoil, which are used as brick aggregate and in road construction, are manufactured from the most of extracted stones. A few publications in national scientific literature are devoted to the research of the geography of mineral resource used in construction. As a rule, they are connected with the construction raw material of specific districts. Thus, Ye. Ivanov researched Opillia [1], V. Burka devoted his research to the Carpathian economical district [2], [3] and M. Syvyi investigated Podiilia district [4], [5]. Few special publications, in particular S. Sakhno and others [6], are known concerning Dnipropetrovsk region building stone as well as its extraction and processing. The minerals of the region are generally characterized in monographs by M. Syvyi, I. Paranko, Ye. Ivanov [5], V. Mykhailov, H. Vynohradov, M. Kurylo [7] some articles are also published by V. Maniuk [8], [9] and I. Pihulevslyi [10] concerning the geology structure issues. A peculiar quantity of publications are related to the ecological problems connected with raw material extraction and efficient resource management in the region, also opportunities of the use of open and partially productive layer of iron ore deposits as building stone are characterized in particular V. Yevtekhov, I. Paranko, Ye. Yevtekhov [11]. Thus, we consider that nowadays there is a high need in conducting complex constructive and geographical analysis of building stone, therefore, that will give an opportunity to evaluate its existing raw material base, the level of regional provision, also to offer possible ways of increasing reserve and extraction amount of highly needed building raw material in our industrial region.

2. Tasks of the research

The main aim of the research is to conduct constructive and geographical analysis of building stone raw materials of the Dnipropetrovsk region, in particular, to highlight briefly qualitative characteristics of rock, to characterize component and territory structure of building stone deposits, their balance reserves, to evaluate building stone provision of regional administrative districts, to analyse raw material extraction during recent years, to study deposit departmental identity, to make conclusions about opportunities of optimization of regional raw building material structure and functioning.

The research has been conducted based on materials of SRDE "Geoinform Ukraine" and Summary balance of mineral deposits of Ukraine. The methods of analytical treatment of statistical information and cartography model construction using Data Graft, Map Info are used in the work. The algorithm of constructive and geographical research of mineral and raw material resources, worked out by the authors in the previous article, has been used.

3. Presentation of the main material of the study

Crystalline Pre-Cambrian rocks of East European platform fundament such as granites and migmatites and also their attendant rocks as granodiorite, quartz diorite, gneiss, amphibolites and quartzites are mainly used as natural construction material in Dnipropetrovsk region. Nowadays sedimentary apron rocks such as limestone, sandstone, which are spread on the North East and South of the region, are not mainly used as building stone. Minor reserves of small deposits of limestone and sandstone, which were processed for local needs last century, left.

Crystalline Pre-Cambrian rocks covered with less thick Cainozoic sediment are spread within south-eastern part of Ukrainian crystalline formations which covers central and south-western part of the region. In the northern and eastern parts Ukrainian crystalline formations border on Don-Dnipro aulacogen (DDA) where Pre-Cambrian crystalline rocks are covered with layers of Paleozoic and Mesozoic sediments total thickness of which arises to 1600 m. A border between these structures goes a bit further south of the settlement line Petrykivka – Novomoskovsk – Pavlohrad – Mezhova. In the north-west of the region crystalline rocks of Ukrainian crystalline formations gradually immerse in the direction of Black Sea Lowland.

Within Ukrainian crystalline formations on the territory of the region Middle Prydniprovia megablock and in the further east Horikhovo-Pavlohrad suture zone are located. These structures are separate with Horikhovo-Pavlohrad abyssal fracture. Among DDA structures within the region the junction zone of Dniprovo-Donetsk lowland with Donetsk cover-folded area.

43 deposits of raw material are thoroughly developed and taken to balance in Dnipropetrovsk region in order to extract gravel and quarrystone with total reserve of more than 526276,23 thousand m^3 (table 1). Among them 19 deposits are with the reserves of more than 614201 thousand m^3 and they are exploited [12]. Raw material is mainly presented with the deposits of granitoids, in the composition of which there are gneisses, migmatites, also granodiorites, quartz diorites, tonalites. The deposit of monomineralic quarzites is developed and exploited in Horikhovo-Pavlohrad suture zone.

Pre-Cambrian structures open in the Dnipro valley, its flowings and hollows as rock outshorts, quaquaversal upwell or sometimes continuous extended outcrop. Mostly they are covered with less thick layers of quarternary and Neogene sediments.

The most widespread rocks on the territory of the region are plagiogranitoid of Dnipropetrovsk complex (AR_1 dn) which open along the banks of the Dnipro river, in the interstream area of the Bazavluk river and the Kamianka river, river bottoms of the Mokra Sura river, the Tatarka river, the Voronyi river, the Ploska Osokorivka river, the Nyzhnia Tersa river and Serednia Tersa river covering the area of 1500 km^2. Among complex rocks the leading role goes to plagiogranites and plagiomigmatites, the less spread connected with them are quartz diorites, granodiorites and tonalites.

Plagiogranite biotite, amphibole-biotite are the rocks that are of light grey, grey colour, medium-grained, more seldom porphyroblastic structure, massive, often gneiss similar composition.

Plagiomigmatites are grey rocks with thin-striped, indistinctly-banded, knotty composition, granoblastic structure with the elements of porphyroblastic and lepidoblastic structure connected with mutual transition with plagiogranites.

Granodiorites biotite, amphibole-biotite occur alongside with plagiogranites and plagiomigmatites in common array being dominant at specific areas. They have grey, dark grey or sometimes green-and-grey colour, medium-grained structure, massive, knotty, gneiss similar composition.

Tonalites are rocks similar to granodiorites, differ with less quantity of quartz, dark minerals, absence or a small quantity of potash feldspar, are of grey colour, medium-grained structure massive composition.

Quartz diorites are green-and-grey, dark grey rocks with medium-grained or less frequent coarse-grained structures, massive, knotty or less frequent knotty-and-striped composition. They create separate bodies with the area of the first km^2 up to tens of km^2 in the Dnipro river valley and along Horikhovo-Pavlohrad abyssal fracture.

Plagiogranitoids of Dnipropetrovsk complex as final products of anatexis of the rocks of aul series, often they contain xenolith of metamorphic rock.

Within Pryazovia megablock a similar role is played by plagiogranitoids of Remivskyi complex (AR_1 rm) which are also represented with the association of interconnected plagiogranites and plagiomigmatites. Among the previous mentioned plagiomagmatites biotite sometimes with amphibole, pyroxene, garnet have the principal spread. The rocks are grey, green-and-grey sometimes with rosy shade, not coarse or medium-grained striped and gneiss similar composition. Biotite plagiogranites differ with light grey colour, medium-grained structure and massive composition.

In the west and south of the region Mesoarchean granitoid rocks of Inhulets, Demuryne and Tokivske complexes are more widespread, and they open in the valleys of the Inhulets river, the Saksahan river, the Bazavluk river and the Kamianka river.

Plagiogranites and plagiomigmatites biotite, amphibole-biotite of the Saksahan complex create dome shaped massives. The rocks are of grey colour, medium-not coarse structure and massive composition. Plagiomigmatites of similar consistence differ with striped and knotty composition. In the periphery of massives hybrid rocks as diorites, granodiorites and migmatites of the same consistence are locally developed. Granitoids of the Inhulets complex open in the valley of the Inhulets river and its flowings – the Zhovta river and the Zelena river. Plagiogranites and plagiomigmatites biotite, amphibole-biotite of grey colour and grained structure prevail in the complex composition. Microcline plagioclase granites and migmatites of grained, sometimes inhomogeneously grained structure, grey, rosy-and-grey colour, massive (granites), striped and knotty composition (migmatites) occur in the subsidiary quantity. Rocks of these complexes are similar between each other and are considered to have been formed in the

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result of ultrametamorphic processing more ancients granitoids of the Dnipropetrovsk complex and basaltoid rocks of Sura suit, more homogeneous in their composition and contain less patch of metamorphic rocks.

Microcline plagioclase granitoids of the Demuryno complex create dome shaped massives among the rocks of the mentioned complexes, more often are related to fracture structures. Their genesis is connected with potassic metasomatosis of plagiogranitoids. They differ with their Microcline plagioclase with bigger grains of rosy microcline. Rosy, rosy-and-grey medium and coarse-grained biotite granites and migmatites as well as homogeneously grained – gneiss similar being associated with granodiorites are widespread among granitoids.

Granitoids of the Tokivske complex create homonym dome shaped massive of the compound composition in the south-western part of the region. In its central part diorites amphibole and migmatites of diorite composition occur alongside with granites. Granites are massive, microcline plagioclase, having grey-and-rosy, grey-and-red sometimes red colour, medium grained or inhomogeneously grained structure.

Within Horikhovo-Pavlohrad suture zone (Vasylkivske deposit) Vovchansk Paleoarchean layer monomineralic quarzites are extracted as building stones which underlay among gneisses, high-alumina shale rocks, jaspilites, amphibolites. Rocks are inhomogeneous due to composition features, have adulteration of garnet, feldspars, other layers and lenses of composition rocks.

Granitoid rocks including quarzites are capable for producing gravel of different purposes. They meet the functioning standards, in particular, All Union State Standard B V.2.7-75-98 Construction materials. "Pit gravel and gravel solid natural for construction materials, goods, constructions and work. Technical conditions" [13], All Union State Standard B V.2.7-2040:2009 Construction materials. "Pit gravel from natural stone for ballast layer of railway. Technical conditions.", All Union State Standard B V.2.7-30:2013 "Materials nonmetalliferous for pit gravel and gravel bases and for automobile roads cover. General technical conditions" [13].

Due to the size of reserves in the region deposits may be divided into: 4 big granitoid deposits (Novomykolaivske, Nadezhdivka, Nedaivoda, Novopavlivka) with the reserves more than 30 mln tons and 5 medium size deposits (Rybalske, Komisarivka, Devaldovo, Tokivske) with the reserves of 15-30 mln tons. There is 1 big deposit in every district: Dnipro, Synelnykove, Kryvyi Rih and Nikopol districts. The most part of medium (3) are located in Kryvyi Rih district, 1 in Dnipro district as well as 1 in Kamianske region. 1 quarzite depoait is situated in Synelnykove district (Vasylkivske deposit). Other deposits are related to small (10 deposits).

Deposits being not developed (24 deposits) are presented with small deposits with general reserves less then 10000 thsousand m^3. Zhovtneve amd Marianivka migmatite deposits of Kryvyi Rih district and Savrivske migmatite deposit of Kamianske district have been presented and related to medium deposits, nowadays are taken out of operation. Nowadays they serve as drowned open pits and are udes with recreational aim.

The only developed sandstone deposit in Dnipropetrovsk region is known as Andronivske and has general reserve of 60 thousand m^3.

The location of building stone deposits within the region is highly inhomogeneous. Deposits are located on the area of three administrative districts: 6 deposits of Dnipro region, 5 deposits in Kryvyi Rih district as well as 5 deposita in Kamianske region and therefore the amount of all developed raw material reserves is almost 88%. There are some being developed deposits of building stone – 2 deposits in Synelnykove district and 1 deposit in Nikopol district. Deposits of building stone are not represented in Novomoskovsk and Pavlohrad districts at all (figure 1).

The figure 2 demonstrates raw material provision of administrative districts and division density through the whole region. The map chart represents the maximum division density of construction raw material in central and south-western districts of the region, i.e. in Kryvyi Rih district (312 m^3/km^2) and Dnipro district (226 m^3/km^2). A little lower density indices are distinctive for Nikopol district (187 m^3/km^2) and significantly differ in Kamianske and

Synelnykove districts 226 m^3/km^2 respectively.

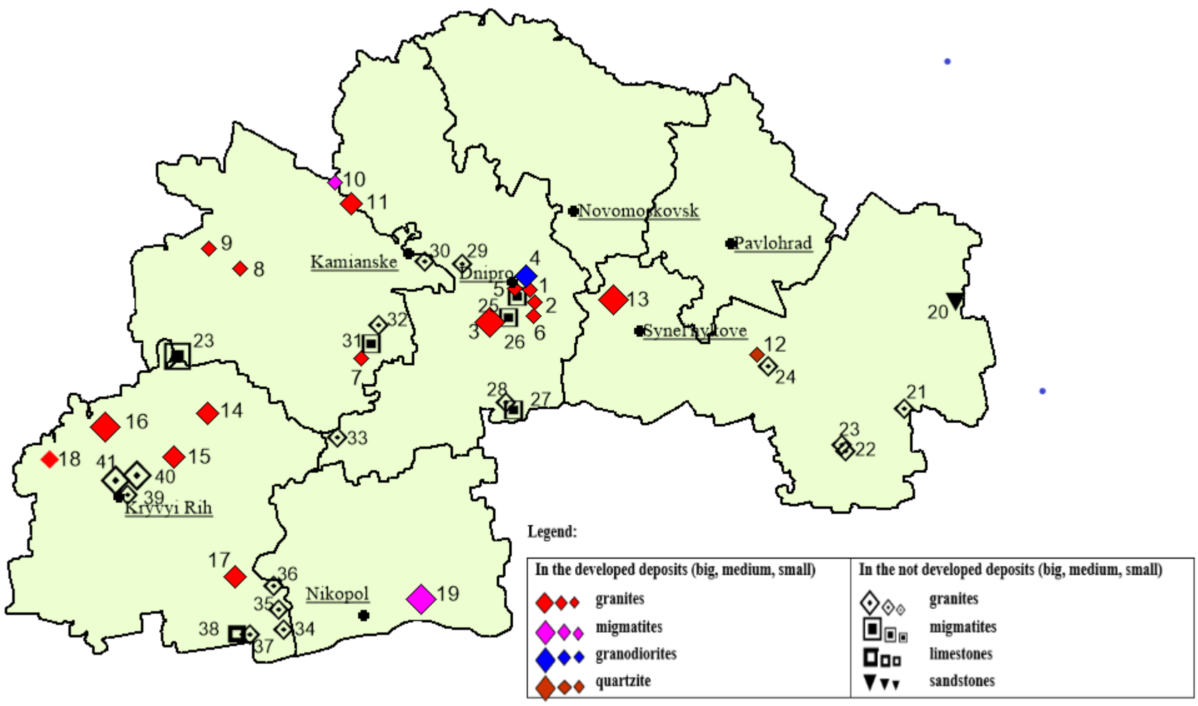

Figure 1. The scheme of location of building stone deposits in Dnipropetrovsk region (source: Geoinform Ukraine) [14].

Deposits being developed: *1. Liubymivka, 2. Liubymivka 1 Section Pershotravneva, 3. Novomykolaiivske, 4. Rybalske, 5. Chaplynka, 6. Petrivske, 7. Boltyshka, 8. Erastivske, 9. Komisarivka, 10. Myshuryno-Rizke, 11. Borodaiivka, 12. Vasylkivske Section Balka Labzunova, 13. Nadezhdivka, 14. Devladovo, 15. Kolomoiivske, 16. Nedaivoda, 17. Tokivske, 18. Khrystoforivka Section № 2, 19. Novopavlivske.*

Not developed deposits: *20. Andronivske, 21. Havrylivka, 22. Velyka Mykhailivka (Pokrovsk), 23. Velyka Mykhailivka, 24. Vasylkivske, 25. Pervomaiske Section North-west, 26. Zvonetske, 27. Kamiano-Zubylivka, 28. Bashmachka, 29. Taromske Section№1, 30. Trytuzne, 31. Olnivske, 32. Kudashivka 3, 33. Chernihivske, 34. Pidstepnianske, 35 Ust-Kamianka, 36. Mariivka, 37. Marianske, 38. Marianske, 39. Karachuny, 40. Zhovtneve, 41. Marianivka, 42. Savrivske.*

Raw material provision (m^3/person) demonstrates a bit different picture (figure 3). Synelnykove district (268,8 m^3/person) and Nikopol district (257 m^3/person) are maximally provided. Kryvyi Rih and Kamianske districts correspondently take medium position with the indices 239 m^3/person and 141,9 m^3/person. Dnipro district takes the last place due to this index (table 1). Such situation can be explained with population density and territory industrial development.

Building stone extraction also differs in the districts of the region. The maximum indices of extraction are fixed in Dnipro district (471,76 thousands. m^3/year), it is almost total building stone extraction of all districts as a whole unit, in particular, Nikopol, Synelnykove, Kryvyi Rih and Kamianske districts (figure 4).

Among six deposits of Dnipro district Liubymivka granite deposit has the extraction maximum index. Basing on the data provided by Geoinform Ukraine in 2017239,8 thousand m^3

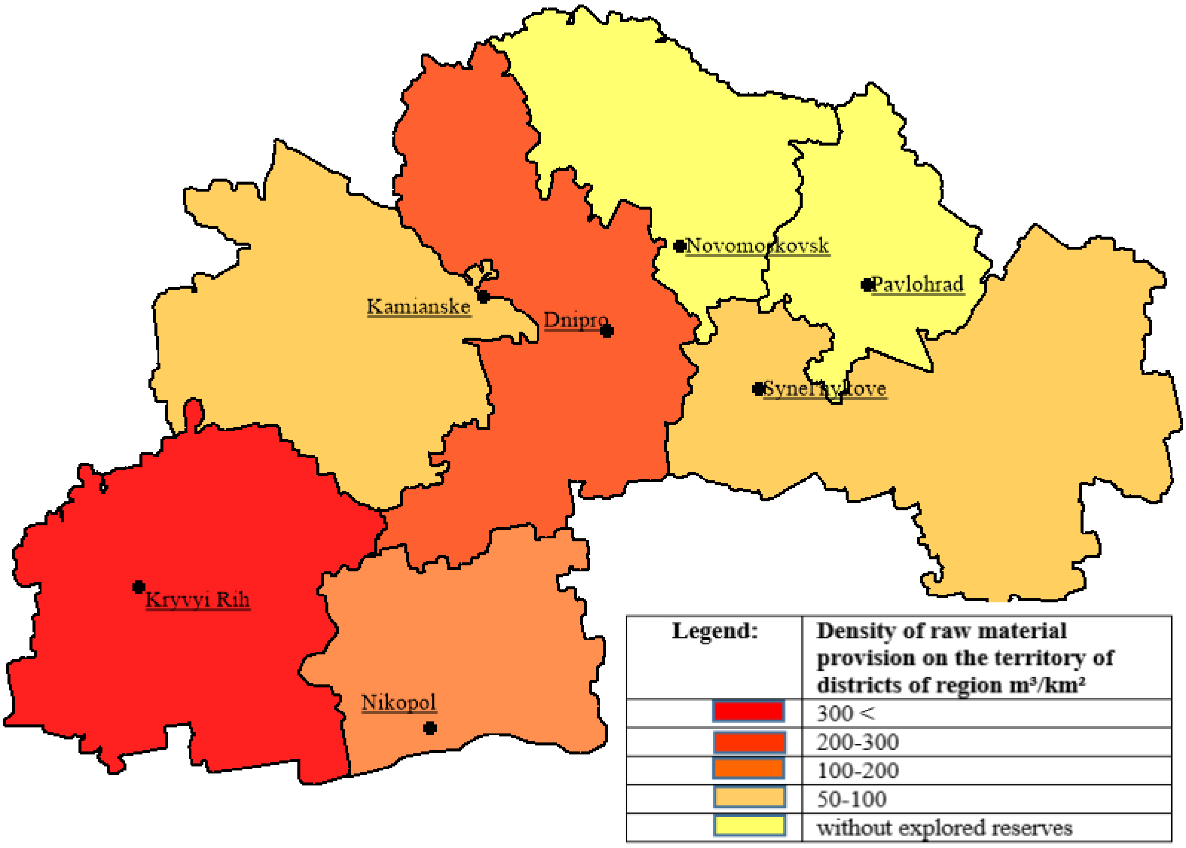

Figure 2. Density of raw material provision on the territory of districts of Dnipropetrovsk region m^3/km^2 (source: Geoinform Ukraine) [14].

Table 1. The provision with developed building stone reserves of the administrative districts of Dnipropetrovsk region (source: Geoinform Ukraine) [12].

	Balance reserves A+B+C thousands m^3 on 1.01.2018y.				
Administrative district deposits	In the developed deposits	In the not developed (thousands. m^3/year)	extraction with raw material m^3/km^2	Intension of the territory provision m^3/person	Raw material
Dnipro	93925,89 (6)	29577 (6)	471,76	226	108
Kamianske	40052,21 (5)	20689 (4)	0,188	94	141,9
Synelnykove	50371,41 (2)	3621 (5)	39,92	91	268,8
Kryvyi Rih	119893,144 (5)	58810,45 (7)	98,934	312	240
Nikopol	62417,69 (1)	2923 (3)	154,082	187	257
Novomoskovsk	0	0	0	-	-
Pavlohrad	0	0	0	-	-

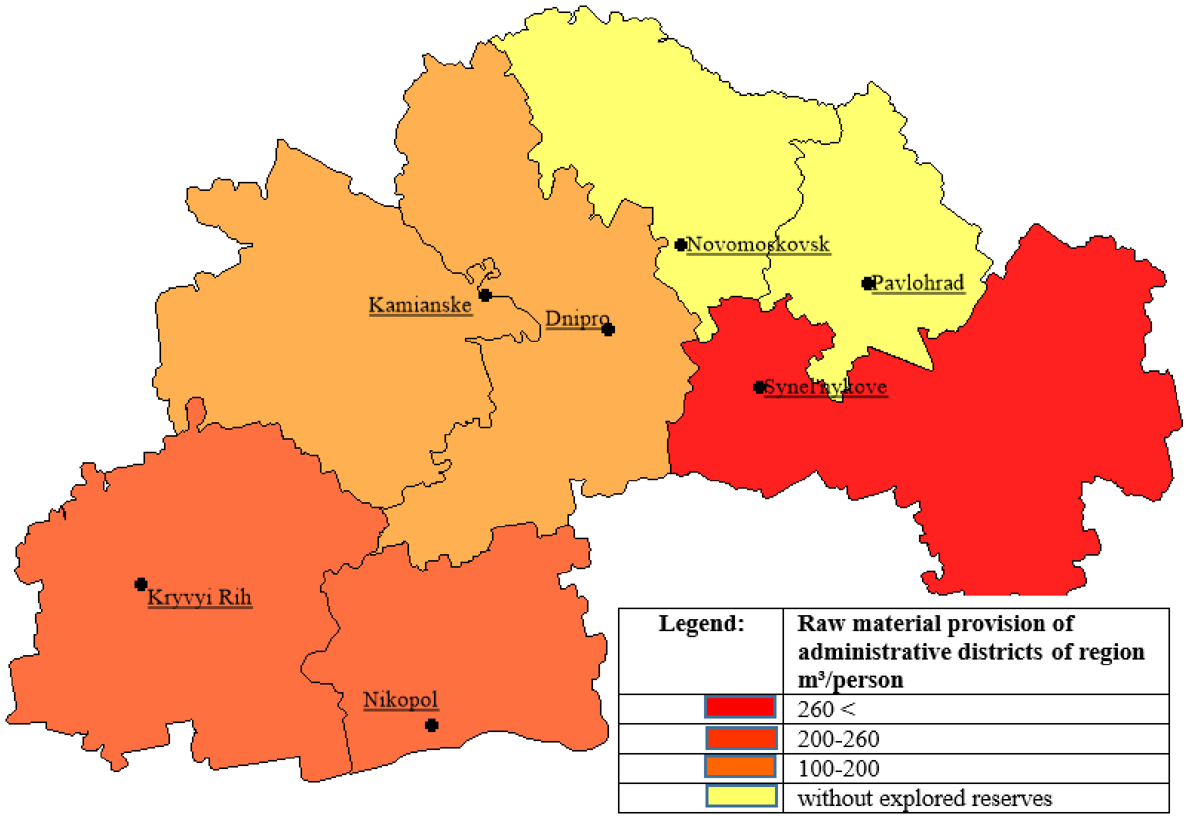

Figure 3. Raw material provision of administrative districts of Dnipropetrovsk region m^3/person (source: Geoinform Ukraine) [14].

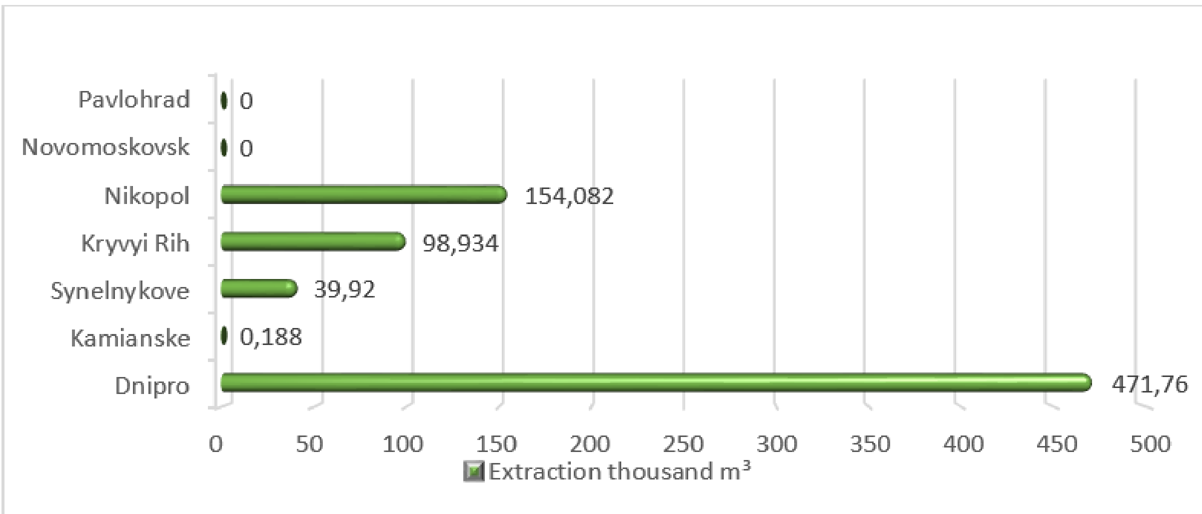

Figure 4. Building stone extraction in districts of Dnipropetrovsk region in 2017 (source: Geoinform Ukraine) [14].

were extracted here. This deposit is developed by LLC "Liubymivka open pit" that also owns Chaplynka granite deposit with the extraction of 31,4 thousand m^3. The enterprise provides extraction of granite that is not changed and faulted by rotting, therefore, these rocks are capable to be used as raw material for manufacturing pit gravel and ledgestone, rock fines.

Rybalske granodiorite and migmatite deposit (183,36 thousand m^3) is the second in production capacity and is related to the category of medium. The territory of open pit exhausted space amounts approximately 40 hectares and the maximum depth is up to 120 m. The maximum area of the open pit will become 85,7 hectares by the end of extraction.

Novomykolaiivske granite deposit, although being related to the category of big deposits, has minimum indices among six deposits of Dnipro region, in particular 17,2 thousand m^3 with general extraction project capacity 167,9-168,8 thousand m^3, i.e. deposit potential is used at 10% nowadays.

The extraction of mineral resources being suitable for producing ledgestone and pit gravel is executed by drilling and blasting using the method of vertical down hole blasts. Deposits and open pits are located nearby settlements with developed infrastructure and do not demand additional investments. Ground mass of building stone reserves in Dnipro district are located on marginal nonarable lands.

Only one granite and migmatite deposit is developed in Nikopol district, that is called Novopavlivske and is related to the category of big deposits. The extraction amounts 154,084 thousand m^3 with project capacity 500 thousand m^3, (% of use) with the area 109,7 hectares. Granite pit gravel of seven fractures is manufactured from extracted building stone and is used for building and highway, speedway and railway repair. Novopavlivske sandstone and pit gravel mixture is used by asphalt plants during asphalt and flagstone manufacture as well as paperboard and ruberoid plants use it as dusting powder for ruberoid. Ledgestone is used for storage dam and basement construction and building facade finish. Increasing demand on open pit products is explained with its high quality. They meet the first construction group due to the sanitation and radiation characteristics (All Union State Standard referce).

Granite extraction in Kryvyi Rih district is produced on 5 developed deposits, 3 of them are related to the category of medium deposits, in particular Devladovo with the extraction of 20,25 thousand m^3, Kolomoivske with 74,2 thousand m^3 and Tokivske with 3,866 thousand m^3 (grey granites) and 0,618 thousand m^3 (red granites). The extraction is temporally stopped in the big deposit Nedaivoda and a small one Khrystoforivka. The reason of extraction stop is caused by the deposit location near conservation area “Inhulets steppe”.

Kamianske district is almost equal to Kryvyi Rih district due to the quantity of deposits but building stone extraction is manufactured only in Boltyshka deposit (0,188 thousand m^3). As it was mentioned gneiss and granite deposits can be used for siding goods manufacture. Granites are extracted for producing quarrystone, pit gravel and granitic subsoil in Erastivske, Komisarivka, Mishuryno-Rizke and Borodaivka deposits but the enterprises are marginal. Building stone extraction is either stopped or is produced on not full capacity there. Erastivske open pit, being owned by stock company “Ukrzaliznytsia”, has worked at a loss of 1935 thousand hryvnia during 7 months in 2020 (based on data of “Centre of industry manqgement”), so that the question is arisen about its further functioning.

Two developed building stone deposits are located in Synelnykove district and only one of them is excavated. Vasylkivske quarzite deposit is related to the category of small deposits. In 2017 quarzite extraction amounted 39,92 thousand m^3. Besides building pit gravel these rocks are suitable for producing ferro-alloys and silica blocks. The area of Vasylkivske deposit is 36,21 hectares. Nadezhdivka granite deposit (big deposit) is not exploited nowadays.

As it was mentioned above Erastivske granite deposit is exploited by state stock company “Ukrzaliznytsia”, extraction in other deposits are exploited by different commercial structures and as a rule LLC. Due to the statistics of statistics main office of Dnipropetrovsk region the dynamics of granite extraction during 2011-2022 was analyzed (figure 5). The chart demonstrates clear trend in increasing of granite extraction by enterprises of the region according to demand increase on goods in the region as well as in the whole country.

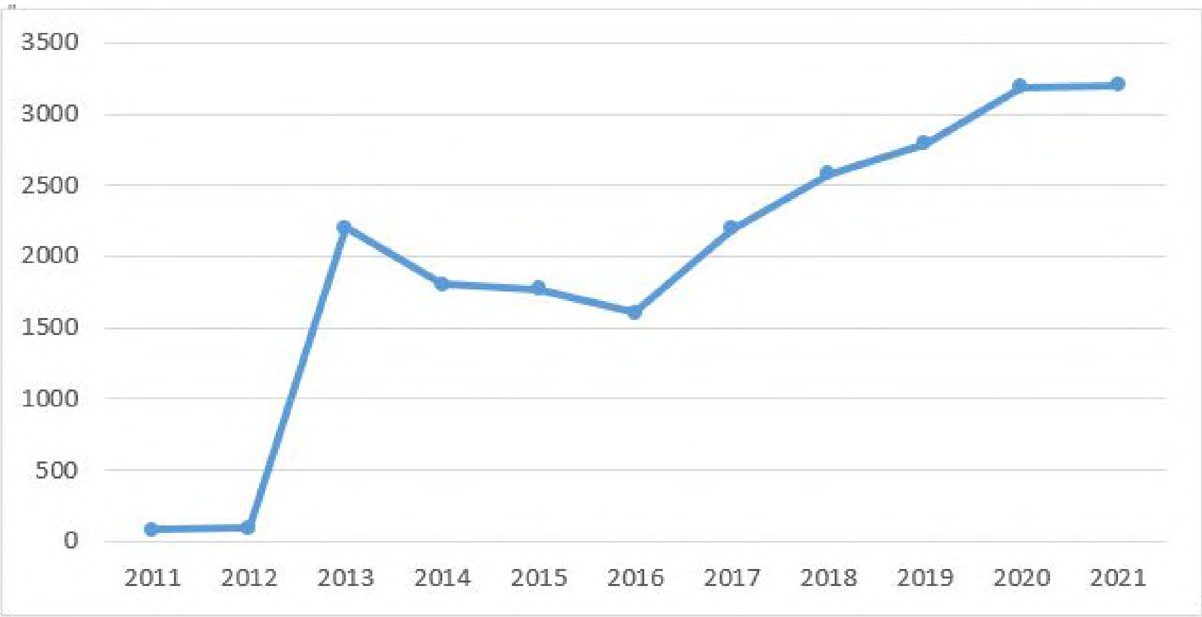

Figure 5. Dynamics of granite extraction in Dnipropetrovsk region in 2011-2021(thousand tons) *(based on data of statistics main office in Dnipropetrovsk region)* [15].

During next years the increase of building stone extraction is planned due to the increase of construction tempo. The increase of extraction volume can be achieved by the extraction increase in existing building stone deposits (Nadezhdivka, Novomykolaiivske, Novopavlivske etc.). Thus, according to issues about enterprise planned activity which needs to be evaluated in the impact on environment, also prospective technical and economical indices of further industrial development of granites within open pits (provided extraction project annual capacity) demonstrate further provision with granite reserves for 50-60 years with medium project capacity 150-160 thousand m^3, however, it may cause fast exhaust of existing reserves.

Extraction increase is possible provided that implementing in exploitation new developed mineral resource areas. Thus, in the end of 2019 a new head of State Service on Geology and Mineral Resources of Ukraine presented “Investment map of mineral resource user” and announced that State GeoMineral resources will follow the direction of maximization of land at auction. In the middle of January the information about 75 land parcels with 26 kinds of mineral resources was published on the website www.geo.gov.ua in order to be sold at auctions. 4 building stone deposits are located on the territory of Dnipropetrovsk region including Ust-Kamianka, land parcel North-Tokivske (bought on 01.02.2022), Kudashivka and Komisarivka (still are the lots). So that big problems do not exist with the choice of objects for investments, but if the new deposit extraction is appropriate as constantly increasing great receiving pits after iron ore extraction and processing. Determined state police being realized on the legal system is necessary to cope with the issues connected with mineral resource complex use and ecological rehabilitation of mining and processing districts [16]. Real actions are not observed in this direction nowadays.

With significant increase of building stone demand within the region and Ukraine raw material deficiency payment is possible as a result of import from other regions.

While planning increase of building stone extraction volume it is significant to take into account the fact that increase of extraction volume will cause decline of the ecological situation within the region. As a consequence of open development pollutes air with emissions from drilling and blasting operations, digging off and downloading operations. Potential acoustic impact of planned activity supposes noise and vibration pollution the sources of which are installation and construction works, mining, loading ang unloading, crushing machines, automobiles and other additional equipment that is used on the objects. Negative impact on soils is possible due to the air pollution and immediately by taking out land parcels in order to locate and exploit basic, subsidiary and additional enterprise buildings connected with mineral resource use. Besides hydrological and hydroecological regimes of extraction regions also change. The level of subsoil water also changes around open pits that are exploited, consequently, it may cause the decline of surface and subsoil water quality as the most vulnerable components of geological environment, some negative processes can occur as drowning, flooding and bogginess in case of stopping extraction and drowning open pits. Slope processes like erosion, gravitation etc. become active in extraction zones. Such zones require further land restoration and transformation of drowned open pits into recreational areas.

4. Conclusions

Constructive and geographical analysis of building stone raw material of Dnipropetrovsk region has allowed to find out the following:

1. Granites, quarzites and migmatites that are used as a raw material for producing pit gravel and ledgestone are extracted in 19 deposits that are developed as building stones.
2. The list of deposits that are not developed (24 deposits) is perspective for increase of building stone extraction and therefore should be overviewed as some deposits are out of exploitation and extraction cannot be renewed (Zhovtneve and Marianivka deposits of Kryvyi Rih district and Savrivske migmatite deposit of Kamianske district).
3. Building stone deposits are located on the territory of Dnipro, Kryvyi Rih, Kamianske, Synelnykove and Nikopol districts, moreover 88% of developed reserves are concentrated in first three mentioned deposits. 2 districts of the region – Pavlohrad and Novomoskovsk building stone deposits have not been explored out yet.
4. Density indices of construction raw material provision are the highest in Kryvyi Rih, Dnipro and Nikopol districts and twice more prevails corresponding indices of Synelnykove and Kamianske districts.
5. Population provision with general construction raw material reserves differs from indices of raw material density division. The best provided are Synelnykove (268,8 m^3/person), Nikopol and Kryvyi Rih districts that is explained by peculiar indices depending on population density and industrial exploration of the territory.
6. The extension of building stone extraction is possible due to the increase of increase of extraction at the exploited open pits and exploitation start of new sections the amount of which arises almost to 20 in the region but they are related to the category of small deposits. Exploitation start of new sections and significant increase of building stone extraction may cause decline of the ecological situation in the region.
7. The capacity of some parts of enterprises are used unreasonable. A need in investment or changing their owners is arisen. Open pits work not on the full capacity although tendency of increasing raw material extraction is observed during last 5 years because of demand increase on building stones.
8. It is demanded to study the problem of using parts of great amount of accumulated mining and industrial waste of iron ore and other raw material extraction in the district as construction material. Moreover, part of them meet All Union State Standard B V.2.7-34-2001 Construction material. “Pit gravel for building from clift rocks and waste of dry

magnetic concentration of ferruginous quartzites at ore dressing integrated works and mines of Ukraine. Technical requirements".

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Magnetite and hematite quartzites - common features and technological differences

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012034 doi:10.1088/1755-1315/1049/1/012034

Magnetite and hematite quartzites - common features and technological differences

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Abstract. In the process of developing deposits of magnetite quartzites, hematite quartzites are simultaneously involved in mining. But the processing of hematite quartzites is associated with significant difficulties, so they accumulate in warehouses, landfills and spread uncontrollably in the environment. A detailed study of the features of the composition, structure and technological properties of hematite ores made it possible to develop a new method for complex processing in a vortex air-mineral flow. Under laboratory conditions, a number of commercial products were produced from them: iron ore concentrate, sinter ore, clinker ore, mineral paint and quartz sand, without waste accumulation. The formation of magnetic floccules is reduced in the air stream. Therefore, this technology also improves the processing of magnetite ores.

1. Introduction

In the process of developing deposits of magnetite quartzites, hematite quartzites are involved simultaneously with mining. The enrichment of this raw material is associated with significant difficulties [1–4], so it accumulates in warehouses, in dumps and spreads uncontrollably in the surrounding environment. The reserves of hematite quartzites remain insufficiently demanded in many mineral deposits of the world. Therefore, many companies are looking for economical and environmentally friendly technologies for the enrichment of this raw material [5–7].

2. Objects

Magnetite and hematite ferruginous quartzites of the Krivoy Rog iron ore basin. Here, magnetite quartzites (figure 1) are mined by 5 mining and processing plants. At the same time, hematite quartzites (figure 2) are mined along the way and moved to warehouses and mining dumps. In the landscape, these objects form elevated plateaus. Therefore, hematite quartzites spread uncontrollably in the natural environment under the influence of precipitation and wind (figure 3)

Both varieties of quartzite are equally poor iron ores. However, there are important differences between them. They determine a close interest in some ores, and indifference to others. The authors of the article argue the fallacy of both the first and second approaches.

3. Purpose

To show the common features and technological differences between magnetite and hematite quartzites in economic aspect. To assess the possibilities of industrial application of hematite

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Figure 1. Silicate-magnetite quartzites of the Central GOK.

Figure 2. Dump hematite quartzites of the Ingulets GOK.

Figure 3. Hematite quartzites and continental fauna in the alluvium of the Saksagan river.

Figure 4. Hematite quartzites in the fertile soilin the south of the Krivoy Rog basin, microscope, magnification 10^X.

quartzites and present ways of their processing.

4. Methodology

Comparative analysis of the composition and technological properties of magnetite and hematite quartzites according to foreign and domestic researchers was used in the research. Under laboratory conditions, a complex processing of magnetite and hematite iron ores was carried out in a vortex air-mineral flow, according to [8].

Processing of magnetite and hematite quartzites was performed under equal conditions and by the same method. The original quartzites were crushed on a jaw crusher to a size of 0-10 mm and sent to the rotary mill of the original design of the authors. It provides one ore and air loading channel and several units for unloading various processed products. The maximum efficiency of the process was ensured by adjusting the rotor speed, air speed flow and gap between the rotor and the walls of the working chamber.

The growth of ore and non-ore mineral growths was carried out by destroying the ore grains by striking the rotor blades, striking the grains against the inner armor of the mill and colliding the grains with each other. The movement of particles in the working chamber of the mill took place on a toroidal trajectory. The discovered monomineral particles were removed from the working chamber through different unloading units, depending on the size, morphology, hardness and other physical and mechanical properties of the mineral particles. Unopened adhesions continued to circulate in the working chamber until opening into monomineral particles.

After unloading from the rotary mill, the products were divided on sieves into several size classes and cleaned using air separators: magnetic and gravity. Thus achieved significant purity and high quality of the final products of processing of magnetite and hematite quartzites.

5. The results of a comparative analysis of magnetite and hematite quartzites

5.1. Useful components of ores

Magnetite is the only ore mineral in magnetite quartzites that is actually extracted into iron ore concentrate. It is represented by idiomorphic crystals, irregularly shaped grains and intergrowths. It has pronounced magnetic properties and therefore forms floccules in the pulp of enrichment factories. Floccules also capture non-metallic minerals and this makes it difficult to produce high-quality iron ore concentrate (figure 5, figure 6, figure 7, figure 8,).

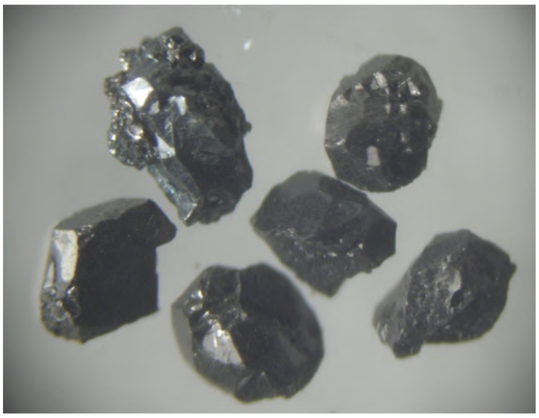


Figure 5. Idiomorphic crystals and intergrowths of magnetite; binocular microscope. Magnification 25^X.

Figure 6. Idiomorphic crystals and intergrowths of magnetite; metallographic microscope. Magnification 80^X.

Residual magnetite, hematite (martite, iron mica), goethite and lepidocrocite can potentially be extracted from hematite quartzites into concentrate. However, goethite, hydrogoethite, and hydrohematite contain hydroxyl (OH), SiO2 Al2O3, sometimes Na2O, and other compounds that can reduce the quality of iron ore concentrate (figure 9, figure 10, figure 11, figure 12,)

The total content of iron is higher in hematite quartzites (due to the partial removal of silica), and the magnetic iron content is higher in magnetite ones, due to the oxidation of magnetite under supergene conditions.

5.2. Ballast minerals of magnetite quartzites

Quartz and silicates of metamorphic origin. Quartz is intergrown with magnetite, silicates and contains numerous mineral inclusions (figure 13, figure 14). In hematite quartzites, quartz (including marshalite), sedimentary silicates (hydromicas, kaolinite and other clay minerals) are ballast. Also hydrohematite and limonite. Due to the low content of iron and impurities of alumina, silica, alkalis, these minerals are undesirable in iron ore concentrate, as they reduce its quality.

Figure 7. Magnetic floccules preventing the production of high-quality iron ore concentrate.

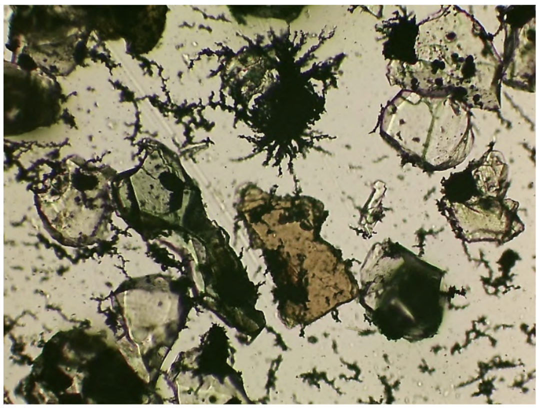


Figure 8. Magnetic floccules preventing the production of high-quality iron ore concentrate; petrographic microscope, immersion preparation. Magnification 300^X.

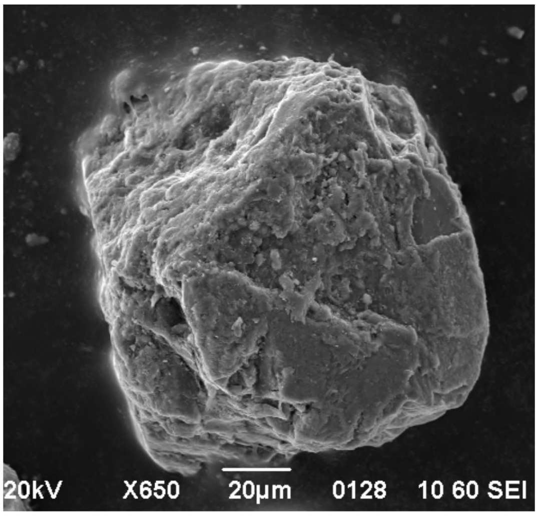
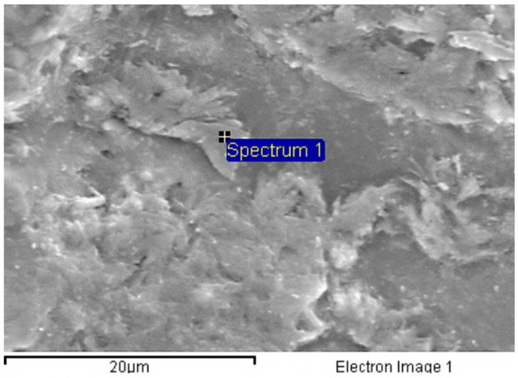


Figure 9. Hematite pseudomorph after magnetite (martite) with sculptures of supergene dissolution of faces.



Element	Weight%	Atomic%
O K	35.72	64.55
Al K	1.19	1.28
Si K	2.94	3.03
Fe K	60.15	31.14
Totals	100.00	

Figure 10. Branched aggregates of lepidocrocite on the matrite surface.

5.3. Harmful mineral impurities of magnetite quartzites:
sulfides (figure 15), alkaline silicates, apatite [9]. The composition of hematite quartzites includes sulfates, alkali metal halides (figure 16, figure 17), apatite altered in the weathering crust, close to phosphorite.

5.4. The anatomy of mineral individuals and aggregates
in magnetite quartzites was formed under hypogene conditions of high pressures and temperatures (amphibolite facies of metamorphism). Their structure is dense. Hematite

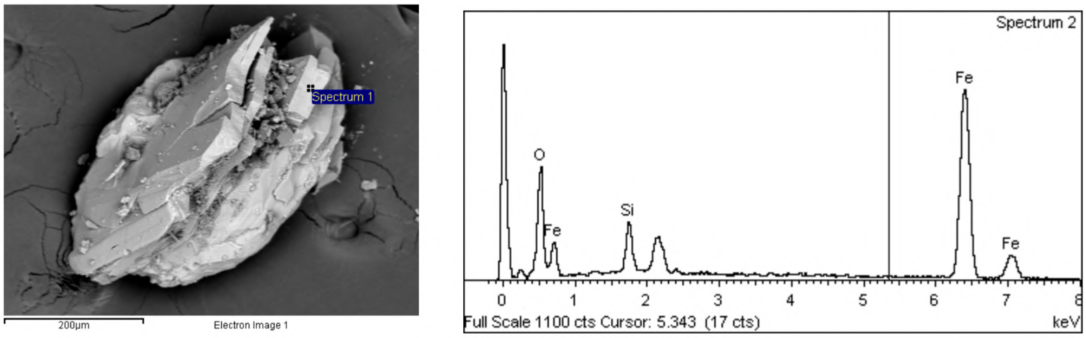
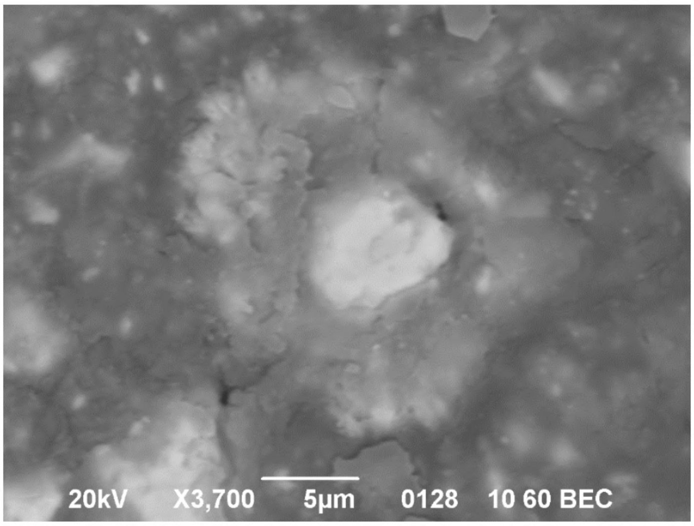


Figure 11. Lamellar crystals of hematite (iron mica).



Goethite

Element	Weight%	Atomic%
O	22.68	45.35
Na	4.91	6.83
Al	5.26	6.24
Si	5.54	6.31
Fe	61.60	35.28
Totals	100.00	

Figure 12. Replacement of martite by limonite.

quartzites are dominated by mineral individuals and aggregates formed under supergene conditions of the weathering crust. They are porous, loose and can crumble when squeezed by hand. Therefore, the hardness of minerals, as well as the strength and other physical and mechanical properties of magnetite quartzites are much higher than that of hematite quartzites.

These features and differences should be taken into account when choosing a technology for processing magnetite and hematite quartzites.

Many magnetic (including roasting-magnetic, high-gradient), electrostatic, gravity, flotation and mixed technologies for the enrichment of magnetite and hematite ores are described in the literature [1–6, 10–12]. Their analysis indicates a much higher efficiency of enrichment of magnetite quartzites by known methods and technologies. As a result, hematite quartzites were beyond the economic interests of mining companies.

Employees of our institution developed a fundamentally new method for the complex processing of hematite raw materials [8]. It uses a gradient of many physical properties and features of ore and non-metallic minerals: magnetic, density, mechanical, morphological. The separation takes place in the suspended state of mineral particles under the conditions of a vortex air-mineral flow. The laboratory unit consists of a feed unit, a rotary mill, cyclones, magnetic and gravity separators, unloading units and an electronic control unit.

Magnetite and hematite quartzites of the Krivoy Rog iron ore basin were used in the tests.

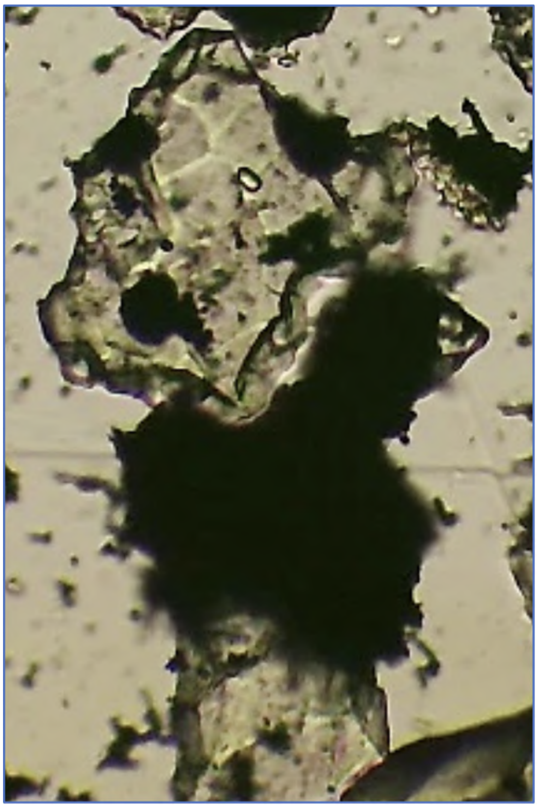


Figure 13. Quartz in magnetite quartzite intergrown with magnetite and silicates and their inclusions; petrographic microscope, immersion preparation. Magnification 500^X.

Element	Weight%	Atomic%
O K	67.06	78.14
Si K	32.94	21.86
Totals	100.00	

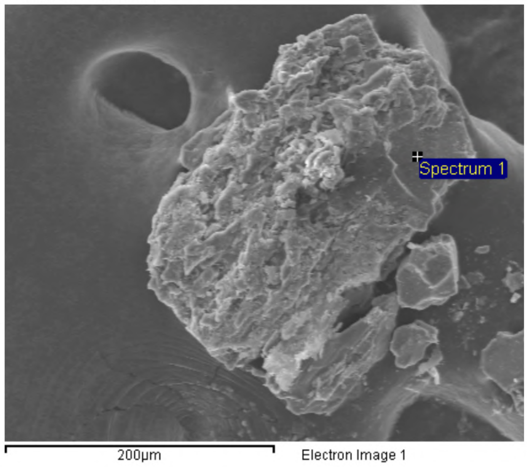


Figure 14. Marshalitized quartz with leaching voids in hematite quartzite; scanning electron microscopy, microprobe analysis.

Figure 15. Pyrite in the composition of magnetite quartzites; binocular microscope. Magnification 10^X.

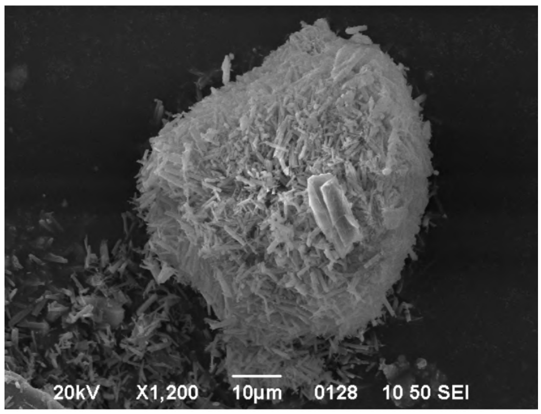


Figure 16. Pseudomorph of gypsum along the pyrite hexahedron; scanning electron microscopy, microprobe analysis.

Iron ore concentrate and enrichment tailings were produced from magnetite quartzites (table 1). Iron ore (goethite-hematite) concentrate, sintering ore, clinker raw materials, mineral pigments, quartz sand were produced from hematite quartzites (figure 18, figure 19, figure 20, figure 21,

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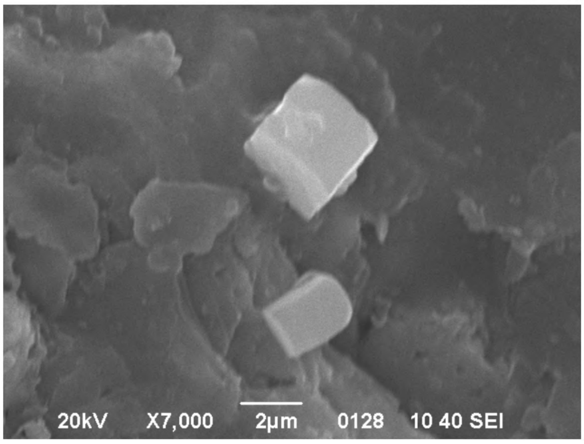


Element	Weight%	Atomic%
Mg	3.34	5.20
Cl	40.87	43.66
K	45.83	44.39
Fe	9.96	6.75
Totals 100.00		

Figure 17. Sylvite on the surface of layered silicates in hematite ore of mine production; scanning electron microscopy, microprobe analysis.

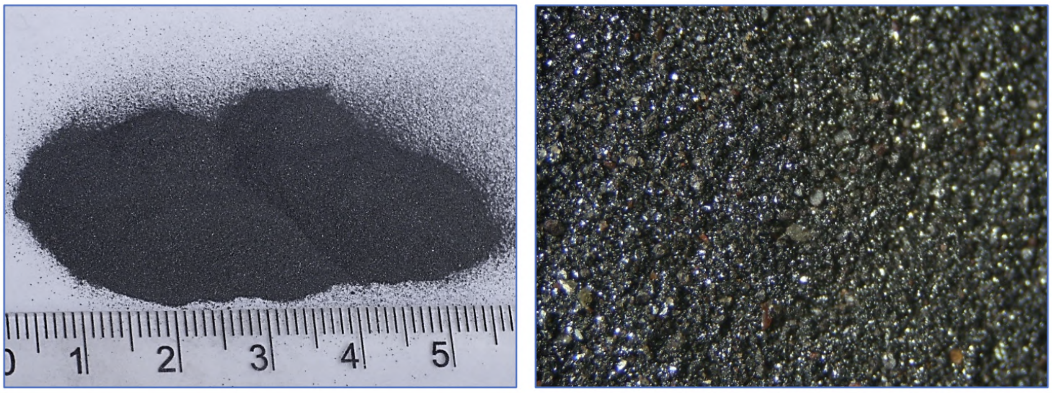
figure 22).

All iron ore processing products are dry. They are produced without the participation of water, flotation agents and without heating.

Table 1. Products of enrichment of magnetite and hematite quartzites in a vortex air-mineral flow.

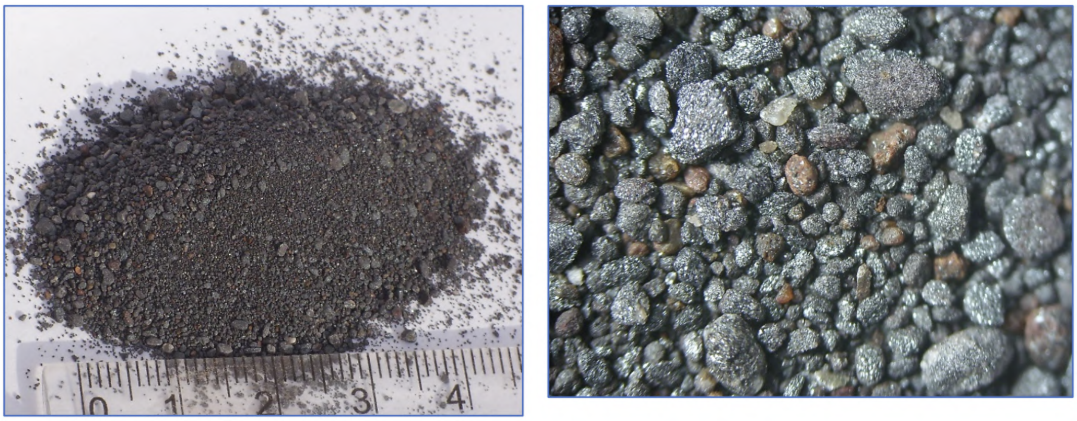
Product	Mass fraction of components, %	
	Fe_{total}	SiO_2
Magnetite quartzites		
Magnetite quartzite Ingulets deposit	34,05	43,21
Magnetite concentrate	66,80	7,85
Tailings	9,8	73,92
Extraction into useful product, %	87,2	0
Hematite quartzite		
Hematite quartzite Skelevat deposit	32,6	50,9
Hematite concentrate	68,6	1,33
Sinter ore	61,4	12,1
Clinker ore	48,6	29,5
Mineral pigment	37,9	41,3
Quartz sand	1,3	97,6
Extraction into useful product, %	98,7	98,6

Complex processing of ferruginous quartzites is based on the use of the above features of the composition, structure and physical and mechanical properties. The initial ore is crushed in the working chamber of the rotary mill in the vortex mode of air blowing. The size of the ore particles is reduced due to self-grinding and impacts on the mill armor. The mineral grains opened from the intergrowths are carried out by the air flow outside the working chamber. Then they are deposited in a series of air cyclones and bag filters, in accordance with the physical



a b

Figure 18. Iron ore (hematite) concentrate: a - general view; b – under a microscope. Magnification 20^X.



c d

Figure 19. Sinter ore: c - general view; d – under a microscope. Magnification 10^X.

properties and morphological features of the particles. Unopened splices remain in the chamber until the splices are destroyed and opened. Opened ore grains are discharged through outlets at the bottom of the mill. The final cleaning of products is carried out using magnetic and gravity separators.

This technology allows disintegrating and separating ore at the same time. In addition, iron ore concentrate and other products remain dry and are sold in this form.

6. Discussion of results and conclusions

From the given data it follows that as a result of the processing of magnetite quartzites, two products are produced: concentrate and enrichment tailings in the form of silicate-quartz finely divided sand. Processing of hematite quartzites in a vortex air-mineral flow allows to produce a larger number of products, and this leads to an increase in their liquidity.

In the dynamic conditions of the working chamber of the installation, where particles collide with each other and with the chamber armor at a high linear speed, magnetic floccules are practically not formed. This increases the efficiency of separation of ore and non-ore particles,

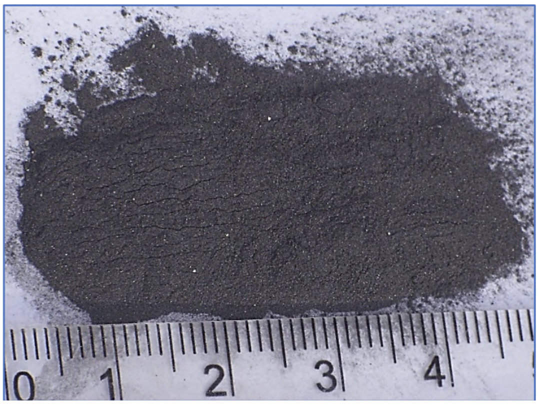


Figure 20. Clinker ore: general view.

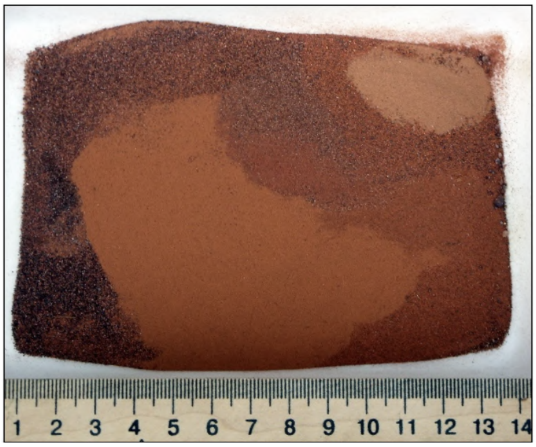
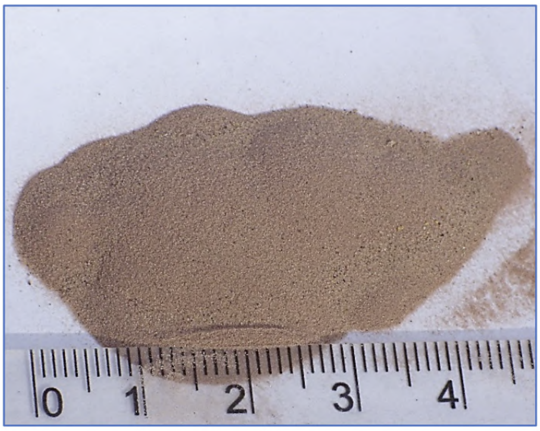


Figure 21. .Raw materials for the production of dry mineral paints: general view.



g

h

Figure 22. Quartz sand: g - general view; h – under a microscope. Magnification 15^X.

in comparison with the magnetic separators of modern processing plants. In addition, the magnetic properties of iron oxides in hematite quartzites are much weaker.

In addition to the chemical composition, ore minerals: magnetite, hematite, goethite, lepidocrocite, hydrogoethite and hydrohematite differ in hardness, specific gravity, and morphological features. This allows working with hematite raw materials to separate them into various products. At the same time, the purity and quality of the iron ore concentrate increases. In its composition, the total content of SiO2 and Al2O3 is no more than 2-3%. This corresponds to modern standards of metallurgical companies. And minerals with a lower iron content are used to produce other marketable product: sinter ore, clinker raw materials, paints, etc.

The destruction by impact forms a cuboid shape of the newly formed particles. Lamellar hematite (iron mica) as a result of collisions splits along rhombohedral cleavage planes, acquires an isometric shape and, as a result of gravitational differentiation in a vortex air-mineral flow, is unloaded into the iron ore concentrate receiver together with magnetite. In this case, tabular and lamellar silicate individes are removed from the working chamber into a bag filter.

Thus, the processing of magnetite quartzites by wet magnetic separation is the most energy-intensive and resource-intensive due to the high hardness of the ore, the negative effect of flocculation, the formation of wet polymineral tailings and high losses of magnetite in them. More efficient is the processing of magnetite quartzites in a vortex air-mineral flow. It leads to the formation of dry tailings, which can be used as fillers, for example, in road construction. The most favorable option is the complex separation of hematite quartzites in a vortex air-mineral flow. It ensures maximum savings in electricity and mineral resources, ensures the production of high-quality iron ore concentrate, suitable for the direct reduction of iron and other demanded products. The absence of water, flotation reagents and heating makes the process environmentally friendly and compliant with the principles of the circular economy.

Taking into account the above data, in modern conditions, in the short and long term, the use of hematite quartzites is more promising and should replace the extraction of magnetite quartzites in many deposits of the world.

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Commercial products of mining and metallurgical companies in river sediments of industrial regions

To cite this article: L V Berozkina *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012035

Commercial products of mining and metallurgical companies in river sediments of industrial regions

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Abstract. Modern alluvium is a complex multicomponent system that includes both natural and man-made material. In the process of research on the pollution of river sediments with industrial waste, the authors established the presence of commercial products of mining and processing enterprises in the sediments. It includes crushed granite, metallurgical slags, ores and concentrates, coal and other products. Significant volumes of inputs of these materials into the ecosystem motivate the development of special technologies aimed at additional production of mineral products through the complex processing of modern river alluvium. In addition to economic benefits, the implementation of these projects will improve the state of the environment in regions with significant technogenic load.

1. Brief description of the study region

1.1. The Kryvyi Rih iron ore basin as a complex man-made deposit

The Kryvyi Rih iron ore basin is the largest basin in Ukraine with deposits of rich iron ores, the main mining center of the country, located in the Dnipropetrovsk region.

Giant mining enterprises of the Ukrrudprom concern are concentrated in the basin: five large mining and processing plants include ten quarries with a depth of more than 300 m for the opencast mining and 17 mines with a depth of 80-1300 m for the underground iron ore mining. The largest production facilities of the metallurgical industry are OJSC ArcelorMittal Kryvyi Rih and a coke plant, as well as plants for the production of cement, raw materials for the paint and varnish industry, construction materials and other enterprises. Mining of crude iron ore and its processing into iron-containing products, as noted above, is carried out by five processing plants: "Yuzhniy GOK" Mining and Processing Plant (UGOK); Novokryvyi Rih of ArcelorMittal (NKGOK); Central GOK, Ingulets GOK and Northern GOK of Metinvest.

Currently, the average depth of Kryvbas quarries is up to 400 m (UGOK quarry), the height of heaps and dams - sludge storage - up to 100 m (heaps Hannivsky quarry, tailings Voykivske, Mykolaivske), the depth of mines - up to 1400 m ("Rodyna", "Jubileyna") [1]. According to V P Palienko's calculations: the total area occupied by quarries in Kryvbas is 33.34 km^2, dumps - 60.0 km^2, tailings - 52.74 km^2, subsidence zones above the minefields - 34.71km^2 [2] Mining complexes now occupy almost 40 thousand hectares and are an important component in the operation of the modern Kryvyi Rih landscape-technical system [3].

The volume of Kryvbas waste is estimated at 10 billion tons and accounts for more than 30 % of the total industrial waste of Ukrainian enterprises. More than 80 % of iron ore is extracted here and 20 % of Ukraine's metal is produced. In this regard, the territory of the Kryvyi Rih basin is one of the most man-made geoecosystem in the world.

Industrial waste of the Kryvyi Rih basin is classified as a complex man-made deposits because they contain different types of waste and are studied comprehensively. The quite high complexity of Kryvyi Rih iron ore deposits is due to the peculiarities of genesis, geological conditions and the composition of ferruginous quartzites, containing, lateral and overburden. Within the deposits, the rocks discovered by quarries are represented by granites, migmatites, gneisses, amphibolites, etc. The cover is composed of various loess loams, clays, sands, limestones, talc shales and other rocks. The technogenic resources includes three main types of man-made waste that require further processing:

- Heaps of rocks. More than 2.16 billion m^3 of rocks have been accumulated in heaps on the territory of the Kryvbas
- Dumps of sludge waste, enrichment of ferrous quartzites from processing plants. The total amount of sludge waste in sludge storage facilities is over 2.4 billion m^3
- Waste slag of the metallurgical plant. The waste of the ArcelorMittal Kryvyi Rih and the Kryvyi Rih TPP of Dniproenerho OJSC is 76.2 million tons. These include:
  – smelting and blast furnace slag;
  – metallurgical sludge;
  – rolled scale;
  – ash-slag dumps [4].

1.2. Ingulets river system

There are 8 rivers at the territory of Kryvyi Rih. But only two cross the city directly - the Ingulets river and the Saksagan river. The bottom sediments of these rivers were studied by authors.

The length of the Ingulets River is 549 km. The drainage basin is 14870 thousand km^2. The width of the riverbed near Kryvyi Rih is 25-30 m, and the depth is up to 1.7 m. The terraces of the river valley are buried under heaps of poor rocks, the sludge storage and other industrial buildings. In the southern part of Kriviy Rih the river valley is totally changed: river banks are look like canyon due to heaps of poor ore of the processing plant of ArcelorMittal and UGOK.

Economic activity in the Ingulets river basin has a complex and diversified structure. Combination of the main directions of production with the features of the water use system functioning formed a number of other powerful natural and man-made systems. The specific water management and the river basin operation puts the Ingulets River into a list of special types of rivers in Ukraine. [5]

2. Preconditions of the research

Ourdays is the world of huge anthropogenic and industrial pressure on the natural geoecosystems.

The intensity of human activities during the last centuries causes a significant violation on the existing balance of the nature. Along with the scientific and technological progress, the scale of the impact on the environment is increasing, which leads to undesirable changes of air, water, and soil physical, chemical, and biological characteristics, and these can have adverse effects on humans, animals, and plant lives. Among serious environmental problems, the investigation of increasing pollution of the hydrosphere is particularly important. [6]

The most sensitive to different pollution is aquatic ecosystems. Pollutants are various: domestic sewage water, organic and petrochemical agents, fertilizers, microplastic pellets and the last but not least – industrial waste. Industrial sewage contains trace metals in large quantities and organic pollutants. Huge amounts of mine tailings are accidentally (or not) spilled into rivers.

River ecosystems are under pressure from several different stressors. Among these, inorganic pollutants contribute to multiple stressor situations and the overall degradation of the ecological status of the aquatic environments. The main sources of pollution include different industrial activities, untreated effluents from municipal waste waters and intensive agriculture. [7]

Heaps of industrial wastes containing various hazardous materials may be dangerous to the surrounding environment. Pollutants released from the heaps can contaminate the water, soil and air, and can affect human health. Therefore, areas where dangerous wastes are stored must be monitored to prevent contamination.

Industrial waste heaps can cause water pollution. For instance, contaminants such as metals, hydrocarbons, organic solvents and polycyclic aromatic carbons can be released from the heap. [8]

In the aquatic environment, sediments have been widely used as environmental indicators for the assessment of metal pollution in the natural water. The principal comportment of metals is a function of the suspended sediment composition and water chemistry in the natural water body. During transportation of heavy metals in the riverine system, it may undergo frequent changes due to dissolution, precipitation and sorption phenomena, which affect their performance and bioavailability. Sediment is an essential and dynamic part of the river basin, with the variation of habitats and environments. The investigation of heavy metals in water and sediments could be used to assess the anthropogenic and industrial impacts and risks posed by waste discharges on the riverine ecosystems. Therefore, it is important to measure the concentrations of heavy metals in water and sediments of any contaminated riverine ecosystem. [9]

Recently, studies of bottom sediments have gained an importance. Adsorption of heavy metals by bottom sediments leads to the so-called hidden pollution, which could turn into a real pollution under external factors.

Just because sediments play an important role in contaminant accumulation and transport, they are frequently used to identify contamination sources, study dispersion pathways and mechanisms, and determine the extent of the area involved in contamination and its time duration and evolution.

However, several studies focus their attention only on a few specific abiotic characteristics of sediments (geochemistry or mineralogy) to trace back their origin and/or contamination degree. On the contrary, other studies have shown that the use of multiple approaches is more useful in this research type to understand and highlight the different mechanics involved in the investigated area. [10].

The bottom sediments of rivers are the element of the upper part of the lithosphere section and the lower part of the hydrosphere. They contain the data about structure, composition and conditions for formation of the river valley and drainage basin. The great amount of the man-made materials are added to the natural sources of the sediments in the regions of huge antropogenic pressure and in the territories of industrial, especially mining, centers. It comes with sewage, surface runoff, by direct movement of material stored in the coastal zone to the riverbed. The technogenic component is included in the general cycles of migration and sedimentation of sedimentary substance. In areas of man-made impact and downstream the alluvial sediments are a collection of particles with natural and unnatural origin. [11, 12]

Studies of modern alluvium have shown the presence of significant amount of marketable products of mining and processing enterprises in the bottom sediments of the Ingulets River. This fact testifies not only to significant pollution of the environment, but also to the economic losses of these enterprises. Because waste is what can be sold. The results of such studies prove the need to find and implement new integrated technologies that will minimize production losses, and thus reduce the amount of waste and pollution of geoecosystems.

3. Purpose and methodology

The aims of the study:

- to assess the possibility and the feasibility of using river alluvium in the industrial regions in order to recover lost marketable products of metallurgy and mining and processing;
- to show the advantages of using the integrated technologies for cleaning bottom sediments;
- to demonstrate the economic benefits.

To achieve this goals, a number of methods were used:

- the analysis of granulometric composition of bottom sediment by the sieve method. According to particles' size 12 fractions were got after sieving. Then they were divided on four types: psephites (>2 mm), psammites (2-0,1 mm), siltstones (0,1-0,05 mm) and pelites (<0,05 mm).
- the determination of specific density by the quantitative gydrostatic method. Five parallel experiments were conducted for realistic results. If standard error was more than 0,2, additional five experiments were conducted.
- the evaluation of magnetic component in river alluvium (described [13]). The total compound of magnetic component was compared with the average compound of magnetic component for concrete type of sediments.
- the qualitative and quantitative mineralogical analysis of selected samples of river bottom sediment. The preparation of samples for mineralogical analysis was carried out in accordance with the method of slag analysis with the author's additions and improvements. [14]
- the separation of river alluvium in the vortex air-mineral flow. The initial sample with weight 3-5 kg was divided on two parts by the quartering method. About 1 kg was used for the mineralogical analysis. An other part of the initial sample called the joint sample and was used for the technological research on the possibility of its use. The proposed technological algorithm:
  - (i) The comminution of the joint sample by rotary mill of the author's design. The first sludge part is obtained: dusty product.
  - (ii) The sieving and the air-gravity separation. A vortex air-mineral flow was activated in rotary mill's working chamber. With its help, the growths and lumps of sediment were divided into several products depending on the specific gravity, size, morphology and other properties of mineral grains. The second sludge part is obtained: quartz sand.
  - (iii) The obtained products after the second step of algorithm were divided into several size classes. Each class was further cleaned in a magnetic and gravitational field to improve product quality.
  - (iv) The quality of separation was controlled by the testing of obtained products with optical microscope. In addition the chemical and the spectral analysis, the electron microscopy and the microprobe analysis were used.

  This technology allowed not only to identify the commodity products of industrial enterprises of the Kryvyi Rih basin in the composition of the river sediment, but also to distinguish them into the individual products and to compare with the similar products of the enterprises that produce it.

4. The results of the research

4.1. Sampling and samples

Over the last ten years, 214 samples were taken from the Ingulets river system with tributaries. Of these, 105 different depth samples from 35 wells (the number of layers in the well varies from two to six - depending on the depth of drilling); 58 samples from 12 cross-sections across the river valley; 51 point test.

Sites of sampling, profiling and drilling were selected on the basis of preliminary analysis of the river system taking into account the structure and shape of the riverbed and the nature of the watercourse - the presence of meanders, narrows, dams, reservoirs. Because the conditions of bottom sediments' formation and informativeness of testing materials depends on it. The analysis also took into account environmental conditions - the proximity of enterprises, settlements, agricultural lands and more.

The samples were taken for the purpose of comprehensive assessment of bottom sediments, special emphasis was placed on the determination of anthropogenic load. It means the presence of man-made non-natural components. The analysis of granulometric composition was performed, the specific density, magnetic component, radiological, chemical and qualitative mineralogical analysis were determined for all samples. The presence of marketable products of mining and concentrating enterprises was revealed during the qualitative mineralogical analysis.

According to the sites of sampling the samples are grouped in three zones:

- Zone I relatively low industrial load - samples, taken upstream the Kriviy Rih city
- Zone II extremely industrial load - samples, taken in the southern part of Kriviy Rih
- Zone III post industrial load - samples, taken after Kriviy Rih

The average results are grouped the same way.

4.2. Particle size distribution

Psephites and pelites have almost equal parts in bottom sediments from zone I and zone III. In zone II pelites have little part - only 3,5 %, but psephites and psammites fraction are increase in twice. It means that a great amount of additional rough particles are added to the bottom sediments in this part of river system. (table 1)

Table 1. Granulometric fractions of bottom sediments of the Ingulets River.

Sites of sampling	Psephites (>2 mm)	Psammites (2-0,1 mm)	Siltstones (0,1-0,05 mm)	Pelites (<0,05 mm)
Zone 1	10,1	43,2	3,5	43,3
Zone 2	20,2	75,2	1,1	3,5
Zone 3	10,4	35,9	4,1	49,7

4.3. Specific density

The similar regularity is approved by results of measuring of specific density of bottom sediments. The indexes of density are increase and have wide range in zone II. (table 2)

The specific density indicator allows to identify quite accurately the beginning of the zone of influence of mining and processing plants on the river ecosystem. However, for the final identification of this man-made element and clarification of the zone of its distribution downstream, it is necessary to investigate the presence and amount of magnetic product, petrographic and mineralogical composition of samples in addition to the particle size distribution. But regardless of further studies of lithological characteristics, we can talk about the area within the industrial region, where the specific density and particle size distribution of bottom sediments have significant differences from natural indicators. This allows to single

Table 2. Specific density of bottom sediments of the Ingulets River.

Sites of sampling	Specific density, g/sm^3
Zone 1	2,34 ... 2,48
Zone 2	2,70 ... 3,11
Zone 3	2,34 ... 2,49

out the area where the formation of bottom sediments occurs under the influence of factors of man-made origin.

4.4. Magnetic component
Mining operations in the Kryvbas have a direct impact on such lithological characteristics of bottom sediments as particle size distribution and specific density. Since we are talking about the extraction and processing of iron ore, it is advisable to determine the presence of magnetic particles in the samples. Below are the results of studies of the presence and distribution of magnetic particles in the bottom sediments in the study area. According to table 3 we can see regularity: in samples from zone I part of magnetic component is too low, but in samples from zone II it is too great. Then in samples of zone III part of magnetic component become lower.

Table 3. Part of magnetic component in the bottom sediments of the Ingulets River.

Sites of sampling	Part of magnetic component, %
Zone 1	0,09
Zone 2	2,10 ... 59,55
Zone 3	0,12 ... 0,28

So large part of magnetic components in samples from zone II confirms the presence of mining and processing and metallurgical waste in the bottom sediments of the Ingulets River on territory of Kriviy Rih. The mineralogical analysis was performed to further confirmation of this statement. Due to it the percentage of natural and man-made elements with magnetic properties was evaluated.

4.5. Mineralogical analysis
A large number of allotigenic and autigenic components, mineral formations of industrial origin, as well as organic residues were diagnosed as part of the modern sediment of the Ingulets River.

Iron minerals are very common in the modern sediment of the Ingulets River. They are represented by magnetite, hematite (martite and iron mica), goethite, lepidocrocite, hydro hematite (emulsion hematite). Their presence is constantly observed. It is natural for the river and its tributaries, because they intersect the outcrops of rocks of the iron-siliceous formation of the Kryvyi Rih series.

In addition to the deposited products of the weathering crust, there are unchanged (not oxidized) varieties of rocks and ores of iron-siliceous formation in the sediments. Among the fragments of quartzites dominate the "fresh" appearance, the angular proportions of low-ore (poor) species, such as red-layered, gray-layered, and light gray. There is quartz, magnetite,

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unchanged grains of silicates and sulfides in their composition. According to these features, they correspond to the poor magnetite-quartz growths accumulated in the tailings of mining and processing plants located in the valley of the Ingulets River. (figure 1, figure 2)

Figure 1. Fragment grains of magnetite quartzite. Magnification 30^X.

Figure 2. Martite ore. Magnification 40^X.

Besides, in the samples from zone II was found the iron ore concentrate figure 3, figure 4. The samples of bottom sediments from the Saksagan river

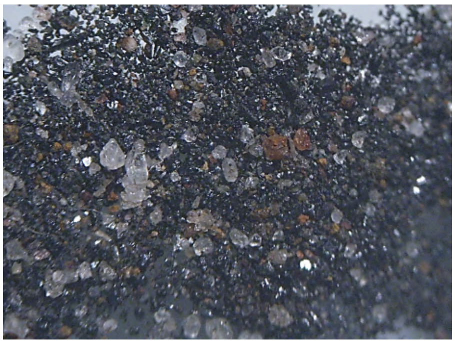

Figure 3. Magnetite concentrate from processing plant in a mixture with quartz and other minerals of alluvium (+0,04-0,063).

Figure 4. Lost magnetite concentrate of processing plant (+0.063-0.1 mm).

The quantitative part of components of bottom sediment in grams per ton (g/t) was determined during the mineralogical analysis.

The combination of natural and man-made iron minerals transform the bottom sediments of the Ingulets River into deposits of iron ore.

4.6. Separation of river alluvium in the vortex air-mineral flow

The technology for separation of river alluvium in the vortex air-mineral flow is based on the physical properties of the particles. The difference in magneticity of the alluvium components provides opportunities for dividing sediments on parts due to influence of the magnetic fields of varying strength.

The Ingulets alluvium from zone II has a great amount of iron oxides, especially magnetite (328538 g/t), hematite (41804 g/t) and goethite (19874 g/t). These are the maximum of the known concentrations of these minerals in the modern alluvium of the studied rivers. Also, in this area, the maximum number of iron-containing man-made formations was determined: magnetic spheres (24 g/t) and particles of metallurgical slag (16 g/t). The share of ore minerals in the joints with quartz is 90-95%.

Enrichment of this man-made placer was performed according to the scheme shown in figure 5.

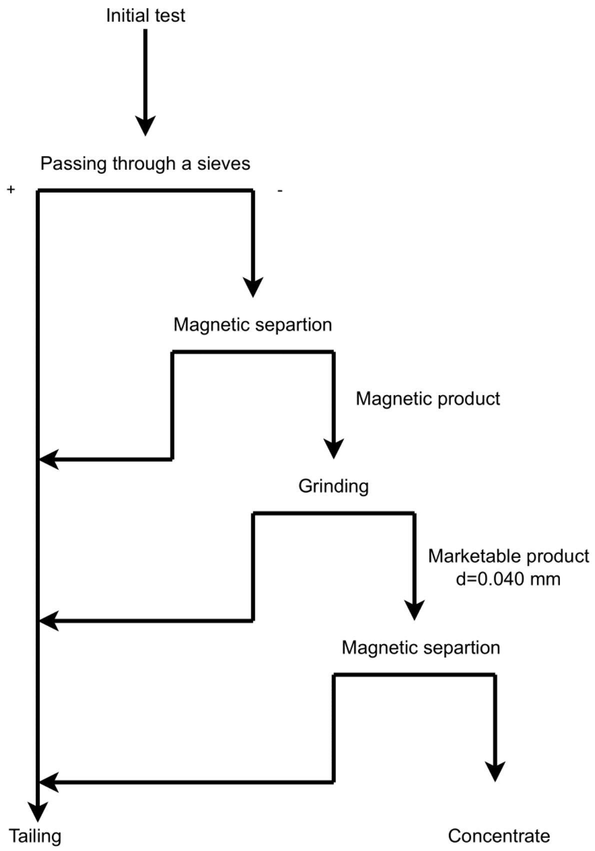

Figure 5. Algorithm of enrichment of river alluvium.

The dried sample material was divided into sieves in the class of 0.5 mm. Particles larger than 0.5 mm, composed mainly of quartz and carbonates, were sent to the tailings of separation. Class 0-0.5 mm was separated in a magnetic field with an intensity of 0.2 T. The non-magnetic fraction was sent to the tailings, and the magnetic product was ground in a rotary mill to a particle size of 0.04 mm to reveal the growths of ore and non-ore minerals and again subjected to magnetic separation in a magnetic field of 0.35-0.7 T. This made it possible to obtain iron ore concentrate in the form of a magnetic fraction and non-magnetic tailings. (figure 6, figure 7)

The enrichment tailings formed at the various stages of separation were combined. The total iron content in the resulting concentrate was 65.4%. This corresponds to the composition of iron ore concentrate of medium quality, produced by mining and processing plants. But the compound and type of this product is different from products of mining and processing plants, because raw stuff is consist of complex of iron minerals with natural and technogenic origin.

Figure 6. Iron ore concentrate from the processing of river alluvium.

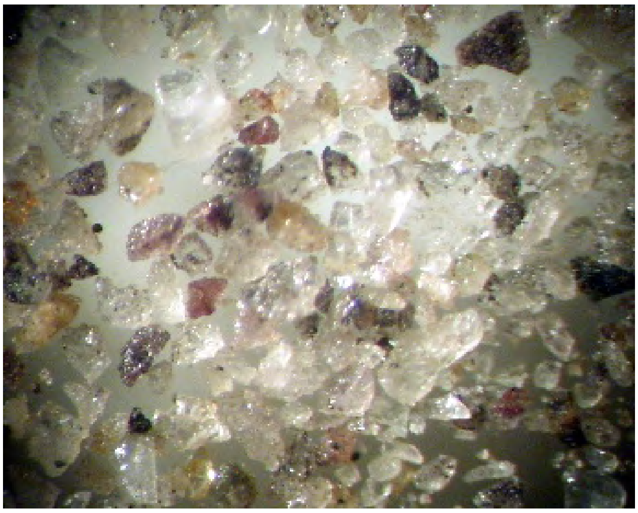

Figure 7. Tailing of enrichment of river alluvium.

5. Conclusions

The authors established the presence of commercial products of mining and processing enterprises in the sediments during studying the pollution of river sediments with industrial waste. It includes crushed granite, metallurgical slags, ores and concentrates, coal and other products. Amount of this materials so great that it will be advisable to use for economic purposes. It is enough to develop and implement the appropriate technology. All products generated in the process of applying the proposed technology can be used in industries. This is a waste-free processing technology.

Lost iron ore concentrate of mining and processing plants as a result of erosion and transportation by storm streams, falls into the river alluvium. In the river system, it mixes with other man-made and natural iron minerals. Among them: hematite, magnetic oxide and metal balls, etc. Due to gravitational differentiation, secondary (redeposited) natural-man-made deposits of heavy iron minerals are formed. These minerals and industrial products can be re-removed from the sludge and produce marketable iron-containing raw materials in the vortex air-mineral flow, according to our technology. Unlike products from processing plants, it consists not only of magnetite, but also contains hematite, goethite, oxide and metal balls, fragments of iron ore agglomerate, particles of metallurgical slag and sludge that fell into the river sediment from various natural and industrial sources.

The main benefit of the proposed technology is water-free enrichment of iron ore. There are no need for any additional reagents and toxic or hazardous agents.

The areas of the riverbed contaminated with man-made components coincide with the places of natural accumulation of iron minerals due to erosion of the weathering crust of iron-siliceous rocks. It also accumulates heavy mineral grains from the heaps of mining and processing plants, tailings and other industrial facilities and morphostructures. The joint sedimentation of ore crystal and lithoclasts coming from three sources significantly changes the natural properties, mineral and chemical composition in some parts of the river.

Not only Kriviiy Rih is faced with this problems. Similar tasks are actual and important for other industrial regions, especially regions of iron ore mining and processing. For example, Anshan town with the Shane river (China), Eisenhüttenstadt with the Oder river (Germany), Parauapebas with the Rio-Parauapebas river (Brazil) and many-many others.

Significant volumes of industrial inputs into the ecosystems encourage the development of special technologies aimed at additional production of mineral products through the complex processing of modern river alluvium. It shows a great potential for economic use. In addition to economic benefits, the implementation of these projects will improve the state of the environment in regions with large technogenic load.

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PAPER • OPEN ACCESS

Kryvyi Rih regional landscape technical system: history of knowledge and specifics of economic development

To cite this article: S V Yarkov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012036

Kryvyi Rih regional landscape technical system: history of knowledge and specifics of economic development

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Abstract. The article is devoted to the study of Kryvbas – a unique landfill for understanding the structure of landscapes. In the history of studying the nature and landscapes of Kryvbas, the authors have identified two main stages: initial knowledge (ancient times – the first half of the XIX century) the second half of the XIX – beginning of the XXI century), which gave the opportunity for 130 years to form one of the largest not only in Ukraine but also in the world landscape and technical system. The formation of this original landscape-technical system is due to three factors: a) detailed studies of the nature and landscapes of Kryvyi Rih region, b) the richness and diversity of natural resources of the region, c) intensive development. The authors paid special attention to the functional-genetic classification of anthropogenic landscapes of Kryvbas, their characteristics and mapping. The authors note that among the industrial ones, special attention should be paid to mining and industrial landscapes, in particular dumps, which are the most suitable landscape complexes not only for reclamation works, but also for cultivating the entire landscape and technical system of Kryvbas.

1. Introduction

1.1. The problem statement

Kryvyi Rih region is a unique landfill for the study of industrial landscapes, within which a powerful landscape-technical supersystem has been formed, which combines landscape-engineering and landscape-technogenic components. Modern study of this pronounced zone of technogenesis is extremely important for the sustainable future not only of the region, but also to some extent of the geosystem as a whole, because Kryvyi Rih region is characterized by abnormally rapid changes in the structural organization of geocomponents and landscape complexes and relationships. Some aspects of the researched problem are covered in the works of classical and anthropogenic landscape science, landscape geochemistry, ecology, constructive geography and geobotany, in particular in the works of such scientists – T. Andrienko [1], D. Armand [2], S. Berg [3], M. Grodzinsky [4], V. Dokuchaev [5,6], G. Denisyk [7,8], A. Isachenko [9], V. Kazakov [10], O. Marynych [11], F. Milkov [12], V. Pashchenko [13], V. Petlin [14], P. Pogrebnyak [15], M. Solntsev [16], O. Smetana [17], V. Sukachov [18], Y. Tyutyunnik [19–21], V. Fedotov [22, 23], P. Shishchenko [24] etc.

The study of the modern structure of mining landscapes of the Kryvyi Rih landscape-technical system is not possible without a retrospective analysis of its development, and therefore this aspect is currently in the field of our scientific research. At the same time, we are aware that the research conducted is only a small part of the knowledge of the general image of the Kryvyi Rih regional landscape-technical system.

1.2. The objective of the article
The objective of the proposed publication is a retrospective analysis of the knowledge and specifics of economic development of the Kryvyi Rih regional landscape and technical system.

1.3. Methodology
The study is based on the theoretical foundations of anthropogenic landscape science, constructive geography and geobotany. The authors used interrelated approaches (landscape-dynamic, constructive-scientific), principles (historicism, complexity and natural-anthropogenic combination) and research methods (retrospective, systemic, structural, etc.).

2. Results and discussion
The nature and landscapes of Kryvyi Rih region as a kind of historical and geographical region of the central part of Ukraine have long been of interest to scientists, but have been studied unevenly. Their uniqueness was recognized in the process of economic development, especially from the second half of the XIX century. Based on the analysis of the scientific literature in the history of the study of nature and landscapes of Kryvyi Rih region, we have identified two stages, which we describe below.

1. Stage of initial knowledge of nature (ancient times – the first half of the XIX century). There are no direct written data that would record the beginning of this stage, but it is indirectly confirmed by archaeological materials. People began to actively inhabit the central part of Ukraine from the Upper Paleolithic (40–35 thousand years ago). The use of animals, plants, fishing, and later the development of animal husbandry and agriculture contributed to the diverse knowledge of nature associated with these forms of economic activity. Undoubtedly, this knowledge was at the household level, but it was purposeful. People studied only what was necessary for direct use – flora and fauna, in part – the soil. Knowledge of soils was due to the development within the Right Bank of Ukraine Trypillia Neolithic hoe-agricultural culture (V–IV thousand years ago). In the absence of writing, the transmission of knowledge (from father to son, from generation to generation or genus) and their dissemination took place orally and through practical skills. The first, original (oral) information bank of practical knowledge about the nature of certain regions of the Right Bank of Ukraine was created [25]. Moreover, people first tried to record their knowledge of nature in graphic images: rock paintings, individual stones and animal bones. No such materials have been recorded within Kryvyi Rih region, but they are available in the adjacent regions [25]. The illiterate period of learning about the nature of Kryvyi Rih region requires more detailed, related research by archaeologists and geographers.

With the advent of writing, the need for geographical knowledge is realized at the level of society. This was a kind of period in the knowledge of the nature of Kryvyi Rih region, and it is confirmed by Greek and Roman ancient sources. Almost all recognized Kryvyi Rih Regional Landscape Technical System: History of Knowledge and Specifics of Economic Development ancient Greek authors mentioned the ancient Ukrainian lands (Black Sea and steppe regions) in their works [26]. But, perhaps, the Hellenes really discovered Scythia after Herodotus's History of Apodeikis (Description of History) in 9 volumes. For almost a thousand years of ancient Greek culture, the idea of the permanence of the spatialimage of Ukraine with well-defined coordinates has been preserved. Some descriptions were illustrated with cartographic images. The descriptions were complex: nature, population, economy, customs, traditions, etc.

Examples of complex descriptions of rivers became classic, in particular Gipanis (Southern Bug) and Borisfen (Dnieper), steppe and partly forest-steppe of Ukraine – Herodotus, Strabo, Ptolemy and others.

Much more information about the nature of the Kryvyi Rih region can be found in chronicles (late 1st millennium AD – XIII century), which was due to the origin, formation and intensive development of Kievan Rus and, accordingly, economic development of the Right Bank Ukraine.

Geographical information about the northern steppe regions of the Right Bank of Ukraine is in the chronicles, travel notes of Arab and Byzantine authors. These are mainly fragments of descriptions of the nature and population of certain regions of the Eastern Slavs – the Dnieper, the Northern Black Sea coast and natural objects – rapids on the Dnieper, individual rivers and more. Chronicles have become a qualitatively new form of describing the nature of Ukraine. Their complete collection consists of thirty-seven volumes. Chronicles are the only written sources that provide reliable chronologically recorded material about the nature of the forest-steppe and steppe of Ukraine, especially about adverse events: climatic, hydrological, biological and solar eclipses. The territory of Kryvyi Rih region at that time belonged to the Wild Steppe, where mostly Turkic tribes roamed. However, this does not mean that these steppe areas were unknown to the outside world. Thus, the meridional trade routes from the southern steppe regions of the Black Sea to the northern forest-steppes, laid in the Bronze Age and well mastered in ancient times, gradually turned into the famous Dnieper way from Vikings to Greeks in the early Slavs and Kievan Rus.

After the Tatar-Mongol invasion, the steppe part of Ukraine was occupied by nomads and often suffered devastating raids by Crimean Tatars, and is recorded in chronicles and historical documents as wild steppe or wild field. Later (XV–XVI centuries), rich in natural resources and sparsely populated Right-Bank Ukraine, especially the southern forest-steppe and steppe, attracted the interest of Western Europeans, who have already begun to develop intensive capitalist relations. This interest is well illustrated by the famous Description of Ukraine by G. Boplan [27]. In France alone, it has been republished 12 times [25]. This description contains detailed and true information about individual natural components – rocks, rivers, fertile lands, partly climate and plants. Repeated reprints of Description of Ukraine and other works by Western European authors show that in the sixteenth and seventeenth centuries. Right-bank Ukraine was well known, its nature studied and described in detail [25]. Undoubtedly, this also contributed to the fact that since the middle of the eighteenth century. Active economic development of not only the forest-steppe, but also the steppe regions of Ukraine begins, maps of individual provinces are drawn up in connection with the general demarcation of the Russian Empire. The stage of initial knowledge of Kryvyi Rih region ends with the fact that in addition to descriptions of nature, in the second half of the eighteenth century elements of scientific research and research are launched, expressed by academic expeditions (1768–1774) and intelligence of individual scientists. It was at this time that V. Zuev [28] found iron ores (iron slate) of Kryvbas. Their discovery gave impetus to new, more detailed studies of the nature of Kryvbas and became the starting point of its anthropogenic changes in the future.

2. Stage of knowledge of the nature of Kryvbas for the purposes of industrial development (second half of the XIX century – the beginning of the XXI century). The rapid development of industry in the second half of the nineteenth century not only in Western but also in Eastern Europe led to the active search for minerals, including fuel (coal, oil) and ore (iron, manganese, polymetallic, etc.). Favorably located in spatial terms, Kryvbas has attracted the attention of many scientists. Naturally, their attention was focused mainly on geocomponent research and primarily on the search for iron ore. It is here, in Kryvyi Rih, that a galaxy of wonderful and famous geologists has grown up. Their discoveries are recorded and analyzed in many scientific works,especially (as a result) in the Encyclopedia of Kryvbas [29]. In the second half of the XIX century. Exploration of iron ores of Kryvbas was successfully conducted by R. Kulshin

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012036 doi:10.1088/1755-1315/1049/1/012036

(1825-1837), M. Barbot-de-Marne (1866–1867), L. Strippelman (1872), S. Gartung (1872-1873), L. Semechkin (1874), S. Kontkevich (1878–1887), V. Domger (1875), P. Pyatnitsciy (1881). The results of their research have made it possible since the 80s of the XIX century actively extract iron ore and form a new industrial area.

In the late XIX and early XX centuries geocomponent research of Kryvbas is significantly expanding. Scientists are in the field of view of all components of nature, although their study is uneven. Productive geological research is conducted by A. Mikhalsky (1886–1888), M. Szymanowski (1888), geological and geomorphological – M. Sokolov (1896), V. Tarasenko (1914). At the end of the XIX century Klosovsky organizes the first meteorological network in the Middle Dnieper, which includes the areas of Kryvbas (Kryvyi Rih meteorological station was established in 1881); Zemstvo expeditions conducted in 1882-1916 under the leadership of V. Dokuchaev contributed to the study of soils. More attention is paid to geobotanical research of the steppes in general and the Kryvyi Rih region in particular – E. Lindeman, I. Akinfeev, A. Beketov, A. Grossheim (1917), I. Pachosky (1890-1915), I. Ryabkov (1898) and others. Hydrological research was conducted in conjunction with geological; less attention was paid to the river network and wildlife.

The First and Second World Wars weakened the process of learning about the nature of Kryvyi Rih region and only in the middle of the twentieth century Studies were continued. Among the scientists of this time geocomponent research was conducted by: geological and geomorphological – Y. Belevtsov, Y. Polovinkina, V. Natarov, D. Sobolev, G. Malakhov, V. Bondarchuk and others; groundwater – A. Alekseev, R. Ponov and others; climate – employees of Kryvyi Rih and Dovchyntsev meteorological stations; vegetation cover – I. Dobrovolsky,V. Danko, V. Tarasova, V. Tereshchenko and others; surface waters – V. Natarov, P. Kalinin, V. Popov and others.

In the early 50's of the twentieth century. in Ukraine Landscape research begins together with geocomponent ones. They were exploratory and initially performed ancillary functions in the conduct of research on physical and geographical zoning. This is most vividly reflected in the fundamental work Physical and geographical zoning of the Ukrainian SSR [30]. In this work, Kryvyi Rih is referred to the Ingulets, Saksagan valley-beam district, the characteristics of landscape complexes are given at the level of local types. Partially complex studies of the nature of Kryvyi Rih region were conducted earlier and were published in the form of separate chapters (essays) in monographs [31]. The most detailed physical-geographical description of Kryvyi Rih region was made only in the early 90's by L. Bulava, but this work was deposited, not published [32].

During the twentieth century, as a result of intensive development of iron ores, not only geocomponents but also landscape complexes of Kryvbas have been radically rebuilt. Accordingly, the content of scientific research is changing – the object of study are anthropogenic geocomponents, landscapes and environmental problems inherent in the zones of technogenesis. Geological research is conducted by V. Reshetnyak, M. Semenenko, E. Shnyukov, B. Pirogov, I. Paranko, V. Evtekhov, E. Lazarenko; geomorphological – M. Semenyuk, I. Dobrovalsky, V. Shanda, I. Comisar, A. Denisov et al. The vegetation of rock refuse is studied by V. Chayka, M. Smetana, V. Kucherevsky, S. Yarkov and others.

The first attempts to study the changed landscapes of Kryvyi Rih region began in the 50-60s of the twentieth century. These attempts also do not belong to geographers,but to geologists – V. Bondarchuk and T. Klevtsov. In particular, landscapes formed under the influence of mining and mining techniques, V. Bondarchuk suggested calling it mining. In the meaning of the term mining landscape he focused on landscape and geomorphological features, and saw the difference between them only in appearance: color is a characteristic feature of the iron ore landscape [33].

Studies of anthropogenic landscapes of Kryvyi Rih region began only in the 80s of the twentieth century. Y. Tiutiunnik, L. Bulava and especially in the 90s and now – V. Kazakov.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012036 doi:10.1088/1755-1315/1049/1/012036

In addition to landscape scientists, industry experts, including geologists, zoologists, and geobotanists, have begun to conduct research related to landscape science. In this regard, the most interesting are the studies of I. Malakhov, O. Smetana and M. Smetana. In the works of I. Malakhov often focuses on the identification of factors of technogenesis in the geological environment from landscape perspectives; It is shown that the Kryvyi Rih iron ore basin is a typical object for studying man-made changes in the geological and, in general, natural environment. I. Malakhov compares the natural and man-made parameters of Kryvbas ecosystems, considers some aspects of management of man-made processes in the natural environment [34].

If we take into account that changes in zoocenotic complexes of steppes are still insufficiently studied, the study of O. Smetana and N. Smetana on the structure of the terrestrial mesoform of Kryvbas is extremely relevant [35]. The structure of a biocoenotic group or its components is inextricably linked to the state of the environment and can therefore be an indicator of ecotoxicological effects. These authors were able to determine the most informative indicators of structural organization of terrestrial mesofauna groups to assess the degree of anthropogenic transformation of biogeocenoses, ecological status and indication of the most important soil formation processes in anthropogenically disturbed and man made biocenoses of Kryvyi Rih region. The research coincides with the research of landscape scientists at the level of facies and, in part, tracts.

The relative flatness of the Kryvyi Rih iron ore basin, typical steppe climatic conditions and soils give the impression of simplicity of natural conditions, and there were no reports of natural resources until the second half of the nineteenth century.In fact, the Kryvbas region is extremely interesting and rich in nature, which has attracted many researchers. Thanks to their research, it was proved that Kryvyi Rih region is unique in its natural and, later, social features.

Having paid attention to the periodization of the history of knowledge of Kryvyi Rih region, we intend to dwell briefly on the specifics of economic development of this region.

Kryvyi Rih region, as it is now, began to take shape in 1881, when, due to the beginning of iron ore mining, the first industrial complexes appeared. Iron ore mining was started by O. Pol that started not only the mining industry in the area, but also a consistent geological study of Kryvbas. In 1835, P. Kulshin, an engineer in the mining department, began his research work. His book, published in 1839, contained the first qualified description of aspid and iron-quartz shales, brown coal seams, and quartz cores with copper. M. Barbot-de-Marne, doctor, professor of geology at the St. Petersburg Mining Institute, wrote in 1869 that ore layers here themselves come to the surface. In 1872, at the invitation of O. Pol the mineral fields of Kryvyi Rih region were studied by mining engineers from Germany, Gartung and Stripelman. After translating their work, O. Pol published a book in 1875, where for the first time it was about the occurrence in Kryvyi Rih region of powerful deposits of ores with high iron content (70%). In 1874, the mining engineer Felsko wrote that Kryvyi Rih could be called the Golden Horn. In 1880 S. Kontkevich published the work Geological description of the vicinity of Kryvyi Rih in the Kherson province, which was about the layers of ferruginous quartzites. Information from the study of S. Kontkevich reached Western Europe, and these data were included in the 19-volume work of French geographer Jacques Elise Reclus Earth and People.

Convinced of the industrial significance of the iron ore deposit, O. Pol, together with French financiers and entrepreneurs, founded The Kryvyi Rih Iron Ore Joint Stock Company in 1880. This year can be considered the beginning of constant and significant industrial development of the Kryvyi Rih iron ore basin. Initially, these were only iron ore mining sites. In 1884 the first Ekaterinoslav railway was built, which connected Kryvbas with Donbass, which gave impetus to the development of the metallurgical processing industry. From 1892 to 1917 the Gdansk Iron Foundry operated in the city – the first metallurgical complex for iron ore processing.

The development of ferrous metallurgy, with a break during the Civil War and postwar devastation (1918–1922), continued. This was due to the construction in 1934 of the Kryvyi Rih Metallurgical Plant and the Coke Plant in 1936. Water resources of the region have been actively used since 1932, when the first stage of the Karachunov Reservoir on the Ingulets River and the Kresiv Reservoir on the Saksagan River (1948) was put into operation. In 1952, the Mining and Cement Plant was launched, which gave a significant impetus to the development of construction geosystems to meet the needs of industrial and residential construction.

In the 1950's and 1960's, the 5 largest mining and processing plants in Europe for the extraction, enrichment, and processing of poor iron ores began to operate: the Southern, Novokryvyi Rih, Central, Northern, and Ingulets. Along with them, mines continue to operate, where rich iron ores, to a lesser extent iron quartzite, are mined underground in mines.

During the 60–70's of the twentieth century a number of machine-building plants are under construction: Kryvyi Rih Central Ore Repair Plant (1961). Kryvyi Rih Diesel Plant (1966), Kryvyi Rih Electric Plant (1971), Remgormash Plant (1975) and others. In the same years, the light (wool spinning, shoe and garment factories), food (bakery, dairy, bakery, etc.), construction (Kryvyi Rih silicate plant, house-building plants), chemical (Kryvyi Rih meer factory) industries developed. The length of the railway of the Kryvyi Rih branch of the Dnieper Railway increases to 985 km.

The main difference between the development of the nature management system and the population in Kryvyi Rih region since the 80's of the XIX century there was a narrow specialization - ferrous metallurgy, mining and processing of iron ore. To achieve this goal, the able-bodied population was concentrated extensively, developed as ancillary transport, construction, engineering, light, food, chemical industries, created reservoirs and water canals, Kryvyi Rih region power plant. All this was to serve the Kryvbas mining and metallurgical complex.

Natural resources were also used to a limited extent. The main valuable raw materials were and still are iron, iron ore. Other mineral resources – building materials (sand, clay, limestone, granite), meerschaum – were of secondary importance in the system of nature management. The peripheral zone of Kryvbas supplies food to the population of Kryvyi Rih region, which is obliged to work on metal. Forests and reservoirs around Kryvyi Rih play a conservation and recreational function. There is a close interaction of nature, economy and population, which takes place in a small and compactly organized area. Interacting with each other, these factors for 120 years have formed a special, unified space-time integral structure, which is traditionally called Kryvbas, Kryvyi Rih, Kryvyi Rih region. Kryvbas has outgrown its original meaning only as the Kryvyi Rih iron ore geological and mining basin.

The phenomenon of Kryvbas is wider and deeper, it combines nature, technology and man, gave grounds for the formation of a kind of social mentality in Kryvyi Rih. Close interaction of nature, economy and man, narrow specialization of the economy is the basis for the development of Kryvyi Rih region unique for Ukraine anthropogenic landscapes.

From the second half of the XIX and to the beginning of the XXI century the natural steppe landscapes of Kryvbas have been radically replaced by mainly industrial and residential ones. The processes of technogenesis affected no more than individual geocomponents, and the landscape as a whole, created new, unprotected for steppe zones anthropogenic landscapes.

The main classes of such landscapes are industrial (mining rock refuse, dips, quarries and factory), transport (in other interpretations – road landscapes), recreational, residential (residential and non-residential), agricultural, forestry, water management, beligerative (military), service, wastelands (landfills, industrial rock refuse, abandoned and demolished settlements, etc.), protected areas (reserves and monuments that develop under moderate pressure from man) and other landscapes, which are presented in the map below.

We characterize some modern landscapes of Kryvyi Rih region, mapped in figure 1.

Residential landscapes (from the word "settle") are anthropogenic landscapes of settlements

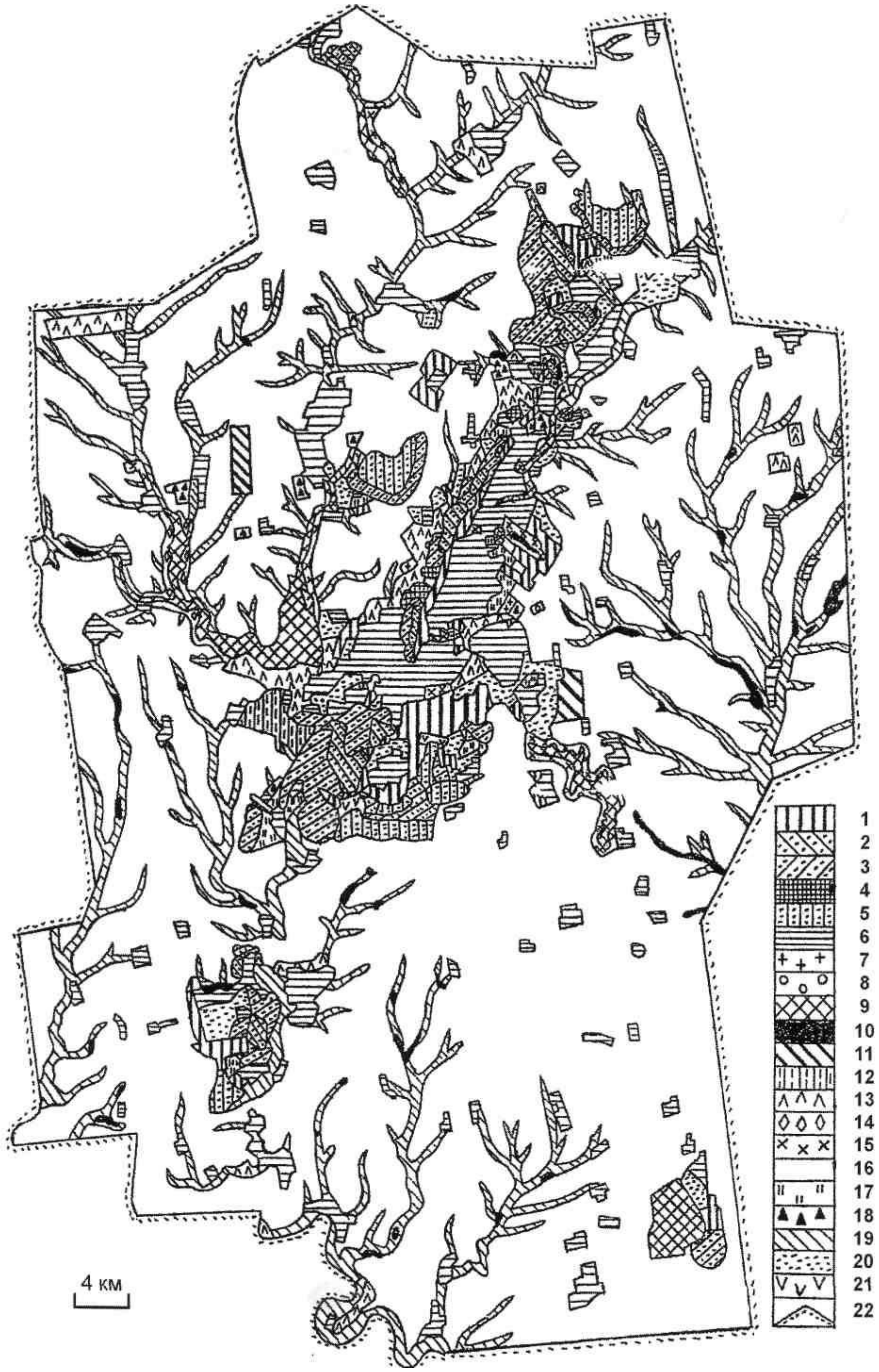

Figure 1. Modern landscapes of Kryvbas.
1 – factory; 2 – mining; 3 – dumps; 4 – about free; 5 – extractive; 6 – non-residential; 7 – residential; 8 – serving; 9 – reservoirs; 10 – pond; 11 – transport; 12 – beligerative; 13 – forestry; 14 – tourist; 15 – forest parks; 16 – field; 17 – garden; 18 – garden; 19 – pasture; 20 – country; 21 – post-industrial PTC; 22 – borders of Kryvbas.

with their buildings, streets. The city of Kryvyi Rih region with its economy and population is an active form of human influence on nature. Natural landscapes were radically rebuilt. In Kryvbas, urban landscapes together with mining are harbingers of the formation of a more powerful anthropogenic landscape.

The structure of urban landscapes, in our opinion, has a number of specific features:

- in the urban landscapes of Kryvyi Rih region all natural components and landscape complexes have undergone radical changes, while in agricultural landscapes – mainly soil cover, anthropogenic aquatic – surface waters and so on. Moreover, they can be rebuilt repeatedly and in the end bear little resemblance to their natural counterparts;
- some landscape complexes within the city level facies, tracts, types of areas disappear completely: covered and leveled ravines and gullies, lakes; floodplains are being flooded; hills are cut off. In Kryvyi Rih, the scale of such transformations, in our opinion, reaches the level from physical and geographical areas to the region, but does not yet affect the zonal formations. The city has radically rebuilt or re-created landscape complexes that have lost the ability to self-development.

The structure of urban landscapes introduces new anthropogenic components - technomass and technocomponent (asphalt pavement, residential and industrial buildings) and created on their basis landscape complexes, the functioning of which is directed and controlled by man. There is a technicalization of natural landscapes - filling them with different techniques [36]. At the same time, urban landscapes continue to be an integral part of nature and continue to develop according to its laws.

Residential landscapes of Kryvbas are divided into 2 subtypes: non-residential (cemetery) and residential, with such genera as low-, medium-altitude and high-altitude geosystems.

Service landscapes are represented by subtypes of household, managerial, scientific-educational, trade, and by their properties are close to residential and are formed on a paragenetic basis.

Agricultural landscapes (AGL) of Kryvbas are divided into field, garden, garden, pasture and country. These landscapes are the oldest of the anthropogenic -ones formed in Kryvyi Rih. Organizational heterogeneity of agricultural landscapes allows us to divide them into two groups: the actual SGL and agricultural landscape engineering systems.

Forestry landscapes – planted forests. Forest plantations with genera: forest protection and forest-strip landscape complexes. It should be noted that there are no natural forests left in Kryvyi Rih. Here the forests are planted by man. They now occupy an area larger than before the active transformation of the natural landscapes of Kryvyi Rih region. In Kryvyi Rih plantings you can find almost all types of trees that form natural forests. All silvicultural landscapes belong to the type of perennial, partially regulated anthropogenic complexes. With the successful selection of trees, planting sites and the necessary forestry equipment, they can exist for decades or even centuries.

Water management landscapes– reservoirs, ponds, canals and settling tanks, built mainly in the 50-60s of the twentieth century, during the most active economic development of water resources of Kryvbas. In the vicinity of Kryvyi Rih region, only 9 reservoirs with a total area of 9,340 hectares have been created for water supply and public utilities; there are 25 reservoirs for agricultural purposes.

Gradually changing the natural landscapes of rivers and their floodplains, water-anthropogenic landscapes have become carriers of information about the state of river basins and surrounding areas. This applies primarily to ponds created in the floodplains of Visuna, Bokova, Zhovta, Zelena and other small rivers of Kryvbas.

Road (transport) landscapes have subtypes: railway, automobile, aviation, pipeline and electrical, pedestrian. Two hundred years ago, several roads passed through Kryvyi Rih, the most famous being the Kyzykyrmen (Black Way). Now all Kryvyi Rih region is crossed by highways. Now road landscapes are a complex system of various anthropogenic complexes. In their structure there are actually anthropogenic landscapes (abandoned sections of roads, quarries, swampy depressions formed as a result of road construction and roadside forest belts), landscape-technogenic and landscape-engineering systems. These complexes include existing railways, highways and dirt roads, interchanges, overpasses, stops, and for the past 15-20 years and service facilities. Landscape-technogenic geosystems are represented by drainage structures, bus stops, wells, numerous monuments of the historical past, etc. These are azonal landscape complexes, the development of which is determined by the technical unit, and the functioning depends in part on natural conditions.

Beligerative landscapes are landscape complexes of military origin: military training grounds with fortifications, ramparts, trenches, explosion funnels, dugouts, etc. They can often be found in Kryvyi Rih, especially in the area of the 17th tank division. Of particular interest are the tracts of single mounds – the simplest beligerative complexes. Their age – from several millennia (Bronze Age) to several hundred years. More often it is graves, but also guard mounds. Currently, most of the single mounds of Kryvyi Rih region are plowed. Every year they become less noticeable. Almost all mounds of Kryvbas must be protected.

Recreational landscapes. In the structure of anthropogenic recreational landscapes by age the youngest. Purposeful formation of recreational landscapes began in Kryvyi Rih at the end of the XIX century construction of parks for citizens (F. Marshavtsev Park) and in the estates of landowners. Despite the youth of these landscapes, their role will continue to grow in the future. Thus, the possibility of recreational development and formation of recreational neo-landscapes at the expense of other classes of anthropogenic landscapes, including industrial.

Desert landscapes have subtypes of post-industrial, post-residential, landfill, agricultural, water-desert. These are the so-called ”abandoned” lands after their use. The development of these landscape complexes is complex and diverse. If agricultural dependent lands can be transformed into zonal steppe landscapes through the process of synthetic genesis, then post-residential or industrial ones have unpredictable development and can be replaced by new ones.

Industrial landscapes. Taking into account the peculiarities of development, landscape structure and impact on the environment, industrial landscapes should be divided into industrial and mining. In fact, industrial landscapes are formed around large industrial enterprises or areas. Mining landscapes are those that are formed under the influence of mining and mining techniques. These landscapes, in comparison with other industrial landscapes, have the most significant impact on the material composition, development and structure of natural and anthropogenic landscapes.

In the region of mining, all components of the natural environment have been radically changed, specific, depleted and less stable, compared to natural, mining landscapes with a more differentiated, contrasting and dynamic structure.

Field landscape research and analysis of literature sources on mining (technogenic) landscapes allowed for the zone of technogenesis of Kryvbas to make a system of typological structures, presented in the table 1.

In landscape studies of man-made (mining) landscapes, facies types are not always distinguished due to their significant diversity, small area and short-term operation. Facies are of paramount importance in the cognition of the synthetic genesis of plant groups of man-made landscapes, they are clearly distinguished and studied in detail. They are the basis for further research on the synthetic genesis of plant communities and man-made landscapes in general.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012036 doi:10.1088/1755-1315/1049/1/012036

Table 1. A system of typological structures.

Typological structuresof the zone of technogenesis of Kryvbas	Characteristics of typological structures
Man-made tracts	are distinguished as a result of differences in the lithological composition of soil mixtures, relief and phytocenotic cover;
Man-made landscape areas	system of interconnected tracts, sufficiently separated in the structure of localities under the influence of morphological or any other factor;
Man-made areas	system of tracts and landscape areas, the formation of which is due to one way of technological (mining) activities in similar geological-geomorphological and hydrogeological conditions. Depending on the physico-chemical composition of extractive rocks, the peculiarities of their interaction with water and physico-geographical processes, the types of man-made areas are divided into options (iron ore, manganese, granite, sandstone, limestone, etc.);
Man-made landscapes	system of tracts, landscape areas and areas formed in areas with the same type of technological schemes of economic activity. As an example: due to the development of minerals formed quarry-dump, underground – mine subsidence-heap types of man-made landscapes;
Man-made facies	is distinguished on the basis of the unity and homogeneity of soil mixtures, moisture and vegetation in the corresponding micro shape of the surface and is often an indicator of various processes that characterize a typological structure of the man-made landscape.

3. Conclusion

The analysis of literary and cartographic sources allowed to distinguish two stages in the history of landscapes, as well as economic development of Kryvbas: the stage of initial knowledge of nature (ancient times – the first half of the XIX century) and the stage of nature research for industrial development (second half of the XIX century – the beginning of the XXI century).

Periods differ in time intervals and results, but really show the course and features of the formation of a complex and unique landscape-technical system of Kryvbas. This system was formed on the basis of unique reserves of mainly iron ores, partly other types of minerals. In the process of its operation (over 120 years) geocomponents and landscape complexes with an area of over 100 thousand hectares have been involved and radically changed. Here were formed industrial and residential landscapes that have no analogues in world practice. Their structure is unique and includes fragments of all other currently available classes of anthropogenic landscapes. Among the industrial ones, mining landscapes, in particular, deserve special attention. They are the most suitable landscape complexes not only for reclamation works, but also for cultivation of the whole landscape-technical system of Kryvbas.

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Hydrological simulation and assessment of the optimal parameters of the water replenishment of the floodplain lake and old riverbed on the Uzh river

To cite this article: S V Velychko and O V Dupliak 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012037

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012037 doi:10.1088/1755-1315/1049/1/012037

Hydrological simulation and assessment of the optimal parameters of the water replenishment of the floodplain lake and old riverbed on the Uzh river

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Abstract. One of the tasks in modern approach of the water resources management is improving environment health by the way of the river restoration. On the urban area it is impossible to provide full river restoration, but at the same time it is possible to create the environment close to natural. In our work on the example of the river Uzh located inside the city provides the assessment of the restoring possibility of the part of the floodplain by water replenishment of the old riverbed during the vegetation season. Flood control dyke construction interrupted the connection between old riverbed and river and as a result floodplain lake became muddy, silted up and lost its attractive form. To assess the possibility of the floodplain lake replenishment, the simulation of some scenarios were carried out: natural condition, water replenishment during flood, pumping water, raising water level in the river Uzh near the lake. The connection of the lake and the old riverbed with the river will improve slightly the storage capacity of the lake and allows to provide the depth of up to 1.0 m in the lake during flood, but the water will be absent in the old riverbed during the dry season. Hydraulic calculation showed that replenishment during spring floods and pumping water were not possible due to high hydraulic conductivity of the gravel and pebble soils. The old riverbed replenishment is possible by raising water level in the river Uzh, which will ensure the free water flow into the lake and into the old riverbed during the dry season.

1. Introduction

Water management was aimed to solve flood, social and economic problems of the population, which led to a significant deterioration of riverbeds, the destruction of the floodplains natural state in the XX century. Now, Ukraine implemented the Water Framework Directive, which requires the change in attitudes towards water resources. The river restoration or rehabilitation is one of the priority measures improving the health of the aquatic environment.

In the work [1], river restoration measures are divided into management measures (monitoring of water quality and quantity) and engineering measures aimed at improvement of the river health. The integrated approach is the most modern and includes providing the river with enough room, free movement of sediments, increasing biodiversity, reducing anthropogenic impact [2–4]. The too modified riverbed situated in the city is almost impossible to restore to its natural state due to the significant changes in the environment state and the absence of the free space for natural regime.

Thus, partial measures are often used, which depend on the communities economic capabilities: bank stabilization, clearing of the riverbeds [5], using aquatic plants and animals to clean riverbeds and floodplain lakes from anthropogenic pollution [6], expanding inter-dyke room [7, 8], restoration of tortuosity and multi-sleeved channels, connection of the riverbed and the floodplain by hydraulic structures in the dykes or its destruction [9], restoration of natural regime of water and sediments [10]. In addition to economic constraints, according to the work [11] in which restoration projects in different countries were compared, the degree of river restoration is influenced by national specificity, which does not allow to develop a single ideal mechanism for assessing the effectiveness and necessary measures of the river restoration on the urban areas.

If full river restoration in the city is not possible, then what measures of the river restoration to use and with what factors to assess the restoration effectiveness. In the work [12], 110 river rehabilitation projects in rural and urban areas were analysed in France. The most projects in the rural areas were implemented to restore aquatic environments; restoration of longitudinal connection; restoration near natural patterns of river hydromorphology. The dominated projects on the urban areas were aimed to flood protection, to improve the quality of the citizens life, the aesthetics of the river landscape. In Ukraine, most river restoration projects relate only to clearing the riverbed and restoring riffles.

The author [13] proposed the main components of sustainable development of the aquatic environment in the city: clean water, green slopes, flood protection and automated control system. But in addition, the social component is very important in the rural environment, namely the creation of a comfortable environment for recreation [14].

Thus, river restoration is becoming more difficult in the cities due to the flood protection requirement, housing construction and recreation. According to the authors' researches [15–17] biological methods of river restoration, namely the connection of river and floodplain and floodplain water replenishment provide the local species biodiversity increasing and improve water quality. At the same time, it should be noted that the full restoration of the natural regime of river in rural area is not possible, the river requires periodic intervention [15]. Thus, in cities it is possible to create and maintain an urbanized near natural environment, which at the same time provides improve the health of riparian ecosystems, recreational and aesthetic needs of the citizens.

In our work floodplain restoration of the part of the Uzh River inside the Bozdos Park in the centre of Uzhhorod was assessment. The river floodplain replenishment would create the favourable environment for the flora and fauna of the park and the additional recreational area for citizens in the park during the dry season (June-September).

The aim of the work is environmental assessment of the water replenishment possibility of the old riverbed and floodplain in the park and operating volume of the floodplain lake.

The following tasks were solved for this aim:

- to analyse the hydrological data of the Uzh river on the study area;
- to determine the floodplain lake volume in modern conditions;
- to simulate the water accumulation in the lake after the connection with the river;
- to calculate the necessary operating volume of the lake for water replenishment of the old riverbed during the dry season.

2. Materials and methods

The Uzh river source is situated in the Carpathian mountains and the lower part of the river reaches the plain. The lower part of the Uzh River located in the Transcarpathian lowlands was studied in the work. The Uzh river crosses the Uzhgorod city. Free meandering of the riverbed in the city was limited by the flood protection dyke construction. In 1954, Bozdos Park was established inside of the river loop and old riverbed and the lake were connected to the river

Uzh by tubular spillways for floodplain water replenishment. Over the last 30 years tubular spillways were blocked by sediments and point bar formed on the left bank of the river Uzh near park. Now the connection between the floodplain in the park and the river is lost, there is no water in the old riverbed. Floodplain lake turned into two small silted lakes (figure 1).

Figure 1. Current state of the floodplain lake: 1 – floodplain lake, 2 - old riverbed, 3 – dyke, 4 – tubular spillways for water replenishment.

The operating volume of the floodplain lake in the ice-free period (March-November) was calculated by the water balance method according to the general equation [18]:

$$Pf - E_0 f + SI - SO + RI - RO \pm \Delta W = 0, \tag{1}$$

where ΔW – change in storage, m^3; P – precipitation, m; f – lake area, m^2; SI – seepage inflow from river, m^3; E_0 - evaporation from the water surface in the ice-free period, m; SO – seepage outflow from the lake, m^3; RI – surface river inflow through the intake structures, m^3; RO – surface outflow from the lake into the old riverbed, m^3.

The calculations were carried out for the years of different probability: mean annual flow, low-flow of 75%, 95% probability. Water levels in the years of different probability were calculated using the data from the Uzhhorod hydrologic station, located at a distance of 2.1 km above the park. The water levels fluctuation in the river near the lake is 107.6-108.5 m during the dry season (figure 2). The temperature, wind speed, precipitation data were taken from the Uzhhorod climate station. Evaporation from the water surface during the ice-free period was calculated by the method described in the work [19].

The seepage inflow from river and the seepage outflow from the lake to the downstream calculated by the equation [20]:

$$SI(SO) = K\frac{L}{2d}(H_1^2 - H_2^2), \tag{2}$$

where K – hydraulic conductivity, m/s; L – seepage length, m; d – distance between river and lake, m; H_1, H_2– water levels in the river and lake, m.

The top layer is silty loam with the pebbles and gravel inclusion of 15 to 25%, its hydraulic conductivity is 0.2-1 m/day. The gravel-pebble soil with loamy and clay aggregate is located below silty loam. Its hydraulic conductivity is 30-50 m/day. Hydraulic conductivity of the floodplain soils were obtained based on the results of field research conducted in 1988.

The replenishment of the floodplain is carried out by the tubular spillway. The discharge of tubular spillway under gravity flow is determined by the equation [21]:

$$Q = \varphi w_c \sqrt{2g(H_1 - H_2)}, \tag{3}$$

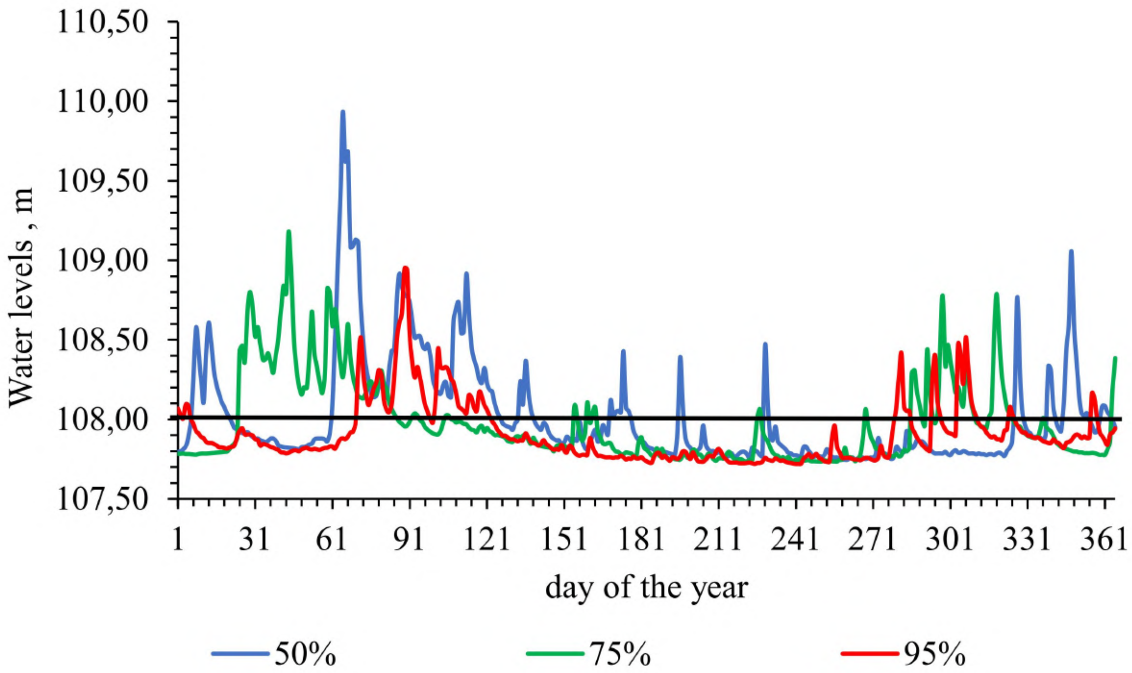

Figure 2. Water levels fluctuation in the Uzh river for mean annual flow 50%, low-flow of 75% and 95% probability.

where Q – discharge, m^3/s; φ – velocity coefficient; w_c – pipe area, m^2; H_1, H_2– water head before and after tubular spillway, m.

The tubular spillway supplies water from the river to the lake during the dry season. Since the river has low water levels during the dry season, it is not possible to supply water directly from the river into the old riverbed. Therefore, water replenishment of the old riverbed is carried out through the lake using its operating volume.

The operating volume was calculated for the following scenarios:

- current conditions (dyke separates floodplain from river);
- restoration of the connection between the floodplain and the river.

During the period of extreme floods in the river, the tubular spillway is closed with the gate to prevent turbid water and debris from river entering the lake. The outflow from the lake to the river was not taken into account, because the gate will be closed during this period, and water will flow into the old riverbed for its replenishment.

3. Results and discussion

The study of the current state of the relationship between river and floodplain showed (figure 2) that the water levels in the river cannot provide the constant flow into the old riverbed, as evidenced by visual observations of the lakes and old riverbed. Thus, it is necessary to consider the possibility of water replenishing using operating volume of the lake.

Now the floodplain lake consists of two separate lakes, which are fed by rainwater and groundwater from the Uzh river. If the water level rises in the river, the water level rises too in the lakes, and thus the operating volume of the lakes is increased. At the same time, the gravel-pebble soil around the lakes has high hydraulic conductivity, which leads to significant seepage losses into the river downstream. The simulation of lakes operation in modern conditions and the water balance calculation showed that water levels do not exceed 108.0 m during the vegetation season (March – October) even in the mean year (50% probability), so water from the lakes can flow into the old riverbed only during spring flood. Water levels fluctuation in the lakes is shown on the figure 3. The average total month volume of the lake's ranges from 11.6 to 16.0 thousand m^3 during the vegetation season.

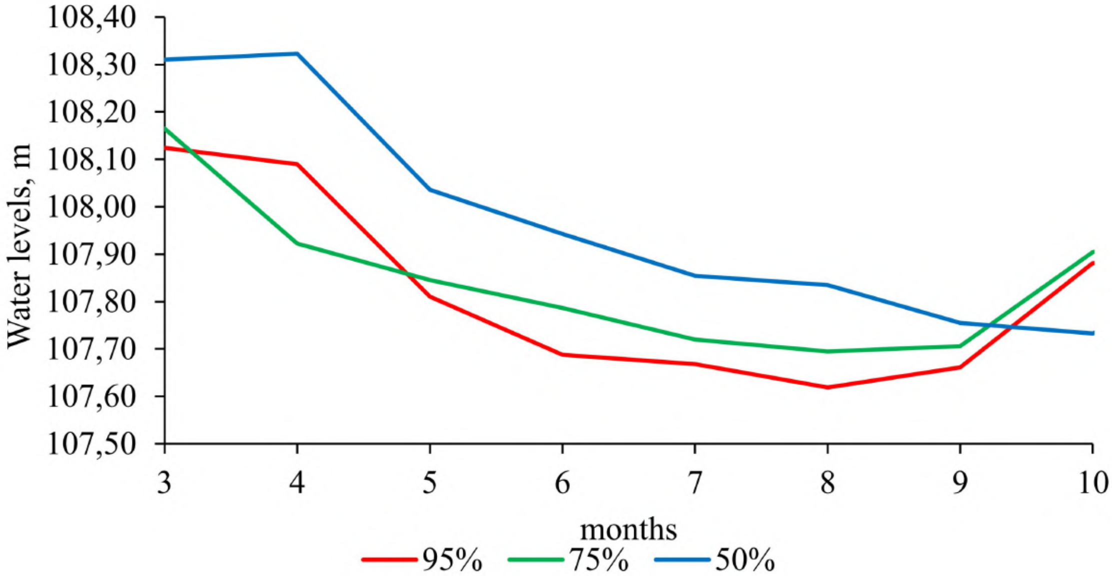

Figure 3. Lakes water levels in current condition.

The second simulation scenario is water replenishment of the floodplain by connecting the lake with the river by tubular spillway. It allows to fill the lake up to the water level in the river. The results of water level simulation in the lake is shown on the figure 4. We can see that the water level in the lake is kept above the bottom level (108.0m) of the old riverbed during the mean year, and therefore it is possible to supply water into it. It is possible to keep the water depth of 20cm in the old riverbed by creating the backwater at the end of the old riverbed. It is not possible to supply water into the old riverbed during the dry season in the low-flow years of the 75% and 95% probability. The average total month volume of the lake that can be created by water replenishment is 16.5-23.8 thousand m^3.

It is possible to increase the water depth and the operating volume in the lake to 69.8 thousand m^3 by clearing the lake bottom and deepening it to the level of 107.0 m. Clearing will improve the ecological condition of the lake, but it will not change the flow amount into the old riverbed.

To ensure five times the water exchange in the lake and old riverbed, it is necessary to supply the water with flow rate of 0.01 m^3/s during the dry season. The water depth will range from 1.0 to 0.7m in the low-flow years and from 1.8m to 1.2 m in mean year in the lake. The water depth will be 0.2m in the old riverbed during the dry season in mean year.

From the point of view of the components of the water balance after the connection of the lake with the river, the loss part of the water balance is compensated by taking water from the river to the lake (table 1). But to supply water into the old riverbed in the low-flow year it is necessary to raise the water level in the lake up to 109.8 m. Which will create the water level of 1.8 m in the old riverbed.

It is possible to raise the water level up to 109.8m in the lake by pumping water into the lake from the river.The results of water level simulation in the lake is shown on the figure 5.

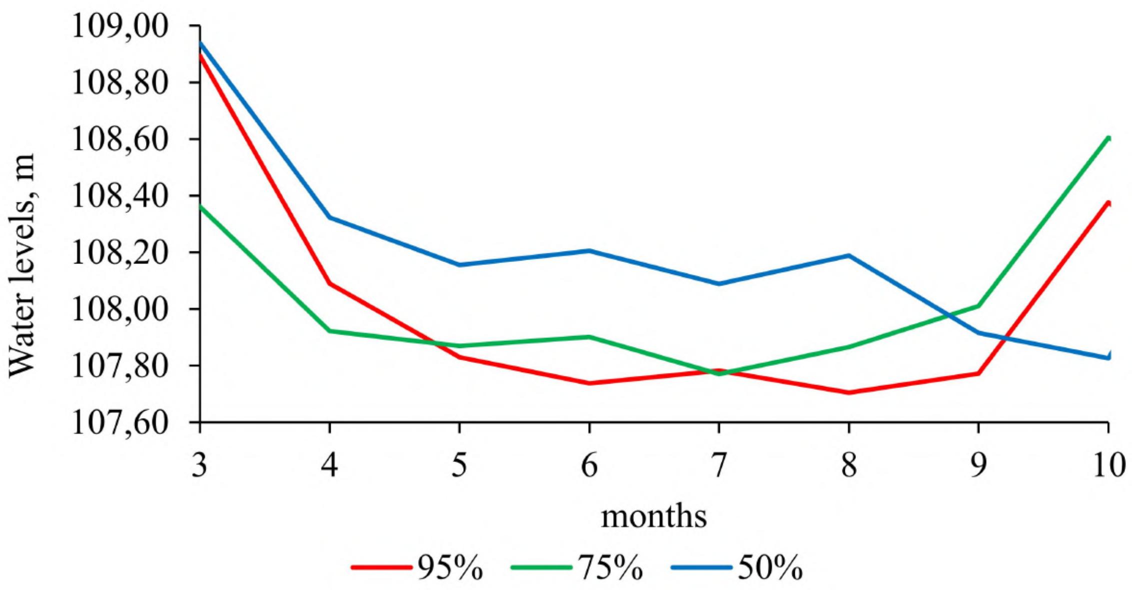

Figure 4. Lake water levels after restoration.

Table 1. Components of floodplain lake water balance, thousand m^3.

Year	Inflow	Precipitation	Evaporation	Seepage losses	Outflow	Change in storage
Current condition						
95%	32.9	14.3	17.6	31.4	0	1.8
75%	19.1	17.6	15.9	15.7	0	-5.6
50%	20.5	23.3	16.9	15.9	0	-10.9
After restoration						
95%	125.1	17.4	21.1	71.1	48.6	-1.7
75%	142.5	20.1	17.7	66.3	61.7	-16.9
50%	229.2	27.4	19.3	102.1	109.4	-25.7
The water level raise by raising the water level in the Uzh river near the park						
95%	215.1	26.7	45.1	85.0	93.2	-18.5
75%	222.5	30.5	39.9	85.9	122.7	-4.5
50%	172.0	29.1	36.7	84.1	141.0	-12.7
The water level raise by pumping water into the lake						
95%	617.3	23.7	39.6	437.9	117.4	-46.1
75%	466.0	22.7	29.9	308.1	139.8	-10.9
50%	429.3	22.5	28.9	329.2	131.5	37.7

The pumping will lead to slightly increasing the water losses due to evaporation because of the water surface increasing, and due to seepage losses because of increased seepage pressure. The seepage loss will not lead to water loss by the ecosystem, because the lake is located between the upstream and downstream of the Uzh river inside the loop. But evaporation and seepage losses with average amount of 65%, are converted into operational losses, and pumping is not acceptable from an economic point of view, a similar situation and conclusions were made by the authors [11] during field research of the pumping water replenishment of floodplain lake. Other way to increase the water level in the lake is to raise the water level in the Uzh river near the park during the dry season. Raising river water levels during the dry season and connecting the river with the lake will ensure high lake levels and outflow into old riverbed even during the minimal water flow in the river. The comparing of the economic and social components of the water level raising by pumping water or raising water level in the river Uzh requires further research and calculations.

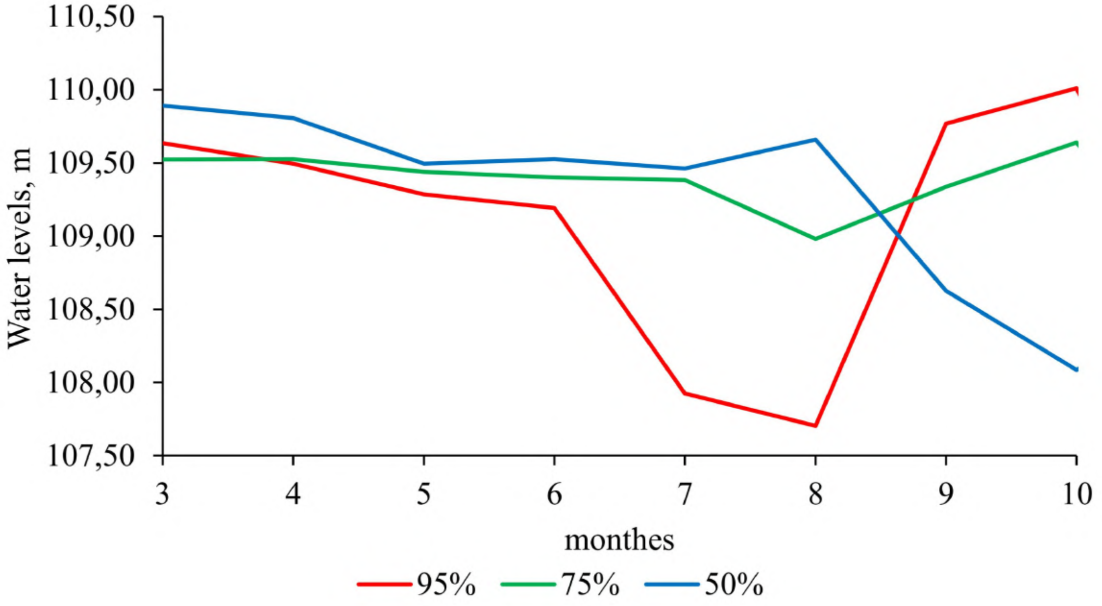

Figure 5. Lake water levels after pumping water into the lake.

4. Conclusions

1. It is almost impossible to provide the river with enough room to restore its natural state in urban conditions, because flood protection is the integral part of the safe existence of the population. So, we cannot destroy the dykes to restore the Uzh river but as the simulation showed it is possible to restore the connection between the floodplain and the river by water replenishment and supplying water to the old riverbed.

2. In current conditions, when the lake is cut off from the river, climatic conditions significantly affect the water accumulation in the lake, the maximum operating volume is 16.0 thousand m^3 in the lake in the summer – autumn period. Low water levels in the river do not allow to supply water into the old riverbed.

3. The river restoration by connecting the lake with the river allows to replenish the lake with surface water, which leads to the rapid water levels increase in the lake. Operating volume of the cleared lake up to the 69.8 thousand m^3 will be enough to replenish the old riverbed for one month. So, only floods accumulation during the high-water period (spring and summer floods) are not enough for supply water into the old riverbed during the dry season.

4. It is possible to store enough water in the lake for water supply into the old riverbed only during the high-flow years with frequent floods in the summer-autumn period.

5. Existing water levels in the Uzh river are not enough to create the necessary ecological conditions: the depth in the pond higher than 1.5 m and water outflow into the old riverbed in the summer-autumn period of the dry year. The required level of the lake for water replenishment of the floodplain in the park is 109.80 m, it is equal to the volume of 142-164 thousand m^3.

6. According to the research of many authors, an integral part of the river restoration is the rainwater and domestic wastewater treatment and control of its outlet.

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Drainage reconstruction in the zone of excessive moisture during the cultivation of blueberries on poorly water-permeable clay soils

To cite this article: S V Klimov and A V Klimova 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012038

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012038 doi:10.1088/1755-1315/1049/1/012038

Drainage reconstruction in the zone of excessive moisture during the cultivation of blueberries on poorly water-permeable clay soils

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Abstract. To ensure efficient agricultural production in the humid regions of Ukraine, drainage of wetlands is one of the first places. The area of drained lands is make up to 9.7% of the total arable lands in Ukraine. In 1990, 1,976.500 hectares were used in active agricultural production, and the share of arable land on drained lands was 70.7%. Of the more than 1130 drainage systems with an area of more than 2.2 million hectares only 37% were built between 1980 and 1990, i.e. younger than 35 years. The remaining 63% of systems have been built and operated for more than 35 years. Since the 1990s, the construction of new and modernization of existing drainage systems in Ukraine has been almost non-existent. Maintenance of the systems was significantly reduced, which led to a significant deterioration in their technical condition, a change in the water regime of soils and the development of degradation processes. Traditionally, in Ukraine, a significant (1.4 million hectares) area is drained with ceramic drainage. We show the experience of reconstruction of the drainage system, which is located in the Pre-Carpathian Upland region of the Ukrainian Carpathians, the Middle Carpathian terrace plain, where a Drainage of Clay Pipes was built more than 35 years ago. The results of the analysis of the reasons of unsatisfactory drainage operation, identification of the most critical zones with the use of field research and earth remote sensing data are presented. To eliminate local wetlands, plastic drainage with a diameter of 50 mm is proposed. To increase the efficiency of its work on heavy clay soils with a filtration coefficient less than 0.01, the backfilling of the trench with local material – gravel with a fraction of 5 ... 25 mm with geotextile protection. During the construction of the new drainage, ceramic drains of the previously constructed drainage were found. They were cleaned mechanically and connected through a filter backfill to the newly built drains.

1. Introduction

To ensure efficient agricultural production in the humid regions of Ukraine, the drainage of waterlogged lands occupies one of the first places. The area of drained land in Ukraine is 9.7% of the total area of arable land [1]. In 1990, 1,976.5 thousand hectares were used in active agricultural production, and the proportion of arable land on drained lands was 70.7%. Of the more than 1.13 thousand built drainage systems with an area of more than 2.2 million hectares, only 37% were built from 1980 to 1990, that is, today they are less than 35 years old. The remaining 63% of the systems have been built and have been in operation for over 35 years. Since the 1990s, the construction of new and modernization of existing drainage systems has not been carried out. Operational activities on already built systems have been significantly reduced, which led to a change in the water-physical properties of soils and the development of degradation processes. In Ukraine, a significant (1.4 million ha) area is drained by pottery drainage [2], [3].

The work aims to describe the reasons that led to the negative technical condition of drainage in the zone of excessive moisture in Ukraine and also describes a new approach to drainage renovation with limited funding on the example of reconstruction of drainage system the cultivation of blueberries on poorly water-permeable clay soils.

To achieve this aim, the following tasks were set:

- taking into account the agro-soil, topographic, hydrological and climatic features of the territory of the study area, determine the causes of local waterlogging, which lead to a decrease in the yield of blueberries;
- choose the most optimal way to localize the identified malfunctions of the existing drainage;
- describe the technology of renovation of the drainage system by the method of building a new drainage against the background of the maximum preservation of the efficiency of the existing drainage system.

2. Materials and methods

As is known, the main reasons for the unsatisfactory reclamation state of drained lands are the physical wear and tear of the elements of the drainage system (DS), violation of the rules for operating the system and the agricultural use of the drained lands themselves, the inconsistency of the applied design standards with modern requirements, miscalculations in surveys and calculations of the parameters of the drainage system, poor construction quality [4].

Therefore, for the successful use of the territories with built, but faulty drainage, it is necessary to carry out restoration work, which will ensure the optimal water regime of soils, and, accordingly, agricultural production at the required level. The issues of expediency of carrying out the reconstruction of drainage systems from an economic point of view are described in [5], and the use of systems with selective drainage in the reconstruction of drainage in the zone of Ukrainian Polissya is given in [6]. In addition to economic benefits, the reconstruction of drainage systems is often necessary to preserve the natural environment, in particular, from the negative factors of waterlogging in the drainage system itself and in the territories adjacent to it.

Therefore, the priority tasks of the Comprehensive Program for the Development of Land Reclamation and Improvement of the Ecological Condition of Irrigated and Drained Lands [7] are restoration of the functioning of reclamation systems that are in an unsatisfactory technical condition, but have not yet lost their potential, through the reconstruction and technical re-equipment of the on-farm system, which does not need significant capital investments [7]. The task was to ensure the sustainable functioning of the existing 3.15 million hectares of drainage systems, to reconstruct the drainage systems and improve the ecological condition of drained lands on an area of 46 thousand hectares, and from 2006-2010. another 134 thousand hectares (total 180 thousand hectares).

However, insufficient funding of both the program (out of the envisaged UAH 6.7 billion, actually UAH 5.1 billion, or 76.1%, was allocated from the state budget), and the entire structure of the State Water Agency led to the failure to fulfill the tasks set for the reconstruction of reclamation systems (figure 1) [8].

Fixed assets (minimum in 2006 - 76%, maximum in 2016 - 96%, and on average for 2015 ... 2021 - 93% of the funding of the State Water Agency included in the State Budget of Ukraine) are spent on the operation of national and inter-farm state drainage systems (figure 2). However, 36...45% of them are spent on wages, another 31...43% is spent on utilities and energy, and development costs are only 0.4...0.7% [9].

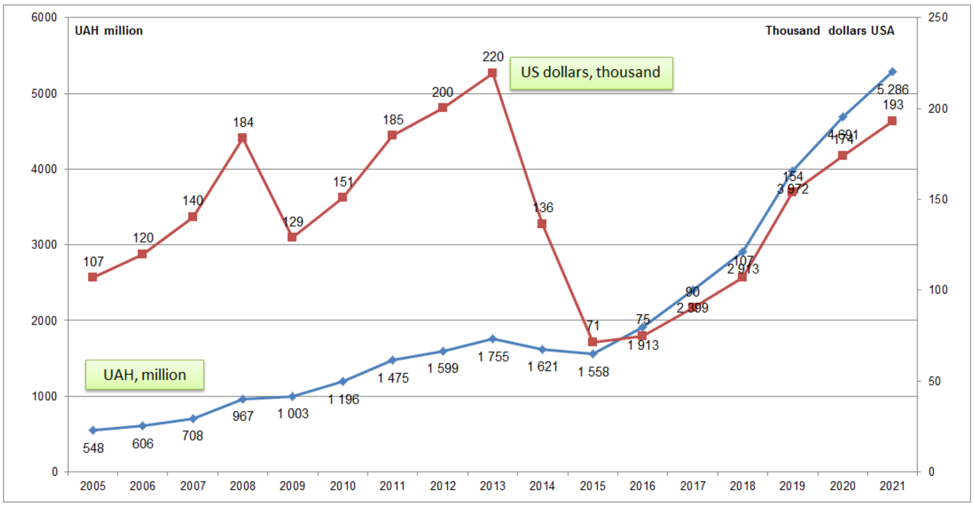

Figure 1. Funding for the operation of nationwide and inter-farm state drainage systems according to the State budget of Ukraine in hryvnias (UAH) and in terms of US dollars.

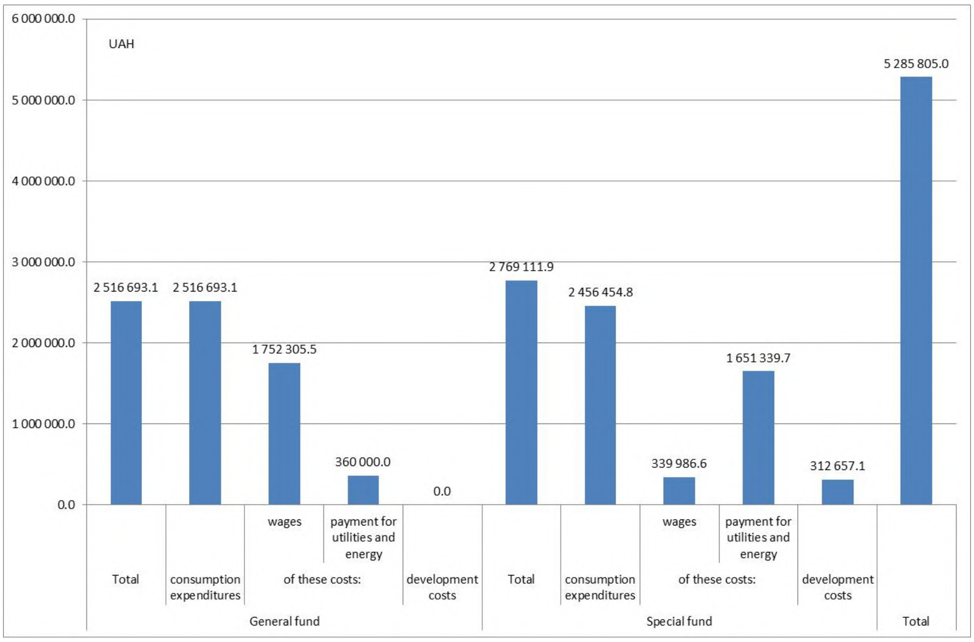

Figure 2. Structure of expenditures of the State budget of Ukraine in 2021 for the operation of the state water complex and water resources management.

Taking into account these amounts of funding, the possibility of reconstruction of the drainage systems is in rather small volumes than it have to be expected, further exploitation of the lands of a particular drainage system without its reconstruction will lead to significant material losses or endanger the population as flooding houses and structures, polluting drinking water, etc.

Consequently, the urgent need to carry out work to restore the functioning of the drainage on the one hand and the lack of funding on the other, encourages finding new approaches to drainage renovation, different from the option of building a new drainage network [10], [11]. In particular, it is proposed to carry out work on the partial reconstruction of areas whose damaged drainage, according to observations, leads to crop losses, and to leave the drainage that performs its functions.

3. Results and discussion

This paper shows an example of the reconstruction of the existing drainage from the newly built drip irrigation system with an area of 39.9 hectares for growing blueberries. The blueberry bushes are irrigated by a drip irrigation system built in 2019, and drained by a ceramic drains built over 35 years ago.

The object is located in the Precarpathian elevated region of the Ukrainian Carpathians. The geomorphological region is the Middle Carpathian (Pridnestrovian) terraced plain. According to agro-soil zoning, it is an accumulative-denudation piedmont weakly dissected plain (N1 sQ) with sod-medium- and strongly podzolic surface-gleyed, mainly loamy, soils. In general, the Samborsko-Dolinsky region is transversely dissected, with sod-brown soils.

According to the hydrological zoning of Ukraine, the object of study is located within the Dniester-Prut region of high water content of the Ukrainian Carpathians. The Carpathian mountainous section of the Dniester River basin, where the drainage system under reconstruction is located, is mainly the upper right-bank part of the catchment area with a highly developed hydrographic network and is the main area for the formation of the Dniester River runoff. Here, from 800 to 1500 mm of precipitation falls annually, and the increased storm load on the northeastern slopes of the Carpathian Mountains causes excessive moisture in this zone and the occurrence of numerous flash floods, which is a characteristic feature of the Dniester regime as a whole. The average long-term values of the annual runoff module are the highest (4.70-5.33 l/s km2), and at the very source of the Dniester River this figure reaches 10.0 l/s km2. Therefore, about 26 off-farm drainage systems were built in the Dniester river basin until 1990, with a total area of 208329.0 ha. Among them are the largest: Vereshchitskaya, Tershakovskaya, Bolozovsky, Tysmenitskaya, Shiretskaya, Dniester-Strvyazhskaya, Bystritskaya, Berezhnitskaya. Taking into account similar climatic, hydrological and soil conditions, the given experience of drainage reconstruction can be extended to a large area.

On (figure 3) shows the data for the reconstructed drainage area in terms of precipitation, as well as the maximum (Ms_max, Mr_max), average (Ms_a, Mr_a) and minimum (Ms_min, Mr_min) moisture values of the surface soil layer (Ms) and the root zone (Mr) for the period 2016 ... 2021. In particular, in 2020, the maximum amount of precipitation over the past 6 years was observed, which led to wetting and significant inhibition of plant development in a significant part of the system.

Also, in recent years, there has been a tendency for an increase in the frequency of cloudburst [12], [13], which significantly changes the conditions for the operation of drainage. In the study area, in particular in 2020, there were 15 cloudburst with an intensity of more than 20 mm/day, 8 with an intensity of more than 30 mm/day, and 2 with an intensity of more than 40 mm/day (figure 4, table 1). This uneven annual rainfall is another factor leading to an increase in the number and duration of waterlogged periods for plants.

Table 1. The amount of cloudburst on the drainage field, which is being reconstructed.

	2016	2017	2018	2019	2020	2021
more than 20 mm / day	12	7	3	9	15	9
more than 30 mm / day	4	4	1	4	8	3
more than 40 mm / day	2	2	1	2	2	1

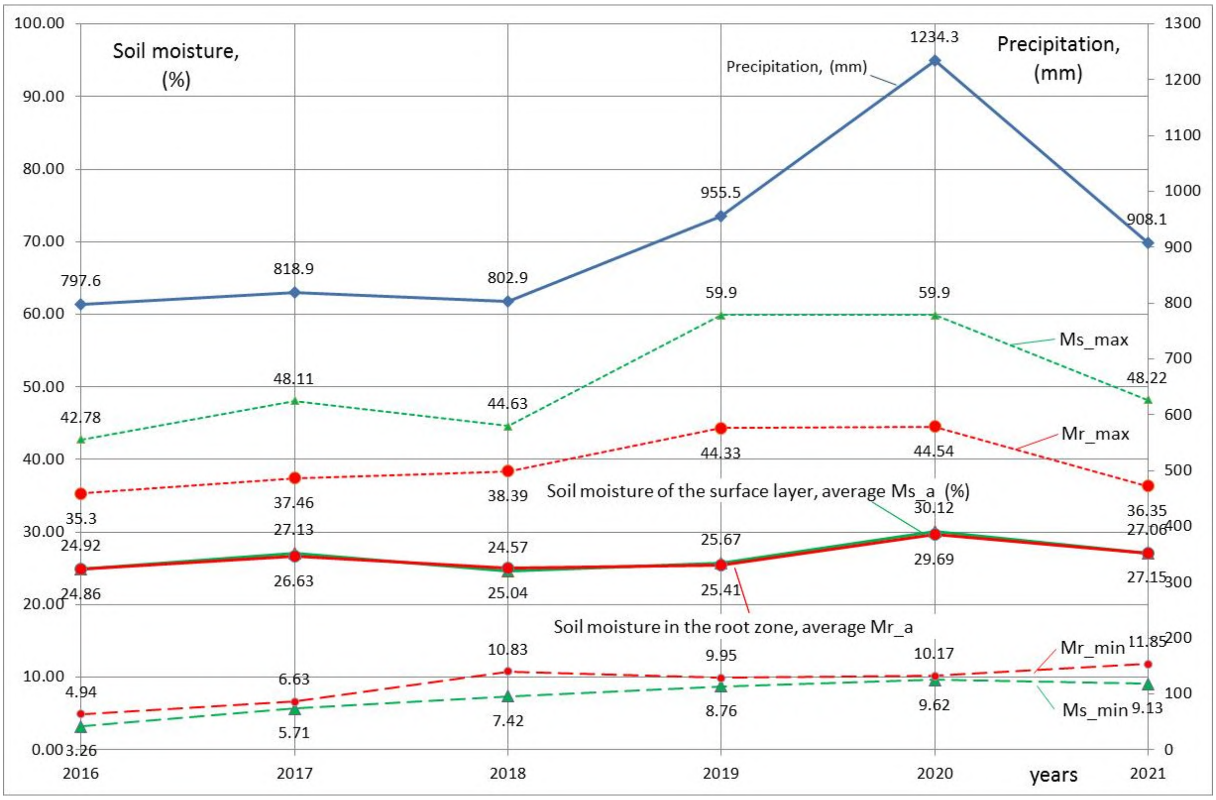

Figure 3. Data for the reconstructed site in terms of precipitation, as well as maximum (Ms_max, Mr_max), average (Ms_a, Mr_a) and minimum (Ms_min, Mr_min) moisture values of the surface soil layer (Ms) and root zone (Mr) for the period 2016 ... 2021.

To find out the reason why the drainage system built more than 35 years ago does not adequately drain excess groundwater over the entire area, which causes local waterlogging of crops, field and in-house studies were carried out in 2020-2021. The following causes of waterlogging have been found:

– the presence of a large number of closed depressions, in which melt water and storm water stagnate, which is due to the accepted agricultural technology for growing blueberries (figure 5) and the existing relief (figure 6);

- heavy mechanical composition of soils with a very low filtration coefficient (0.01 ... 0.005 m / day); – against the background of a generally high annual precipitation rate, there is a tendency for an increase in the maximum frequency and intensity of precipitation, which, against the background of a low infiltration capacity of soils, cause a high standing of the groundwater level;

- partial failure of the constructed drainage (as a result of natural processes of precipitation accumulation, soil shifts, destruction during the construction of trenches during the construction of pressure irrigation pipelines of the drip irrigation system and errors in the construction of drainage lines).

To find the actual location of the drains and compare them with archival design data, we abandoned traditional search methods (excavation and manual search) and terrestrial geophysical methods, including magnetic gradiometry and ground penetrating radar (GPR) [14], [15], [16], [17], due to inefficient GPR for providing detailed maps of subsurface drainage systems in large farm fields, significant labor losses and time [18], and when excavating – also due to the high probability of damaging the proper drainage.

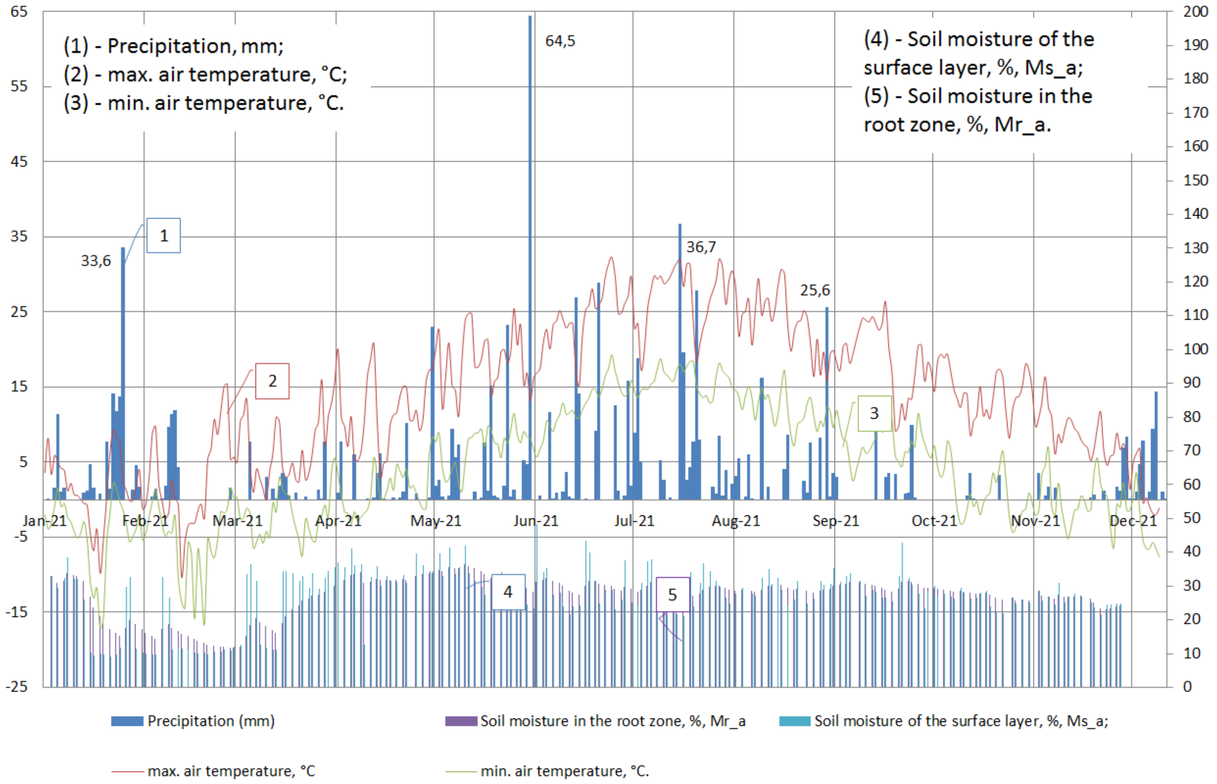

Figure 4. Precipitation, air temperature, Soil moisture of the surface layer and in the root zone on the drainage field, which is being reconstructed.

Figure 5. Local depressions, in which stagnant water from melting snow and storm water.

Therefore, visible (VIS) satellite images of the site of different years were analyzed (figure 6). Multispectral (MS) and thermal infrared (TIR) images, as recommended when using of unmanned aerial vehicles (UAVs) in [18], [19], [20], were not used due to the low resolution of available satellite images. Sites of soil located directly above the drains, differ from more remote sites in terms of the conditions for plant growth, and primarily in terms of the amount of moisture

(a) (b)

Figure 6. Detection of drains (Google Earth, date of shooting 07.20.2004, view from a height of 1 km, contrast adjustment +65%), (a) without, and (b) with drawn drains.

in the root layer [20]. Copies of archival schemes of subsurface drainage system installation were used to distinguish linear features representing drain lines from those representing farm field operations [18]. figure 6 shows a fragment of an drained area in natural colors. Vegetation corresponds to rich green shades, a higher density of vegetation corresponds to brighter shades.

Figure 7. Using historical Google Earth images (shooting date 26/10/2006, view from a height of 1 km, contrast adjustment + 50%).

The obtained data on the placement of ceramic drainage were confirmed by visual inspection when the drainage collectors exit into open channels.

Satellite images also make it possible to identify problem areas in which drainage does not fulfill its functions or relief features create local zones of systematic waterlogging (figure 7). In such zones, the vegetation has an excellent color (figure 7), which is especially evident when using multispectral (MS) images. For example, in the image NDVI - Normalized Differential

Vegetation Index (B8A-B04) / (B8A + B04), (figure 8), zones in which NDVI-index is 0.35 are clearly visible, while zones with unoppressed vegetation have NDVI –index from 0.5 to 0.6.

Figure 8. NDVI image, date October 23, Sentinel-2 L2A, cloudiness 9%, angle 29°, 34 UGV.

After identifying the causes of waterlogging, the state and location of the existing pottery drainage, it was proposed to reconstruct the drainage network by installing additional drains in places of the greatest waterlogging (figure 9). To prevent the destruction of the existing pottery drainage, the depth of laying new polymer drains is taken at the level of the soil freezing depth (0.7 m) for the given area. This is on average 0.2 m higher than the existing pottery drains.

Drainage pipe PVC DN 50 (drainage) and DN 100 (collectors) was protected from silting by gravel filling, fractions 5…20 and 20…40 mm. The filter bed was placed in a “pocket” made of thermally bonded Typar SF 27 geotextile (figure 10, (a), figure 11). The tube was laid on a layer of crushed stone, which was poured on top of the geotextile to increase water susceptibility. The geotextile was wrapped around the drainage filling (figure 11 a, pos. 3) at 0.2 ... 0.3 m from the soil surface, and the trench was further covered with crushed stone (figure 11, a, pos. 1). This was done to protect the geotextile from being torn apart by agricultural implements during tillage.

When digging trenches, the existing pottery drainage was sometimes accidentally exposed. Then it was mechanically cleared to an accessible distance (figure 10, c), the destroyed tube was replaced with a perforated plastic one. To unload the part of the pottery drain located above, it was hydraulically connected to a new plastic drain through a filtering sanding (figure 11, b) and a pit filled with crushed stone (figure 11, b, pos. 9). The crushed stone in the pit was also protected from the ground by a layer of geotextile (figure 11, b, pos. 10).

4. Conclusions

In Ukraine, as in a number of other countries [5], [6], a significant number of drainage systems are operated, which, due to climate change, failure of individual drainage elements or a change in the purpose of the territory, do not fully provide drainage functions. With limited funding or in other cases, for example, if there is a desire to preserve perennial plantings, only part of

Figure 9. Layout of drains and collectors during the reconstruction of local areas.

(a) (b) (c)

Figure 10. Laying drainage: (a) - drainage sprinkling of crushed stone, protected by geotextiles; (b) - connection of drains to the collector through a coupling; (c) - randomly unearthed pottery drains.

the drainage system may be reconstructed. In this case, it is important to accurately map the existing drainage lines, find the places and causes of local waterlogging, and insert additional drainage with the possibility of intercepting the drainage flow from the existing one.

The method presented in the article for localizing disrepairs in existing drainage using new and archival satellite images can significantly reduce the complexity and duration of field studies to identify and mapping disrepairs of drainage. After accurately determining the location of existing drainage lines, the technology used to build shallow drainage on top of the existing one

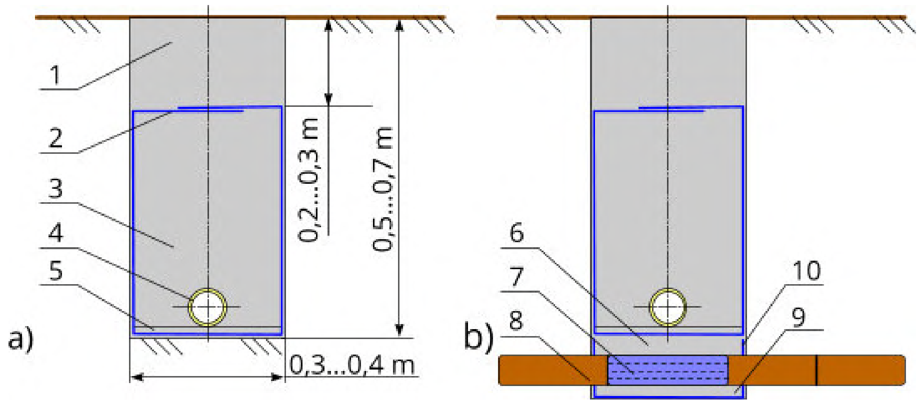

Figure 11. Scheme of laying drainage: a - with sprinkling of crushed stone and geotextiles; b - with the organization of the inclusion of pottery drainage; 1, 3, 5, 6, 9 - crushed stone sprinkling; 2, 10 - geotextile; 4 - corrugated polyethylene perforated drain; 7 - repair perforated pipe; 8 - pottery drainage.

allows you to maximize its performance and provide the necessary water regime for agricultural crops on poorly permeable soils.

This work is a continuation of the work [11], where theoretical and practical implementations are given introduces the application of a conformal mapping methodology for solving boundary value problems in order to calculate the filtration process in a horizontal drain, provided that the drains are installed at a different depth.

In the future, it is necessary to study in more detail the filtration process between drains intersecting at different depths and filter designs that will allow maximum unloading of the water flow from old drains to new ones, while protecting the latter from solid deposits entering them.

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To cite this article: V V Osadchyi and V S Yeremieiev 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012039

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012039 doi:10.1088/1755-1315/1049/1/012039

Methods for statistical analysis of the results of monitoring the avifauna on the territory of wind farms

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Abstract. An algorithm for processing the results of monitoring the dynamics of ornithocomplexes on the territory of wind farms using statistical methods is proposed. The solution of the most frequently encountered problems in the analysis of bird migration in the wind farm zone is considered: 1) An algorithm for the primary statistical processing of information on the number of birds of various species, flight altitude and the time of their stay in the zone of interaction with turbines during monitoring has been developed in two ways: a method of route census and observations in accordance with the recommendations of the Scottish Natural Heritage Foundation. 2) The features of the application of correlation and regression analysis have been considered, which allow determining the dependence of the number of birds on a number of factors using the Student, Pearson and Fisher criteria in the presence of strong noise interference. 3) An algorithm of statistical analysis is proposed using a trend approach based on the Student, Irwin, Durbin - Watson, Pearson and Fisher criteria. The considered statistical methods were tested on the results of migratory bird census on the territory of the Prymorsk-1 wind farm located on the coast of the Sea of Azov, which were obtained by a group of researchers led by V Siokhin and P Gorlov.

1. Introduction

The intensive development of wind energy has a significant impact on the avifauna. Numerous observations of researches testify to the need to expand research on the dynamics of ornithocomplexes on the territory of wind farms with the involvement of information technologies and statistical methods of information processing [1–3]. A large number of studies have been devoted to the study of the wind energy impact on ornithological complexes [4–7]. One of the main tasks of monitoring birds on the territory of the wind farms is to obtain data on the dynamics of their quantitative and species characteristics, as well as the height and direction of migration in different seasons [8, 9].

The results of long-term observations over several years make it possible to predict the impact of wind power on the ecological situation associated with changes in the avifauna. Currently, there is an extensive information related to the interaction of birds with wind turbines in various regions, which has been accumulated during the processing of the results of monitoring the territory of wind farms and adjacent regions for several decades [1–3, 9, 10]. The use of various methods of observation expands the possibility of predicting undesirable impact on the avifauna and taking effective measures to reduce this impact.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012039 doi:10.1088/1755-1315/1049/1/012039

When organizing observations, the recommendations of the Scottish Natural Heritage Foundation (SNH) [5, 11–13] are often used, which provide for the fulfillment of a number of requirements. In particular, it is assumed that monitoring should be carried out in several areas, which in terms of their landscape and biotope characteristics adequately reflect the entire territory of the wind farm. A sufficient amount of time is allocated for observations, covering the main periods of bird migration in the region. Generally, research should be carried out in spring and autumn during the bird migration, as well as during the breeding period and in winter. Observation is carried out simultaneously by several researches [8, 11, 12]. During monitoring, the following parameters are recorded:

(i) Date, time of the day, species of counted birds and their number at the sites.
(ii) Direction of flight, flight altitude and type of flight (transit, forage, demonstration).
(iii) The time spent by each bird flying below the edge of the wind wheel H_1 , above its edge H_2 and in the risk zone of collision with the rotor blades at heights between H_1 and H_2 .

The results of observations in accordance with the recommendations of the Scottish Natural Heritage Foundation make it possible to determine the activity coefficient of birds of the j species in the risk zone of collision with turbines at the k site $K^{Risk(k)(j)}$, which is necessary to predict the interaction of birds with rotor blades. Its value is [13]

$$K^{Risk(k)(j)} = \sum_i n_i^{Risk(k)(j)} t_i^{Risk(k)(j)}, \tag{1}$$

where $n^{Risk(k)(j)}$ - the number of birds of the j species in the i group recorded in the k site in the RZ during the time interval $t^{Risk(k)(j)}$.

In a similar way, it is possible to characterize the activity of birds for other heights, as well as in various monitoring areas and the wind farm territory as a whole. For example, the activity coefficient of birds in the k site is determined by the formula

$$K^{(k)(j)} = \sum_i n_i^{(k)(j)} t_i^{(k)(j)}, \tag{2}$$

An alternative way to obtain information about the behaviour of birds on the territory of the wind farm is the method of route census (RAM) [11, 14]. In this case, all birds sitting on the ground and in flight are taken into account. For the last group of birds, the number of individuals of each species, the direction of migration, the height and the type of flight (transit, forage, breeding) are determined. Generally, there are recorded those birds that are located at a distance of no more than 500 m to the left and to the right of the direction of the observer movement along the selected route.

The effectiveness of the analysis of the recorded data largely depends on the adequacy of statistical samples and the correctness of the application of statistical methods. The peculiarity of the processing of primary information in ornithology is associated with the presence of a number of objective reasons, which often make it difficult to obtain reliable conclusions. Therefore, the creation of algorithms that ensure the correct processing of observation results is of great practical importance. This research paper is devoted to the description of the methods of mathematical statistics adapted to the study of the dynamics of ornithocomplexes on the territory of the wind farms.

2. The purpose of the work and setting the task

The purpose of the paper is to develop an algorithm for the use of statistical methods in the analysis of the results of monitoring the avifauna on the territory of the wind farms in solving the following problems:

(i) Primary statistical processing of information on the number of birds of various species, flight altitude and time of their stay at the observation sites, obtained by the SNH [8, 12, 13] and RAM [8, 9, 14] methods.
(ii) Correlation and regression analysis to determine the dependence of the number of birds on various factors using the Student, Pearson, Fisher, Irwin criteria.
(iii) Trend analysis of the results of monitoring the wind farm territory based on the Student, Irwin, Durbin - Watson, Pearson and Fisher criteria.

3. Work results

3.1. Primary statistical analysis of the observation results

The number of birds that are recorded in the process of monitoring on the territory of the wind farms varies from several dozens to several thousand individuals and more. Therefore, information processing is carried out with the involvement of computer technologies based on mathematical statistics [1, 9, 11] . In this section, we will focus on the traditional methods of primary statistical processing of observational results, which are usually used in the study of avifauna on the wind farm territory. observed results

The following parameters serve as objects of statistical analysis on the wind farm territory: the number of birds, the number of species, the time spent at the registration site, and the activity coefficients of individuals of various species at different heights, determined by formulas (1), (2). Let $X = x_1, x_2, \ldots x_n$ is the number of values that are obtained during the registration of individuals at one of the registration sites during n days. The degree of scattering of each xi relative to the average value $x_a = \sum x_i/n_x$ is estimated using the empirical variance $s_x^2 = \sum(x_i - x_a)^2/n_x$ or the corrected variance $s_x^2 = \sum(x_i - x_a)^2/(n_x - 1)$. The average statistical deviation is taken equal to $s_x = \sqrt{s_x^2}$. Statistical data of ornithological research are distinguished by large values of s_x, therefore, in some cases (for example, in the graphical interpretation of the results), a smoothing operation is used. The easiest way to smooth is to convert the original data to new values using the formula

$$x_k = (x_{k-1} + x_k + x_{k+1})/3, k = 2, 3, ..., n - 1., \tag{3}$$

The weak point of smoothing is the decrease in the number of elements in the original row statistics, which is equal to *n-2* with a single smoothing. Along with the simple operation (1.1), where the averaging is performed over three elements, other methods of linear and nonlinear transformation are used, which are widely used in economic and sociological research [15].

In many cases, there is a problem of comparing monitoring results obtained in different situations, as well as when comparing data at two sites or for different seasons of the year. Let $X = x_1, x_2, ..., x_n$ and $Y = y_1, y_2, ..., y_n$ are two samples, each consisting of n_x and n_y elements. Let us denote the mean sample values as x_a, y_a. The verification of the hypothesis about the equality of mathematical expectations is carried out in the case of a known random variable distribution law at a given significance level q. Various methods are used to identify the distribution law [15]. As an example, let's consider the use of the Pearson's criterion [16] when establishing the normal law of data distribution for the sample $X = x_1, x_2, ..., x_n$. Let's divide the sample into m equal intervals $h = (x_n - x_1)/m$. Let us denote the number of elements in the k interval as n_{xk}. The Pearson criterion is calculated by the formula

$$\chi^2 = \sum_{k=1}^{k=m} (n_{xk} - n_{xk})^2/n_{xk}, \tag{4}$$

where $n'_k = hn_x p_k/s_x$ - a theoretical value of the number of elements in the k interval, corresponding to the normal random variable distribution law for the analyzed sample, p_k - the probability that the random variable is in the k interval,

$$p_k = exp(-z_k^2/2)/\sqrt{2\pi}, z_l = (x_k - x_a)/s_x, \tag{5}$$

x_k - the average value of the elements in the k interval. If the value of the χ^2-criterion calculated by the formula (4) is less than the critical value χ^2_{kr} for m-3 degrees of freedom at a given significance level q, then the sample obeys the chosen law. For $\chi^2 > \chi^2_{kr}$, the hypothesis about the possible use of the normal distribution law is rejected. The normal distribution law is characterized by two parameters - the mathematical expectation a and the general variance δ^2. In practice, instead of a, the average value of x_a, is used, and instead of the general variance, the empirical variance s_x^2 is used. During the primary processing of row statistics, it is recommended to analyze the possibility of the appearance of anomalous values associated with technical errors in obtaining data or processing the original information. The rejection of erroneous data can be carried out by the Irwin's method. The method is based on determining the coefficients $\lambda_i = |x_i - x_{i-1}|/s_x, i = 2, 3, ..., n_x$. The values of λ_i are compared with the critical parameter λ_a. If $\lambda_i > \lambda_a$, then the i element of the row statistics is rejected. Parameters λ_a depending on the sample size for the 5% significance level are presented in table 1.

Table 1. Critical Irwin values λ_a depending on the sample size n.

λ_a	2.8	2.3	1.5	1.3	1.2	1.1	1.0
n	2	8	10	20	30	50	100

It should be noted that the rejected element may not be the result of a measurement error, but reflect the influence of an unknown factor. But here mathematics is powerless. The decision on rejection is made by the researcher. Testing the hypothesis about the equality of two mathematical expectations of the average value is performed using the Student's T-test [17]

$$T = |x_a - y_a|/s\sqrt{(n_x n_y)/(n_x + n_y)}, \tag{6}$$

where $s = \sqrt{((n_x - 1)s_x^2 + (n_y - a)s_y^2)/(n_x + n_y - 2)}$

If T is less than the critical value T_{kr} for the significance level q for $\upsilon = n_x + n_y - 2$ degrees of freedom, then the hypothesis of equality of means is true. For $|T| > T_{kr}$, the hypothesis is rejected. Sample values of variances s_x^2, s_y^2 characterizing the scatter of the results of specific measurements generally differ, therefore, before using the formula (6), one should make sure that the general variances $\delta_x^2 = \delta_y^2$ are equal. Testing the hypothesis about the equality of general variances can be carried out using the Fisher criterion

$$F = \begin{cases} s_x^2/s_y^2, if s_x^2 > s_y^2 \\ s_y^2/s_x^2, if s_y^2 > s_x^2 \end{cases}, \tag{7}$$

If the value of F is less than the critical value F_{kr} with a given significance level, then the general variances are equal. Otherwise, the hypothesis of equality of dispersions is rejected. Checking the homogeneity of variances with a large number of samples is carried out using the Duncan method and other methods. As an example, we will make a primary statistical analysis of the monitoring results at three vantage points (VP) belonging to the territory of the Prymorsk-1 wind farm. The site sizes of VP1, VP2 and VP3 were respectively 0,50 km^2, 0,86 km^2 and 1,23 km^2, figure 1. Observations were carried out during the spring period of the bird migration in 2017 [11].

Figure 1. Scheme of the location of bird vantage points on the territory of the wind farm.

The results of daily registration of the total number of birds $n^{(k)}$ at the k site per 1 km^2, which flew in transit during the spring migration period, are presented in table 2.

Table 2. The total number of birds flying in transit through the first $n^{(1)}$, second $n^{(2)}$ and third $n^{(3)}$ observation sites on different days.

Days	13.03.17	14.03.17	25.03.17	02.04.1	03.04.17	04.04.17	28.04.17
i	1	2	3	4	5	6	7
$n^{(1)}$	74	106	264	102	70	62	238
$n^{(2)}$	43.0	76.7	30.23	25.58	1.26	90.7	59.3
$n^{(3)}$	32.5	39.0	108.9	85.4	23.6	52.0	63.4

At the first stage, we reject possible erroneous measurements using the Irwin method. According to table 1, Irwin's critical value λ_a for the 5% significance level with the number of measurements n=7 is about 2.4. Coefficients λ_i for all row statistics in accordance with the data in table 2 is much less than the critical value. The exception is the measurement $n^{(2)} = 1.26$, which was carried out on April 3, 2017, when λ_i turned out to be 3.1.

The results of variance calculations of s_x^2, standard deviations sx and the Pearson's criteria χ^2 according to the data of table 2, from which the measurement $n^{(2)} = 1.26$ obtained on April 3, 2017 is excluded, are presented in table 3. The values of x^2 were calculated for four intervals: m=4. The Pearson's criterion is recommended to apply for large samples. Therefore, the obtained data should be treated with caution.

The critical value of the Pearson criterion for the 5% significance level at m-3=1 (m=4) degrees of freedom is 3.8. The calculated value x^2=6.7 for the first area is greater than the critical value, so the first row statistics do not obey the normal random variable distribution law.

Checking the homogeneity of variances in the number of birds in different sites using the Fisher's formulas (7) gave the following results for a 5% significance level: $F_{23} = 1.4$ at $F_{kr} = 5.0$, $F_{13} = 7.6$ at $F_{kr} = 4.3$, $F_{12} = 10.4$ at $F_{kr} = 5.0$. Here, the numerical indices in the notation of

Table 3. Values of variances s_x^2, standard deviations s_x from the mean value x_a and the Pearson's criteria χ^2 after rejection of erroneous measurements.

Sites	OP1	OP2	OP3
n	*7*	*6*	*7*
x_a	131	54.3	57.8
s_x^2	6048	564	800
s_x	77.8	23.7	28.3
x^2	6.7	2.8	3.1

the F_{ij} criteria refer to the numbers of the monitoring sites. The calculation results showed that the hypothesis about the homogeneity of the variances of the analyzed row statistics can only be accepted when comparing the number of birds in the second and third sites, where the Fisher criterion $F_{23} = 1.4$ is less than the critical value $F_{kr} = 5.0$. In other cases, the homogeneity hypothesis is not fulfilled.

Let us test the hypothesis about the equality of the average number of birds in the second and third sites. The Student's T-test calculated by the formula (6) is 0.0088, the critical value of T_{kr} for the 5% significance level at 11 degrees of freedom is 2.2. Since the value of T is several times less than the critical value T_{kr}, it can be argued that the mathematical expectations for the number of birds in the second and third sites are the same.

3.2. Correlation and regression analysis

Methods of correlation and regression analysis are a powerful tool in identifying relationships between different parameters or determining the influence of one factor on another. Let's consider two samples X, Y with the same number of elements n. The presence of a linear correlation between them is determined by the correlation coefficient

$$r_{xy} = (\sum_{i=1}^{i=n} x_i y_i - n x_a y_a)/n s_x s_y, \tag{8}$$

where $s_x = \sqrt{s_x^2}, s_y = \sqrt{s_y^2}$ – standard deviations.

The significance of the coefficient (8) is checked using the Student's T-test for q=n-2 degrees of freedom:

$$T = |r_{xy}\sqrt{n-2}/\sqrt{1-r_{xy}^2}|, \tag{9}$$

If the value of T is greater than the critical value T_{kr} at the chosen significance level q, then there is a relationship between the parameters X and Y. Otherwise, the dependency is considered not installed. The existence of a correlation dependence allows us to represent it in the form of a linear regression equation

$$y = a + bx, \tag{10}$$

where $a = y_a - r_{xy} x_a s_y/s_x, b = r_{xy} s_y/s_x$.

The coefficients a and b can also be found by the least squares method (LSM). The LSM method allows us to find the regression equation in the case of linear and nonlinear multifactorial models in a more general form

$$y(x_1, x_2, ..., x_n) = a_0 + b_1x_1 + b_2x_2 + ... + b_{12}x_{12} + b_{13}x_{13} + \dots b_{14}x_{14} + \dots, \quad (11)$$

The adequacy of the regression equations (10), (11) is checked using the Fisher criterion, based on a comparison of two variances. One of them $s_y^2 = \sum(y_i - y_a)^2/(n-1)$ determines the dispersion of the observation results y_i from the average value y_a. The second dispersion of adequacy $s_{ad}^2 = \sum(y_i - y_a)^2/(n-2)$ characterizes the degree of deviation of the recorded data y_i from the values calculated using the regression equation at $x = x_i$:

$$F = s_y^2/s_{ad}^2, \quad (12)$$

If the value of F is greater than the critical value F_{kr} with a given significance level q with two degrees of freedom equal to n-1 for the variance s_y^2 and *n-2* for the variance s_{ad}^2, then mathematical models (10), (11) adequately describe the situation under study. Otherwise, the equations are not adequate.

As an example, we will study the possibility of the existence of a correlation dependence between the activity coefficient $K^{(3)}$ on the total number of birds $n^{(3)}$ per 1 km^2 based on the results of monitoring in the spring migration season in the third site of the Prymorsk-1 wind farm. The initial data are given in table 4.

Table 4. The number of birds $n^{(k)}$ and their activity coefficients $K^{(k)}$ in the third site of the wind farm on different days of observation.

Days	13.03.17	14.03.17	25.03.17	02.04.1	03.04.17	04.04.17	28.04.17
$n^{(3)}$	32.5	39.0	108.9	85.4	23.6	52.0	63.4
$K^{(3)}$	1407.3	1634.0	3669.0	1974.9	894.4	1879.6	2083.8

The correlation coefficient r_{xy} and the Student's T-test calculated by formulas (8), (9) are 0.92 and 5.2, respectively. The critical value of T_{kr} at 5 degrees of freedom for the 5% significance level is 2.57. Since the Student's criterion is greater than the critical value of T_{kr}, then the relationship between the statistical samples in table. 4 exists and we can proceed to the construction of the regression equation (10). In the case under consideration, it has the form

$$K^{(3)} = 432.9 + 26.00n^{(3)}, \quad (13)$$

The Fisher criterion calculated by the formula (12) is 5.3, which is greater than the critical value $F_{kr} = 4.95$. The use of the Student's and Fisher's criteria in this case allows us to draw the same conclusion: the mathematical model (13) is adequate.

3.3. Trend analysis

Let us pay attention to the situation, often encountered in the ornithology, when the measured Student's criterion is comparable to or somewhat less than its critical value. In this case, it is recommended to use the following methods of processing observations:

- evaluate the significance of the regression coefficient b in equation (10),
- apply the Fisher criterion,

- use the method of the trend analysis of the study of time series analysis.

Time series differ from row statistics in that the values of its elements depend on the previous elements [15]. Nevertheless, the trend analysis algorithm, in our opinion, can be extended to the results of ornithological research with some reservations. Of practical interest, for example, is the assessment of the possibility of changing the number of birds in a given region under the influence of anthropogenic factors over time.

The main task of the trend analysis is to identify the trend of changing one factor as another one changes. The mathematical side of the trend model is also expressed by formulas like (10), (11). When identifying a trend in ornithological research, we single out two components: the main one that determines the development trend, called the trend, and the random one e_i, responsible for the deviation from the trend. The deviation value e_i is determined by the difference between the measurement result y_i and the value of functions (10), (11): $e_i = y_i - y(x_i)$. A necessary condition for successful data processing using the trend is the fulfillment of the following requirements [15]:

- e_i deviations are random;
- different e_i deviations do not depend on each other, i.e. there is no autocorrelation;
- deviations obey the normal distribution law.

Let us consider the procedure for carrying out the trend analysis. At the first stage, the randomness of deviations is checked. The randomness is tested using turning points. A turning point is the result of a measurement, for which one of the following conditions is met:

$$y_{i-1} < y_i > y_{i+1} \; or \; y_{i-1} > y_i < y_{i+1}, \tag{14}$$

If the number of turning points m is greater than the critical value m_{kr}, then the deviations are considered random. The critical value for the 95% confidence level is given by the formula

$$m_{kr} = 2 * (n-2)/3 - 2\sqrt{(16n-29)/90}, \tag{15}$$

where n - the number of elements of the row statistics. Checking deviations for autocorrelation is carried out using the Durbin-Watson test d according to the formula

$$d = \sum_{i=1}^{n-1} (e_i - e_{i+1})^2 / \sum_{i=1}^{n} e_i^2, \tag{16}$$

The calculated value of d is compared with the tabular values d_1 and d_2. There may be two cases here:

a) The value of d does not fall within the interval from 2 to 4. For $d > d_2$, there is no autocorrelation. If $d < d_1$, then there is a relationship between the deviations. When the condition $d_1 \leq d \leq d_2$ is fulfilled, it is impossible to make an unambiguous conclusion.

b) The value of d falls within the range from 2 to 4. In this case, the parameter *d=4-d* is determined. Further, the analysis is carried out in accordance with the algorithm given in paragraph (a), where the parameter d is used instead of *d*.

Checking the compliance of deviations with the normal distribution law is performed using the Pearson's χ^2-criterion (4). In addition to it, the Westergaard method, the DR criterion and other criteria are used [15].

When the above conditions are met, the trend analysis is started. The initial data from n measurements are divided into two approximately identical groups. The first group includes the first n1 measurements, the second - the remaining n_2 elements: $n = n_1 + n_2$. Let us introduce the notation for the average values and variances of elements in each group: $y^{(1)} = \sum y_i^{(1)}/n_1, y^{(2)} = \sum y_i^{(2)}/n_2, s_(1)^2 = \sum(y_i^{(1)} - y^{(1)})^2/(n_1-1), s_(2)^2 = \sum(y_i^{(2)} - y^{(2)})^2/(n_2-1)$. First, the hypothesis about the equality of variances in groups is tested using the Fisher criterion

F (7). When the value of F is less than the critical value F_{kr} with a given level of significance, the general variances are equal and it is possible to proceed to assessing the presence of the trend using the Student's T-test (6). If the value of T is greater than the critical value of T_{kr}, then the trend exists. Otherwise, there is no trend.

As an example, we will study the possibility of a trend in the number of birds N based on the results of $n = 11$ observations in 2010-2011. The initial data are presented in table 5. The equation for the dependence of the number of birds in thousands on the year of observation x, obtained by the LSM method, has the form

$$N = 454.5 - 0.223x, \tag{17}$$

The last line in the table 5 contains the deviations e_i of the observed values of N_i from the values of $N(x_i)$ obtained using the regression equation (3.4). The standard deviation was $s_x = 0.36$.

Table 5. The initial data for determining the possibility of existence of a trend in the change in the number of birds N_i in thousands based on the results of n=11 observations from 2000 to 2010.

x_i, Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
i	1	2	3	4	5	6	7	8	9	10	11
N_i	9.3	8.7	8.6	8.1	8.5	8.0	7.4	7.7	6.3	7.2	7.3
$e_i = N_i - N(x_i)$	0.30	-0.08	0.041	-0.24	0.09	0.11	-0.27	0.25	-0.92	0.20	0.52

Let us carry out a rejection of possible anomalous values by the Irwin method. The critical value of the Irwin parameter λ_a in accordance with the data in table 1 equals about 1.5. The maximum value of the parameter λ_i refers to the deviation for number 9 related to measurements in 2008: $\lambda_9 = |y_9 - y_8|/s_x = |-0.92 - 0.25|/0.36 = 3.25$. Since λ_9 is greater than λ_a, the result of the measurement in 2008 should be discarded. In all other measurements, the parameter λ_i is less than the critical value, so they are saved for further analysis. The corrected data after rejection are given in table 6.

Table 6. Adjusted data to determine the possibility of the existence of a trend in the number of birds N_i in thousands based on the results of n=10 observations from 2000 to 2010.

x_i, Year	2000	2001	2002	2003	2004	2005	2006	2007	2009	2010
i	1	2	3	4	5	6	7	8	9	10
N_i	9.3	8.7	8.6	8.1	8.5	8.0	7.4	7.7	7.2	7.3
$e_i = N_i - N(x_i)$	0.31	-0.10	0.005	-0.31	0.28	0.02	-0.43	0.07	-0.04	0.25

The regression equation obtained by the LSM method for the dependence of the corrected data has the form

$$N = 397.80 - 0.1944x, \tag{18}$$

where x is the year, N is the number of birds in thousands.

The last line in table 6 contains the e_i deviations of the observed values of N_i from the values of $N(x_i)$ obtained using the regression equation (18). As expected, the standard deviation of the new model has decreased compared to equation (17) from 0.36 to 0.23.

At the first stage, we check the requirement for randomness of deviations by the method of turning points. In accordance with condition (14), the turning points are the results of seven deviations (m=7) with numbers 2-5, 7-9 in table 6. The critical value m_{kr} for ten measurements n=10 is 2.92 according to the formula (15). Since m is less than m_{kr}, the deviations are random.

Next, we check the deviations for autocorrelation. The lower and upper critical limits of the Durbin-Watson test for 1% significance are $d_1 = 0.32, d_2 = 1.30$. The Durbin-Watson criterion calculated by the formula (16) is d=1.95. The value of d is greater than the upper bound of d_2, so there is no autocorrelation.

Let us check the correspondence of deviations to the normal distribution law using the Pearson's χ^2-criterion. Let us break down the sample of n=10 deviations of table 6 on m=4 intervals of size $h = (e_{max} - e_{min})/m$. From table 6 it follows that the maximum and minimum values of deviations are equal to $e_{max} = 0.31, e_{min} = -0.43$. Therefore, h=0.185. The Pearson χ^2-criterion calculated by the formula (4) is 2.36. The critical value χ^2_{kr}, for the 5% significance level is 3.8. Since the inequality $\chi^2 < \chi^2_{kr}$ is satisfied, the random variables ek obey the normal distribution law.

All the conditions for the trend analysis are met, so we can proceed to the study of the adequacy of the regression equation (18). The correlation coefficient r_{xy} between the row statistics N and x and the Student's T-test calculated by formulas (8), (9) for the data of table 3.2 are -0.93 and 7.54 respectively. The critical value of T_{xy} at 8 degrees of freedom at a 5% significance level is 2.31. Since the Student's criterion is greater than the critical value of T_{kr}, then the relationship between the statistical samples in table 6 exists.

The Fisher criterion calculated by the formula (12) is equal to 7.20, more than the critical value $F_{kr} = 4.95$, which indicates the adequacy of the mathematical model (18). In the case under consideration, the conclusions obtained using the Student's and Fisher's criteria coincide.

Fisher's method is more stringent compared to the Student's method with small correlation coefficients at the level of 0.5-0.7, which can lead to different results. In this case, it is advisable to conduct additional trend studies. Let us split the data in table 6 into two identical groups. In the first group we will include the first five measurements, in the second - the remaining measurements. Means and variances in each group are $N^{(1)} = 8.64, N^{(2)} = 7.52, s^2_{(1)} = 0.15, s^2_{(2)} = 0.086$. We will check the homogeneity of the variances of the groups under consideration using the Fisher criterion (7) $F = 0.15/0.086 = 1.74$. The critical value of F_{kr} for the 5% significance level at 4 degrees of freedom of the numerator and 4 degrees of freedom of the denominator is 6.39. Since $F_{kr} > F$, the variances are homogeneous.

Let us evaluate the presence of the trend using the Student's T-test (6). After substituting the average values of deviations and variances of each group into the formula (6), we have: T=12.9. This value is greater than the critical value $T_{kr} = 2.31$ for 5% significance level at $n_1 + n_2 - 2 = 8$ degrees of freedom, so the hypothesis of a trend is accepted. Consequently, the number of birds in the period from 2000 to 2010 is declining. If the average annual number of birds in the first 5 years was estimated at the level of 8640 individuals, then in the last five years it decreased to 7520 individuals.

Let us compare the results obtained with the help of regression and the trend analyses. Using the regression equation 18, it can be found that the average annual number of birds in the first 5 years of observations was about $N^{(1)}_{Trend} = 8610$, and in the last 5 years it was about

$N_{Trend}^{(2)} = 6540$ individuals. The difference between the two methods for assessing the trend is at the level of 0.3

3.4. Development of an algorithm for statistical analysis

Numerous studies of the avifauna on the territory of the wind farms indicate great difficulties in organizing monitoring, collecting information, and in the process of statistical processing of the data obtained [1, 5, 6, 8, 9, 11, 13]. The impossibility of duplicating observations under absolutely identical conditions and the influence of uncontrollable factors associated with meteorological and other conditions are partially compensated by long-term observations up to 1-10 years. However, even in this case there are situations when the measured parameters of the dynamics of ornithocomplexes do not fit into the classical schemes of statistical regularities. In this case, it is necessary to pay special attention to rejecting erroneous measurements, identifying individual anomalous data, and careful checking the adequacy of the obtained mathematical models.

The reliability of conclusions based on the results of statistical analysis depends, first of all, on the correctness of the application of the criteria used. The use of each of them requires the fulfillment of certain conditions. For example, the use of the Student's, Irwin's, Durbin -Watson's, Pearson's, Fisher's and other criteria implies the obligatory compliance of the studied sample with the chosen random variable distribution laws. Based on the material presented in this paper and the accumulated experience of statistical studies in a number of publications [1,6,8,11,12,15–18], we can propose the following algorithm for statistical processing of the results of monitoring the wind farm territory.

Step 1. Selection or development of an information system to ensure the storage of observation results in the form of tables or databases, convenient for systematizing the information received and their subsequent analysis. Examples of such information and computer systems are presented in papers [5, 7, 8].

Step 2. Primary statistical processing of monitoring results, which consists in determining the average values of row statistics, variances, rejecting the results of erroneous measurements and identifying the random variable distribution law.

Step 3. Testing hypotheses about the coincidence of mathematical expectations in a comparative analysis of the number of birds and other parameters that determine their behavior in different monitoring sites and in different seasons.

Step 4. Calculation of correlation coefficients between various parameters that characterize the dynamics of ornithocomplexes depending on the census method, weather, seasonal or other conditions.

Step 5. Correlation-regression analysis. Construction of mathematical models that determine the dependence of one parameter on another parameter.

Step 6. Trend analysis to identify the possibility of changes in the number of birds over time or the direction of change in one parameter as another parameter changes.

The proposed algorithm is focused on processing the results of monitoring the dynamics of ornithocomplexes on the territory of wind farms, obtained by the SNH and RAM methods, although they can also be used in the case of other observation methods.

4. Conclusions

An algorithm for analyzing the results of monitoring the dynamics of ornithological complexes on the territory of wind farms has been developed using statistical methods. The proposed algorithm allows solving the following problems: 1. Carrying out primary processing of information on the number of birds of various species, flight altitude and time spent on observation sites using the Student's T-test, Fisher and Pearson criteria. 2. Construction of regression equations that determine the dependence of the number of birds on various factors using the Student's T-test, Fisher and Irwin criteria. 3. Trend detection when studying the time dependence of the number of birds or the direction of change of one parameter as another parameter changes using turning points and the Student's T-test, Fisher, Irwin and Durbin-Watson tests. The proposed statistical methods have been tested in the analysis of the results of monitoring ornithocomplexes on the territory of the Prymorsk-1 wind farm.

Aknowledgement
The authors of this paper are grateful to Anastasia Gorlova (Horlova) for translation into English.

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IOP Conference Series: Earth and Environmental Science

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To cite this article: B Havryshok *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012040

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012040 doi:10.1088/1755-1315/1049/1/012040

Retrospective and geographical features of forestry use of lands in Podilski Tovtry

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Abstract. Forest cover is an important component of the landscape and is responsible for the conservation of other components. Forests of the Podolian Upland are distinguished by a high natural resource potential and a significant risk of manifestation of unfavorable natural processes. The aim of our research is to study the forest cover of Podilski Tovtry and analyze the dynamics of its changes for the period from 1880 to the present. Forestry nature management in Tovtry is second only to agriculture in terms of the area of occupied land. Forests of the reef zone and adjacent territories within the Ternopil oblast are part of the Ternopil forestry enterprise and the Medobory Nature Reserve. Within the study area, forests of a relatively large area are confined to the summit surface and slopes of the main ridge. Our research has established that in the period from 1880 to 1930, there was a significant decrease in forest cover practically throughout the entire study area, which is associated with both the need for firewood and agrarian overpopulation and the desire to expand the arable land. A direct relationship was found between the decrease in forest cover and the approach to villages and hamlets. After the Second World War and until the present, there have been no significant changes in forest cover. In some areas, even an increase in forested areas was found. Active forest expansion was observed at the beginning of the two thousandth years amid a decline in agricultural production.

1. Problem statement

The forest cover is an important component of the landscape, it is responsible for the preservation of its other components such as relief, soil, surface and ground water, fauna, etc. The ecological impact of forest ecosystems on the state of the natural environment in general, on the nature, pace and direction of exogenous processes, human living conditions, etc. is enormous.

Given the important ecological stabilization and economic functions of the forest, the processes associated with a decrease in the area and deterioration in the quality of plantations require study. Timely identification and justification of the harmful effects of deforestation and the development of measures to improve the situation will contribute to the formation of a favorable geoecological situation in the territory. The forests of the territories of the Podolian Upland, which have long been mastered by humanity, are of particular ecological and geographical importance. They are distinguished by a high natural resource potential and a significant risk of unfavorable natural processes.

2. Materials and research methods

The study of forestry land use and the ecological role of the forest is the subject of research by many domestic and foreign scientists. S. Hensiruk [1] studied the features of forestry as a branch of nature management in different regions of Ukraine. The study of forest management on the territory of the Podilski Tovtry is devoted to the publications of such scientists as K. Moskaliuk [2], V. Bondarenko [3]. They concern mainly the territory of the Medobory Nature Reserve and reveal one aspect, namely the possibility of reproducing and preserving autochthonous forest stands in protected areas where intensive economic activity used to take place. The current state and dynamics of the forest cover of Podilski Tovtry remain insufficiently explored. This is especially true of the territories northwest of the Medobory Nature Reserve.

Beech stands have recently received special attention from researchers. Their study on the territory of Ukraine is devoted to the publications of H. Krynytskyi with co-authors [4] and S. Myklysh, Yu. Myklysh, etc. [5]. They considered the region of Podilski Tovtry as the extreme eastern area of natural growth of Fagus silvatica L. The monograph by N. Tekalo, M. Matusiak et al. [6] and a short article by O. Mudrak et al. [7] are devoted to the ecological features of reforestation and afforestation in Podillia. The Tovtry in both studies are part of a much larger region. Some aspects of the territorial features of the use of forest fund lands within Tovtry were studied by B. Havryshok, M. Syvyj [8].

The purpose of our research is to study the forest cover of the Podilski Tovtry reef zone and analyze the dynamics of its changes over the period from 1880 to our time. According to the purpose, the following tasks were formulated: select multi-temporal topographic maps of the study region; divide the sheets of maps into squares with a side of 2 km (registration areas) and determine the forest cover of each of them; determine the change in forest cover over the period from 1880 to the present and build an appropriate cartogram; trace current trends in the development of forest cover; develop recommendations for the development of forestry in the region.

3. Results and discussion

Forests in the study area are unevenly distributed. Their distribution depends on the physical and geographical conditions, primarily the relief, geological structure, climate, as well as the economic use of the territory. Forest management of natural resources in Tovtry is second only to agriculture in terms of the area of occupied land. The forests of the reef zone and adjacent territories within the Ternopil oblast are part of the Ternopil forestry establishment (Mshanets, Zbarazh and Skalat forestry) and Medobory Nature Reserve.

V. Shafer [9], analyzing the flora of the region, divided Medobory into northern and southern parts, drawing a border between them approximately between the Vikno and Krasne massifs of the reserve. He qualified the forests of the northern part as Podillia oak forests, noted their change and the presence of only minor forest areas with initial signs. Oak remained the dominant species. The forests of the southern part of Medobory according to Shafer are forests of the Central European type. By the beginning of the 20th century, there were practically no older and primary forest stands left. V. Bondarenko and co-authors [3] note that the wide distribution of the hornbeam in the Podillia oak forests was the result of patronage for this species in forestry as a fast-growing and unpretentious breed.

To analyze the forest cover of Tovtry and the surrounding area, we have built the corresponding maps. Forest cover is calculated for the land use areas of territorial communities as a percentage of the areas occupied by forests to the total area. The highest forest cover is characteristic of the Tovtry Ridge itself and the territories to the northeast of it.

In particular, within Vikno, Krasne, Sadzhivky, Rashtivtsi of the starostynsky districts of the Hrymailiv united territorial community, it exceeds 40 percent and Horodnytsia, Postolivka (Husiatyn united territorial community), Reniv, Hai-za-Rudkoiu (Zaliztsi united territorial

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012040 doi:10.1088/1755-1315/1049/1/012040

community) is 30-40 percent. The least forested areas are in the vicinity of the villages of Kretivtsi, Stryivka, Maksymivka, Halushchentsi, Zelene, Okhrymivtsi, etc. and the town of Skalat, whose forest cover is less than one percent.

The forest cover of the northwestern part of Tovtry and the surrounding area has been affected by a complex combination of natural and anthropogenic factors for at least two centuries. During the last century, the role of human activity in the transformation of vegetation has increased markedly. In this regard, we consider it appropriate to identify the long-term dynamics of the region's forest cover.

To trace the dynamics of the forest cover of the study area, multi-temporal maps were used (1880, 1930, 2020) [10], [11]. For the convenience of calculations, the entire territory is divided into accounting areas with an area of 4 km^2, which coincides with the squares of the map grid at a scale of 1:100 000. Such cartometric studies were carried out on each of the three time slices. Based on their results, forest cover cartograms were constructed for 1880, 1930 and 2020. After that, the change in forest cover for the period 1880 - 2020 was determined by calculating the difference in the values of this indicator for each accounting area. Punsons of modern settlements were superimposed on the last site, which made it possible to reveal a relationship between a decrease in forest cover and proximity to settlements (figure 1).

In addition to cartometric studies, a visual analysis of the maps was carried out according to the indicated time slices and modern satellite images obtained from the Google Earth system. This allowed us to trace the change in the configuration of forest tracts, to analyze the current trends in the expansion of forests on lands that are not involved in agricultural production.

In the middle of the XVII century H. Boplan wrote In Ukraine and Podillia, villages are surrounded by forests with hiding places, where in summer people hide from predatory Tatars [12]. Deforestation proceeded slowly and met the needs of the subsistence economy of local residents. The intensification of this process was impossible due to the constant threat of nomad attacks. The modern picture is fundamentally different from that described by H. Boplan. Forests are located in separate islands between massifs of arable land and occupy mainly territories unsuitable for agriculture.

The great need for firewood and building material, along with agrarian overpopulation, led to the destruction of forests at the end of the 19th and early 20th centuries, which is clearly seen when comparing multi-temporal topographic maps. For example, a significant area was cut down in the northeast of the Malynnyk forest massif in the vicinity of Novosilka (formerly Novosilka Skalatska). During the period from 1880 to the present, the forest area has decreased by 2.6 km^2. In the late 1920s, a grange of the same name appeared on this territory. The last one was destroyed during the Soviet Union time and at present this territory is arable land on the slopes of the beam (figure 2).

During the same period, the area of forests in the vicinity of the city of Zbarazh has significantly decreased. The forest area Zbarazh Forest was completely cut down and separate farms appeared in its place, and a railway ran through the forest area to the west of the village of Zaluzhzhia. To the east of Ihrovytsia, at the foot and on the slope of Mount Zembova, there was the forest area Obrozivka, which was the western continuation of the currently existing forest tract Dubivtsi . Its area in 1880 was about 1.7 km^2. By 1930, the forest was completely cut down, and only the toponym remained on the map. Subsequent changes in this area were not significant and were mainly associated with a change in configuration and a slight increase in the forest area in the Dubivtsi and Pozharnytsia tracts (figure 3).

A significant decrease in forest cover has also occurred in the territories that are now part of the main massif of the Medobory Nature Reserve. The forest area between the villages of Ostapie and Turivka (the Mantiava tract) has decreased by approximately 2.7 km^2 for the period from 1880 to the present due to cutting down areas in the area of Mount Nazarova, where the Palamarka grange arose, as well as on the northern and eastern outskirts of the forest. A

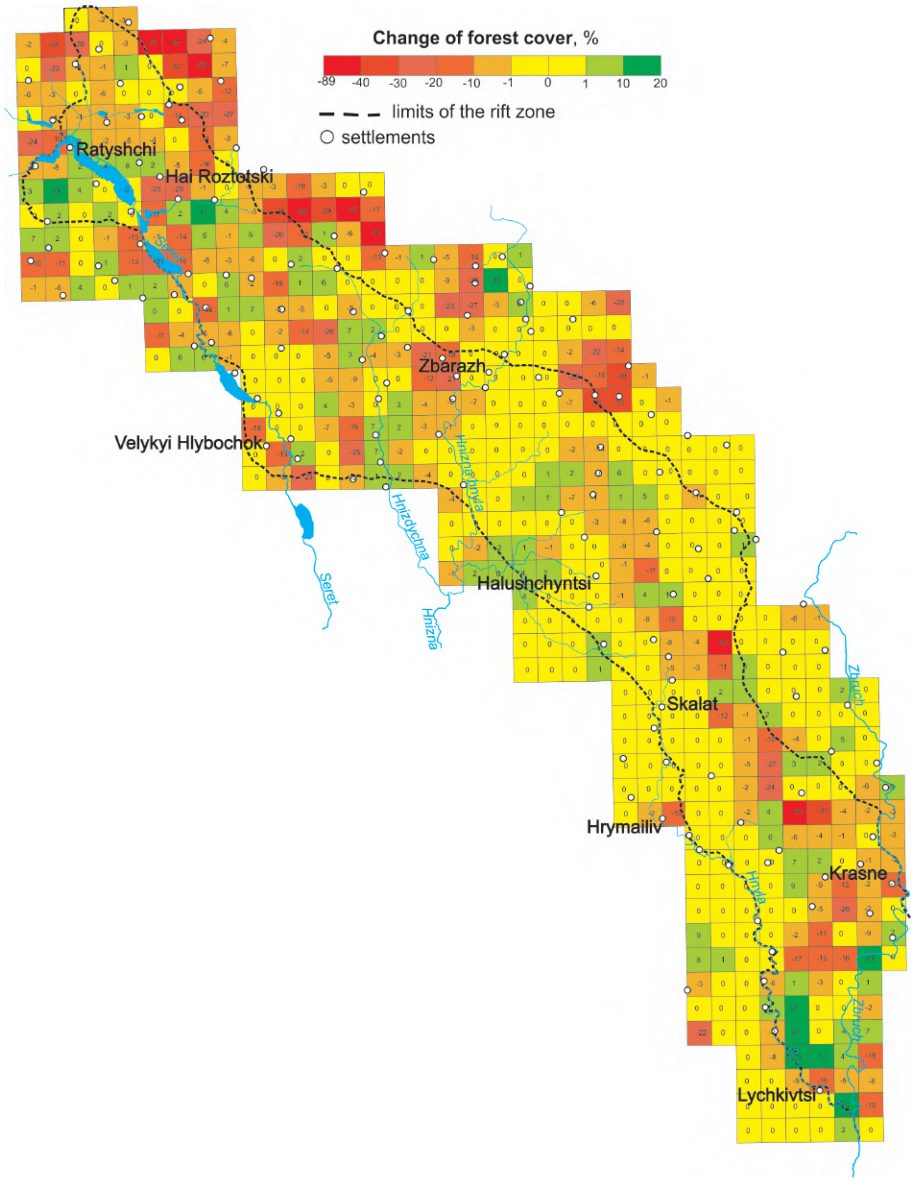

Figure 1. Changes in the forest cover of Podilski Tovtry and adjacent territories over the period from 1880 to the present (calculated for the area of the accounting plot; reduced on a scale of 1:100,000).

little south of the specified period of time, about 3.2 km^2 of forest on the slopes of Mount Monastyrykha was destroyed, and a village of the same name arose in its place. In general, from the end of the 19th to the end of the 20th century, the area of the forest massif north of the village of Krasne decreased by more than 6 km^2. The forest area between Krasne and Lychkivtsi also decreased by more than 5.5 km^2, mainly due to cutting-down to the east of the villages of Krasne and Sazhivka, north of the village of Lychkivtsi, as well as to the east of Mount Yantsova, where in the 1930s the Bilitovka grange appeared on the site of the forest, and after the Second World War a military training ground functioned.

According to I. Kaplun [13], about a hundred years ago, the northern part of the Podilski Tovtry was almost completely afforested, as evidenced by gray podzolics soils on loess loams.

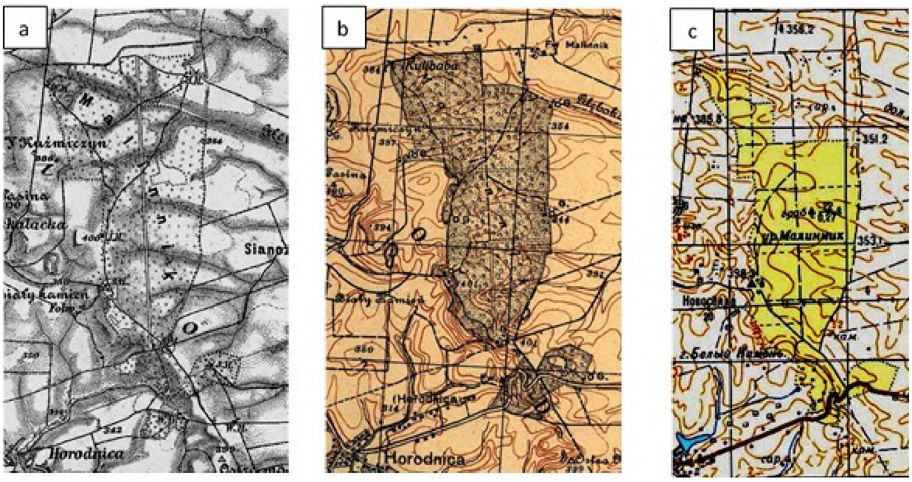

Figure 2. Transformation of the Malynnyk forest massif Map fragments: a) 1880; b) 1930; c) 2020.

As a result of economic activity, part of the forests was destroyed, only the names of individual settlements such as the Chornyi Lis, Dubivtsi, Zarubyntsi remained. We can partly agree with this statement. Of course, once these lands were under the forest. However, our cartometric studies of multi-temporal maps convincingly prove that the forest cover of the northern part of Tovtry has indeed decreased compared to 1880. Nonetheless the analysis of the Austro-Hungarian maps does not give any grounds to assert that the northern part of the Podilski Tovtry was almost completely forested 100 years ago. In the vicinity of the village of Dubivtsi, the area of individual forests even slightly increased, as a result of which the forest tracts of Pozharnytsia and Dubivtsi formed a single forest massif.

As of 1880, the territories northwest of Zbarazh were distinguished by the greatest forest cover. Forests in this territory covered not only Tovtry, but also the nearby plains. At the same time, forests were represented by separate massifs of different areas. The usual forest cover of accounting plots in this area is below 30 percent. Its higher rates (35–70 percent) were characteristic of the territories near the villages of Mshanets, Mylno, Ivanchany. To the southeast of Zbarazh, a clear confinement of forest tracts to Tovtry Ridge was observed. The only exception is the area between Zbarazh and Maksymivka, where Tovtry is low and treeless, and to the east of them was the Lubianky forest. The forest cover of the ride gradually grew from the villages of Maksymivka and Hory-Stryiovetski towards the southeast. Its maximum values (70 - 100 percent) were south of the village of Krasne. When comparing the forest cover as of 1880 and 1930, we see a decrease in this indicator within individual accounting areas, while maintaining common features in the distribution of forests. A decrease in forest cover and an expansion of treeless territories are observed to the north of the village Hai–Roztotski, west of Zbarazh, etc.

On the maps of 1930, as a result of deforestation on the plains, in the section Mala Berezovytsia – Zbarazh, one can quite clearly trace the connection between the extent of Tovtry and the forest cover of the territory. Analysis of the maps revealed a decrease in the area of the Chornyi forest by 3.3 km^2 (from 12.3 to 9.04 km^2). At the same time, the configuration of the massif has also undergone changes. Cut down and plowed areas, to which the farms are confined, are deeply cut into the territory of the forest from the east and south-west. The area of the Lubianky forest decreased by 4.9 km^2 (from 18.8 to 13.92 km^2) as a result of cutting and plowing in its estern and southern surroundings. Forest Lypnyk, in 1880, stretching southwest of the village Zarubyntsi to the river Hnizdychna in a continuous massif with an area of 1 km^2

Figure 3. Transformation of forest massifs between the villages of Zarubyntsi and Zaluzhzhia. Map fragments: a) 1880; b) 1930; c) 2020.

was cut down until 1930, and three small plots overgrown with shrubs, with a total area of 0.5 km^2, remained from it.

Ternopil Voivodeship was the only one in Poland that did not have state forests. Within the limits of the voivodship there were public (gmina), church and private forests. In 1939, by combining private and monastic forests, the Ternopil forestry was formed, assigned to the North-Western Podillia forestry region with hornbeam-oak and beech forests.

On large areas of the study area, a decrease in forest cover is observed. The most active deforestation took place near settlements, as well as in the process of building granges. The maximum reduction in forest cover is -68 percent and -89 percent. Both of these sites are located northeast of the Tovtry Ridge and are associated with the development of settlements. In the first case, the village of Khomivka was formed on the site of the forest, and in the second, the farms building between the villages of Lopushno, Panasivka and Volytsia. A significant decrease in forest cover (-57 percent) occurred near the village of Boliazuby, as well as south of Hai-Roztotski, near Zaluzhzhia, Lubianky, Krasne, etc. To the south-east of Maksymivky

Maksymivka, changes in forest cover are quite clearly associated with the Tovtry Ridge, which is due to the absence of forests on the nearby plains as early as 1880. The most significant changes in this segment can be traced between the villages of Krasne, Sadzhivka and Volytsia, near the village of Monastyrykha (-40 percent) and in the north-east of the Malynnyk forest massif (-42 percent). In general, there is a fairly clear connection between the decrease in the forest cover of the territory and its proximity to the settlement, which, obviously, is due to the economic feasibility of agricultural use of land close to the settlement. In some areas of the study area, there was also a certain increase in forest cover. Its most significant growth is observed in the western environs of the Medobory Nature Reserve, which is probably due to the cessation of economic activity in these territories. This phenomenon is negative, because it leads to a decrease in the areas of poaceous forbs and petrophilic steppe vegetation that are valuable from the scientific and economic points of view.

K. Moskaliuk [2] argues that as a result of grazing domestic animals, the territory of the lateral Tovtry is overgrown with weeds and shrubs. It is impossible to agree with this. Rather, on the contrary, by allowing moderate, regulated grazing of animals and hay cutting, it will be possible to stop the expansion of shrubs and weeds. To date, it is impossible to verify any of the claims, due to too few domestic animals left in the population.

Interesting data on the transformation of Medobor landscapes on the territory of the reserve can be found in the article by V. Shymanski [14]. This Polish researcher, studying the site of the discovery of the Zbruch Idol, gives a description of the section of the Zbruch valley near the village of Lychkivtsi based on a photograph of 1882. The descriptions made by him convincingly testify in favor of the expansion of tree and shrub vegetation in areas taken out of agricultural use.

As a result of long-term economic impact, the natural complexes of the Western Podillia, and in particular Tovtry Ridge, have been significantly changed, their original structure has been disturbed, and the mechanisms of self-regulation have been unbalanced. Forests have undergone especially significant changes, namely, in oak forests, native full-membered cenoses of different ages with oak dominance have been largely replaced by derived groups, the ecological potential of which and the possibility of detecting environmental stabilizing functions by them are limited [3].

The analysis of the species composition of forest stands was carried out on the basis of forest plantation plans of the forestry and our own field observations. Therefore, certain patterns have been established in the change in the composition of forest stands in the direction from the northwest to the southeast. Thuswise, the forests of the Mshanets forestry are composed mainly of oak and pine (silviculture) with an admixture of aspen, sweet cherry, etc. In the Zbarazh forestry, forest stands are represented by hornbeam, oak, linden with an admixture of aspen, sweet cherry, ash, acacia (in separate sections). The forests of the Skalat forestry are composed of ash, ulmus, oak, hornbeam with an admixture of sweet cherry, birch, etc. It also has a place of beech growth: Polupanivka beeches (a natural sanctuary of local significance) in the tract named after. S. Dovbenka (former Kolodiivka forest) and in the forest Malynnyk. Oak, beech, hornbeam with an admixture of linden, sweet cherry, aspen grow in the forests of the Medobory Nature Reserve. In the reserve, active work is underway to form nominally primary oak-beech stands with an admixture of hornbeam, linden, and sweet cherry.

In each forestry, certain areas are occupied by fir, maple, aspen, etc. At the present stage, larix and pine forest plantations are being created on rocky hill of Tovtry Ridge and other lands. The priority of these crops in forestry is due to their unpretentiousness to conditions and rapid growth.

A number of authors, in particular V. Bondarenko et al. [3] focus on the expansion of modern forest vegetation to adjacent lands, the agricultural use of which has been discontinued for certain reasons. The most actively overgrown meadows adjacent to the forest, fallows, abandoned estates. In the conditions of Western Podillia, the evidence of forest expansion into nearby fields is the ditches, with which, in the interwar period, and sometimes even earlier, the owners dug their forest plots. Currently, all of them are covered with trees and shrubs. After conducting research at the Medobory Nature Reserve, V. Bondarenko and co-authors [3] found that over the past 70–80 years, the forest has spread beyond the ditch line by 1–9 m. Similar processes were found by us in the forests northwest of Polupanivka (the area named after S. Dovbenka), near Staryi Zbarazha, Oprylivtsi, Ditkivtsi during research in 2010-2013. A repeat inspection of these territories in 2020 did not yield results. All agricultural lands have been redeveloped with modern powerful equipment of agricultural holdings. The natural succession of sections is again stopped by economic activity. We can still observe the expansion of the forest in small areas of the river floodplains Zbruch, Hnizna, Hnyla. But the species composition of these thickets is too specific.

V. Bondarenko and co-authors [3] note that on the land where agricultural land use has ceased, forests spread through the edge, within which microclimatic, biotic, and coenotic conditions are specifically and predominantly favorable for many tree species. On the majority of the edge of the reserve, among other species, hornbeam, tree-like and shrubby willows, blackthorn predominate and grow intensively. The change in phytocenosis occurs in the direction of a composition close to the previous one, its pace and nature are determined by the species composition of the adjacent forest, environmental conditions, the influence of animals, and the direction of the prevailing winds. First of all, the derelict lands are overgrown with photophilous species, the microclimate characteristic of the forest environment is gradually forming, and the pioneer vegetation is being replaced by shade bearing plants [15].

We obtained similar results in 2010-2013 during field observations in the above-mentioned forest massifs. In 2020, in the area named after S. Dovbenka, active expansion of the forest is taking place in the southwestern and southern directions. From the south, between the forest and the Polupanivka quarry, the land allocated for the expansion of the quarry. They are actively overgrown mainly with hornbeam, sweet cherry and willow. At the border of the forest, the trees are quite dense and go to a height of 2 - 4 m. With distance from it, they become lower and less common. In the species composition, the number of hawthorn and other shrubs is growing. To the south-west of the forest, there are steep slopes of the main strand with outcrops of bedrock, on which the expansion of shrubs and woody vegetation into rocky steppe areas is clearly traced. The predominant species here is hawthorn. Pine is also found and rarely sweet cherry. To the east and north-east of the forest, all the lands are plowed, therefore significant expansion is impossible. However, the forest in this direction since the 30s of the XX century “captured” about 1.5 m beyond the moat.

In the vicinity of Staryi Zbarazha, the expansion of the forest to fallow fields and hayfields is not very active in 2010-2013. On the fallows mostly individual specimens of hornbeam, willow, and hawthorn sprouted. Since 2019, these fallows have been plowed up again. Active expansion of tree and shrub vegetation is observed in the steppe areas near the villages of Staryi Zbarazh, Oprylivtsi, Dubivtsi. These are predominantly forb meadows on humus-carbonate soil, which were used as unproductive pastures and places for spontaneous stone mining. Now the slopes of such hills (for example, Mount Skala in the south of the village of Oprylivtsi) are actively overgrown with hawthorn and other shrubs.

On the northeastern outskirts of Detkovets, the top surface of the Tovtry Ridge is covered with planted pine forest, which is adjoined by several hectares of fallow. On the last one, active overgrowth of self-sowing pine is observed. Pine of all ages and unevenly distributed over the territory. The oldest specimens reach a height of more than 3 m. The adjacent fallows on the slopes are not yet overgrown with forest. When analyzing the public cadastral map, we found that these lands have already been given into ownership for private peasant farming, so the expansion of the forest will definitely not go any further. Very soon these plots will be plowed up and reused for crops.

The priority task should be considered to increase the area of forests to a scientifically substantiated level through the formation of forest cultures on sloping lands adjacent to forests. This requires the development of an appropriate legal framework, because most of the land is private property and the greatest economic effect is brought by their use in agriculture, in particular, when leased to agricultural holdings or farmers. The return on capital in forestry requires a very long time investment and therefore is not at all attractive to land owners. Only the government or separate amalgamated territorial communities can increase the area of forests. This should be done by creating forest corridors (as wide as possible) between existing forest areas, which will contribute to the stabilization of the geo-ecological situation and, in particular, the development of fauna. In order to increase the tourist attractiveness of the existing agro landscapes, it is also advisable to create small forests on the site of abandoned farms and parts of villages, cemeteries and on the slopes of small beams.

Further studies of forest management in this region should be directed to substantiate the optimal ratio of protected and commercial forests, as well as to develop a regulatory and legal framework for the possibility of afforestation of shared and privatized lands, to further develop the problem of restoration.

4. Conclusions

As a result of our research, we found that:

- about 2/3 of the study area is occupied by areas with a forest cover of less than 20 percent;
- forest massifs of a relatively large area are confined to the top surface and slopes of the main ridge and grow mainly on gray and dark gray forest soils. Less common are chernozems carbonated and humus-carbonate soils;
- the species composition changes slightly in the direction from northwest to southeast, however, in general, the dominant species are oak, hornbeam, pine, ash with an admixture of ulmus, sweet cherry, linden and beech;
- in the period from 1880 to 1930, there was a significant decrease in forest cover almost throughout the study area, which is associated both with the need for firewood and with agrarian overpopulation and the desire to expand arable land. On the site of clearings, farms and granges were formed;
- in the period from 1930 to the present day, the forest cover continued to decline, but much more slowly and only in certain areas, while in others it even slightly increased;
- in the late 90s and early 2000s, there was an active expansion of the forest on lands not involved in agricultural production;
- in recent years, most of the areas where the forest was expanding have been uprooted and plowed up again. Unfortunately, it was not profitable to change the status of the lands legally. Agroholdings are interested in maximum arable land.

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IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012040 doi:10.1088/1755-1315/1049/1/012040

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Model substantiation of strategies of economic behavior in the context of increasing negative impact of environmental factors in the context of sustainable development

To cite this article: R V Ivanov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012041

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012041 doi:10.1088/1755-1315/1049/1/012041

Model substantiation of strategies of economic behavior in the context of increasing negative impact of environmental factors in the context of sustainable development

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Abstract. The concept of sustainable development considers environmental, social and economic issues in general. And the goals of resource conservation and socio-economic development do not contradict each other, but contribute to mutual reinforcement. The purpose of this study is to build and test an economic and mathematical model for the formation of strategies for the behavior of an economic entity with an increase in the impact of negative environmental factors. The proposed strategies and their models are based on the income-expenditure balance equation, which takes into account both quantitative and qualitative characteristics. The constructed models are considered in the state space. The research methodology is based on building models in the form of linear combinations of functions of a homogeneous external impact and various spatial combinations of economic sources (sinks). The study makes it possible to assess the dependence of the amount of resources used for life support on the chosen adaptive strategy. Within the framework of the proposed model, it was found that the criterion for the effectiveness of the applied strategy can be an indicator of satisfaction with the state, the preservation of which, simultaneously with the preservation of the size of resources used, corresponds to the direction of optimization. This approach is consistent with the concept of sustainable development.

1. Introduction

Many modern problems of a global nature are primarily related to the exhaustibility of non-renewable natural resources, their irrational use, environmental pollution, and deterioration of environmental factors. As a result, it became necessary to develop strategies for the development of mankind that would prevent the deterioration of the quality of the environment, eliminate the consequences of such deterioration, and contribute to the formation of conditions for providing resources not only to the current generation, but also to the future.

The concept of sustainable development has become a priority model for the development of most countries. Its appearance was a requirement of the time for solving pressing acute problems of both socio-economic and resource-environmental nature. The most progressive concept today is the triune concept of sustainable development. Within the framework of such an understanding of sustainable development, environmental, social and economic issues are considered as a whole, and the goals of resource conservation and socio-economic development not only do not contradict each other, but can also contribute to mutual reinforcement [1]. This understanding of sustainable development implies the achievement of a high standard of living, a prosperous economy and the conservation of resources. Within the framework of this concept, an important factor in the effective solution of environmental problems is the development of environmental awareness in the process of performing by economic entities of their main functions, the use of appropriate forms of economic behavior.

The authors of the study [2] draw attention to the need for changes in values, attitudes and behavior for the transition to global sustainability, linking them with such subcomponents of sustainable development as the environment, population, consumption, technology, etc.

Thus, the study of economic behavior strategies in the context of sustainable development and the development of a methodology for qualitative assessment of the result of their use are relevant.

The emergence of the concept of sustainable development as a direction of economic analysis is associated with the 1972 report “The Limits to Growth” [3], the main idea of which was to assess the natural and environmental limits of the development of the world economy and the development of society. At the same time, in the article [4], the formulation of the core of the modern concept of sustainable development under the name “tectological general scientific concept” is attributed to A. Bogdanov and dates back to the beginning of the 20th century. It was only in 1987 that the concept of sustainable development received the status of a scientific phenomenon.

We agree with the definition of G. H. Brundtland [5] that sustainable development involves meeting the needs of the subject in the current cycle without harm to meet the needs in the next cycle.

At the present stage of development of the concept of sustainable development, there is a tendency to transfer the problem from the global and macroeconomic levels to the level of enterprises and households, which both take an active part in causing harm to the environment and become subjects of its elimination (reduction) [6]. The sustainability of an individual microeconomic entity is not just a concept, but also an object of sustainable development, which opens up opportunities for modeling, design, organization and management [7].

The study [8] proposes a model for optimizing the economic and environmental factors of the logistics system of enterprise management, which allows assessing and taking into account the impact on the environment.

The article [9] proposes a multi-agent simulation model of the feedback mechanism of dynamic interaction between the behavior of residents when making decisions and the safety of life in the city under the influence of the environment and politics. But the social sustainability of the city is at the forefront. The study [10] proposes an evolutionary game model with four participants, including governments, financial institutions, businesses, and consumers. Analog modeling provided an analysis of the impact of each parameter on the changes and development of the green financial market. It should be noted that the articles [9, 10] primarily studied the features of organizational management on the part of state structures.

In the article [11] it is noted that sustainable development belongs to the category of concepts that, in a generalized form, reflect some ideal model that is difficult to represent using accurate quantitative calculations. But this only expands the possibilities of its interpretation and the use of interdisciplinary approaches. An example of such an approach is a generalized analytical model of economic behavior under the conditions of an internal income-cost balance [12], built on the basis of a phenomenological assumption about an isomorphic relationship between the processes of production-consumption in the economy and emission-absorption in continuum mechanics, mentioned by W.B. Zhang [13] . The proposed method was used to analyze economic behavior under the established influence of exogenous factors and with their strengthening [14], but the environmental component was not taken into account in these studies.

The aim of the study is to substantiate the formation of economic behavior strategies as a response to the deterioration of environmental performance. To achieve this goal, it is necessary to complete the following tasks: within the framework of existing methods of economic and mathematical modeling, build a model for adapting an economic entity to changes in the state of the ecological environment; conduct model experiments to identify cause-and-effect relationships between the motives for the formation of a strategy of economic behavior, its form and results.

2. Presentation of the basic research

Classical economic theory traditionally interprets economic behavior as a rational desire to control resources and minimize costs while achieving the goals set by the economic entity. Instead, institutional economics provides for bounded rationality [15]. The institutional economy is characterized by such a type of management as self-organization [16] and a synergistic approach to management [17]. The main goal of the functioning of the economic entity in this case is equilibrium. At the same time, the motives of economic behavior are determined by the level of satisfaction of the economic subject, which depends on social, cognitive or emotional factors [18]. In this case, the equilibrium is ensured by the implementation of the law, which in the article [12] was called the "law of conservation of motivation"

$$M\left(r,\theta\right)+\frac{V^2}{2}=M_0, \tag{1}$$

where M_0 is a constant value that characterizes motivation in a state of equilibrium (satisfaction). Taking into account the understanding of sustainable development, we will set it by the value $M_0 = 0$. The term $M(r;\theta)$ in equation (1) is called motivating, the term $\frac{V^2}{2}$ in equation (1) is called compensating.

Note that the proposed model is built in the space of states, which in the spherical coordinate system $(r;\theta;\varphi)$ are described by the quantitative coordinate r (corresponds to the magnitude of the deviation from the balanced state), qualitative coordinate θ (characterizes improvement-deterioration), innovation coordinate φ (development indicator). The origin of coordinates $(0;0;0)$ corresponds to the equilibrium state of the system under study.These coordinates are related to the Cartesian rectangular coordinate system $(x;y;z)$ by the equalities

$$\mathrm{x}=\mathrm{r}\ \sin\theta\ \cos\varphi;\ \ \mathrm{y}=\mathrm{r}\ \cos\theta;\ \ \mathrm{z}=\mathrm{r}\ \sin\theta\ \sin\varphi. \tag{2}$$

Equation (1) shows that the motivation $M(r;\theta)$ depends on the quantitative and qualitative changes in the state of the economic entity. The component $V = V(r;\theta;\varphi)$ determines the speed and direction of changes in economic behavior. The spatial components of the velocity $V = V(r;\theta;\varphi)$ are given by the expressions

$$\mathrm{v_r}=\frac{1}{\mathrm{r^2}\sin\theta}\frac{\mathrm{d}\Omega}{\mathrm{d}\theta};\mathrm{v}_\theta=-\frac{1}{\mathrm{r}\sin\theta}\frac{\mathrm{d}\Omega}{\mathrm{dr}};\mathrm{v}_\varphi=\frac{C_0\Omega}{\mathrm{r}\ \sin\theta}. \tag{3}$$

The flow function $\Omega(r;\theta)$ in its meaning coincides with the concept of an economic action, as a reaction of a microeconomic entity to its economic state [19]. The coefficient C_0 will be called the "innovation coefficient".

Taking into account the previously formulated phenomenological assumption, taking into account formulas (1), (3) and using the models available in continuum mechanics [20], the model for the formation of economic behavior can be represented as follows

$$\frac{\partial^2\Omega}{\partial r^2}+\frac{sin\theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{sin\theta}\frac{\partial\Omega}{\partial\theta}\right)+C_0^2\Omega=0. \tag{4}$$

If $C_0 = 0$, then equation (4) is simplified

$$\frac{\partial^2\Omega}{\partial r^2}+\frac{sin\theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{sin\theta}\frac{\partial\Omega}{\partial\theta}\right)=0. \tag{5}$$

Note that equations (4), (5) are partial differential equations [21]. Some of the solutions to equation (5) were proposed and described in articles [14, 22], as models of constructs, combinations of which can be used to build models of economic behavior:

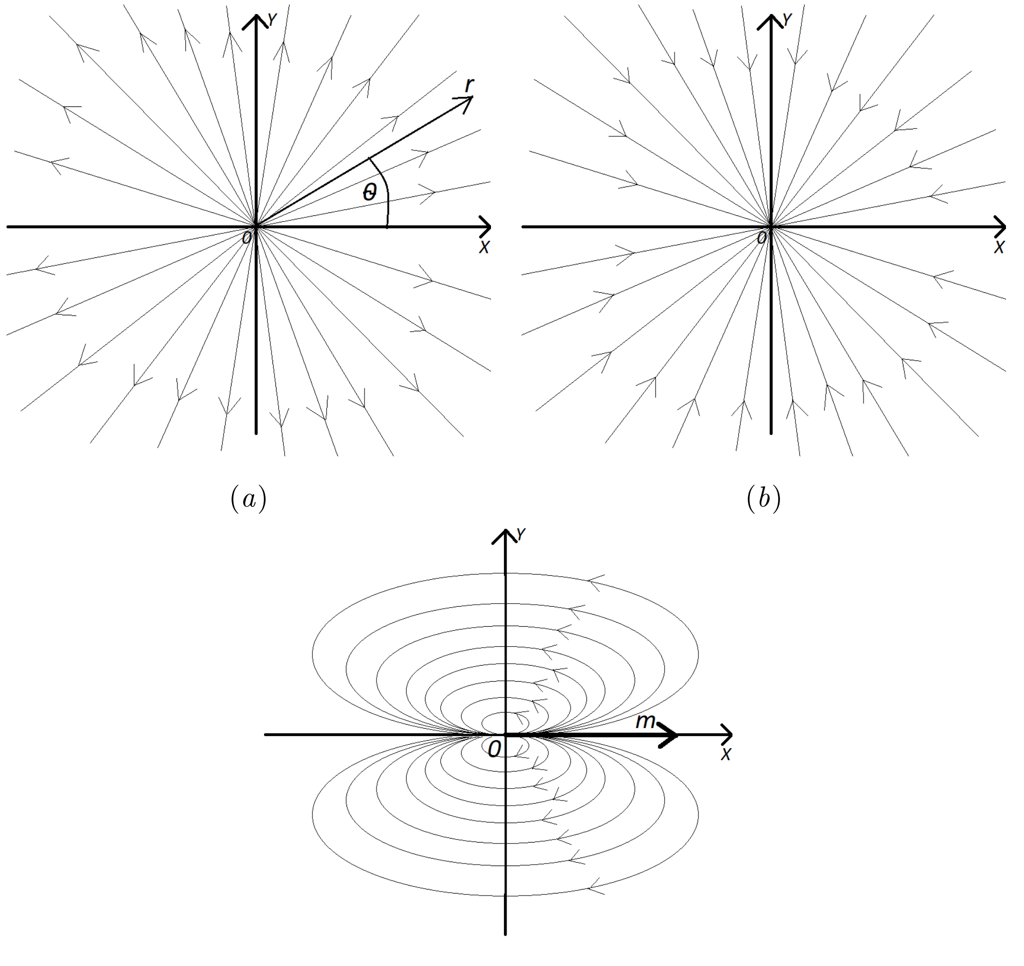
1. Economic source (sink)
$$\Omega_{\mathrm{ES}} = (1 - cos\theta\ )\Omega_0\ , \tag{6}$$
where $\Omega_0 = \pm\frac{P}{4\pi}$ (P is the intensity of the economic source (sink)).
2. Economic dipole
$$\Omega_{\mathrm{ED}}=\frac{\mathrm{m}\ \sin^2\theta}{4\pi\mathrm{r}}, \tag{7}$$
where m is the moment of the economic dipole [22], the absolute value of which characterizes the ability (potential) of an economic agent to improve the condition or to counter the factors that tend to worsen it. The moment of economic dipole should be considered as a characteristic of potential economic energy [19].
3. Uniform external influence
$$\Omega_{\mathrm{EI}} = -\frac{1}{2}V_\infty r^2 sin^2\theta\ , \tag{8}$$
where V_∞ is a characteristic of the intensity of external influence (EI).

Often the triune concept of sustainable development is illustrated by the Wett diagram, in which ecological, social and economic processes are considered equivalent, and the relationship between them provides weak stability [23]. But the authors of this article believe that the image of these components of sustainable development in the form of concentric circles is more accurate: the environment is represented by the outer circle, since it is of paramount importance; secondary is society; the economic component is located inside the specified construction, the existence of which in the article [23] is associated with strong stability.

It should be noted that the environment in this case is not only a supporting component, but also a limiting one. That is, socio-economic development, which is provided by environmental resources, is limited by the objective capacity of the environment. The negative value of function (8) in the presented study is consistent with such a limiting influence of environmental factors.

Returning to the meaning of the flow function $\Omega(r;\theta)$, we note that in the state space their combinations can reflect cognitive-reflexive and information-communicative processes that form an assessment of the state of an economic entity in the context of sustainable development with a concentric structure of interaction.

A typical example is an economic dipole (see figure 1c), which is formed as a result of the balance of quantitative and qualitative characteristics of an economic entity, as a combination of an economic source (point of production) (see figure 1a) and an economic sink (point of consumption) (see figure 1b) with the same intensities and located at an infinitesimal distance from each other in the state space [22]. In the absence of external restrictions, the flow lines corresponding to the flow functions (5), (6), (7) form an infinite field (see figure 1a, figure 1b, figure 1c). Flow directions are shown in figure 1a, figure 1b, figure 1c. Figure 1a shows the relationship between polar coordinates $(r;\theta)$ and Cartesian coordinates (x, y). On figure 1c



(a) (b)

(c)

Figure 1. Flow structure: economic source (a), economic sink(b) and economic dipole (c).

shows the direction of the economic dipole moment m. The circulation structures of the economic dipole (see figure 1c) can be classified as a soliton (stable non-linear wave), which was the result of the internal interaction of the microsubject to ensure a stable form of the socio-economic state [19].

As an object of a model experiment, it is proposed to use households, which are social phenomena and one of the most important subjects of economic activity with clearly defined relations of production, distribution, exchange and consumption. Using the example of a household, article [22] introduced the concept of “economic dipole”.

Taking into account the theoretical foundations of the spatial interaction of flows [20], the interaction model of an economic entity satisfied with the level of its state and the external influence limiting this level is represented by a linear combination of the economic dipole flow function (7) and the external influence flow function (8)

$$\Omega_0 = \Omega_{\mathrm{ED}} + \Omega_{\mathrm{EI}} = \frac{\mathrm{m}\ \sin^2\theta}{4\pi\mathrm{r}} - \frac{1}{2}V_\infty r^2 sin^2\theta\ . \tag{9}$$

The moment of the economic dipole m in this case is aimed at meeting the flow, which corresponds to the external influence.

The purpose and result of such interaction is to establish a balance corresponding to the sustainable development of the system as a whole. So, adapting to the established influence of the external environment, the economic entity seeks to be satisfied with the balance of its income and expenses to ensure life.

Such a balance in the case under consideration corresponds to the condition

$$\Omega_0 = 0. \tag{10}$$

Using condition (10), the relationship between the parameters of the flow function (9) can be represented by the expression

$$\mathrm{r}_s = \sqrt[3]{\frac{m}{2\pi V_\infty}}. \tag{11}$$

Analysis of expression (11) allows us to conclude that the balance of internal and external flows occurs on the surface of a spherical shape, the radius of which is $r = r_s$.

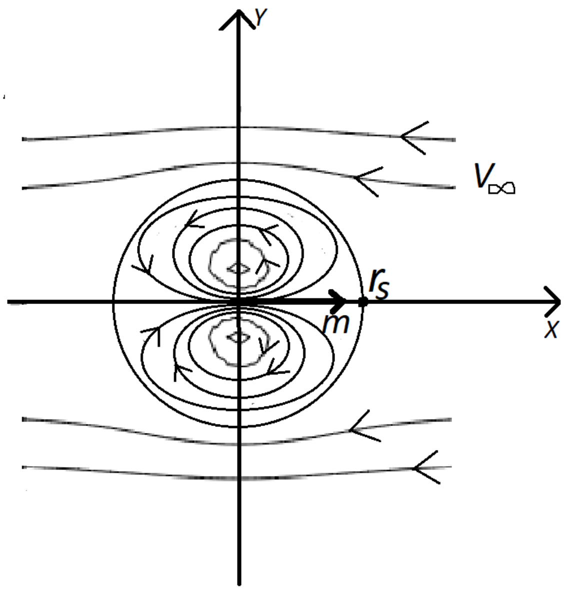


Figure 2. Flow structure of flow function (9).

The inner region, which is formed by the flow of the economic dipole, will be called the "stability zone" [12] (see figure 2).

Its size is difficult to give a clear qualitative and quantitative characteristic. Our study used the following principles:

1. The size of the "stability zone" corresponds to the opportunities that an economic entity has to carry out economic activities. For the flow function (9) this is the area of a circle of radius $r = r_s$ (see figure 2).
2. The quantitative indicator of satisfaction with the available opportunities corresponds to the coordinate of the point of the "stability zone", which lies on the horizontal axis in the positive direction. In figure 2 it is r_s.
3. The qualitative indicator of satisfaction SAT (satisfaction) with the available opportunities is determined from the ratio

$$\text{SAT} = \frac{S_R}{S_L}, \tag{12}$$

where S_L is the area of the part of the "stability zone" located in the left half-plane relative to the vertical axis; S_R is the area of the part of the "stability zone" located in the right half-plane relative to the vertical axis. For the flow function (9) (see figure 2) $S_L = S_R$; $SAT = 1$.

Dependence (11) allows us to consider such situations of the ratio of possible values of the economic dipole moment m and the parameter of external influence V_∞:

1. The economic dipole moment m is much larger than the parameter of external influence V_∞ (external influence can be neglected).
2. The moment of the economic dipole m is much less than the parameter of external influence V_∞(leads to the destruction of the economic entity).
3. The moment of the economic dipole m and the parameter of external influence V_∞ are commensurate values (as a result of the adaptation of the economic entity to external influence, a structure similar to figure 2).

2.1. Passive reaction to the deterioration of environmental factors

Consider a situation where the negative impact of environmental factors increases (the external impact parameter increases V_∞). The most trivial in this case is the passive strategy, which is characterized by the fact that the economic dipole moment m remains unchanged. With such a strategy of economic behavior, it is obvious that the greater the external influence, the smaller the size of the "stability zone", the fewer opportunities.

There are several reasons for this decrease. One of the consequences of the deterioration of the state of the environment is the deterioration in the quality of the usual set of food products. As part of ensuring the stability of the internal socio-economic state, the change in the economic behavior of households is expressed in attempts to restore the loss of quality. This can be expressed in the transition to more environmentally friendly products [24]. While maintaining the economic dipole moment m, the implementation of such a strategy of economic behavior requires the use of additional resources and a decrease in available opportunities.

Another reason is related to the fact that the "stability zone" limits not only the possibilities of using material resources, but also the available human capital, which is provided by education, qualifications, health, etc. [25]. For a household, this is also a decrease in the opportunities for the implementation of the reproductive function.

Let us consider as model initial data the values: $r_s = 1$, $m = 1$, $V_\infty = 0,16$, which satisfy relation (11).

In our study, first of all, it is not absolute changes in indicators that are important, but relative ones. So, if environmental indicators deteriorate by 2 times relative to the initial value $V_\infty = 0,16$, then the use of a passive strategy will lead to a decrease in satisfaction by almost 21 percent ($r_s = 0,7924$). The "stability zone" in this case will decrease from the initial 3,1416 will decrease to 1,977. That is, the available opportunities will decrease by 37 percent.

But the attitude towards such changes will remain neutral: $SAT = 1$.

The natural consequences of such economic behavior is the gradual depletion of available resources, the amount of which may decrease to a level capable of providing only basic needs. In our opinion, the strategy under study can be identified as irrational.

2.2. Reactive response to the deterioration of environmental factors

In an effort to maintain the amount of available resources, the reactive strategy for adapting an economic entity to the deterioration of environmental factors provides for a change in the structure of consumption. In the framework of the proposed model, this means that in the face of increased negative external influence, the balanced state in the form of an economic dipole is being transformed. Keeping equal absolute values of the intensities of the economic source and economic sink, their relative position in the state space is corrected. This reflects the behavior of an economic entity aimed at compensating for the deterioration of environmental factors.

The flow structure in this case in the Cartesian coordinate system (x, y) is described by the function:

$$\Omega_1 = -\frac{1}{2}V_\infty y^2 + m(1 - \frac{x}{\sqrt{x^2+y^2}}) - m(1 - \frac{x+a}{\sqrt{y^2+(x+a)^2}}). \tag{13}$$

Obviously, as a result of a change in the habitual structure of consumption in the direction of a deterioration in its quality level, the topology of the “stability zone” will also change - it will take on the shape of an ellipse.

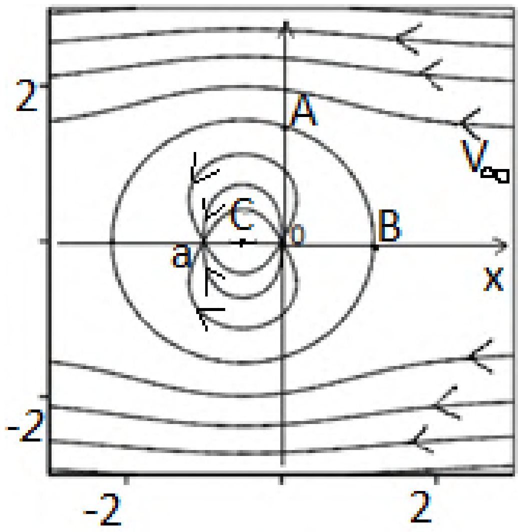


Figure 3. Flow structure of flow function (13).

On figure 3 the flow structure of the flow function (13) is presented at $V_\infty = 0,5$; $m = 1$ and $a = 1$ (the value $a = 1$ is illustrative).

To assess changes in the internal socio-economic structure and the size of the “stability zone”, we use the formulas [20]

$$V_\infty = \frac{m}{(L-\frac{a}{2})^2} - \frac{m}{(L+\frac{a}{2})^2}, \tag{14}$$

$$V_\infty = \frac{2ma}{h^2\sqrt{h^2+\left(\frac{a}{2}\right)^2}}. \tag{15}$$

L, h is major and minor semi-axes of the ellipse (“zones of stability”) (see figure 3). These ratios make it possible to determine the level of consumption adjustment while maintaining internal resources, the value of which for the elliptical shape of the "stability zone" is calculated by the formula

$$SZ_1 = \pi Lh. \tag{16}$$

Recall that at $r_s = 1$, $m = 1$, $V_\infty = 0,16$ the "stability zone" is estimated by the value

$$SZ_0 = \pi {r_s}^2 \approx 3,1416. \tag{17}$$

Using relations (14)-(17), it was found that when the negative influence of external factors doubles relative to the initial value $V_\infty = 0,16$ and the value of $m = 1$ is maintained, the value of a should be equal to $a \approx 0,159$. That is, the correction is such that satisfaction with the structure of consumption decreases by almost 16 percent.

The quantitative indicator of the overall satisfaction of the economic entity with its state after applying the described reactive strategy is estimated by the length of the segment of the OB (see figure 3).

$$OB = L - \frac{a}{2} \approx 0,92. \tag{18}$$

The value of the qualitative assessment of the overall satisfaction of the economic entity with its state after applying the described reactive strategy is carried out according to the formula (12). In the situation under study, S_R is defined as the area of the segment perpendicular to the major axis of the ellipse (see figure 3).

$$S_R = Lharccos\left(\frac{CO}{L}\right) - CO \times OA =$$

$$= 1,003 \times 0,997 \times arccos\left(\frac{0,008}{1,003}\right) - 0,008 \times 0,992 \approx 1,4115.$$

$$S_L = SZ_1 - S_R \approx 3,1416 - 1,4115 \approx 1,73$$

.

$$SAT = \frac{S_R}{S_L} = \frac{1,4115}{1,73} \approx 0,816. \tag{19}$$

2.3. Active response to the deterioration of environmental factors

An active form of economic behavior in the face of an increase in the negative impact of external factors involves actions aimed at eliminating the consequences of such an impact while maintaining overall resources and the level of satisfaction. Such economic behavior ensures the sustainable development of the system as a whole.

Such economic behavior implies an active participation in reducing the deterioration of environmental factors. For households, this implies direct participation in the use and promotion of such technologies for individual use as home treatment facilities [26], household biogas systems [27], etc.

From the point of view of the proposed economic and mathematical model, an active form of economic behavior leads to an increase in the value of the moment of the economic dipole m, at which the shape and size of the "stability zone" is preserved.

To quantify the change in the economic dipole moment m, we use relation (11). When the negative impact of external factors doubles relative to the initial $V_\infty = 0,16$ and $r_s = 1$, the moment of the economic dipole m should also double and equal $m = 2$. Such an increase implies the use of technologies that allow more efficient use of available resources, innovative technologies.

3. Conclusions

1. The proposed approach to modeling the formation of economic behavior has been successfully tested in the space of states, in which the state of the socio-economic system is determined by a combination of spatial and energy indicators. The formation of flows is provided by motivation to maintain a stable balance between the processes of interaction of the socio-economic system with the external environment.
2. Models of economic behavior are built in the form of linear combinations of such elements as economic source, economic sink, economic dipole, external influence. Models of economic behavior are built for various states of the internal and external environment, in conditions of stability and the strengthening of the negative influence of environmental factors, the formation of passive, reactive and active forms of economic behavior.
3. A study of the properties of the proposed models showed that the adaptation of an economic entity is accompanied by the emergence of processes of self-organization of material and information flows.
4. It is shown that the most effective in terms of satisfaction and availability of resources is the active economic behavior of responding to the deterioration of environmental factors. This is consistent with the concept of sustainable development.
5. The constructed model is normative and does not allow studying transient processes in the formation of economic behavior. But the proposed method allows us to evaluate the relative changes in such quantitative and qualitative indicators as opportunities, motivation, satisfaction. It also makes it possible to establish and investigate cause-and-effect relationships in the formation of economic behavior in the context of sustainable development.

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To cite this article: O M Korchuganova *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012042

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012042 doi:10.1088/1755-1315/1049/1/012042

The wastes of Luhansk region chemical and energy enterprises and their impact on the environment

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Abstract. The chemical and energy industries are one of the most powerful generators of solid industrial waste. Such enterprises have water treatment plants. The result of the water treatment process is the formation of a water treatment sludge. The sludge composition includes carbonates and hydroxides of calcium, magnesium, iron, aluminum, and coagulated natural organic materials. A significant amount of waste in the form of fly ash and fuel slag is generated in the process of burning coal at power plants. Such wastes are usually classified as "low-risk". Nevertheless, when wastes are stored in the storage, they create environmental and economic problems. Large areas of land are alienated for storage. Dust emissions and filtration losses are observed in the process of waste storage. The wastes impact of the Luhansk region enterprises on the environment has been studied. Waste storage facilities are located on the left bank of the Seversky Donets River in the zone of Dnieper-Donetsk structure articulation and the Voronezh anteclise. Features of the territory geological environment are explained by the presence of geological disturbances, loamy-sandy and carbonate rocks, manifestations of carbonate karst. The wastes degrade the quality of surface and ground waters used for water supply in the region.

1. Introduction

The most powerful generators of solid industrial waste after mining are the chemical and energy industries. Very often they form a significant amount of waste very similar in chemical composition and hazard classification kind. Thus, powerful water treatment plants operate at chemical and thermal power plants. Chemical companies are the largest consumers of water, the average cost of which is about 1 million m^3/day. Water is used as a component of raw materials and a reaction medium, for heating or cooling of reagents. The most common industrial use of water in heat exchange equipment for steam production and in cooling water systems requires low alkalinity and hardness [1].

Raw water that enters the plant is treated, primarily by chemical reagents. Reagent softening of water is based on its treatment with substances that bind Ca^{2+} and Mg^{2+} ions in water. Lime, soda ash, and other substances are used as water softeners. During this process [1] a large amount of wastewater is formed, which is called sludge water. The sludge enters the sludge storage in the form of "sludge" water. The solid substances are sedimented. The upper layer of water is pumped for further water treatment, and the sludge deposits and accumulates until the sludge storage is full.

The same sludge is formed not only at chemical enterprises but also at power plants. When stored in storage, sludge creates environmental and economic problems. Given the operation age and obsolescence of engineering equipment, it should be noted that filtration from such facilities is 10-25 % of the water supply. The components of the liming sludge are able to leach into the natural environment due to the increased pH value in the sludge storage and filtrate from it [2]. The high alkalinity of water in the process of liming is maintained to ensure the efficiency of further water purification [3]. Because sludge storages are an integral part of water treatment plants, they need to be released and restored.

The composition of the sludge mainly includes carbonates and hydroxides of calcium, magnesium, iron, aluminum, coagulated organic impurities. Such wastes are usually classified as "low-risk", but nevertheless, when stored in dumps, the sludge affects the environment [4].

The largest power plant in the region is the Luhansk Thermal Power Plant (TPP) in the town of Shchastya. In the coal burning at the power plant, a significant amount of waste is generated in the form of fly ash and fuel slag. Ash and fuel slag are mixed with water treatment waste and disposed of in so-called ash slag dumps, such waste is also classified as "low risk".

Despite the relative safety, the methods of waste processing proposed in scientific publications are quite diverse. In almost all developments, the organic component plays the role of ballast or harmful impurities. In order to develop effective methods of waste disposal, information on organic impurity content is required. The source of organic impurities is river water. The quantitative and qualitative composition of impurities in storage depends on meteorological conditions and seasonal fluctuations. Thus, in the spring flood period, after the ice melts, the water contains a minimum amount of soluble salts and is characterized by the maximum amount of suspended solids that are captured from the soil surface by rapid flows of meltwater. In summer, the composition of annual water is determined by the ratio of the share of surface and groundwater runoff.

Organic impurities include humic substances leached from soils and peatlands, as well as organic substances of various types that enter the water together with agricultural effluents and other types of insufficiently treated effluents. Most scientific research in recent years has identified organic impurities in the water as natural organic matter (NOM), which is characterized as a complex matrix of organic materials present in natural waters. The amount, nature, and properties of NOM differ significantly in waters of different origins and depend on the biogeochemical cycles of the environment [2]. Organic impurities in various water bodies that are sources of drinking or industrial water supply are studied quite often. However, NOM studies that have been included in the sludge, especially their transformation in waste storage processes have not been studied. To control this parameter, it is necessary to develop methods for analyzing the organic component of sludge. The chemical composition of the Seversky Donets river changes significantly depending on the predominant in their balance of waters of different origin categories (surface-slope, soil-surface, etc) [5]. Seasonal fluctuations in the chemical composition of water could necessitate some changes in water treatment processes. Thus, in the water treatment plant of Severodonetsk "Azot" in the spring, when the content of colloidal particles in the water is increased, aluminum sulfate is used as a coagulant instead of iron sulfate.

Luhansk TPP uses coal for energy production, during the combustion of which ash is formed. For the last two decades, fly ash used as an industrial product has received special attention. In [6] the possibilities of using coal ash as raw material are considered: as a reclamation agent in agriculture, in the production of glass and ceramics, in the production of zeolites, in the formation of mesoporous materials, in the synthesis of geopolymers, for use in catalysts and catalyst carriers, as an adsorbent for processes of gases and sewage, as well as for the extraction of metals. It was found that there is significant potential to increase the utilization of coal ash such as row and purified. Unfortunately, in the case of Luhansk TPP, the proposed methods

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012042 doi:10.1088/1755-1315/1049/1/012042

are unsuitable due to the co-storage of ash, slag, and sludge from water treatment.

Another large accumulation of waste in the Luhansk region, which belongs to the 4th class of danger is the famous "white seas" of OJSC "Lysychanska Soda". The company no longer produces products, and waste remains. Solid waste from the soda production process using Solvay technology is formed as a result of the distillation of ammonia from the pregnant liquid. The solid part of the distillery suspension mainly comes from the lime, which is maintained in excess, which can ensure the complete decomposition of NH_4Cl. Solid wastes contain calcium carbonate, calcium sulfate, magnesium hydroxide, calcium hydroxide, silica, and alumina. The average solids amount of the distiller effluent is estimated at 240 kg/t of soda ash [7].

All these types of waste are characterized except the hazard class, a significant content of water-soluble calcium compounds, alkaline reaction, and the location of their storages in the immediate vicinity of the largest waterway in the region Seversky Donets River. In the described territory, these enterprises and their waste storage facilities are the largest agents of man-made impact on the geological environment and its components. The groundwater of the Cretaceous-marl aquifer, which is the most important source of drinking water supply for the population of the region, was most affected In addition, the placement of slug and ash storages of enterprises on the area of natural-historical karst process in Cretaceous-marl rocks of the Upper Cretaceous period contributed to karst activation and creation of conditions for the development of man-made karst. It creates a significant threat to the population's health.

The main threats associated with industrial waste storage and ash dumps of thermal power plants are the alienation of large areas of land, hydrochemical and thermal pollution of groundwater and surface water, intensification of exogenous geological processes. Water pollution can occur both due to filtration losses of industrial effluents from storage facilities and due to unauthorized discharge of industrial waste into water bodies due to upfilling storage tanks, as well as overflow of liquid waste through dams with significant water rise located near water bodies due to abnormal floods. Pollution of components of the geological environment can also occur due to sawing of ash dumps, which are especially relevant for cogeneration thermal power plants, which are located either within or in the immediate vicinity of settlements.

2. Materials and methods

The number of landfills, their area, and location, owners of landfills was determined by the registers of waste disposal sites in the Luhansk region [8].

2.1. Samples preparation

Two samples of sludge from the decarbonization department of PJSC Severodonetsk Association "Azot" was used for the research of sludge chemical composition: one was selected immediately after the process and the second was stored in sludge storage for several years. The precipitates formed during the whole operation time consist of water softening products and coagulation products - $CaCO_3$, $Mg(OH)_2$, $Ca(OH)_2$, $Fe(OH)_2$, $CaSO_4$, $Al(OH)_3$, $Fe(OH)_3$, and organic components. The precipitates that were selected immediately after the process did not contain $Al(OH)_3$, because at that season only iron (II) sulfate was used as a coagulant. Iron (III) hydroxide, aluminum hydroxide and the organic component are included in the sediment due to the coagulation process. Soluble organic compounds, usually present in water, are humic acids - a mixture of macromolecular compounds that contain various functional groups. They interact with coagulants and precipitate in the process of liming-coagulation at a pH value >10.

Humic substances of natural waters are divided into three groups:

- humic acids, which are usually found in water bodies in colloidal form;
- colloidal compounds of fulvic acids;
- dissolved fulvic acid compounds [9].

To determine the chemical composition of water treatment waste, sludge samples were taken after centrifugation, which reduces the moisture content of sludge in the summer and directly from the sludge storage. Therefore, the first sample was not stored in the sludge storage, the second was stored for several years and can be defined as an averaged sample. To analyze the chemical composition of the sludge sample was fined, dried to constant weight at 100 ℃, weighed on an analytical balance to the nearest 0,0001 g, and dissolved in a mixture (3:1) of hydrochloric and nitric acids. The solutions were transferred to 50 ml volumetric flasks. The solution volume was made up to 50 ml with distilled water.

2.2. Samples examination
Calcium and iron content was determined by the titrations based on complexation reactions. In addition to the content of inorganic substances, the content of organic matter was determined. The organic component was analyzed as organic carbon by a method based on the organic carbon oxidation by potassium dichromate proposed in [10]. The method of analysis is based on the following: organic compounds are decomposed by a mixture of potassium dichromate solutions and sulfuric acid when heated, and the residue of dichromate is titrated with a solution Mohr salt. Because iron ions are present in the solution, the use of phenanthroline as an indicator is not suitable.

It was proposed to modify the method: after the decomposition of organic compounds to bind iron ions in the complex with phosphoric acid, and apply reverse titration of the residue of potassium dichromate with Mohr salt, in the presence of Diphenylamine indicator.

2.3. Environmental assessment
To study the waste storage effects on the geological environment an approach was used, which includes integrated processing and analysis of databases of geological and hydrological-hydrogeological information, laboratory and mathematical modeling. Information on groundwater pollution was obtained by sampling from observational wells located at landfills. Proven and approved methods and techniques, in particular, chemical methods of analysis were used in the process of laboratory research. Processing of the obtained results was carried out using the methods of mathematical statistics.

3. Results and Discussion
Information of wastes was determined by registers [8] is presented in table 1.

The largest in area and mass are ash and slag dumps - waste containing slag and ash from coal combustion. Fly ash is captured with the help of various gas scrubbers, the vast majority of coal-fired power plants have installed hydro-ash removal systems, which were built in Soviet times. Ash and slag dumps, account for up to 90% of all waste, depending on the ash content of a particular brand of coal and the characteristics of the combustion process. Ash is a fine material and consists of particles with a size of 0.1-0.005 mm, the particle size of the slag 20-30 mm. The chemical composition of ash and slag waste depends on the mineral composition of the fuel and varies depending on the coal deposits. The content of oxides in ash and slag waste: SiO_2 37-63%, Al_2O_3 9-37%, Fe_2O_3 4-17%, CaO 1-32%, MgO 0,1-5%, SO_3 0,05-2,5%. In the ash there is unburned fuel up to 6-7% to 25%, in the slag, as a rule, it is absent. Elements such as Ti, K, Na are present in small quantities. In some coals, there are even precious metals: Au, Ag, Pt, liquid, and scattered elements. Fly ash has unique adsorption and binder properties that can be used in wastewater treatment of various compositions and origins [11].

Most often, ash and slag are not separated at Ukrainian thermal power plants. The maximum amount of water-soluble impurities is given by ash. The solubility of slag components is so low that it characterizes it as a substance that does not have any contaminating effect. Water treatment waste is also dumped in ash dumps.

Table 1. The largest landfills in Luhansk region.

Landfill owner	Denomination	Coordinates	Total amount, t	Total area, ha	Distance from landfill to the Seversky Donets River, km
		Severodonetsk			
PJSC "Severodonetsk Association Azot"	Sludge storage of decarbonization station	48.924303, 38.471735	208286,7	8,065	1,4
	Sludge storage of industrial sewage	48.924303, 38.471735	648777,7	13,6	1,4
	Sludge storage of physical-chemical cleaning	48.924303, 38.471735	55548,38	13,6	1,4
	Sludge storage №2	48.924303, 38.471735	1353,600	1,8	1,2
"Severodonetsk TPP"	Sludge storage	48,923532, 38,469084	37366,90	4,72	1,2
	Ash dump	48,924321, 38,463677	4027500	33,64	1,2
		Shchastia			
Luhansk Thermal Power Plant	Ash dump №1	48.779881, 39,266604	16000000	879	2,3
	Ash dump №2	48.779881, 39,266604	26440000	84,6	2,3
	Section № 6 of Ash dump №2	48.769198; 39.257924	2085999,6	5,73	2,88
	Ash dump №3	48.779972; 39.261684	10789932,4	96,36	2,4
		Lysychansk			
OJSC "Lysychanska Soda"	Storage of industrial effluents №3	48.891345, 38.490663	1,079 million t	23	0,6
	Storage of industrial effluents №2	48.891984, 38.493092	3,5 million t	50	0,8
	Storage of industrial effluents №4	48.892451, 38.495245	4,13 million t	60	0,95

Water treatment wastes are formed in chemical and energy enterprises and have similar chemical compositions. Waste from the decarbonization department of PJSC Severodonetsk Association "Azot" was analyzed, the results of the analysis are presented in table 2.

Therefore, the chemical composition of water treatment sludge is quite stable. Because sample 2 was taken in the summer when iron (II) sulfate was used as a coagulant at the plant, the iron content was slightly higher. Sample 1 was taken directly from the storage, so it also contains the precipitate obtained in the spring, when the coagulant used aluminum sulfate. The amount of organic carbon in the accumulated sludge is due to natural causes - the biological growth of natural material that comes with river water. The hydroxide content is reduced due to the absorption of CO_2 from the air.

Table 2. The content of the main components of waste water treatment,% wt.

Component	CaO	MgO	CO_2	$Fe(OH)_2$	Organic carbon	Hydroxides, water and etc
Sample 1	38,41	17,65	34,51	0,80	0,80	7,83
Sample 2	44,10	5,50	16,50	1,87	0,47	31,56

According to OJSC "Lysychanska Soda" [12], the amount and chemical composition of the solid part of the sludge entering the sludge storage was determined. For the years of operation, the liquid part of the distillery liquid had been dumped into the Seversky Donets River during the flood. Thus, about 12.7 thousand tons of sludge were formed and placed annually in sludge storage facilities. The sludge consists of 19.5% calcium chloride, 23.5% sodium chloride, 4.8% ammonium chloride. The storage №1 is not present in the list, its age is more than 100 years, the drive has been reclaimed.

The locations of all the studied objects have an eastern geological structure, which allows us to identify common features of their impact on the geological environment.

The enterprise PJSC "Severodonetsk Association Azot", its storage facilities, as well as sludge storage facilities of OJSC "Lysychanska Soda" and ash dumps of the Severodonetsk TPP are located on the territory of Lysychansk-Rubizhnoye Mining District, which involves the middle reaches of the Siversky Donets River. The ash dumps of Luhansk TPP are located down stream. All the objects are located on the sandy terraces of the left bank of the Seversky Donets in the territory which in geological and structural terms belongs to the Starobilsk-Millerovo monocline of the southern wing of the Voronezh anteclise. This is a zone of articulation of two large structures of different ages - the ancient Eastern European platform and the Donetsk folded structure of the Hercynian age. The structure is complicated by the system of brachianticlinal folds, and in the area of Lysychansk-Rubizhnoye mining district also by the system of tectonic disturbances - regional (Severodonetsk and Krasnoretsk tectonic faults) and accompanying tectonic disturbances of the 2nd and 3rd order create favorable conditions for the migration of pollutants.

In the zone of active water exchange, there are three aquifers developed - technogenic-alluvial and alluvial of sporadic distribution and an aquifer of the fissured-karst zone of the Upper Cretaceous chalk-marl deposits, which is widespread. The geological and hydrogeological section is represented by bulk soils with up to 2 - 3 m thick, well-permeable Quaternary sandy-argillaceous deposit with thikness of 0 to 30 m, and a chalk-marl deposit with a thickness of 200-250 m.

Aquifers are hydraulically connected with each other and with the surface waters of the Seversky Donets River and its tributaries. Hydraulic communication with surface waters in most cases also has a negative impact on groundwater quality.

Large reserves of Cretaceous waters, their good quality, and usable conditions determine the Cretaceous-marl aquifer as the main source of local and centralized water supply. In addition, due to the low capacity and high permeability of alluvial deposits, it does not have natural protection against pollution, which led to its depletion and deterioration of water quality in large areas.

Areas of groundwater contamination of the Cretaceous-marl aquifer in the area affected by the storages of PJSC "Severodonetsk Association Azot" have been observed since 1976 - the time of the beginning of observations at the Rubizhnoye - Lysychansk Research and Production Site. They were formed as a result of the operation of industrial sites, storage ponds of PJSC "Severodonetsk Association Azot" and OJSC "Lysychanska Soda" and the accompanying filtration of highly mineralized and polluted wastewater into groundwater aquifers. Filtration losses through the destroyed sections of the dams and possibly the bottom of the storages are estimated to be quite significant and averaged 20-25% of the volume of effluent entering the storage.

Many years of intensive exploitation of groundwater of the Upper Cretaceous horizon by water intakes: Shchedryshchevsky, Novosyrotynsky (now liquidated), "Lisova Dacha", Borivsky-I contributed to the spread of pollution not only downstream but also in the opposite direction. As a result, a significant area of groundwater pollution was formed in the described area.

A stable center of chemical and thermal pollution of groundwater has formed around the storages of OJSC "Lysychanska soda" due to long-term filtration of highly mineralized effluents. The main pollutants in the source of pollution are chlorides, as well as ammonium and iron, the concentrations of which in groundwater in the tens and hundreds of times higher MPC. Analysis of the hydrochemical characteristics of groundwater of the Cretaceous-marl horizon in the perennial section shows a heterogeneous change in their quality in area and depth.

As a result of gravitational differentiation and pollution by man-made solutions of fresh water within the dome of spreading in depth, two zones were formed:

- zone of partial pollution to a depth of 35-40 m of water with a dry residue of 0.2-1.0 g/dm^3;
- below – zone of complete pollution with the spread of groundwater with a dry residue up to 10-40 g/dm^3.

The total penetration depth of man-made solutions is 80-90 m. The groundwater temperature of the Upper Cretaceous aquifer in the area of the reservoir is 1.1-1.6 °C higher than the background values of 8-9 °C. Long-term operation of the fractured karst aquifer by five water intakes located around the "Lysychanska Soda" storage facility has led to a significant change in the hydrodynamic conditions of the fractured karst aquifer and intensification of man-made solutions leakage in the aquifer. Pollution of ground karst waters and changes in their hydrodynamic and geotetemperature regime has led to more than a tenfold increase in the rate of dissolution of chalk-marl rocks [13].

The results of the groundwater monitoring conducted in 2019 show that despite the closure of "Lysychanska Soda", its storage facilities continue to pose a threat to the geological environment. Thus, according to the results of hydromonitoring in the area of storage facilities of the former enterprise in 2019, as in previous years, areas of groundwater pollution were identified by various ingredients: phenols, nitrogen compounds, iron compounds, chlorides, heavy metals (manganese, lead). For some components, there is a hundredfold excess of the MPC (iron). The highest concentrations of pollutants were found in the southern contour of the reservoirs, ie downstream. Most of the pollution sites are local in nature, but, of course, all of them are derived from the presence in this area of a real source of pollution - the above-mentioned storage ponds.

As of 2019, in the area of sludge storages operation of Severodonetsk TPP and PJSC Severodonetsk "Azot", located next to the "Lysychanska soda" storage, groundwater aquifer marl-chalk stratum are most highly mineralized - dry residual 87.5 MPC). The value was observed below the sludge accumulators near the Seversky Donets riverbed. The maximum content of chlorides (159 MPC), manganese (56.4 MPC), lithium (19.3 MPC), lead (10.0 MPC) was observed here. The highest content of ammonium (21.1 MPC), nitrites (15.5 MPC), nitrates (4.7 MPC) was determined in the observation wells in the area of the buffer pond and sludge storage of TPP.

In the area below the industrial site of PJSC "Severodonetsk Azot", between it and the Seversky Donets river groundwater of the Upper Cretaceous has almost the maximum indicators of the all components content. Values were observed in wells №№ 82k, 51k, 68k, located 0.75-

1.0 km west of the industrial site and affected by the residual contamination of groundwater of the Upper Cretaceous with brines of the "Lysychanska Soda" storages.

An analysis of long-term test data shows that since 1998 groundwater abstraction from the Upper Cretaceous aquifer has decreased by 5-6 times. Therefore, modern sources of pollution are outside the depression funnels of existing water intakes. Contours of pollution sources are not extended by water intakes in directions opposite to the natural flow of groundwater, but are formed naturally. Despite this, the threat of toxic compounds entering drinking water remains. In general, the following types of pollution are typical for the zone of impact of the above objects on groundwater: salt, ammonia, iron compounds, phenol. Sometimes exceeding the maximum allowable concentration reaches tens or even hundreds of times. The conditions conducive to the intensification of the chalky-marl karst process also remain.

The results of groundwater status regime monitoring in the area of influence of Luhansk TPP indicate that the main sources of impact on groundwater and surface water in this area are ash dumps, industrial sites, and smoke emissions. Within the industrial site, there are a number of facilities (fuel oil and fuel storage, coal storage), which can be considered as local sources of groundwater pollution.

As of 2017, the groundwater of Quaternary alluvium in the area of Luhansk TPP influence exceeded in terms of macro indicators, groups of nitrogen compounds, some trace elements, and organic compounds. Groundwater with high salt content was observed in the area of the industrial site, ash dumps, and drainage ditches. In general, the most polluted groundwater is common in the area of ash dumps № 2 and № 3, drainage ditch, and industrial site of Luhansk TPP. This situation has been observed for many years [14]. Additional sources of pollution are waste from other parts of the plant, such as used lead-acid batteries and fluorescent lamps. Due to the course of chemical reactions during operation, corrosion processes, and the destruction of the batteries cases, sulfuric acid, and lead compounds are released into the environment. As for fluorescent lamps, they contain about 6% phosphor and mercury. Depending on the type, each lamp contains 5 to 500 mg of mercury. Once in the landfill and then in groundwater, the phosphor turns into a more dangerous stable compound - methylmercury.

4. Conclusions

In general, industrial waste storage facilities and ash dumps of TPPs are undoubtedly a source of pollution and disturbance of the geological environment and its components in any area. But they pose a significant threat in areas close to river protection zones and in areas of groundwater deposits and geological development zones. An important role is played by the presence of conditions conducive to the natural protection of the geological environment. It is a matter of concern that groundwater contaminated with salts, heavy metals and phenols is widespread in the immediate vicinity of drinking water intakes, posing a threat to public health. And the launch of processes in karst massifs when mixing man-made solutions with natural waters can lead to a 10-fold increase in karst denudation and lead to the transfer of these processes from the category of potentially dangerous to the category of emergencies that can cause significant material and people health damage.

To reduce the impact on the environment methods are developed and offered in numerous scientific publications. So, for processing of sludge of water treatment the following methods are offered:

1) Recycling of coagulants, which is usually acidic leaching of iron or aluminum compounds and subsequent separation of the mixed solution. In [15] it is proposed to perform separation using ion exchange resins. The authors of [16] tried to reduce the use of fresh coagulants by adding sludge to the coagulation process.

2) The use of sludge as raw material for building materials - bricks and cement. As sludge from water treatment is not identical in composition to natural raw materials, most publications

suggest using it as an additional component to other raw materials. In [17] the possibility of making low-porosity ceramic bricks with the addition of lime sludge to clay was investigated. In works [18, 19] it is proposed to obtain bricks with the addition of water treatment sludge. The authors of the paper [20] propose to use calcined waste for the purpose of burning the organic component. In [21], waste was used to partially replace shale clay in brick production.

3) The use of sludge in the natural environment for the application to the soil to reduce acidity [22], or in the man-made environment to improve wastewater treatment [23][13].

The proposals for the solid waste disposal of the Solvay process are quite diverse: for the neutralization of acid soils, the production of binders, Portland cement, alunite cement, concrete blocks, bricks, and roads.

In developed countries, ash slag is generally called a by-product of thermal power plants. Power plants carry out pre-sale preparation of the product, bringing its characteristics to the requirements of official regulations. In Western Europe and Japan, ash dumps have been virtually eliminated at thermal power plants. Fly ash enters the silos built next to the main buildings of the TPP. For example, in Germany at many power plants, the capacity of silos is 40-60 thousand tons, from which samples are taken for laboratory analysis of ash, and in which it is brought to compliance with regulatory requirements. Germany has the largest ash company on the European continent, Bau Mineral (BM), a subsidiary of the power system. This company is a link between thermal power plants and the construction industry. BM has its own system of transportation and storage of TPP by-products. Areas of use: additives in concrete, mortar, cement, silicate products, brick production, underground, and road construction. In Ukraine, ash slag, unfortunately, is officially called waste, and power plants offer consumers just waste, not a technologically advanced product. Ash slag from dumps have high humidity and are not classified by chemical and particle size distribution.

Acknowledgments
The authors express their sincere gratitude to the Department of Ecology and Natural Resources and the Department of Industry, Transport, and Communications of the Luhansk Regional Civil-Military Administration for their assistance in obtaining the necessary information.

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IOP Conference Series: Earth and Environmental Science

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To cite this article: T P Ostapchuk *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012043

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012043 doi:10.1088/1755-1315/1049/1/012043

Conceptual foundations of the mechanism of management of enterprise interaction with environment

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Abstract. The environment plays an important role in shaping the living conditions of local communities, and the state of the environment determines the opportunities for achieving the goals of sustainable development. The purpose of the article is to provide further development of the conceptual foundations of the mechanism of management of enterprise interaction with environment. The authors formed an approach to structuring the mechanism of management of enterprise interaction with environment, considering economic, environmental, and adaptive components. For practical approbation of individual components of the proposed mechanism in a part of the instrumental block the ways of decreasing the negative impact of the enterprise on level of pollution of the atmosphere as of a component of environment were considered. The constructed correlation and regression model for determining the impact of individual pollutant emissions on the overall state of air pollution formed a basis for identification of two most significant types of emissions (carbon monoxide emissions and emissions of non-methane volatile organic compounds). Based on the analysis of ME "Zhytomyrvodokanal" data, whose activities are related to the waste generation and management and which, at the same time, provides environmental services, the measures were proposed to decrease the corresponding emissions from the enterprise activities.

1. Introduction

The modern world is characterized by the emergence of a significant number of challenges that affect the living conditions of the population, determine the prospects for socio-economic relations development both within a country and around the world. One of the most important challenges are those related to the ecology and the environment state. Recent decades have been characterized by rapid industrial development and, at the same time, deteriorating environmental conditions. The growth of production, negative anthropogenic impact, transportation – these and other factors cause significant negative impact on the environment, which, in turn, leads to worsening ecology condition, climate changes, negative impact on people's living conditions and health. It is worth noting that such negative trends are significantly intensifying and becoming a hazardous situation for humanity. All this necessitates the implementation of economic entities functioning mechanisms built on the principles of sustainable development. The implementation of the sustainable development concept provides an opportunity to harmonize the economic aspects of the business entities functioning with ecological and social components that determine the impact on the environment.

The environment determines the conditions of living and activities of local communities, significantly influencing the set of parameters that are related to the sustainable development goals (SDGs). In particular, the state of the environment directly determines the possibilities of achieving such sustainable development goals as SDG 2 “Zero hunger”, SDG 3 “Good health and well-being”, SDG 6 “Clean water and sanitation”, SDG 7 “Affordable and clean energy”, SDG 12 “Responsible consumption and production”, SDG 13 “Climate action”, SDG 14 “Life below water”, SDG 15 “Life on land” [1]. It is clear that the state of the environment affects the achievement of other sustainable development goals, but those mentioned above depend on the parameters of the environment greatly.

Like other UN member states, Ukraine has joined the process of implementing the sustainable development goals. In the process of consultations at both the national and regional levels, the SDGs were adapted to the realities of Ukraine.

This confirms the need for urgent implementation of measures aimed at reducing the negative impact of economic entities on the environment. It is expedient to implement this task through the mechanism of management of interaction with environment.

The mechanism of management of enterprise interaction with environment is a set of methods, levers, tools, and means of influencing the processes of interaction of the entity with environmental factors. The formation of such an effective mechanism determines the possibility of reducing the negative impact of economic entities on the environment, as well as the introduction of the concept of sustainable development in the enterprise activity. Therefore, the formation and development of a mechanism of management of enterprise interaction with environment is an important scientific and practical task, the success of which affects the future of society as a whole.

2. Literature review

The importance of a defined set of problems in terms of ensuring the harmonious development and safe living conditions of society, reducing the negative footprint of economic entities on the environment leads to significant scientific interest in this field of research, which has grown significantly in recent years.

An important role in the formation of theoretical foundations of environmental management and sustainable development is played by the study of previous scientific achievements. In particular, the study of J. F. Molina-Azorin et al. [2] focuses on the relationship between environmental management, human resource management, and “green” human resource management based on the analysis of scientific publications. Researchers identify the need to distinguish between the concepts of human resource management and “green” human resource management and emphasize the importance of involving individual employees in the overall environmental policy of the enterprise. The research of S. Roohy Gohar M. Indulska [3] is devoted to the peculiarities of achieving the goals of sustainable development through business process management. The paper analyzes the publishing activity in the scientific literature on the role of information systems and business process management in ensuring the sustainability of business entities. The authors analyze the level of development of the concept of green business process management in the scientific literature.

Peculiarities of the company’s interaction with the environment are the subject of environmental management research. V. Pechancová et al. [4] determine that the implementation of environmental management systems and “green” tools is becoming an urgent task for economic entities, due to both legislative and social factors. The authors study the peculiarities of the implementation and realization of environmental management systems at the enterprises of the Czech Republic with a key emphasis on medium and large enterprises.

P. T. Huong et al. [5] determine the features of the implementation of "green innovations" in the context of environmental management and investigate the impact of the implementation of such innovations on the activities and performance indicators of the enterprise. Scientists have proven that there is a relationship between the implementation of environmentally friendly measures and the efficiency of economic entities.

In the research of M. Lemkowska and D. Wiśniewska [6] the features of the combination of environmental insurance and environmental management systems are considered using correlation analysis.

G. Jilani et al. [7] emphasize the need to apply both a complex and individual approach. Researchers have identified the relationship between corporate social responsibility and the environmental behavior of individuals on the example of Pakistan. The main attention is paid to the non-business component, in particular, the formation of pro-environmental behavior of students under the influence of corporate social responsibility.

An important role in the set of issues of environmental management and management of interaction with environment is played by waste management. In particular, a group of authors led by G. Salvia [8] consider the peculiarities of stakeholders interaction in the waste management process on the example of Kenyan city Kisumu. The authors apply the attention-based view from organization theory to define the key problems in the relevant sphere and ways of their solving. I. Kolodiichuk and V. Kolodiichuk [9] examine the waste management system on the example of Ukraine. On the statistical data basis, the scientists propose to use the coefficient of territorial security of utilization capacity which enables the analysis of the waste disposal capacity in the territorial aspect. The authors also suggest the stages of solving the waste problem in Ukraine. N. Bulavinova et al. [10] have analyzed main trends in research of responsible investment in the context of sustainable development, which are directly connected to current problems of management of enterprise interaction with the environment.

The research of G. Qian et al. [11] is conducted from the hazard analysis standpoint. The research emphasizes the fact that sustainable management of waste and related hazards is a triune function of efforts from government, communities, and individuals. The paper analyzes the hazards from pollution according to different sources and defines the appropriate strategies of such hazards minimization.

Recognizing the importance of scientific and practical results obtained by these and other researchers, we should note that the complexity of the problems associated with ensuring effective interaction of the enterprise with the environment, the fragmentation of the relevant mechanism determine the relevance of this article.

3. Objective of the research

The purpose of the article is to provide further development of the conceptual foundations of the mechanism of management of enterprise interaction with environment. An appropriate mechanism of management of enterprise interaction with environment will not only increase the environmental orientation and social responsibility of the economic entity, but also will provide a positive impact on the formation of financial results by reducing unproductive expenses of environmental orientation. The defined objective involves solving the following tasks: identification of structural components of the relevant mechanism of interaction and their characteristics; practical approbation of individual components of the defined mechanism, in particular, in a part of its instruments; offering measures (instruments) for ME "Zhytomyrvodokanal" in order to reduce the negative anthropogenic impact of the enterprise on the environment.

4. Methodology

The basis of the research is a systematic approach, which involves considering the management of the enterprise interaction with environment as a complex polystructural process, integrated into the overall management system of the enterprise. For solving the tasks of the research, the following methods were used: monographic, logical, classification, methods of analysis and generalization – to identify the structure of the mechanism of management of enterprise interaction with environment, drawing conclusions; statistical method and method of constructing distribution series and time series – to form a database for research; method of correlation and regression analysis – to form a model of the impact of individual pollutants emissions on the overall rate of air pollution; methods of analysis and synthesis, the method of scientific deduction – to determine measures (instruments) for reducing the negative impact of ME "Zhytomyrvodokanal" on the environment; graphic and tabular methods – to illustrate the results of the research.

5. Results of the research

The problem of organizing the interaction of enterprises with the environment on the basis of integrity, sustainability, and holism today is one of the most urgent given the role of the environment in shaping the living conditions of people. The environment forms a direct impact on people's health condition, and the climatic changes (which are the result of negative anthropogenic impact on the environment) have threatening consequences for the future of both individual countries and the planet as a whole. The growing concern of the world scientific community about the state of ecology and the environment is explained by extremely negative trends in this area. These negative trends, in turn, require intensified efforts to implement the concept of sustainable development both at the macro level (global and individual countries) and at the micro level (individual enterprise level).

Solving the problems of sustainable development ensuring also requires involvement of individuals. It is clear, that the main negative impact as well as the biggest environmental efforts are in the sphere of responsibility of enterprises and organizations, however, it is individuals who are able to influence the activity of enterprises and organizations [7]. J. F. Molina-Azorin et al. on the basis of a considerable research of scientific publications also define the role of "green" human resources management which is understood as the coordination of traditional human resources management practices with the goals and tools of environmental management [2]. According to the authors, for companies seeking to implement the concept of environmental management, it is important to focus employees on achieving environmental goals, considering the environmental aspects of individual positions, and the introduction of environmental criteria in the motivation system [2].

We believe, that one of the most expedient and effective ways of ensuring the sustainable development concept implementation in the activity of individual economic entities is the development and practical approbation of a relevant mechanism of management of enterprise interaction with environment (figure 1).

The mechanism of management of enterprise interaction with environment is a complex polystructural and, at the same time, integral system of elements, the mutual action of which is aimed at minimizing the negative impact of the business entity on natural factors and, if possible, at the implementation of environmental measures. We believe that the main components of such a mechanism should be defined as following: program and target, instrumental and methodical, support blocks.

According to figure 1 we will specify the peculiarities of the mechanism of enterprise interaction with environment. Environment is an external element relative to the mechanism. The environment, on one hand, defines the economic entity functioning conditions, on the other hand – is exposed to anthropogenic impact due to the activities of the enterprise.

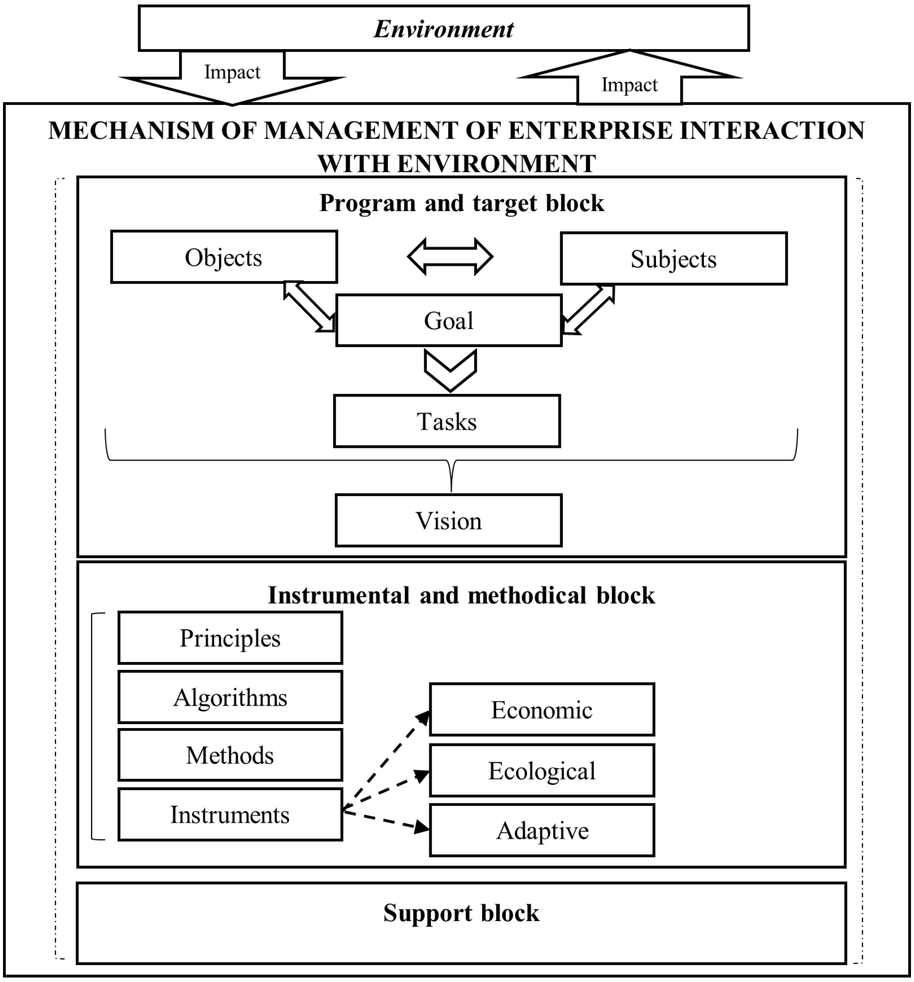

Figure 1. The structure of the mechanism of enterprise interaction with environment.

The internal structure of the mechanism of enterprise interaction with environment consists of three key components.

The program and target block defines the general orientation and basis of functioning of the mechanism of enterprise interaction with environment. The main components of this block are the following:

– objects (key phenomena and processes of economic activity);

– subjects (managers of all levels who perform functions and duties according to their position within the organization, thus, those individuals who are able to influence the sustainable and ecological oriented behavior of economic entity [7]);

– goal (ensuring optimal interaction of the enterprise with environmental factors in order to reduce the negative impact of the business entity on the environment);

– tasks (the tasks are defined according to the overall goal of the mechanism functioning and may include the following: estimating the factors of environment; analysis of the impact of enterprise on the condition of environment; defining the instruments and ways of implementation of enterprise environmental measures; ensuring the minimization of negative anthropogenic impact).

The mentioned components in the complex form the vision of the economic entity in relation to its interaction with environment. In this context we propose to understand vision as the state of interaction with environment and the image that the enterprise seeks to form as a positioning element.

Next block – the instrumental and methodical – includes principles, algorithms, methods, and instruments.

We consider it necessary to include the following key principles of the mechanism of management of enterprise interaction with environment:

– integrity and structuring;
– complexity and systematics;
– economy and substantiation;
– social responsibility and environmental friendliness;
– rationality and relevance.

These principles are not exhaustive and exclusive, at the same time, their observance in the process of organizing the interaction of the enterprise with the environment will increase the efficiency of the process.

Algorithms as a mechanism component include sets of actions which are appropriate to be undertaken in certain economic processes and / or operations. Such algorithms relative to enterprise interaction with environment should include:

– algorithm of estimating the state of environment factors;
– algorithm of estimating the enterprise impact on environmental factors;
– algorithm of substantiation of measures for ensuring the proactive interaction of the enterprise with environment;
– algorithm of estimating the measures efficiency.

We believe that the methods of ensuring the enterprise interaction with environment are expedient to be considered through the prism of classic management methods, namely economic, organization and administrative, social and psychological. Such approach is defined by the fact that management of enterprise interaction with environment is an integral component of the general management system of the enterprise, so it is based on the use of relevant methods.

The instruments of management of enterprise interaction with environment are the specific means of influencing the interaction processes. In our opinion it is advisable to identify the following three groups of instruments:

1) economic – are based on the use of market mechanisms, which are mediated by flows of financial resources. The key economic instruments in such context include: environmental payments; environmental taxes and fees; payments for resource use; penalties for environment pollution; environmental liability insurance, etc. It should be noted that environmental insurance is one of the most up-to-date and important instruments of environmental management which correlates with ISO 14001 standard [6];

2) ecological – involve the use of regulative and environmental mechanisms and include the emissions limits; means to reduce relevant emissions; waste management tools, etc.;

3) adaptive – are oriented on the ensuring the adaptation of the enterprise to the conditions of environment and may include a wide range of tools, the use of which is appropriate in certain economic operations (for example diversification, management "according to the weak signals", reengineering, etc.). The specific choice of adaptive instruments is defined by a great number of factors, such as environment condition, the degree of anthropogenic impact of the enterprise on environment, corporate culture and social responsibility of the enterprise, resource (in particular, financial) capabilities of the economic entity. V. Pechancová et al. define that the availability of resources is one of the most important factors of influence on the choice of environmental management instruments. According to the analysis conducted by the researchers it was revealed that the representatives of small business face the challenges while implementing the environmental practices due to the resource scarcity and absence of strategic thinking [4].

The last component of the mechanism of management of enterprise interaction with environment is the support block, which includes the resource support of managerial processes as well as of processes of proactive interaction with environment (the measures aimed at reducing the negative impact). The specific set of resources will vary under the influence of a great number of factors (for example, size and type of activity of the enterprise, its management structure, the scale of negative impact of environment, etc.). The most common resource groups that can be involved to the relevant mechanism are: human, financial, technical, organizational, informational, natural, etc.

The structure of the interaction mechanism proposed by the authors provides an opportunity to organize all the components of the relevant mechanism, which, in turn, will increase the efficiency of the respective processes.

Theoretically developed basis of the mechanism require empirical testing. Considering the proposed structure, we believe it is expedient to substantiate the instruments of enterprise interaction with environment using the empirical data. For the specific recommendations substantiation, we propose to use the enterprises which are quite peculiar in their activity in the process of interaction with environment. In particular, in further research we will orient on the economic entities whose activities are related to the generation and management of waste and which, at the same time, provide environmental services. Such choice is defined by the fact that the mentioned subjects are characterized by the double impact on the environment: positive from the perspective of environmental services provision and negative from the perspective of environment pollution with emissions.

One of the most important stages of management of enterprise interaction with environment is the substantiation of specific instruments for reducing the negative anthropogenic impact of enterprise activity on environment. Moreover, in the process of determining specific instruments from the standpoint of an individual entity, it is necessary to consider not only the impact of the entity on the environment, but also the general state of the environment to achieve maximum efficiency. We believe that the appropriate substantiation should be based on a factor approach, which allows to identify the most important factors of negative impact for a particular region and / or business entity.

The economic entities activity forms a negative impact on all the environment components: land, water, air, biological diversity. For the need of substantiation of instruments for efficient interaction we will consider the example of air pollution by emissions. In order to determine the priority measures to ensure the reduction of negative impact on the environment, we consider it appropriate to find out which emissions are the most significant from the point of view of air pollution by economic entities of Ukraine. In order to build a factor model, we use the indicator of pollutant emissions into the atmosphere from stationary sources of pollution by regions (TAP – total atmosphere pollution) as the dependent variable. The data is collected for year 2020 using the information of the State Statistics Service of Ukraine [12]. To take into account the level of concentration of pollutants, the emission indicator per 1 km^2 was determined. The emissions of metals and their compounds, substances in the form of suspended solid particles, nitrogen oxide, nitrogen dioxide, ammonia, sulfur dioxide, carbon monoxide, methane, non-methane volatile organic compounds, polyaromatic hydrocarbons, carbon dioxide into the atmosphere from stationary sources of pollution in 2020 were selected as independent variables ($X_1, \ldots, X_{11}$). The dependent and independent variables are given in table 1.

According to the calculated TAP indicator, the highest indicator of air pollution belongs to stationary sources of Donetsk region and of the city of Kyiv, which came out on top in terms of air pollution. Donetsk region is characterized by a significant content in the air of emissions of metals and their compounds, sulfur dioxide and carbon monoxide. The atmospheric air of Kyiv is saturated with emissions of particles suspended matters, nitrogen dioxide, non-methane volatile organic compounds, methane, and carbon dioxide. However, Kyiv region has a neutral

Table 1. Analysis of pollutant emissions in the atmosphere from stationary sources of pollution by regions of Ukraine in 2020*.

Regions	TAP	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
Vinnytsya	2.949	0.001	0.496	0.003	0.257	0.041	1.635	0.212	0.077	0.217	0.000	160.282
Volyn	0.252	0.000	0.077	0.002	0.026	0.004	0.015	0.060	0.013	0.048	0.000	22.925
Dnipropetrovsk	16.753	0.019	1.636	0.006	0.847	0.033	1.901	8.608	0.058	3.634	0.000	641.561
Donetsk	28.320	0.097	2.201	0.012	1.397	0.006	8.047	11.455	0.021	5.042	0.000	839.398
Zhytomyr	0.396	0.000	0.110	0.001	0.048	0.014	0.025	0.070	0.016	0.109	0.000	24.171
Zakarpattya	0.259	0.000	0.024	0.002	0.050	0.000	0.014	0.084	0.010	0.075	0.000	15.144
Zaporizhzhya	5.720	0.017	0.365	0.004	0.917	0.011	2.482	1.826	0.060	0.031	0.003	477.544
Ivano-Frankivsk	10.103	0.002	1.210	0.053	0.806	0.024	6.881	0.220	0.338	0.556	0.000	734.325
Kyiv	2.366	0.001	0.601	0.004	0.231	0.028	0.960	0.095	0.056	0.372	0.001	130.780
Kirovohrad	0.435	0.012	0.169	0.001	0.036	0.005	0.030	0.109	0.026	0.039	0.000	34.522
Luhansk	1.332	0.000	0.161	0.001	0.184	0.021	0.332	0.421	0.021	0.180	0.000	75.765
Lviv	3.482	0.001	0.295	0.005	0.253	0.010	1.005	0.179	0.092	1.635	0.000	135.961
Mykolayiv	0.455	0.011	0.109	0.002	0.100	0.005	0.019	0.066	0.018	0.116	0.000	85.098
Odesa	1.280	0.002	0.107	0.001	0.043	0.037	0.033	0.104	0.023	0.929	0.000	47.432
Poltava	1.594	0.001	0.250	0.002	0.293	0.022	0.098	0.329	0.394	0.201	0.000	55.284
Rivne	0.506	0.000	0.102	0.061	0.207	0.012	0.018	0.066	0.017	0.021	0.000	103.341
Sumy	0.878	0.002	0.105	0.001	0.092	0.015	0.135	0.265	0.061	0.194	0.000	54.345
Ternopil	0.686	0.000	0.099	0.001	0.064	0.066	0.025	0.118	0.022	0.289	0.000	35.260
Kharkiv	2.997	0.002	0.805	0.005	0.322	0.006	1.280	0.289	0.086	0.198	0.000	247.958
Kherson	0.625	0.000	0.033	0.000	0.012	0.005	0.020	0.027	0.011	0.516	0.000	11.566
Khmelnytskiy	0.881	0.001	0.109	0.004	0.250	0.031	0.075	0.256	0.050	0.100	0.000	111.190
Cherkasy	2.461	0.001	0.358	0.002	0.414	0.269	0.222	0.119	0.028	1.033	0.000	114.621
Chernivtsi	0.217	0.000	0.055	0.000	0.030	0.004	0.023	0.041	0.051	0.010	0.000	17.286
Chernihiv	0.656	0.000	0.093	0.001	0.072	0.072	0.062	0.063	0.043	0.249	0.000	42.867
Kyiv city	30.400	0.055	3.320	0.031	8.809	0.053	3.887	2.271	3.689	8.217	0.000	5462.486

*X_1 – emissions of metals of metals and their compounds, tons per 1 km; X_2 – emissions of particles suspended matters, tons per 1 km^2; X_3 – emissions of nitrogen oxide, tons per 1 km^2; X_4 – emissions of nitrogen dioxide, tons per 1 km^2; X_5 - ammonia emissions, tons per 1 km^2; X_6 – emissions of sulfur dioxide, tons per 1 km^2; X_7 – emissions of carbon monoxide, tons per 1 km^2; X_8 – emissions of non-methane volatile organic compounds, tons per 1 km^2; X_9 – emissions of methane, tons per 1 km^2; X_{10} – emissions of polyaromatic hydrocarbons, tons per 1 km^2; X_{11} – emissions of carbon dioxide, tons per 1 km^2
Source: State Statistics Service of Ukraine [12]

place among the other regions in terms of air pollution.

Among the leaders of the environmental rating on the minimum level of air pollution Zakarpattya and Kherson, Chernivtsi regions should be mentioned; Zhytomyr, Luhansk, Ternopil and Chernihiv regions can be referred to the second group of pollution in the ranking.

In terms of zonal stratification, the most polluted air is in the south-east of the country, and the cleanest is in the south and south-west, in some places in the north of the country.

One of the main prerequisites for determining the dependence of the effectiveness of the regional indicator of air pollution on various emissions of harmful substances when using the method of regression analysis is the linear independence of factors. To ensure this condition, the presence / absence of linear relationships between independent model variables was checked, i.e. factors multicollinearity was investigated. The most complete way to investigate multicollinearity is to construct a correlation matrix for all the identified factors, which were grouped above in table 1 (figure 2). The corresponding calculations were performed with the use of software GNU Regression, Econometrics and Time-series Library (Gretl).

After calculating a correlation matrix of harmful emissions into the atmosphere, we have found the presence of high collinearity between regressors X_1, X_2, X_4, X_9, which should be eliminated for further calculations.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
X_1	1.0	0.8	0.2	0.6	-0.1	0.7	0.8	0.4	0.8	0.1	0.6
X_2	0.8	1.0	0.4	0.8	0.0	0.8	0.7	0.7	0.9	0.0	0.9
X_3	0.2	0.4	1.0	0.4	-0.1	0.5	0.1	0.3	0.3	0.0	0.4
X_4	0.6	0.8	0.4	1.0	0.1	0.4	0.2	1.0	0.9	0.1	1.0
X_5	-0.1	0.0	-0.1	0.1	1.0	-0.1	-0.1	0.1	0.1	-0.1	0.1
X_6	0.7	0.8	0.5	0.4	-0.1	1.0	0.7	0.3	0.6	0.1	0.5
X_7	0.8	0.7	0.1	0.2	-0.1	0.7	1.0	0.1	0.6	0.0	0.3
X_8	0.4	0.7	0.3	1.0	0.1	0.3	0.1	1.0	0.8	0.0	1.0
X_9	0.8	0.9	0.3	0.9	0.1	0.6	0.6	0.8	1.0	-0.1	0.9
X_{10}	0.1	0.0	0.0	0.1	-0.1	0.1	0.0	0.0	-0.1	1.0	0.1
X_{11}	0.6	0.9	0.4	1.0	0.1	0.5	0.3	1.0	0.9	0.1	1.0

Figure 2. The correlation matrix of independent variables (model 1).

Table 2. Regression indicators for the TAP Model.

	Coefficient	Standard error	t-statistics	P-value
const	0.825282	0.423067	1.951	0.0639
X_7	2.18050	0.140679	15.50	<0.0001
X_8	6.76226	0.534052	12.66	<0.0001
Mean dependent variable	4.640061	S. D. dependent variable	8.303063	
Sum squared residuals	79.88899	S. E. of regression	1.905602	
R-squared	0.951716	Adjusted R-squared	0.947327	
F(5, 19)	216.8210	P-value (F)	3.32e-15	
Log-likelihood	49.99549	Akaike criterion	105.9910	
Schwarz criterion	109.6476	Hannan-Quinn criterion	107.0052	

Subsequently, factors X_3, X_5, X_6, X_{10} and X_{11} were eliminated by iterative testing of the model. No linear relationship was found between emissions of carbon monoxide and non-methane volatile organic compounds in the atmosphere from stationary sources (correlation level less than 0.7). The results of the calculations of regression analysis are given in table 2.

According to the calculated data, 2 factors that reflect emissions into the atmosphere are linearly independent, as the value of the statistical indicator differs significantly from 0. The correlation matrix is normal. $R^2 = 95\%$.

According to the results of the $F - test$ (Fisher's test), the constructed model is considered adequate for the sample data, because $Ffact(216.82) > Fcrit(2.26)$ (with a probability of error of 0.1). The regression model (model 2) will look like this:

$$Y = 0.825 + 2.18X_7 + 6.762X_8 \tag{1}$$

where Y – the indicator of pollutant emissions into the atmosphere from stationary sources of pollution by regions (TAP – total atmosphere pollution), tons per 1 km^2; X_7 – emissions of carbon monoxide, tons per 1 km^2; X_8 – emissions of non-methane volatile organic compounds, tons per 1 km^2.

Thus, as a result of the constructed model 2, the most important factors influencing the overall rate of air pollution from stationary sources are carbon monoxide emissions and emissions of non-methane volatile organic compounds.

As already mentioned, to ensure the practical testing of the built model we will use the data of entities whose activities are related to the generation and management of waste and

Table 3. Dynamics of emissions in the atmosphere of ME "Zhytomyrvodokanal", tones.

Pollutants	2017	2018	2019	2020	Deviation 2020 to 2017
Nitrogen dioxide	7.106	6.483	6.148	6.143	-0.963
Sulfur compounds	0.754	0.702	0.533	0.535	-0.219
Carbon monoxide	29.240	28.925	28.806	29.018	-0.222
Solid substances	0.894	0.850	1.142	1.122	0.228
Chlorine	0.003	0.012	0.012	0.012	0/009
Non-methane volatile organic compounds	0.360	0.290	0.079	0.080	-0.280
Total	38.357	37.262	36.720	36.910	-1.447

Source: data of reports of ME "Zhytomyrvodokanal"

which, at the same time, provide environmental services. The specific list of such economic entities is determined by local environmental authorities in the territorial context. Further proposals will be considered on the example of Municipal Enterprise "Zhytomyrvodokanal" (ME "Zhytomyrvodokanal"), the subject of which activity are water collection, treatment, and supply, as well as sewerage. At the same time, the activity of this enterprise is also related to emissions into the atmosphere (table 3).

According to the data of table 3 we should note the overall reduction of emissions volumes into the atmosphere from the activity of ME "Zhytomyrvodokanal". At the same time, the defined with the model 2 factors (emissions of carbon monoxide and of non-methane volatile organic compounds) are present in the emissions of the analyzed enterprise. So, we will propose the measures for the formation of instruments of ensuring the interaction of the enterprise with the environment considering these emissions.

One of the ways of reduction of negative anthropogenic impact on environment is the implementation of the appropriate management systems. The research of S. Roohy Gohar and M. Indulska emphasizes the role of green business-process management (BPM) in the securing the sustainable development of the economic entity. According to the scientists, the concept of green BPM is formed on the basis of understanding, analysis, and constant improvement of existing (current) business-processes with focusing on their environmental impact [3].

It is common in the world for eco-friendly companies to implement effective management systems with an environmental focus. In particular, we believe it is expedient to organize management with compliance to the ISO 14001:2015 standard [13]. The standard proposes to implement management systems using PDCA cycle with considering the ecological goals. The implementation of ISO 14001 standard in the management system of ME "Zhytomyrvodokanal" will contribute to increase of the overall level of environmental friendliness of the enterprise as well as it will have a positive impact on investment attractiveness from the standpoint of attracting foreign capital for financing the development projects. It should be noted that the cost of the certification procedure is relatively insignificant for the studied enterprise. Approximately the cost of certification procedure itself is about 50 ths. UAH. However, this amount does not include costs that must be incurred to bring the management system in line with the standard.

The implementation of "green innovations" is an important tool for reducing the negative anthropogenic impact on environment. According to P. T. Huong et al., green innovations include possible technology improvements, which enable energy-saving and waste recycling [5]. Moreover, green innovations can include solutions related with software use as well as with use of appropriate equipment, which enable to reduce waste and the use of hazardous materials by recycling or reusing them [5]. The implementation of green innovations not only forms a positive impact on the image of the enterprise as of an eco-friendly subject, but also promotes increasing the efficiency of its functioning and competitiveness [2].

In particular, the source of carbon monoxide emissions in the activities of ME “Zhytomyrvodokanal” are combustion processes in small plants (boiler house activities at the enterprise). Thus, “green innovations” for reduction of carbon monoxide emissions from the activities of ME “Zhytomyrvodokanal” may include, for example, the installation of modern boilers, a sound approach to fuel selection, the use of filters that will reduce emissions. It is clear that such technological solutions are not new in absolute terms, but from a local point of view, for ME “Zhytomyrvodokanal” they will be innovative approaches to solving problems.

The source of emissions of non-methane volatile organic compounds at ME “Zhytomyrvodokanal” is a gas station located on the territory of the enterprise. Therefore, monitoring the technical condition and use of the gas station is important in the context of reducing this type of emissions. It is clear that the implementation of innovations requires the involvement of appropriate financial resources, which, given the financial condition of ME “Zhytomyrvodokanal” (uncovered loss of the enterprise as of 31.12.2020 amounted to 139003 ths. UAH), is a problem issue. At the same time, there are ways of solving this problem. In particular, we believe such solutions should include the following:

– the use of the mechanism of municipal and private partnership through involvement of investments from business subjects;

– interaction with business subjects to attract non-refundable financing within the concept of corporate social responsibility;

– attracting grant funding from international organizations.

The offered instruments of ensuring the interaction of ME “Zhytomyrvodokanal” with environment are defined in the context of pollution of just one environment component, namely the atmosphere (air). At the same time, it is important to conduct further research in the sphere of reducing the pollution of other environment components (namely, water and land) in order to increase the efficiency of respective interaction and provide the eco-friendly policy of the enterprise.

Considering the peculiarities of the ME “Zhytomyrvodokanal” activity subject (sewerage), it is extremely important to provide the efficient policy of waste management for this enterprise. This thesis is confirmed by the systematic discharge of wastewater in the Teteriv River and, consequently, its pollution.

According to G. Salvia et al. the problem of waste management is one of the most important in modern world, as the absence of the system approach to solving the problems in this area causes negative consequences for environment as well as for health of the local communities [8]. As for Ukraine, according to the research of I. Kolodiichuk and V. Kolodiichuk major part of Ukraine’s regions is characterized by the imbalance in the amounts of waste generated and capabilities for their disposal. In particular, only 3 regions of Ukraine are provided with their own capacities in sufficient quantities for waste disposal [9].

According to G. Qian et al. the main strategies of waste management can be presented as follows:

– minimization of waste sources and promotion of ideas regarding recycling / reuse of waste;

– elimination or reducing the hazards through the landfilling;

– control of hazardous waste sources with engineering means;

– administrative control and personal involvement;

– hazard management during natural disasters [11].

Therefore, the development of effective instruments in the relevant sphere is a promising and extremely important sphere of further research regarding ensuring the efficient interaction of ME “Zhytomyrvodokanal” with environment.

6. Conclusions

Ensuring the efficient interaction of the enterprise with environment is aimed at the solution of several tasks on macrolevel (promoting the achievement of SDGs) as well as on microlevel (reducing the negative impact of enterprise activity on environment, increasing its investment attractiveness, reducing the costs related to irrational resource use and penalties, etc.). The results of the research enabled the further development of the conceptual foundations of functioning of the mechanism of management of enterprise interaction with environment. The proposed by the authors structure of mechanism consists of program and target, instrumental and methodical, and support blocks and makes it possible to implement the complex approach to the solution of the problems of economic entities interaction with environment. The empirical approbation of the mechanism provisions was carried out through the prism of substantiation of interaction instruments. One of the components of the environment, namely air, was chosen for a more detailed analysis of the negative factors which can be managed by an individual entity. In particular, the impact of certain types of pollutant emissions on the overall level of air pollution was analyzed on the basis of data on individual regions of Ukraine. It was found with the use of regression analysis that the main types of emissions that have the most significant impact on the total atmosphere pollution indicator are the carbon monoxide and non-methane volatile organic compounds emissions. Empirical substantiation of the elements of the instrumental and methodical block in terms of specific measures for ensuring the interaction of the enterprise with the environment was carried out on the example of ME "Zhytomyrvodokanal", whose activities are related to waste generation and management and which provides environmental services. The dynamics of emissions of pollutants into the air from the enterprise economic activity was analyzed. Based on the conducted regression analysis and relevant findings, as well as on the basis of the analysis of statistical data on emissions of ME "Zhytomyrvodokanal" the reserves to reduce the negative impact on the environment were identified. The instruments for reducing the corresponding emissions have been proposed for this enterprise. It was found that the prospects for further research are in the field of substantiation of specific instruments for the interaction of the enterprise with the environment in relation to other components of the environment.

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The state of the European Union – Ukraine Association Agreement implementation on the air quality

The state of the European Union – Ukraine Association Agreement implementation on the air quality

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Abstract. The comparative analysis of laws and regulations on air quality, air protection, and its monitoring in the EU and Ukraine has been carried out to analyse the state of the European Union – Ukraine Association Agreement. The main features of the strategic documents "Europe 2020" and "Ukraine 2020" air pollution control are discussed. The analysis of air quality monitoring regulations, air quality control methods, and peculiarities of citizens' alerts in the EU and Ukrainian legislation is provided. It is proven that the methods approach to limiting pollutant values differs in Ukraine and the EU. EU uses limit value', 'target value', alert threshold', 'information threshold' and 'critical level' and Ukraine uses limiting values. The limit values/permissible concentrations of carbon dioxide, sulfur (IV) oxide (average daily value), and lead are stricter in Ukraine. However, the permissible concentrations of PM10, sulfur (IV) oxide (short-term value), Arsenic, Cadmium, and Nickel are much lighter in Ukraine than in the EU. The dioxin content in ambient air is not regulated in Ukrainian legislation. Also, citizens' monitoring systems and data provision differ and should be harmonised for the EU's standards. The current state of roadmap implementation is firstly presented. It is demonstrated the necessity to harmonise the Ukrainian law and regulations on air quality control and air protection with the EU law.

1. Introduction

Implementing science-based environmental approaches and standards in legislation and everyday practice is an significant part of sustainable development. European Union standards are one of the most progressive in the field. They are usually preventive, consider global consequences, meet the requirements of sustainable development and are science-based. Implementation of the European Union laws and regulations into Ukrainian environmental laws is an part of the effective integration of Ukraine into the European community according to the EU-Ukraine Association Agreement [1, 2]. Therefore, it is valuable to provide a comparative analysis of the Ukrainian legislation to correspond to European laws and regulations. One of the parts of the EU's environmental policy is ambient air quality control and air protection. P

The main environmental policy goals are determined by strategic documents for the EU and Ukraine. Also, strategic documents are an essential part of the sustainable development of society. Moreover, other legislative acts aim to implement strategic documents' goals. So, this paper analysing strategy and EU's environment documents and their implementation state in Ukrainian legislation.

2. Literature review

A commitments of Ukraine in the field Environment (including air quality) is declared in Annex XXX of the Association Agreement between the European Union and its Member States and Ukraine incorporating Chapter 6: Environment [1, 2]. Furthermore, the general state of the fulfilment of the commitment is described annually in Reports prepared by the European Commission [3], the Ukrainian government [4] and by the Ukrainian Center of European policy [5]. However, it does not provide a detailed analysis of the scientific aspect of European integration in specialized fields, inducing practical aspects and compressing analyzing the existing state of the standards and those declared in European Law.

The science-sound analysis is provided in very few papers. Dmitrieva et al. provided an analysis of the implementation of the monitoring quality in Ukraine and the state of its corresponding to the requirements declared in Directive 2008/50/EC [6]. It was proven that in Ukraine, no standards declare the amount and location of the monitoring posts. In addition, the list of the action that needs to be done to harmonize the current state of the air quality monitoring system to European standards is described. Bashtanik et al. has declared the necessity of the Directive 2008/50/EC implementation in Ukrainian Law [7, 8]. In addition, Directive 2008/50/EC has been used to evaluate the dust air-pollution dynamics in certain Ukrainian cities [9].

Despite that, scientists in countries with high rates of European integration, such as [10, 11], Serbia [12, 13] and Moldova [14, 15] and inside of the EU [16, 17] provide scientific analysis of both, state of implementation (harmonization) and detailed analysis of legislation on air quality. However, there is no science-sound analysis of the state of implementation and analyzing the current state of legislation in Ukraine and the state of harmonization to the EU standards. Also, it seems relevant to analyze limiting valises in the EU and Ukraine, which will be helpful for further researchers to evaluate measured data on air quality using both, actual Ukrainian standards and European ones. Plans related to the improvement of the air quality is declared in both, Europe 2020 and Ukraine 2020, but there is no analysis of them related to air quality. Therefore, this research aims to analyse EU's legislation and the current state of its implementation in Ukrainian legislation according to Association Agreement, including, state of air quality monitoring system, types of limiting values, comparing of limiting values of pollutants, alerting system and publicity access to the data.

3. Methods of analysis

Both, Ukrainian laws and regulatory documents were analysed. As the main document, EU-Ukraine Association Agreement was used to analyse. Deduction, induction, and synthesis were used to analyze the documents. Reports of both the EU and Ukraine on the Agreement implementation were considered.

4. Results and discussion

4.1. Comparison of the strategic documents Europe 2020 and Ukraine 2020 strategies on the air quality goals

The EU's member states were guided by the Sustainable Development Strategy Europe 2020, adopted in 2010 [18], based on the principles pledged in the previous strategy, "A Secure Europe In a Better World" [19]. Among others, it proclaims the 20/20/20 climate/energy target. According to this target, greenhouse gas emissions in the EU should be reduced by at least 20% compared to the 1990 level, or even by 30% if it is possible; the renewable sources should cover at

Table 1. Content of produced gas.

Goal	Europe 2020	Ukraine 2020
Greenhouse gas emissions	Decrease by 20% (compared to 1990)	Not regulated
Getting energy from renewable sources	Provide 20% of consumed energy from the renewables	Implementation of alternative energy sources (without quantitative indicators)
Increase the energy efficiency of production	Increase by 20% compared to 2010	By 20 % till 2020

least 20% of energy consumption; and energy efficiency should be increased by 20% compared to 2010. The strategy envisages a reduction of dependence of economic growth on resource supply (resource efficiency), proclaims a low-carbon economy approach, including increasing the use of renewables, transport sector modernization, and energy efficiency steady improvement [18].

The strategy Europe 2020 in the field of ambient focuses to affect [18]:

(i) Particulate matter (PM2.5) and ozone effects on public health and the environment;
(ii) Acidification (control of emissions of sulphur (IV) and ammonium oxide, nitrogen) and eutrophication (nitrogen precipitated above critical loads);
(iii) Impact of ozone on vegetation;

The strategy involves the implementation of:

(i) Euro-5 standards for cars and vans;
(ii) Euro-6 standards for heavy vehicles;
(iii) Revision of national emission limits;;
(iv) Regulation of low-power combustion plants;
(v) Reduction of ammonia emissions in agriculture;
(vi) Review of legal acts in the field of air quality [18].

In Ukraine, the strategy of sustainable development in Ukraine 2020 was adopted in 2015 [20]. The document partially describes the strategic aspects of ambient air regulation, particularly greenhouse gas emissions. Comparisons of the Ukraine 2020 and Europe 2020 for climate/energy targets are presented in table 1.

As shown in table 1, the Europe 2020 strategy provides more clear climate/energy strategic goals and clearly defines quantitative indicators to evaluate the progress in the strategy implementation for greenhouse gas emissions and renewable energy supply. Instead, Ukraine 2020 strategy only identifies energy efficiency improvements, while other aspects of the strategy do not have clear criteria for progress assessment. But as for the goals of Ukraine, they would not be enough to solve the problem taking into account that the Ukrainian mean energy intensity of GDP is higher than the world's mean by 2.6 times [18–20].

According to the EU-Ukraine Association Agreement, Ukraine has a strategic plan for EU law implementation. Therefore, it is necessary to analyse the integration state, and the article aims it.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012044 doi:10.1088/1755-1315/1049/1/012044

4.2. Basic legislation of the EU and Ukraine on air quality

The EU regulatory framework for air quality monitoring includes the following regulatory documents:

(i) Directive 2008/50/EC on ambient air quality and cleaner air for Europe [21];
(ii) Directive 2004/107/EC relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air [22];
(iii) Council Directive 87/217/EEC on the prevention and reduction of environmental pollution by asbestos [23];
(iv) Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants [24].

The legislation of Ukraine on ambient air includes the following documents:

(i) Law of Ukraine on the "Air Protection" [25];
(ii) Order of Ministry of Health Protection of Ukraine "On Approval of the Hygienic Standard List of Industrial Allergens" [26];
(iii) Order of Cabinet of Ministers of Ukraine "On approval of the procedure for the development and approval of standards for permissible emission of pollutants from stationary sources [27];
(iv) "Maximum permissible concentrations of chemical and biological substances in the ambient air of inhabited places" approved by Chief Doctor of Ukraine [28];
(v) Order of Cabinet of Ministers of Ukraine "On approval of the list of the most common and dangerous pollutants whose emissions into the air are subject to regulation" [29].

The framework air quality law of the EU is Directive 2008/50/EC [21], which regulates the main principles of air protection and control of air quality in the member states. Also, there are EU directives that regulate specific indicators, such as Directive 2004/107/EC on the regulation of concentrations of arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air [22], Directive 87/217/EEC on reducing exposure to asbestos into the atmosphere [23] and Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants [24].

Directive 2004/107/EC [22] establishes the targets value for arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air, as well as upper and lower assessment thresholds, location criteria, the minimum number of sampling points for measuring atmospheric pollutant concentrations and sampling methods. Furthermore, the Directive obliged the EU's member states to undertake all necessary measures to ensure that from December 31, 2012 concentrations of Arsenic, Cadmium, Nickel and benzene(a)pyrene and polycyclic aromatic hydrocarbons should be used as an indicator for the carcinogenic risk in the ambient air, according to the assessment and their values should not exceed the limits set by the Directive [22].

Nowadays, limit values for pollutants in the atmosphere in Ukraine are regulated by a document approved by the chief physician of Ukraine, "Maximum permissible concentrations of chemical and biological substances in ambient air of populated areas" [28]. Also, it should be noted that severe standards for air quality may be established for resorts, recreational, and some other special areas (Article 6 of the Law of Ukraine on the "Air Protection" Ukrainian Law on Air protection).

It should be underlined that the approaches to air pollutants' control are different in Ukraine and the EU. European legislation provides such indexes as "limit value", "target value", "alert value", "information value", and "critical level for vegetation and ecosystems" (critical level) [21]. Alert value and information value are intended to inform the population about potentially risky pollutants concentrations. In cases where it is impossible to implement a scientifically substantiated value of the content of pollutants in the air, "mean value" is used. According to Directive 2008/50/EC, target value means the level established to avoid, prevent or reduce harmful effects on human health and/or the environment as a whole, which should be achieved whenever possible within the set period. Directive 2008/50/EC on ambient air quality and cleaner air for Europe also defines types of limitation levels of pollutants in the air as follows [21]:

- 'limit value' shall mean a level fixed on the basis of scientific knowledge, with the aim of avoiding, preventing or reducing harmful effects on human health and/or the environment as a whole, to be attained within a given period and not to be exceeded once attained;
- 'target value' shall mean a level fixed with the aim of avoiding, preventing or reducing harmful effects on human health and/or the environment as a whole, to be attained where possible over a given period;
- 'alert threshold' shall mean a level beyond which there is a risk to human health from brief exposure for the population as a whole and at which immediate steps are to be taken by the Member States;
- 'information threshold' shall mean a level beyond which there is a risk to human health from brief exposure for particularly sensitive sections of the population and for which immediate and appropriate information is necessary
- 'critical level' shall mean a level fixed on the basis of scientific knowledge, above which direct adverse effects may occur on some receptors, such as trees, other plants or natural ecosystems but not on humans.

Thus, the European Union legislation provides control over ambient air, considering both public health and the state of ecosystems, as well as informing the population. The Ukrainian regulatory framework foresees the use of maximum permissible concentrations that considers only human health, not the environment and it does not imply informing the population.

According to the Order of the Cabinet of Ministers of Ukraine, "On approval of the list of the most common and dangerous pollutants whose emissions into the air are subject to regulation" 2001, No. 1598 [27], the most common pollutants are nitrogen (II) oxide, sulphur (IV) oxide and its other compounds, carbon (II) oxide, ozone. In addition, hazardous pollutants include metals and their compounds, organic amines, volatile organic compounds, persistent organic compounds, Chlorine, Bromine, Fluorine, and their compounds, etc. [27].

In general, the approaches to control the level of air pollutants in Ukraine and the EU are significantly different and need to be harmonized. The limit values/permissible concentrations of carbon dioxide, sulfur (IV) oxide (average daily value) and lead are stricter in Ukraine. However, the permissible concentrations of PM10, sulfur (IV) oxide (short-term value), Arsenic, Cadmium, and Nickel are much lighter in Ukraine than in the EU. In addition, the dioxin content of ambient air is not regulated in Ukrainian legislation. Also, in Ukraine, the content of particulate matter (PM2.5) in the atmosphere is still insufficiently regulated, and there is no regulation of all types of particulate matter as defined by Directive 2008/50/EC. Therefore, it's necessary to align these indicators for Ukraine with European Union legislation. Benzopyrene and nitrogen (IV) oxide limit values are identical in Ukraine and the EU (table 2) [21].

Directive 2008/50/EC regulates the requirements for the placement of sampling points in the EU and by the RD 02.04.186-89 "Guidelines for the control of atmospheric pollution" in Ukraine. However, the legislation of Ukraine does not have requirements regarding the number of sampling points. Also, in Ukraine, several industrial zones may do not have the required quantity of sampling points compared to European legistlation or may do not have them at all [6, 21, 30]. On the other hand, Directive 2008/50/EC regulates detailed rules regarding the location of the sampling point [21].

4.3. Transport's emmisions and air quality legislation

According to the Agreement on Association, Ukraine committed to implementing transport EU's legislations. It includes Directive 2016/802 relating to a reduction in the sulfur content of

Table 2. Content of produced gas.

Substance	EU's indicators, mg/m^3				Ukraine's indicators, mg/m^3	
Greenhouse gas Name	AV, 1h	AV, 24h	AV, 1 year	MV, 8 h	MPC, daily	MPC, 30 min
Arsenic			0.000006*		0.003**	-
Cadmium			0.000005*		0.0003***	-
Nickel			0.00002*		0.001**	-
Benzopyrene			0.000001*		0.000001**	-
NO_2	0.2** [21]		0.04**		0.04**	0.2**
Dioxins	Limited by*****				-	-
CO_2				10	5***	3**
PM_{10}		0.05 [21]	0.04**		0.15****	0.5****
$PM_{2.5}$			0.024**			
SO_2	0.35**	0.125**			0.05**	0.5**
Lead			0.0005**		0.0003**	0.001**
Benzene			0.005**		0.1**	1.5**
Asbestos	0.1**					

* Target Value

** Limit Value

*** for cadmium compounds

**** total content of suspended particles

***** Limited by air emissions quantity (not higher than 0.1 ng/Nm^3 over a sampling period of a minimum of 6 hours and a maximum of 8 hours)

All Ukrainian indicators are taken from actual regulations declared in [28] Nitrogen (IV) oxide, Sulfur (IV) oxide, PM10. PM2.5, Lead, and Benzene values were taken from Directive 2008/50/EC; Arsenic, Cadmium, Nickel, Benzopyrene contents were taken from Directive 2004/107/EC; Dioxins limitation is presented according to Directive 2010/75; Asbestos content is presented according to Directive 87/217/EEC AV - Annual value MV - Mean value MPC - Maximum permissible concentration

certain liquid fuels [31], Directive 94/63/EC on the control of volatile organic compound (VOC) emissions resulting from the storage of petrol and its distribution from terminals to service stations [32], Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Council Directive Directive 98/70/EC of European Parliament and of the Council relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC, Directive 93/12/EEC relating to the sulphur content of certain liquid fuels (was replaced by Directive 2009/28/EC), Directive 2000/71/EC to adapt the measuring methods as laid down in Annexes I, II, III and IV to Directive 98/70/EC of the European Parliament and of the Council to technical progress as foreseen in Article 10 of that Directive [33], Directive 2003/17/EC amending Directive 98/70/EC relating to the quality of petrol and diesel fuels [34] and Regulation 1882/2003 adapting to Council Decision 1999/468/EC [35].

However, those Directives are lackey implemented in Ukrainian law. It may be related to transfer and selling of the old EU's transport to Ukraine which is going on due to the lower economical state in Ukraine compare to EU's economic state.

4.4. Citizens' information on air quality state

Informing citizens in the EU member states is provided through the online GIS. Information about the state of the environment in real-time can be seen using sites WAQI (https://waqi.info/) or AQICN (http://aqicn.org) (figure 1). In the EU member states, the air quality index (AQI) is applied that is simple to understand and is calculated according to the formula:

$$I = (I_{high} - I_{low})/(C_{high} - C_{low})(C - C_{low}) + I_{low} \tag{1}$$

Where I – air quality index;
C – the pollutant concentration;
C_{low} – the concentration breakpoint that is C;
C_{high} – the concentration breakpoint that is C;
I_{low} – the index breakpoint corresponding to C_{low};
I_{high} – the index breakpoint corresponding to C_{high}.

An example of information on the site http://aqicn.org is presented in figure 1.

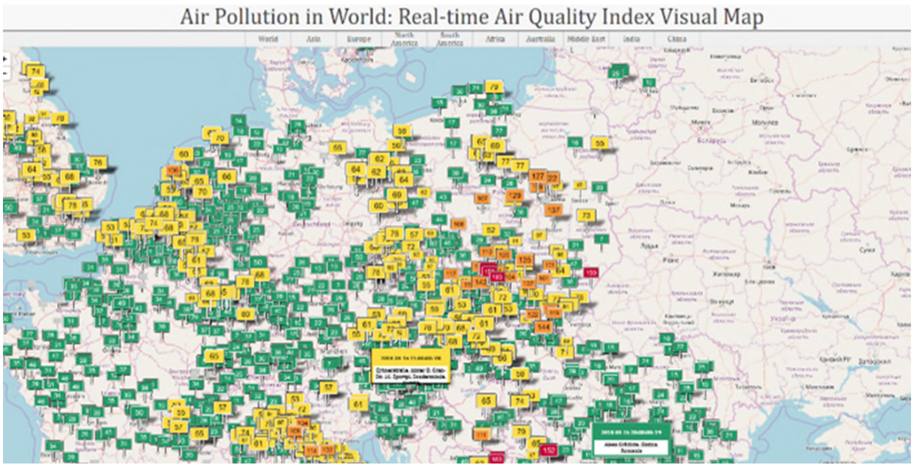


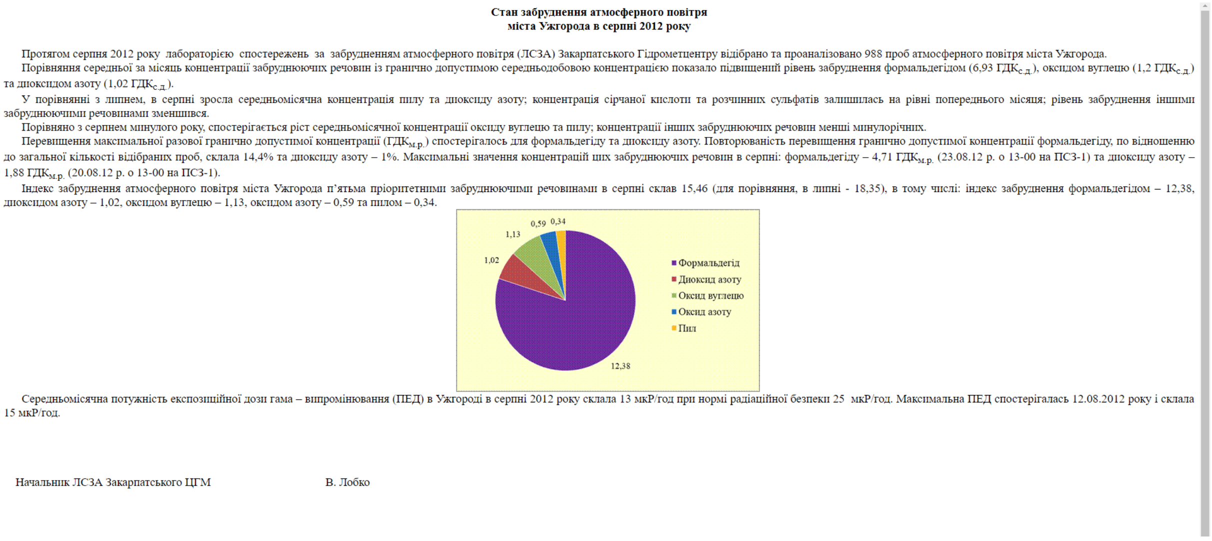
Figure 1. An example of information on the site http://aqicn.org.

This indicator gives a relatively clear understanding of the dangers of air quality. The score varies from 0 to 500. Its lower values indicate high air quality, and higher ones are about the danger state of air quality.

Citizen alert in the EU member states occurs when the concentration of sulphur (IV) oxide is 0.5 mg/m^3, nitrogen (IV) oxide - 0.4 mg/m^3 and ozone - 0.24 mg/m^3; and information threshold for ozone is 0.18 mg/m^3. The critical level of sulfur (IV) oxide is 0.02 - mg/m^3, and for nitrogen oxides - 0.03 mg/m^3 [23].

In Ukraine, comparisons with the maximum permissible concentration are used to inform the population. GIS is not commonly used for informing citizens. The reports on air quality are prepared periodically by Hydrometeorological Centre of State Service of Ukraine for Emergency Situations of Cabinet of Ministers once in several months. Consequently, citizens receive air quality information with a delay of several months. An example of information delivery on the sites of the Hydrometeorological Centre is presented in figure 2 (http://gmc.uzhgorod.ua/ZA/092012.htm, Access data: 02.02.2019).

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012044 doi:10.1088/1755-1315/1049/1/012044



Стан забруднення атмосферного повітря
міста Ужгорода в серпні 2012 року

Протягом серпня 2012 року лабораторією спостережень за забрудненням атмосферного повітря (ЛСЗА) Закарпатського Гідрометцентру відібрано та проаналізовано 988 проб атмосферного повітря міста Ужгорода.

Порівняння середньої за місяць концентрації забруднюючих речовин із гранично допустимою середньодобовою концентрацією показало підвищений рівень забруднення формальдегідом (6,93 $ГДК_{с.д.}$), оксидом вуглецю (1,2 $ГДК_{с.д.}$) та диоксидом азоту (1,02 $ГДК_{с.д.}$).

У порівнянні з липнем, в серпні зросла середньомісячна концентрація пилу та диоксиду азоту; концентрація сірчаної кислоти та розчинних сульфатів залишилась на рівні попереднього місяця; рівень забруднення іншими забруднюючими речовинами зменшився.

Порівняно з серпнем минулого року, спостерігається ріст середньомісячної концентрації оксиду вуглецю та пилу; концентрації інших забруднюючих речовин менші минулорічних.

Перевищення максимальної разової гранично допустимої концентрації ($ГДК_{м.р.}$) спостерігалось для формальдегіду та диоксиду азоту. Повторюваність перевищення гранично допустимої концентрації формальдегіду, по відношенню до загальної кількості відібраних проб, склала 14,4% та диоксиду азоту – 1%. Максимальні значення концентрацій цих забруднюючих речовин в серпні: формальдегіду – 4,71 $ГДК_{м.р.}$ (23.08.12 р. о 13-00 на ПСЗ-1) та диоксиду азоту – 1,88 $ГДК_{м.р.}$ (20.08.12 р. о 13-00 на ПСЗ-1).

Індекс забруднення атмосферного повітря міста Ужгорода п'ятьма пріоритетними забруднюючими речовинами в серпні склав 15,46 (для порівняння, в липні - 18,35), в тому числі: індекс забруднення формальдегідом – 12,38, диоксидом азоту – 1,02, оксидом вуглецю – 1,13, оксидом азоту – 0,59 та пилом – 0,34.

Середньомісячна потужність експозиційної дози гама – випромінювання (ПЕД) в Ужгороді в серпні 2012 року склала 13 мкР/год при нормі радіаційної безпеки 25 мкР/год. Максимальна ПЕД спостерігалась 12.08.2012 року і склала 15 мкР/год.

Начальник ЛСЗА Закарпатського ЦГМ В. Лобко

Figure 2. An example of information delivery on the sites of the Hydrometeorological Centre (http://gmc.uzhgorod.ua/ZA/092012.htm, Access data:02.02.2019).

The air monitoring system used in the EU is more visual and allows users to get real-time information, and provides a qualitative and straightforward notification of citizens about the potential dangers, ensuring the safety of citizens with specific health statuses. Therefore, it is advisable to modify the system of informing citizens in Ukraine to meet the features mentioned above of the EU system.

However, Ukraine provides NGOs control by using both online GIS and AQI. To provide this, measurers developed by Ecocity project nowadays are using. Those measures are located by the different organizations, including the Junior Academy of Sciences of Ukraine and NGO European Studies' Platform for Sustainable Development.

5. Discussion

Generally, the European integration state is presented in the reports prepared by the European Commission [3], the Ukrainian government [4] and by the Ukrainian centre of European policy [5]. Main achievements related to environmental field are related to strategic planning, and it includes [4]:

- Providing the automatic system open environment (not implemented yet) [3]
- Cabinet of Ministers endorsed an updated National Environmental Strategy 2030, Implementing the decreasing of air emission plan [3, 4];
- Drafts of Laws "On Monitoring, Reporting and Verifying Greenhouse Gases" and "On ozone-depleting substances and fluorinated greenhouse gases were approved [4];
- The Order of the Ministry of Environmental Protection of 18.02.2018 № 62 provides for the establishment of current and future technological standards for permissible emissions of pollutants into the atmosphere from existing stationary heat and power plants [4];
- Order No. 62 of the Ministry for Environmental Protection of 18.02.2018 "On Amendments to the Order of the Ministry of Environmental Protection of Ukraine dated October 22, 2008 No. 541" provides for the establishment of current and promising technological standards for permissible emissions of pollutants into the atmosphere from existing stationary heat and power plants [4];

- It was approved Low-carbon strategy of Ukraine to 2050 [4, 36];
- It is provided a law on VOC content in paints (Directive 2004/42/EC);
- a new Law on Strategic Environmental Assessment (SEA) was adopted [4].

The reports show that Directives 2004/107/EU, 1992/30/EC (repelled by Directive (EU) 2016/802), directive 94/63/EU [32], Directive 98/70/EU were not implemented in full-scale foreseen in EU-Ukraine Association Agreement. Directives 2004/107 and 94/63/EU have not been implemented at all [5]. Directives related to oil quality were implemented particularly:

A. was not successful:

- Changes related to the prohibition of usage of fuels with high sulphur content were implemented by the Technical regulations concerning requirements for motor vehicles gasoline, diesel, ship and boiler fuels (PCM No. 927 of August 1, 2013) It is defined as the body of market supervision - the State Inspection (SCM No. 1069 dated December 28, 2016)
- Particularly it is implemented standards on the fuel quality
- Prohibition of etiolated petrol sales is implemented in the Law of Ukraine "On the Prohibition of the Import and Export on the Territory of Ukraine of Evaporated Petrol and Lead Additives to Gasoline".
- Requirements for the quality of gasoline and diesel fuel are set in the Technical Regulation on requirements for motor gasoline, diesel, marine and boiler fuels, approved by the KMU Decree No. 927 dated 01.08.2013.
- From January 1, 2018, only gasoline of Euro5 standard is allowed in Ukraine, the quality requirements of which comply with Directive 98/70 / EC.

B. Was successful

- The monitoring system with requirements of Directive 98/70 / EC is not implemented.

Therefore, in practice, directives on fuel quality are not implemented in Ukraine. According to Association Implementation Report on Ukraine. Work is ongoing to prepare legislation to establish an emissions Monitoring, Reporting, and Verification system. In September 2018, a Law drafts on Ozone Depleting Substances and Fluorinated Greenhouse Gases were registered in the Parliament, envisaging the gradual phasing out of these substances. According to the monitoring of the implementation EU-Ukraine Association Agreement, Directive №2004/107/EC, Directive 1999/32/EC, Directive 94/63/EC, Directive 98/70/EC (implementation deadlines from 2014 to 2017) and Directive 2008/50/EC (implementation deadline in 2018) was in work to implement. However, it does not mean that nothing was done about the integration of European legacy in the field of air quality; it means that these legacy acts were not implemented totally, but they were implemented just particularly.

However, those analyses are not representing all aspects of the euro integrational situation of Ukraine related to air quality. Therefore, we provide own analysis. The only aspect of setting up maximum VOC content limit values for paints is implemented in appropriate Ukrainian law [37]. Other points of the Association Agreement on air quality were not implemented in full scale. The general state of integration of the EU's law is presented in figure 3.

It worth note that state of air quality may be enhanced by using of green technologies, such as anaerbic treatment [38]. However, such technologies may be also unsustainable and cause negative effect on air quality. To ensure sustainability, it is relevant to use modern effective technologies that decrease amount of waste generated by anaerobic treatment such as in works [39] and [40] or modern providing effective technologies to purify both, natural and wastewater such as modern nanotechnologies approaches [41–43]. Also, its sustainability will depend on its optimisation and to define such optimal conditions, using modern informational tools is possible [44].

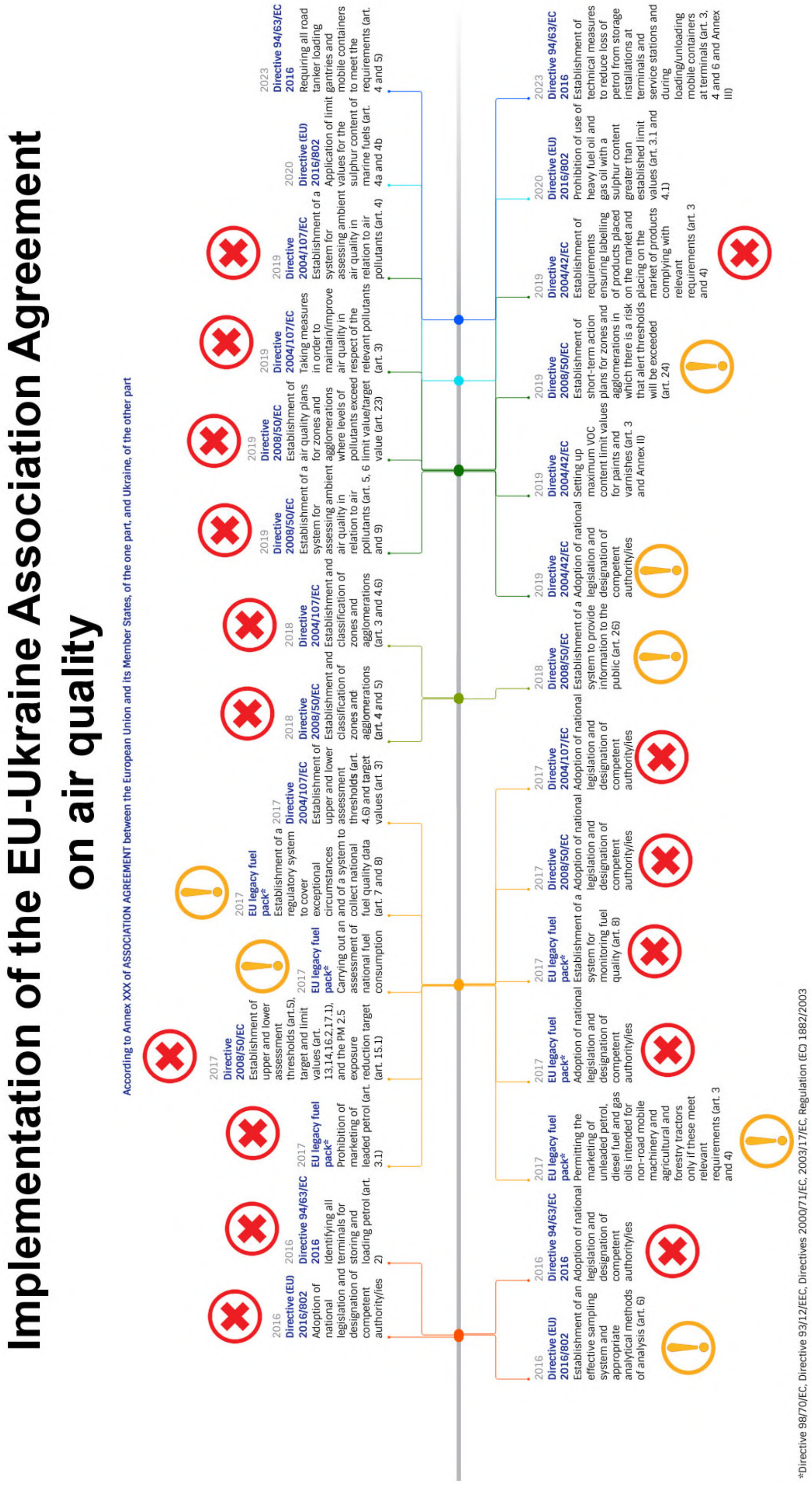


Figure 3. The general state of integration of the EU's law implementation in UA's legistlation on air quality.

6. Conclusions

(i) The strategy Europe 2020 is more specific towards improving the environment and ambient air quality than the Strategy Ukraine 2020. Europe 2020 has more clear climate/energy targets and more clearly defined criteria for assessing the implementation of the strategy for emission control, energy efficiency, and renewable energy development.

(ii) Ukraine's regulatory documents on ambient air protection are partly in line with the EU laws but require some harmonization. The most harmonized part of the regulatory framework for ambient air between Ukraine and the EU is the air quality control methods, and the least harmonized part is regulatory acts related to monitoring the state of the environment (placement of observation posts) and the approach to the air pollutants (maximum permissible concentrations).

(iii) The EU and Ukraine have pretty different approaches to regulating the levels of pollutants in ambient air. Ukrainian legislation foresees the usage of maximum permissible concentrations based on the impact of pollutants on human health. At the same time, the EU legislation also considers the impact of pollutants on the environment. 'limit value', target value', 'Alert threshold', 'Information threshold' and 'Critical level' are used to provide it.

(iv) Almost all regulated values differ between the EU's and Ukrainian standards. So, it is necessary to harmonize Ukrainian laws with EU legislation. An important uncoordinated indicator of the quality of ambient air in Ukraine is the levels of particulate matter (PM2.5). Unlike the EU, in Ukraine, this index is not regulated at all.

(v) It is advisable to improve the system of notifications of citizens about the air quality in Ukraine using the experience of the EU in this field.

Acknowledgments

Analysis and support of the paper provided in term of the Jean Monnet Support of Associations EUforUA (611278-EPP-1-2019-1-UA-EPPJMO-SUPPA) project.

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Awareness of antibiotic resistance for the environmental health and sustainable development: a cross-sectional study

To cite this article: M Galaburda *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012045

Awareness of antibiotic resistance for the environmental health and sustainable development: a cross-sectional study

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Abstract. Antimicrobial resistance (AMR) is a significant threat for global health and has been recognized as a threat to the world's sustainable development affecting several sustainable development goals (SDG). Uncontrolled and unjustified use of antimicrobial drugs in both agriculture and medicine, leads to the emergence of new strains of microorganisms resistant to antibiotics that can be distributed through the environment and poses both direct and indirect threat to public and environmental health. The systematic literature reviews and cross-sectional study to assess the awareness and attitude to antimicrobial resistance among veterinary and medical students of Ukrainian universities demonstrates the relationship between the antibiotic resistance issue and its influence on environmental health as the important determinant of global health and the Sustainable Development Goals. Both medical and veterinary students acknowledged the antimicrobial resistance to a certain extent. However, differences among the responses of target groups demonstrate that medical students are better trained on antimicrobial prescriptions to humans and more familiar with the protocols of treatment of different diseases of humans. Findings can be used for the development of educational activities aiming to improve knowledge on antimicrobial use, particularly in the framework of One Health approach.

1. Introduction

Antimicrobial resistance (AMR) is a significant concern for global health and has been recognized as a threat to the world's sustainable development, impacting the achievements of several of the 17 sustainable development goals (SDG). Still there is no single indicator for SDGs specific to AMR as the challenge of AMR directly involves environmental and compromises social and economic sustainability aspects. Uncontrolled and unjustified use of antimicrobial drugs in both agriculture and medicine, leads to the emergence of new strains of microorganisms resistant to antibiotics [1–3]. The environmental implications of the antimicrobials lifecycle (both human and veterinary) can contribute to the acceleration and spread of resistant organisms [4–7]. Linking antimicrobial consumption in animals, presence of antimicrobials in the environment, the spread of antimicrobial resistant microorganisms to development of AMR infections in humans is complex due to the ecological essence of the selection pressure for resistant pathogens and of indirect routes of transmission through the environment [2, 5, 8–11].

The Global action plan on antimicrobial resistance considers the level of awareness and understanding of AMR among key stakeholder groups, that include the human health, animal health, food sector, environment and plant health sectors, to be one of five strategic objectives [12–14]. Appropriate education and training of future veterinarians and physicians is critical for good antimicrobial stewardship and should be supported by development of curricula that fosters best practice in antimicrobial use [15, 16]. The COVID–19 disruption has significantly impacted the provision of both medical and veterinary education, highly affecting courses teaching clinical and professional skills [17–19]. Under such conditions a e-learning with the delivery of educational resources through the Internet and provision of a supportive online environment in University is critical for sustainability of education activities [20–23].

2. Research objectives

Geoecological research methodology allows at a higher scientific level to approach the assessment of the impact of technogenic processes, namely the placement of wind turbine generators (WTG) and the formation of the wind power plant (WPP) site, on the state of the components of the environment - avifauna and chiropterofauna, which are considered as one of the important bioindicators of the ecosystem state.

The objectives of the research were to assess the role of antimicrobial resistance issues in sustainable development and environmental health, as well as to carry out preliminary evaluation of awareness on antibiotic resistance among veterinary and medical students in Ukraine, as representatives of target stakeholder groups, for their current potential to assure environmental health and the sustainable development goals (SDGs) realization.

For achievement of the objectives the following research questions were addressed:

- Research Question 1 (RQ1): What is the relationship between AMR knowledge and environmental health and SDG?
- Research Question 2 (RQ2): What is the level of AMR awareness among veterinary and medical students?
- Research Question 3 (RQ3): What is the difference between knowledge regarding AMR of veterinary and medical students?

3. Methodology of research

Addressing RQ1, we applied the method of systematic literature reviews (SLRs); For RQ2 and RQ3 a sample survey method was used.

3.1. Study retrieval and datasets

The compliance of current study with the Sustainable Development Goals (SDG) (https://sdgs.un.org/goals) were assessed in the Dimensions.ai database from Digital Science (https://www.dimensions.ai). We chose Dimensions.ai because the free version of the platform provides an open search of more than 124 million publication records and associated metrics for individual users [24].

Search terms have been developed to gather data on the key topic areas (I–V) related to the objectives of our study and ten–year period by application *Publication* year filter were chosen in the range from 2012 to 2021. Sets of keyword searches were narrowed from determining the impact of antimicrobial resistance awareness on sustainable development (set No I) and environmental health as one of the key determinants of global health, along with human and animal heath, when it comes to AMR (set No II) through students' knowledge as the main human resource on antimicrobial resistance awareness (set No III) to the significance of training on AMR key target groups, such as veterinary (set No IV) and medical students (set No V):

- Set No I. (antimicrobial resistance) AND (awareness OR knowledge)) AND (sustainable development);
- Set No II. (antimicrobial resistance) AND (awareness OR knowledge)) AND (environmental health);
- Set No III. (antimicrobial resistance) AND (awareness OR knowledge)) AND (students);
- Set No IV. (antimicrobial resistance) AND (awareness OR knowledge)) AND (veterinary students);
- Set No V. (antimicrobial resistance) AND (awareness OR knowledge)) AND (medical students).

3.2. Instruments and participants
A cross-sectional study was carried out by using a random sample online survey among veterinary and medical students in Ukraine. Non-random criteria were used for selection of individuals, as this research aimed to develop an initial understanding with respect to antibiotic awareness among university students with different backgrounds. Thus, the target population of the study was selected based on the direction of higher education being obtained. The current study did not seek to test any hypothesis about a larger population; thus it was carried out using voluntary responses.

For this purpose, 113 (35.4%) medical and 206 (64.6%) veterinary students (table 1) representing different regions of Ukraine, namely Kyiv, Poltava, Sumy, Vinnytsia, and Zaporyzhiia, were involved in the study, bringing the total number of respondents to 319. The target population included both male (22.57%) and female (77.43%) students from year one (preclinical) to year six (clinical). The majority of respondents reported having taken antibiotics more than a year ago (34.5%) and one fifth have taken them within the past month (19.7%). There was no significant difference in the last intake of antibiotics among veterinary and medical students, however more veterinary students claimed they have never taken antibiotics (3.4% compared to 1.77%). Individuals between 16–18 (55.17%) and 19–24 (40.13%) years old formed the most populous age groups (95.3%). Even though year-one students do not take any core clinical courses, they were enrolled in the study in order to evaluate their awareness on AMR issues based on their theoretical background.

A link to a 25 questions survey was distributed in social messengers to different student groups and conducted online via Google Forms. The instrument was modified from WHO multi-country public awareness survey in the framework of a program to raise awareness of antibiotic resistance among the population [25]. The survey was available online for a period from December 2021 to January 2022. Students were asked questions on their demographic, personal antibiotic use (table 1), attitude, awareness and contributory factors to antimicrobial resistance (https://forms.gle/L5bxTiCJXzrfjPPW9). For self–reported awareness, behavior, knowledge, and attitude towards the antibiotic usage the questionnaire included multiple choice questions, statements testing knowledge using a true or false answer, and statements assessing attitudes and behaviors by seeking agreement using a 5–point Likert scale – strongly agree, agree, neither agree nor disagree, disagree, strongly disagree. In addition, there was an option of 'I do not know /can not remember'.

3.3. Data processing and analysis
The collected data were initially summarized in Microsoft Excel and checked for completeness and consistency. Repeated questionnaires were excluded from analysis. Numerical data were checked for possible data gaps and need for categorization was considered. Descriptive statistics were obtained for all variables of interest from the survey by education background for medical and veterinary students.

Table 1. Characteristics of the respondents ($n = 319$).

Feature	Category of Feature	Veterinary	Number (Percent) Medical	Total
Gender	Female	166 (80.%)	81 (71.7%)	247 (77.4%)
	Male	40 (19.4%)	32 (28.3%)	72 (22.6%)
Age (years)	16– 18	133 (64.6%)	43 (38.1%)	176 (55.2%)
	19–24	67 (32.5%)	61 (54%)	128 (40.1%)
	≥25	6 (2.9%)	9 (8%)	15 (4.7%)
Antibiotics use	Never	7 (3.4%)	2 (1.8%)	9 (2.8%)
	More than a year ago	64 (31.1%)	46 (40.7%)	110 (34.5%)
	In the last year	16 (7.8%)	8 (7.1%)	24 (7.5%)
	In the last 6 months	29 (14.1%)	24 (21.2%)	53 (16.6%)
	In the last months	45 (21.8%)	18 (15.9%)	63 (19.7%)
	Can not remember	45 (21.8%)	15 (13.3%)	60 (18.9%)

The post hoc power was estimated by using G*Power version 3.1.9.4. The minimum sample size required to show a difference between groups was 193 at an alpha probability value of 0.05 and beta of 0.80.

Chi–square and Fisher's Exact Test were used to determine associations at an alpha level of ≤ 0.05. This initial step was for variable selection for further models, possibly logistic regression. The data analysis for this paper was generated using SAS software [26].

4. Results of research

4.1. The results of a systematic literature reviews

The number of records retrieved from each search strategy is summarized in table 2 by research contributions (number of publications), open access supported initiatives (percentage of total publications), research (grants) and publication of their results (clinical trials and policy documents). In terms of qualitative parameters (screening revision by title/abstract) we can assume that medical and veterinary students are of primary concern of the AMR awareness, as the III search of scientific publications shows the above categories targeted. The results of search set V demonstrates that veterinary students are also included in the category of medical students, so the sample of scientific publications on the knowledge of veterinary students (set IV) is the smallest. Another reason may be the study gap in this area but that was beyond the objectives of our research.

The search results in Dimensions.ai revealed the overall growth of publishing activity since 2017, which can be explained by implementation of the EU One Health plan on antimicrobial resistance [27] and growing research interest for environmental pathways and barriers study [28, 29]. The highest number (134) of grant-supported activities for the search set II indicates contribution of environmental health toward One Health concept [8–10, 30]. In the field of

Table 2. Quantitative search results for I – IV sets in Dimensions.ai.

Set	Publications	Open access	Clinical trials	Grants	Patents	Policy documents
I.	62777	19459 (31%)	1	53	1479	5376
II.	156504	58183 (37.2%)	9	134	16545	5167
III.	76430	27572 (36.1%)	19	82	5504	2521
IV.	21489	5603 (26.1%)	1	8	1718	1059
V.	63808	21128 (33.1%)	11	19	4322	2350

research, most publications (results for all 5 searches) cover Biological Sciences, Medical and Health Sciences and Public Health and Health Services. General questions (set I and II) cover the field of Engineering, and Chemical Sciences, as well as, together with the results of search set IV – Agricultural and Veterinary Sciences, others (specialized) – Clinical Sciences, and medical students (set V) – Medical Microbiology.

Considering the fact that antimicrobial resistance challenges sustainability and confronts both environmental and public health and the 2030 Agenda [31], we studied the compliance of the search I–V results with the Sustainable Development Goals. According to the results of the publications metadata description, the considered subject most corresponds to the following SDG:

- SDG 3. Good Health and Well Being (4.0% of the total number of publications – the results of the implementation of set I, 4.4%– set II, 5.0% – set III, 3.7% – set IV, 5.2% – set V), as with effective antibiotics use maternal, neonatal and child deaths can be prevented, and epidemics of communicable diseases and environmental contamination by waste can be managed;
- SDG 2. Zero Hunger (4.4% of the total number of publications – the results for the search set I, 2% – set II, 0.9% – set III, 1.2% – set IV, 0.7% – set V) as the antimicrobial use ensures sustainable food production systems;
- SDG 4. Quality Education (0.3% of the total number of publications – the results for the search I, 0.2% – set II, 0.5% – set III, 0.4% – set IV, 0.5% – set V) – testify the need for relevant training of the target population.
- SDG 12. Responsible Consumption and Production (1.7% of the total number of publications – the results for the search set I, 0.7% – set II, 0.3% – set III, 0.4% – set IV, 0.3% – set V) indicates the importance of responsible use of antimicrobials and significant contribution of environmental health and veterinary medicine for the benefits of humans and skills to meet societal needs.
- SDG 13. Climate Action (1.5% of the total number of publications – the results for the search set I, 0.7% – set II, 0.4% – set III, 0.5% – set IV, 0.3% – set V) – shows potential alterations in the diversity and complexity of environmental microbial populations around the world that may result in selection of resistant isolates.

Therefore, based on the current analysis, we can assume that antibiotic resistance awareness has a significant influence on global health and wellbeing as SDG 3, SDG 12 and SDG 13 correlate with the areas of environmental health, agriculture and food underlined by SDG 2, and supports the need of extra attention to the training of target stakeholder groups (SDG 4 – Quality Education).

4.2. Levels of knowledge around the appropriate use of antibiotics: the results of a survey

Among 319 participants from Ukrainian universities, who completed the survey, the majority of the students of both groups (72.41%) answered that they had consulted their physician regarding antibiotics administration, such as time and duration of administration. Among veterinary students 71.84% claimed that they consulted their physician for the instructions on antibiotics administration, 15.53% referred to the drug's instruction, and 12.63% did not remember or did not contact a doctor. Among medical students 73.45% answered "yes" to the question "Has the doctor (pharmacist) determined the procedure for taking antibiotics?", 15.04% referred to the drug's instructions, and 11.5% did not remember or did not contact a doctor.

Surprisingly high number of respondents of both groups claimed that they bought the antibiotics in the pharmacy – 90.91%, on the opposite only 1 veterinary student bought them via Internet – 0.31%, and 3.45% of respondents stated that they had some left over from the previous prescription or got them from a family member or a friend, 5.33% could not remember where they got the drugs.

Among veterinary students 85.44% agreed that one should stop taking antibiotics once all the pills are taken as prescribed after starting treatment, compared to 95.58% of medical students. Only 4.42% of medical students believed that one should stop taking antibiotics when they get better, as opposed to 12.14% of veterinary students who claimed the same and 2.43%, who did not know when to stop taking antibiotics.

Both categories of respondents disagreed with the statement that "You can use antibiotics that have been prescribed to a friend or family member if they have been used to treat the same disease" – 87.15%, 8.78% agreed with the statement, and 4.08% did not know. There was no significant difference in answers among veterinary and medical students to this question.

On the other hand, almost twice as many veterinary students didn't know if "You can buy the same antibiotics or ask your doctor for them if they have helped you before with similar symptoms", 10.19% compared to 5.31% of medical students. Nonetheless, 69.59% of both categories disagreed with that statement.

There was some misunderstanding around which conditions can be treated with antibiotics (figure 1).

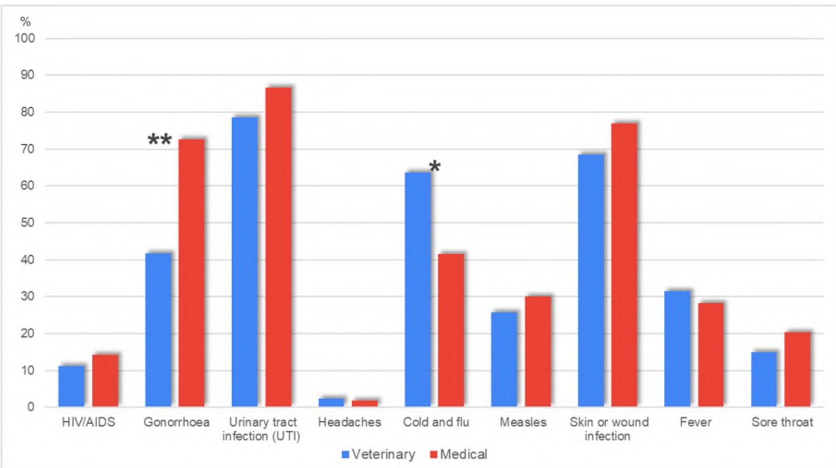

Figure 1. Percentages of options selected by respondents regarding disease conditions treated with antibiotics (* – $P < 0.0002$, ** – $P < 0.0001$).

The majority of respondents (81.5%) associated antibiotics with urinary tract infection treatment and 71.5% surveyed correctly identified conditions such as skin/wound infections as treatable with antibiotics. Around 17% of all surveyed linked antibiotics with sore throat treatment. However, the majority of veterinary students (63.6%) incorrectly believed that disorders of viral etiology such as colds and flu can be treated with antibiotics and there were significant differences ($P < 0.0002$) compared to the medical students' responses. Moreover, 12% of all students stated that antibacterial drugs could be used to treat AIDS/HIV. One third of participants asserted that measles (27.3%) could be treated in the same way.

Medical students were also more certain (72.6%) that gonorrhea is a condition which is treatable with antibiotics compared to those enrolled in veterinary sciences (41.8%) ($P < 0.0001$).

To the pool of questions on the AMR awareness 94.69% of medical students responded that the human population may develop resistance to antibiotics, 4.42% claimed that it may not, and 0.88% didn't know, compared to 82.52%, 6.31, and 11.17 of veterinary students respectively ($p < 0.0001$). Almost a half of all students strongly agreed with the statement that antimicrobial resistance can affect both the health of the respondents and their family – 47.02%, while only 1.57% strongly disagreed with that statement (table 3).

Table 3. Extent of agreement or disagreement to the statement: "Antimicrobial resistance can affect your health and the health of your family" ($n = 319$, $p < 0.0001$).

Education			Grade			Total
	1	2	3	4	5	
Med	4	2	11	24	72	113
% of Total	1.25	0.63	3.45	7.52	22.57	35.42
% of Med	3.54	1.77	9.73	21.24	63.72	
% to Vet	80.00	25.00	14.10	30.77	48.00	
Vet	1	6	67	54	78	206
% of Total	0.31	1.88	21.00	16.93	24.45	64.58
% of Vet	0.49	2.91	32.52	26.21	37.86	
% to Med	20.00	75.00	85.90	69.23	52.00	
Total (%)	5 (1.57%)	8 (2.51%)	78 (24.45%)	78 (24.45%)	150 (47.02%)	319 (100%)

The majority of all students agreed that people should only take antibiotics when prescribed by a doctor – 80.88%, while only 1.88% disagreed with that statement (table 4).

Overall, 32.29% of all respondents strongly agreed that "Antibiotic resistance is one of the biggest challenges facing by society around the world", 26.02% – agreed, 30.41% – neither agreed nor disagreed, 8.78% – disagreed, and 2.51% of students of both categories strongly disagreed. However, medical students who fully agreed with the statement were 1.6 times more than veterinary students (43.36% and 26.21% respectively).

The majority of all students strongly agreed that everyone should use antibiotics responsibly – 93.10%, while only one veterinary student (0.31%) strongly disagreed with that statement.

Only 13.48% of students strongly agreed with the statement that an ordinary person like them does not have much influence on solving the problem of antimicrobial resistance, 19.44%

Table 4. Extent of agreement or disagreement to the statement: "People should only take antibiotics when prescribed by a doctor" ($n = 319$, $p < 0.0001$).

Education	Grade					Total
	1	2	3	4	5	
Med	0	1	1	8	103	113
% of Total		0.31	0.31	2.51	32.29	35.42
% of Med		0.88	0.88	7.08	91.15	
% to Vet		16.67	6.25	20.51	39.92	
Vet	0	5	15	31	155	206
% of Total		1.57	4.70	9.72	48.59	64.58
% of Vet		2.43	7.28	15.05	75.24	
% to Med		83.33	93.75	79.49	60.08	
Total (%)	0	6 (1.88%)	16 (5.02%)	39 (12.23%)	258 (80.88%)	319 (100%)

– agreed, 34.17% – neither agreed nor disagreed, 14.73% – disagreed, and 18.18% of students of both categories strongly disagreed. There was no significant difference in the answers between the groups but it can be the evidence of crucial gaps in awareness of the environmental health integration into One Health and sustainable development.

Almost a half of all respondents (46.71%) strongly agreed with the statement that "I'm worried about how antibiotic resistance will affect my health and the health of my family", whereas 3.13% strongly disagreed with that statement.

Responses to the statement "I do not risk facing the problem of antibiotic resistance if I take the antibiotics prescribed to me correctly" were divided: 28.21% of respondents strongly agreed with the statement, 28.53% – agreed, 26.33% – neither agreed nor disagreed, 8.78% – disagreed, and 8.15% of students strongly disagreed. There was no significant difference in answers of students in both groups.

Most of the students (70.22%) claimed that antibiotics are overused in Ukrainian agriculture, while only 3.76% didn't think so. There was no significant difference in answers of students in both groups.

5. Discussion

This cross-sectional study among Ukrainian veterinary and medical students assessed their self-reported awareness, behavior, knowledge, and attitude towards the antibiotic usage and development of antimicrobial resistance in humans. Addressing the RQ1, preliminary assessment of compliance of the study with the global environmental health and sustainable development needs in the Dimensions.ai database revealed that the AMR awareness among medical and veterinary students is of primary concern and corresponds mostly to the SDG 2, SDG 3, SDG 12, SDG 13 and SDG 4 of the 2030 Agenda [31]. The findings correspond to the recognized SDGs that AMR can compromise sustainable development [32], with the environmental health integrated [7], but also revealed the SDG 4 (Quality Education) involvement. These findings support the need for an appropriate educational environment on the subject [15, 16, 33].

Rational antibiotic prescription and use is crucial in mitigating AMR, and dependent on knowledge and commitment of both veterinary and medical servants. In this research we carried out preliminary assessment of awareness on antibiotic resistance among veterinary and medical students. This study is the first of a kind to assess students' attitude to the antimicrobial resistance in Ukraine. The knowledge was determined by using multiple choice and true or false questions, covering demographic, personal antibiotic use, attitude and awareness of AMR.

The present outcome, as an answer to RQ2, demonstrated that both veterinary and medical students are aware of antimicrobial resistance issues to a certain extent, as well as its capacity to ensure environmental health as an integrated compound of One Health triad. Self-reported antibiotic usage may be considered as responsible. Most surveyed (about 70%) consulted physicians prior to using antimicrobials and almost 91% claimed that they bought the antibiotics in the pharmacy. This results corresponds to the level of awareness of target students groups in developed countries [14, 34, 35, 35, 36] and may indicate that whether AMR issues are embedded across curricula or this is the result of involvement in World Antibiotic Awareness Week (that medical and veterinary curricula have the effect of improving awareness of AMR). Both cohorts surveyed agreed with a high degree of confidence (86,8%; $p < 0.0001$) that the human population may develop resistance to antibiotics and were quite sure (approx. 72%) that antimicrobial resistance can affect both personal health and the health of family members.

This study indicates that there are some knowledge gaps about antimicrobial usage for different pathological conditions among veterinary students. Answering the RQ3, the significant differences ($P < 0.0002$) in responses was found among two groups of respondents about antibiotic prescription for treatment of disorders caused by viruses such as colds and flu, where the majority of vets (63.6%) believed that antibiotics can be used for treatment. Medical students were also more certain (72.6%) that gonorrhea is a condition which is treatable with antibiotics compared to veterinary students (41.8%) ($P < 0.0001$). This may be due to different approaches to the choice of therapeutic methods in human medicine and animal husbandry. This is especially true in the prescription of antibiotics to prevent complications of inflammatory processes of viral etiology by bacterial microflora, which often happens in animal husbandry. On the other hand, it may be evidence that medical students are better trained on antimicrobial prescriptions to humans and more familiar with the protocols of treatment of different diseases of humans. Nevertheless, veterinary students have a desired level of knowledge about responsible use of antimicrobials. However, further statistical analysis is required in order to explore this question in more depth.

6. Conclusions

This study demonstrates the relationship between the antibiotic resistance issue, the Sustainable Development Goals and environmental health (RQ1), as well as represents the students' knowledge and attitude towards antibiotics use and development of antimicrobial resistance (RQ2). Comparison of answers of medical and veterinary students (RQ3) showed that both groups acknowledged the antimicrobial resistance to a certain extent, evidencing capacity to ensure environmental health as an integrated compound of One Health triad. Differences among the responses of veterinary and medical students demonstrates that medical students are better trained on antimicrobial prescriptions to humans and more familiar with the protocols of treatment of different diseases of humans. The outcome of the survey might be used in future research, as well as in the design of preclinical and clinical courses both for veterinary and medical students with the aim to spread knowledge on the proper antibiotic use and prevention of antimicrobial resistance in order to meet sustainable development needs, address SDGs and One health approach.

Acknowledgments

The study was conducted in the framework of the Erasmus+ Jean Monnet project "Integration EU One Health framework and policies in Ukraine" (101048229 — EU4OH —

ERASMUS–JMO–2021–HEI–TCH–RSCH) co-funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

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Assessment of the ecological hybrid threat to industrial area in connection with the vital state of artificial woody plantations in Kryvyi Rih District (Ukraine)

To cite this article: M O Kvitko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012046

Assessment of the ecological hybrid threat to industrial area in connection with the vital state of artificial woody plantations in Kryvyi Rih District (Ukraine)

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Abstract. Among the concepts of sustainable nature management, forest conservation is considered as an important element. The state of forest ecosystem depends on the development trend of the mining and industrial area and the complex of social, ecological, and economic problems of Kryvyi Rih District. The object of this study was assessing the artificial woody plantations as a promising factor for ecological hybrid threat reduce in industrial areas on the example of the Kryvyi Rih Iron Ore Mining and Metallurgical District on standpoint of an ecosystem approach. During 2015-2020, we studied the natural forest ecosystems and the artificial forest plantations, which were located in contrast environmental conditions. Forests are located very unevenly in the Kryvyi Rih District. They are mainly concentrated in River gullies, woody stands of city parks, woody stands of health protection zones, woody stands of city protection forest and woody stands of river protection forest. The woody plantations located on the territories of Kryvyi Rih District are very different in terms of coverage area and don't reach the optimal level. This woody plantations level allows effect the climate, soil, and water resources. The woody plantations also mitigate the effects of erosion processes, as well as provide more clean air. The artificial woody plantations are an important element of environmental safety in Kryvyi Rih District. The main function of the artificial woody plantations is to maintain the soil in an optimal form for operation. It is also the protection of ground water and the stability of the meso- and microclimate in the region, moreover preserving the biodiversity of the territory's ecosystems. The artificial woody plantations perform an anti-stress function for residents. It was established that the quality of reforming the ecological approach to greening the city's territories, as well as preserving artificial woody plantations, was determined by the choice of such a management model and nature management policy. These models together should ensure the competitive ability and long-term development of the artificial woody plantations in Kryvyi Rih District. The maine industrial areas in the world should develop as an environmentally stable and safety metallurgical region in accordance with the principles of sustainable development in the world.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012046 doi:10.1088/1755-1315/1049/1/012046

1. Introduction

Now the role of forests for maintaining ecological stability is generally recognized in Ukraine and the world [1–4]. Among other natural ecosystems only forests have the maximum property for environmental protection in industrial areas [5–8]. They are considered as one of the decisive factors in ensuring mankind's activities and also as an important part in the system of sustainable development of the Kryvyi Rih Iron Ore Mining and Metallurgical District. In addition, artificial woody plantation stands provide people with a softened microclimate in their residential areas and other positive changes in urbanized areas [9–11]. Local communities are slowing down the pace of global warming and generally reducing their negative impact on the microclimate by using artificial forest stands in mining districts [12–15].

Artificial woody plantations aren't directly used in the form of wood resources, technical, medical raw materials and other forest products for population and industry needs. Nevertheless, they must reproduce at forming region natural complexes. Forest resources also include the beneficial properties of forests used to meet public needs. Such properties are the ability of forests to reduce the negative effects of natural phenomena, protect soils from erosion, prevent environmental pollution and purify it, help regulate water runoff, improve the health of the population and its aesthetic education [16–19].

Among the concepts of sustainable nature management, forest conservation is considered as an important element. Forest stands make up 36% of European territory. In different natural areas it cover has significant differences and doesn't reach the optimal level at which forests most positively effect the climate, soil, water resources, mitigate erosion processes consequences, and also provide a greater amount of wood growth [20–22].

The state of the artificial woody ecosystem depends on the development trends and the complex of socio-ecological and economic problems of Forestry in Ukraine. This makes it necessary to reform the forestry management system. The quality of reform is determined by the choice of a management and forest policy model. Studying foreign experience in forest management and comparing typical management models will help to avoid over-evaluating them and potential implementation mistakes. It will also highlight those aspects of management that can be taken into account in the process of reforming the forest ecosystem in Kryvyi Rih District and in Ukraine [7, 11, 23, 24].

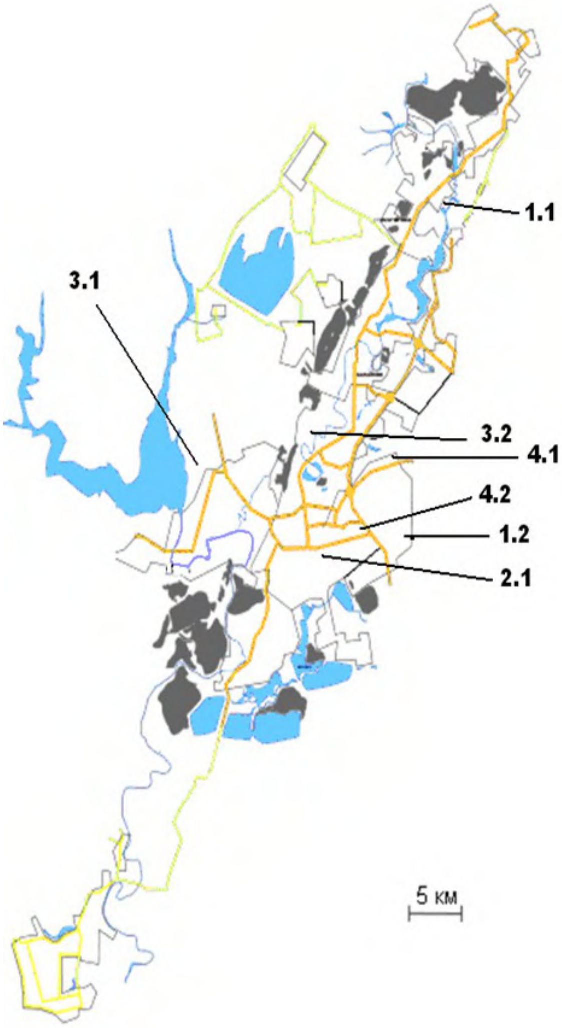
The object of this study was on standpoint of an ecosystem approach to assess the artificial woody plantations as a promising factor for ecologicall hybrid threat reduce in industrial areas on the example of the Kryvyi Rih Iron Ore Mining and Metallurgical District on standpoint of an ecosystem approach.

2. Methodology

Kryvyi Rih Iron Ore Mining and Metallurgical District, Central Ukraine, was chosen for the present study. It is situated between $47°53'54''$ and $48°8'52''$ north latitude and $33°19'52''$ and $33°33'38''$ west longitude. During 2015-2020, we studied the natural forest ecosystems and the artificial forest plantations located in contrast environmental conditions. They represent the main types of tree-shrub stands, in particular garden and park facilities, sanitary, water protection and urban forest protection tracts. Natural phytocenoses from the Gurovsky forest (Dolinsky district, Kirovograd region), located in the floodplain of the Bokova River and 30 km away from industrial enterprises, were used as conditional control.

The test plot study was designed to evaluate all factors controlling the natural phytocenoses and artificial woody plantation state, i.e. air pollution, soil properties, topography, local microclimate conditions and time. The 35 sample plots (20*20 m) were selected by this information base. The sampled locations are shown in figure 1. Field data were collected through direct enumeration and measurement of all trees in every plot. In each plot, all woody stems of diameter at breast height (dbh) > 10 cm were recorded and: 1) their diameter at 1,3 m

(*a*)



(*b*)

Figure 1. Sketch of the study area. (*a.Kryvyi Rih Iron Ore Mining and Metallurgical District, Central Ukraine*) and (*b.Kryvyi Rih Legend: 1 – City parks: 1.1 – Veseloternivsky arboretum, 1.2 – Dovgintsivsky arboretum; 2 – Health protection forests: 2.1 – protection zones of PJSC "ArcelorMittal Kryvyi Rih" 3.– River protection forests: 3.1 – Karachuny forest tract, 3.2 – Dubki forest tract; 4. – City protection forests: 4.1 – Lisove forest tract, 4.2 – Sotsmisto forest tract*).

above ground (in two perpendicular directions by a caliper); 2) their height (by a hypsometer) were measured [25,26]. In natural phytocenoses and artificial woody plantation the relative vital tree state was assessed by V.A. Alekseev [27]. The ecomorphic analysis of woody plant species was carried out according to classic and innovative approach [11].

All data were submitted to descriptive statistics and analysis of variance (ANOVA). The statistical analysis was performed using the program SPSS for Windows. For all statistical analysis, significance was considered P < 0,05 [28, 29].

3. Results and discussion

In Dnipropetrovsk region the forest cover is one of the lowest in Ukraine and amounts 4,8%, with an optimal value of 8,0%. More than 80% of the region's forests are artificial plantings, but the existing areas don't provide sufficient ecological balance and sustainable development of the region. A number of reforestation, afforestation and landscaping activities aimed at fostering respect for nature are planned to be carried out in the region [30, 31].

The State Forestry Agency, which owns 73% of the forests, should be the main driver of environmental initiatives. According to the decision of the Dnipropetrovsk Regional Forestry and Hunting Department the board, it plans to create new forest stands of more than 70 hectares up to 332 hectares planned in 2022. By the end of 2024, foresters will land more than 166 thousand hectares of trees. Robinia pseudoacacia L., Quercus robur L., Pinus nigra, Juglans nigra Hulls will be dominated in Forest crops [7]. An important element among the concepts of sustainable nature management is the preservation of artificial woody plantations in the Kryvyi Rih District. In this area the state of the forest ecosystem in depends on the development trend of the mining and industrial region and the complex of social, ecological and economic problems [10, 11].

Simultaneously with the creation of a new artificial woody plantation research and systematization of existing artificial forest ecosystems remains extremely important in Kryvyi Rih District. As we noted above, in the region artificial woody plantations have an impoverished floral composition; a simplified vertical structure; a certain imbalance in the ratio of dendrometric indicators between the first, second and third tiers of plantings, and sometimes a weakened state of life. In most cases, their trees are under stress due to the constant influence of adverse environmental factors (table 1). However, forest ecosystems have already formed a tree cover in the region. Trees are young and relatively mature. They have accumulated a significant amount of phytomass and potency to form a cenotic phytogenic environment. In addition, trees already perform important environmental, sanitary, and protective phytomeliorative and other functions.

Therefore, for the present their systematization/ordering are extremely relevant and important. The first stage for depth study of artificial tree ecosystems can be a scientific justification for the possibility of using the biogeochemical characteristics of the "leaf litter-soil system" as markers and predictors of the state of trees in forest ecosystems. Thus, according to the results of our research [10, 11], in leaf sediments concentrations of alkaline earth metals (Ca, Mg, K, and Na) should be considered as an accurate ecological and biogeochemical marker. This marker informatively reflects the vital state of woody plant species in the forest ecosystems at industrial areas.

At comparing the indicators of the woody vegetation vital condition, taking into account the indicators of the volume of raw materials for all tiers, it can note the preservation of general trends.

The analysis of the woody plant species from artificial forest communities at Kryvyi Rih region shows that: 1) among the trophomorphs megatrophs(48,1-100%) and oligomezotrophs (1,53-28,71%) are dominated, 2) among the hygromorphs mesophytes (32,73-94,57%) and mesohygrophytes (3,25-41,7%) are dominated, 3) among heliomorphs heliophytes (33,33-89,89%) and sciogeliophytes (5,43-39,67%) are dominated. In most cases, the ecomorphic spectra obtained by classic approach and innovative approach coincide in ordering rankings of the ecomorphic specific weight. However, the contrast between the leading ecomorphs increases. In some cases, the change of dominant ecomorphs and their ranking were detected.

In all major woody tiers, except for tier III, the highest biomass indicators are identified by forest ecosystems in areas with relatively environmentally favorable conditions. The bonitet of a stand depends on the soil-hydrological and climatic characteristics of the biotope reflected by the difference in the growth and accumulation of biomass; thus, accordingly, the bonitet is considered

Table 1. Vertical structure of the stand. Natural(Background) - Gurivsky natural forest; Natural, artificial(Buffer1) - 1.1. – Veseloternivsky arboretum, 3.1. – Karachuny forest tract, 3.2. – Dubki forest tract; Artificial(Buffer2) - 1.2. – Dovgintsivsky arboretum), 3.1. – Karachuny forest tract, 4.1. – Lisove forest tract; Artificial(Impact) - 2.1. – protection zones of PJSC "ArcelorMittal Kryvyi Rih", 4.2. – Sotsmisto forest tract).

	Natural Background age of stand 150-170 years	Natural, artificial Buffer1 age of stand 50-120 years	Artificial Buffer2 age of stand 40-80 years	Artificial Impact age of stand 50-90 years
		Available (%)		
Emergent layer	100	100	100	100
Canopy layer	100	100	75	100
Understory layer	100	75	75	75
Shrub layer	100	75	25	25
Herb layers	100	100	75	–

as an indicator of the stand natural productivity [7,30,31]. Therefore, in the Arboretum "Vesely Terni" and tree stands near the Volovoe village, Artyom 1 tree stands, as well as some areas of water-proof treestands of the Karachunovsky reservoir, the indicators of sites are the highest in terms of total biomass indicators and amount to 87,01 conditional points. This condition of trees corresponds to the category of "healthy". Also crown biomass (88,4 conditional points), leaves (87,7 conditional points) and branches indicators (80,9 conditional points) correspond to the "healthy".

It is proved that in the region the forest cultivar phytocenoses tree species are in a stressful state, because they are constantly affected by adverse environmental factors. We have made the assumption that in the Kryvyi Rih District the artificial forest communities should become one of the key environmental factors determining its ecological safety, both individually in this region and in Ukraine as a whole. To solve this problem, it is necessary to achieve optimal forest cover of this district (8-10%) by creating new plantations and taking into account scientific prerequisites and ordering existing ones.

The results obtained, taking into account statistical processing of the stand viability indicators, show artificial forest stands outside the scope of industrial emissions can be rated as "healthy". The total coefficient of vitality of these plantings is 85,7 conditional points on the V. A. Alekseev scale (the confidence interval is m (+or-) 2,9; the coefficient of variation is 9,8%). Overall vitality indicators are the highest among all identified ecological zones. The crown and branches of woody plants are also "healthy" as they are equal to 85,6 and 86,9 conditional points. The leaves, however, can be considered "weakened", their indicators are equal to 78,1 conditional points.

The vitality indicators obtained by taking into account statistical processing in all areas within territories with relatively low levels of atmospheric pollution are generally quite high. The indicators are equal to 82,9 conditional points, and by V. A. Alekseev scale it is rated as "healthy" (the confidence interval is m (+or-) 2,3; the coefficient of variation is 9,01%). The condition of the crown and leaves is also estimated as "healthy" and is equal to 84.2 conditional points and 83,01 conditional points. However, the condition of the branches is estimated as "weakened" and equal to 78,2 conditional points.

The results obtained in areas with moderate atmospheric pollution and unfavorable environmental conditions for tree vitality indicate a relative "weakening" of woody plants. The viability of these trees is 63,8 conditional points (the confidence interval is m(+or-)3,01; the coefficient of variation is 17,9%). Individual indicators of the crown (63,5 conditional points), leaves (61,7 conditional points) and branches (63,7 conditional points), respectively, are also defined as "weakened". The vitality indicators are the lowest in all areas in the zone with excessive atmospheric pollution and unfavorable environmental conditions. By V.A. Alekseev scale, the condition of trees is assessed as "weakened" and equal to 62,7 conditional points (the confidence interval is m(+or-) 3,6; the coefficient of variation is 13,01%). The condition of the crown, leaves and branches is assessed as "weakened" and equal to 62,3 conditional points, 68,4 conditional points and 60,01 conditional points. All artificial woody plantations have all layers. But the tree undergrowth, shrubs are absent or underdeveloped in some areas From statistical processing of results by tier more detailed data indicate a "weakened" vital state of trees in tier i and ii. These tiers are characterized by indicators of 74,3 conditional points and 60,6 conditional points.

The relevance of our research is determined by the need for scientific understanding of the objective indicators that reflect the real current state of forest ecosystems adversely affecting by environmental conditions at industrial areas. According to leading experts ecomorphic analysis of woody plant species can be as an informative indicator for the current state of these forest ecosystems. Thus, in our opinion, it could be advisable to expand ecomorphic analysis by using woody plant species dendrometric indicators.

In the Kryvyi Rih District the forest ecosystems are located in contrasting ecological conditions. The main types of artificial urban green areas are presented, such as landscape gardening and protective forest stands (sanitary protection, protection of rivers and lakes, protection of cities). In the arid steppe conditions of this district, the ratio of woody plant species to the level of moisture is the most important indicator that determines the future state of these natural and artificial plantings [30, 31]. Therefore, it is extremely advisable to analyze the hygromorphic spectrum of woody plant species. Comparison of ecomorphs of woody plant species in forest ecosystems in Kryvyi Rih District with using tree species analysis and analysis of dendrometric characteristics gave clearer results.

4. Conclusions

Thus, in the Kryvyi Rih Iron Ore Mining and Metallurgical District, the current state of artificial woody plantations can be assessed as conditionally satisfactory, depending on soil conditions and levels of air pollution. A systematic approach to the application of environmental forest management policy will allow significantly reduce the ecologicall hybrid threat in this region and in the industrial areas of the world. The leading biological and dendrometric characteristics of artificial woody plantation stands have a clear ecological conditionality. Vitality State Indicators of artificial woody plantation species in Kryvyi Rih indicate a lack of moisture in the soil and an increased level of atmospheric pollution, which constantly accumulates on the leaves and soil surface, are significant environmental factors.

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Estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production

To cite this article: N A Dotsenko and I V Batsurovska 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012047

Estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production

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Abstract. The article presents the estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production. It is outlined the principle of operation water-lifting equipment in technological processes of agricultural production. It is based on increasing the required pressure for the water supply network by direct repeated use of gravitational forces in the form of weight of the liquid column from natural or artificial pressure. The efficiency of the technological process is assessed by the amount of consumption of water and the speed of flow movement. These parameters (optimization criteria) depend on four main independent factors: the head height; volume of transit tanks; pipe diameter; pipe length. The optimal constructive and technological parameters of water-lifting equipment in technological processes of agricultural production are considered.

1. Introduction

One of the most important problems in the field of agricultural and industrial production is the creation of a modern water supply system. Water supply systems are complex engineering structures that provide both water supply to consumers and drainage and wastewater treatment. The use of water supply systems requires high energy costs, so the creation of systems that will promote energy conservation is necessary for the development of the industry in the country. The water supply system plays an important role in agriculture. The productivity of livestock farms depends on the water supply. To create operational water reserves, water towers are used, the filling of which requires significant energy consumption. Thus, the task of water supply systems is to expand the technological capabilities of the water supply process, increase its reliability, reduce its capital and operating costs, simplify design. Therefore, it is proposed to perform the process of increasing the pressure by gravity in the form of the weight of the liquid column of the required height. To solve it, it is proposed to implement a system of gravity water-lifting equipment that provides an automatic process of reusable pressure, which exists in the system for water supply to the consumer.

An analysis of the technical solutions of the water lift process was performed. In the research were presented the functions of water-lifting aerator technology used in these reservoirs for water quality improvement and its engineering solutions course [1]. The results showed that the technology of water-lifting aerators can effectively control the release of endogenous pollutants, remove volatile contaminants, and reduce the pollution load in reservoirs [2]. Significant opportunities exist to reduce pumping system energy consumption through smart design, retrofitting, and operating practices [3]. The results suggest that a unit increase in the level of farm mechanization increases the demand for hired labour [4]. The authors developed techniques to incorporate differential pressure measurements in flat dilatometer and piezo-penetrometer tests to facilitate in situ measurements under water in a reservoir [5]. Also, hydraulic collecting and pipe transportation are regarded as an efficient way for exploiting submarine mineral resources [6]. The paper presents a comprehensive review of the progress that has been achieved in the past years about cavitation in valves including both mechanical heart valves and control valves [7]. The study investigates the additional installation of a pilot channel running along the canal bottom to constrict the flow width and increase the flow depth [8].

The analytical models of water lifting process in industry were investigated. The paper presents a semi-analytical model that facilitates the optimum design of small-scale hydropower systems [9]. Several practical applications in fluid mechanics have the interest to reduce energy dissipation by reducing the drag or pressure drop [10]. The paper puts forward a formula for the effect of silt sediment on the lifting force [11]. Nevertheless, site-specific factors such as differing discharge conditions, topographical boundary conditions, wastewater volume and composition should be taken into consideration by wastewater practitioners during energy benchmarking assessments [12]. Hydro informatics applies software-based artificial technology for determining these consequences accompanied to water-based approach [13]. The “waterscapes” influence on the administrative geography of the region, which were the locations where these activities took place, and the people in charge of them were integrated within the socio-economic network [14]. Water development, particularly hydropower, provides an important source of renewable energy [15]. Water Engineering Modelling and Mathematic Tools provides an informative resource for practitioners who want to learn more about different techniques and models in water engineering and their practical applications and case studies [16]. The evolution of the major achievements in water lifting devices with emphasis on the major technologies is presented and discussed [17] These technologies are the underpinning of modern achievements in water engineering [18]. The authors investigated some aspects of estimation the processes of quality management system at enterprises [19] and the mathematical modelling of the technology of processing the agricultural production [20] but the estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production was not the specific subject of research.

The aim of the article is to estimate the efficiency of use of water-lifting equipment in technological processes of agricultural production.

2. Methods

Methods of physics, hydraulics, analysis and modelling were used in solving the research tasks. The study of technological parameters of the water-lifting equipment was carried out in the laboratory using the methods of mathematical statistics [21] with data processing on a PC. Experimental studies of the rise of water by water-lifting equipment were carried out on a specially designed installation.

3. Principle of operation water-lifting equipment in technological processes of agricultural production

The principle of operation of equipment for lifting water (figure 1) in technological processes of agricultural production is based on increasing the required pressure for the water supply network by direct repeated use of gravitational forces in the form of weight of the liquid column from natural or artificial pressure. In this case, the natural pressure can be obtained as a result of differences in the height of the water column in waterfalls, rivers, when excess water leaks from ponds and reservoirs, and artificial pressure from any water network in which it is not enough to meet consumer needs.

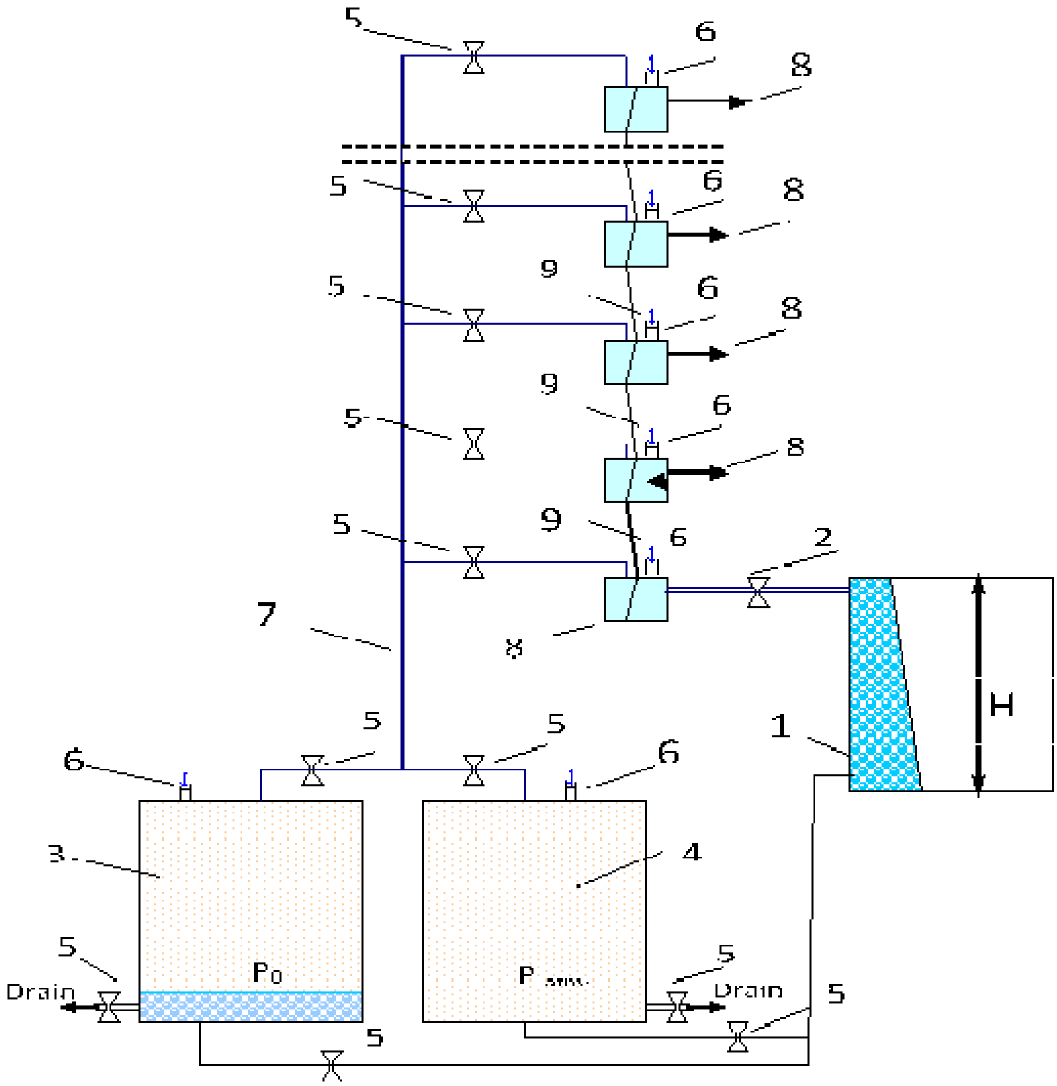

Figure 1. Water-lifting equipment in technological processes of agricultural production: 1 – pressure tank, 2 – tap for filling the transit tank, 3 – right base tank, 4 – left base tank, 5 – ball or screw tap, 6 – valve for sealing or depressurization, 7 – compression air pipe, 8 – transit tanks, 9 – pressure pipelines.

The process of operation of equipment for lifting water in the technological processes of agricultural production is as follows. Through the tap for filling the transit tank 2 with water, from the pressure tank 1, the transit tank 8 is filled with water and sealed with a sealing or depressurizing valve 6. At the same time the right base tank 3 is sealed and filled with water through a ball or screw tap 5, creating at the same time in it compressed air pressure $P_o = R_{atm.} + \gamma h$, where γ is the specific weight of water, and h is the height of the water column pressure H. Then through a ball or screw valve 5, compressed air from the right base tank 3 enters the compression air pipe 7, and then through the valve for sealing or depressurization 6 in the transit tank 8, from which water is expelled by compressed air on the pressure pipelines 9, in the transit tank 8 and fills it, and then repeats the cycle of pushing water from the transit tank 8, that is, after filling it with water, it is also sealed only by means of a valve for sealing or depressurization 6. In the next transit tanks, the process of filling and ejecting water occurs according to the principle described above. In this case, each capacity of the water-lifting equipment starting with the second, provides at a specific level of its rise the value of water pressure $H = \gamma h$. In order to ensure the continuity of the supply of compressed air in the compression air pipe 7 of the device for raising water provides sequential and synchronous inclusion of two tanks: the right base tank 3 and the left base tank 4.

Thus, the process of increasing the pressure in equipment for lifting water of this type can be implemented not only for water supply, but also to use it to obtain sources of cheap, environmentally friendly energy by creating high-pressure hydropower plants of a wide range of capacities. Such installations can be widely used in agriculture, which, like no other industry, needs autonomous water and energy supply. The introduction of this type of installation requires full automation of the process of increasing the gravitational pressure, which eliminates the presence of human.

For experimental studies, the volumes of transit tanks equal to 1 dm, located at a height of 0.5 m, were accepted, and the choice of volumes for base tanks was made on the condition of reliable compressed air supply system for experimental studies. Experimental studies have shown that the optimum value of water flow in the pipeline corresponds to the speed of its movement is 1.2 m/s, and the time of supply of the initial volume of water to the maximum height of the system under consideration is 45 seconds. Studies have shown that taking into account all local system losses and losses along the length of the pipeline, the efficiency of the gravity water lift system is approximately 98%. During the experimental research, all the processes of sealing and depressurization of transit tanks were carried out manually, using conventional ball valves, because in the laboratory it is difficult to create a complete automation of the process of lifting water.

4. Results

The quality of the technological process is assessed by the amount of water consumption (AC) and speed of flow movement (SM). These parameters (optimization criteria) depend on four main independent factors: the head height – H, m (X_1); volume of transit tanks – V, m^3 (X_2); pipe diameter – d, m (X_3); pipe length – l, m (X_4). The above independent factors are selected as the main in this technological process by conducting preliminary experiments and their ranking according to the degree of impact on the quality of work. The levels of setting of independent variables (factors) and the range of their variation, adopted during the experiments, are given in table 1.

Table 1. Levels and range of variation factors.

Factors	Levels of variation			Interval of variation	Dimension
	-1	0	+1		
$X_1(H)$	3	6	9	3	m
$X_2(V)$	2	4	6	2	m^3
$X_3(d)$	0.02	0.04	0.06	0.02	m
$X_4(l)$	3	6	9	3	m

The plan, the average value of AC, SM was calculated. Mathematical models are obtained that adequately describe the The frequency of experiments on each of the optimization criteria was three times. For each line of technological process. The regression equations are:

- for the amount of consumption:

$$AC = 12.5 + 0.58X_1 + 5.4X_2 + 2.1X_3 - 2.6X_4 + 0.63X_1X_2 - 0.6X_1X_3 - 1.3X_1X_4 - \\ -2.8X_2X_3 - 1.06X_2X_4 + 1.5X_3X_4 + 2.1X_1^2 - 5.4X_2^2 - 1X_3^2 + 1.8X_4^2 \tag{1}$$

- for the speed of movement:

$$SM = 0.83 - 0.025X_1 - 0.017X_2 + 0.020X_3 - 0.011X_4 - 0.012X_1X_2 + \\ +0.0056X_1X_3 - 0.042X_1X_4 + 0.048X_2X_3 - 0.013X_2X_4 + 0.0097X_3X_4 + 0.12X_1^2 - \\ -0.09X_2^2 - 0.012X_3^2 + 0.014X_4^2 \tag{2}$$

The analysis of regression equations obtained after statistical processing is usually performed with coded values of factors [21]. The study of the behaviour of optimization criteria depending on the change of independent factors will be carried out using the method of two-dimensional sections.

When substituting $X_3 = 0$ and $X_4 = 0$, the regression equations will look like:

$$AC = 12.5 + 0.58X_1 + 5.4X_2 + 0.63X_1X_2 + 2.1X_1^2 - 5.4X_2^2 \tag{3}$$

$$SM = 0.83 - 0.025X_1 - 0.017X_2 - 0.012X_1X_2 + 0.12X_1^2 - 0.09X_2^2 \tag{4}$$

- for the amount of consumption:

$$AC - 17.218 = 2.183X_1^2 - 5.493X_2^2;$$

- for the speed of movement:

$$SM - 0.8 = 0.119X_1^2 - 0.093X_2^2;$$

The two-dimensional cross section of the response surfaces is shown in figure 2. Consistently fixing the other two factors at level 0 and performing calculations similar to the above, it is obtained the regression equation in the usual form with a new combination of factors.

When substituting $X_1 = 0$ and $X_2 = 0$, the regression equations:

- for the amount of consumption:

$$AC = 12.5 + 2.1X_3 - 2.6X_4 + 1.5X_3X_4 - 1X_3^2 + 1.8X_4^2 \tag{5}$$

- for the speed of movement:

$$SM = 0.83 + 0.020X_3 - 0.011X_4 - 0.0097X_3X_4 - 0.012X_3^2 + 0.014X_4^2 \tag{6}$$

In accordance:

- for the amount of consumption: $X_3 = -1.23$; $X_4 = 0.27$;
- for the speed of movement: $X_3 = -1.153$; $X_4 = 0.795$;

The regression equations in canonical form will take the form:

- for the amount of consumption:

$$AC - 11.10 = 2.0032X_3^2 - 1.153X_4^2;$$

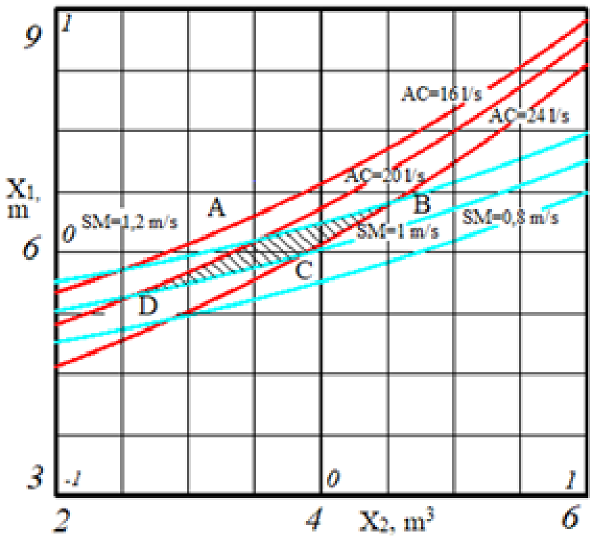

Figure 2. Two-dimensional intersection of response surfaces at $X_3 = 0$ and $X_4 = 0$.

- for the speed of movement:

$$SM - 0.83 = 0.0179X_3^2 + 0.0805X_4^2.$$

When setting $X_2 = 0$ and $X_4 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 0.58X_1 + 2.1X_3 - 0.6X_1X_3 + 2.1X_1^2 - 1X_3^2 \tag{7}$$

- for the speed of movement:

$$SM = 0.83 - 0.025X_1 + 0.020X_3 + 0.0056X_1X_3 + 0.12X_1^2 - 0.012X_3^2 \tag{8}$$

In accordance:

- for the amount of consumption: $X_1 = -0.427$; $X_3 = -0.96$;
- for the speed of movement: $X_1 = 0.084$; $X_3 = 0.852$;

Regression equation in canonical form:

- for the amount of consumption:

$$AC - 12.5 = 2.2X_1^2 - 1.035X_3^2;$$

- for the speed of movement:

$$SM - 0.94 = 0.12X_1^2 - 0.0121X_3^2.$$

The two-dimensional cross section of the response surfaces is shown in figure 3.
When setting $X_1 = 0$ and $X_3 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 5.4X_2 - 2.6X_4 - 1.06X_2X_4 - 5.4X_2^2 + 1.8X_4^2 \tag{9}$$

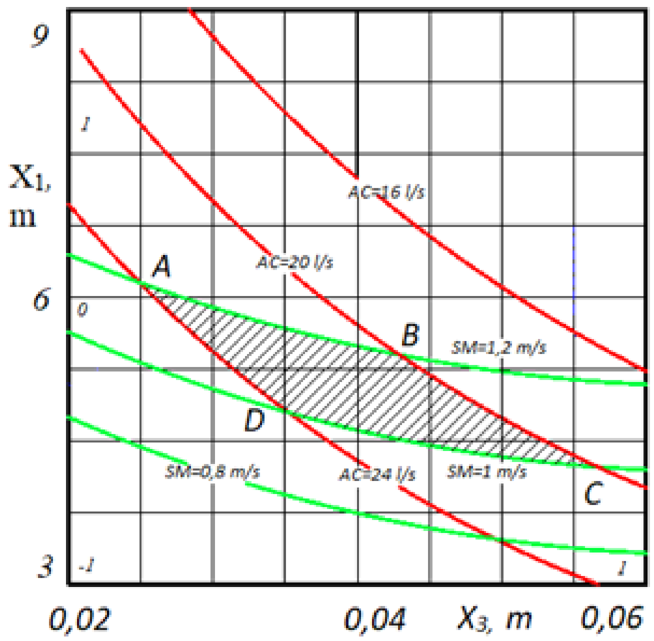

Figure 3. Two-dimensional intersection of response surfaces at $X_2 = 0$ and $X_4 = 0$.

- for the speed of movement:

$$SM = 0.83 - 0.017X_2 - 0.011X_4 - 0.013X_2X_4 - 0.09X_2^2 + 0.014X_4^2 \tag{10}$$

In accordance:

- for the amount of consumption: $X_2 = 0.41$; $X_4 = 0.841$;
- for the speed of movement: $X_2 = -0.121$; $X_4 = 0.336$;

Regression equation in canonical form:

- for the amount of consumption:

$$AC - 10.67 = 1.894X_2^2 - 5.51X_4^2;$$

- for the speed of movement:

$$SM - 0.709 = 0.0144X_2^2 - 0.0904X_4^2.$$

When setting $X_2 = 0$ and $X_3 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 0.58X_1 - 2.6X_4 - 1.3X_1X_4 + 2.1X_1^2 + 1.8X_4^2 \tag{11}$$

- for the speed of movement:

$$SM = 0.83 - 0.025X_1 - 0.011X_4 - 0.042X_1X_4 + 0.12X_1^2 + 0.014X_4^2 \tag{12}$$

In accordance:

- for the amount of consumption: $X_1 = 0.098$; $X_4 = 0.757$;

- for the speed of movement: $X_1 = 0.235$; $X_4 = 0.74$;

Regression equation in canonical form:

- for the amount of consumption

$$AC - 12.21 = 2.69X_1^2 + 1.32X_4^2;$$

- for the speed of movement:

$$SM - 0.87 = 0.12X_1^2 + 0.0099X_4^2.$$

The two-dimensional cross section of the response surfaces is shown in figure 4.

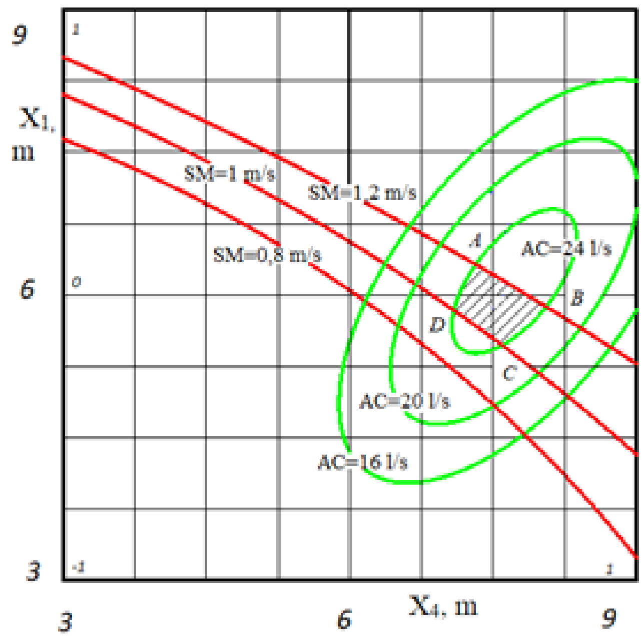

Figure 4. Two-dimensional cross-section of the response surfaces at $X_2 = 0$ and $X_3 = 0$.

When setting $X_1 = 0$ and $X_4 = 0$, the regression equations have the form:

- for the amount of consumption:

$$AC = 12.5 + 5.4X_2 + 2.1X_3 - 2.8X_2X_3 - 5.4X_2^2 - 1X_3^2 \tag{13}$$

- for the speed of movement:

$$SM = 0.83 - 0.017X_2 + 0.020X_3 + 0.048X_2X_3 - 0.09X_2^2 - 0.012X_3^2 \tag{14}$$

In accordance:

- for the amount of consumption: $X_2 = 1.225$; $X_3 = -2.71$;
- for the speed of movement: $X_2 = 0.273$; $X_3 = 1.38$;

Regression equation in canonical form:

- for the amount of consumption:

$$AC - 12.86 = -0.58X_2^2 - 5.89X_3^2;$$

- for the speed of movement:

$$SM - 0.78 = -0.0052X_2^2 - 0.0968X_3^2.$$

After the analysis of two-dimensional surfaces of section (figures 2–4) it is possible to make the following statements. With the value of the existing pressure equal to $5.5 - 6.5$ m and the volume of transit tanks equal to $3 - 4.5$ m^3, the amount of consumption of water will be in the range of $20 - 24$ l/s, and the speed of flow movement will be $1 - 1.2$ m/s (figure is limited by ABCD points, figure 2). The diameter of the pipeline will be 0.04 m, the length of the pipeline will be 6 m. Moreover, with increasing pressure increases the amount of flow, the speed also increases. And if increases the volume of transit tanks, the speed of movement begins to increase, but the amount of consumption decreases. At the existing pressure equal to $4.5 - 6$ m and the diameter of the pipeline, which is $0.025 - 0.055$ m, the amount of consumption of water will be within $20 - 24$ l/s, the speed of flow movement will be 1.2 m/s. The volume of transit tanks will be 4 m^3, with a pipeline length of 6 m (figure ABCD, figure 3). Moreover, increasing the diameter of the pipeline, the flow rate increases, and the speed begins to decline.

At the level of the existing pressure within $6 - 6.5$ m and length of the pipeline equal $7 - 8$ m, the amount of consumption of water will be 24 l/s, at speed of flow movement within $1 - 1.2$ m/s (figure ABCD, figure 4). Moreover, the diameter of the pipeline will be 0.04 m, with the volume of transit tanks equal to 4 m. But with increasing length of the pipeline, the flow rate and speed decrease.

The optimal constructive and technological parameters of water-lifting equipment can be considered as follows: the head height $X_1 = 5...6.5$ m; volume of transit tanks $X_2 = 4...4.5$ m^3; diameter of the pipeline $X_3 = 0.04...0.05$ m; the length of the pipeline $X_4 = 6...7$ m. The optimization criteria are in the range: the amount of consumption of water $AC = 20 - 24$ l/s; the speed of flow movement $SM = 1 - 1.2$ m/s.

5. Conclusion

A review of literature sources on the use of systems and equipment for water supply showed that the known technical solutions for raising water in water bodies usually have low efficiency and require energy consumption during operation. Also, they are not always technological in addressing the issues of increasing the pressure in the water supply network and maintaining it at the level necessary for the consumer. Thus, there is a need to address the issue of improving the quality of water supply to consumers, reducing energy consumption in the operation of the water supply system and maintaining the required pressure in the water supply network by designing water-lifting equipment in technological processes of agricultural production.It was found that the main optimization criteria for assessing the quality of the technological process were: the amount of consumption of water $AC = 20 - 24$ l/s and the speed of flow movement $SM = 1 - 1.2$ m/s.

On the basis of theoretical and experimental studies it is established that these optimization criteria depend on four main independent factors: the head height – H, m; volume of transit tanks – V, m; pipe diameter – d, m; pipe length – l, m. Also, the most favourable constructive and technological parameters of the water-lifting equipment are established, namely: head height $X_1 = 5...6.5$ m; volume of transit tanks $X_2 = 4...4.5$ m^3; diameter of the pipeline $X_3 = 0.04...0.05$ m; the length of the pipeline $X_4 = 6...7$ m.

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To cite this article: V V Vapnichna *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012048

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012048 doi:10.1088/1755-1315/1049/1/012048

Justification of the method of soil densification of the interstation tunnel by jet injection based on computer modeling

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Abstract. The article is devoted to a topical issue - the development of a method of densification of the base of the underground interstation tunnel to prevent further intensive subsidence of tunnel structures. Based on computer-mathematical modeling, the work establishes experimental dependence between the angle of inclination of jet grouting piles and the amount of subsidence of the distribution plate on which the tunnel structures rest upon. Inspection of the technical condition and analysis of defects in a comprehensive comparison with subsidence graphs allowed us to identify the main typical deformations during subsidence of a shallow tunnel built from blocks of a solid-section frame, namely their characteristic features, geometric parameters and placement points.

1. Introduction

The importance of underground lines cannot be overestimated. Traffic flows throughout the city depend on their reliable technical condition. The closure of only one of the central lines can lead to a transport collapse throughout Kyiv. When designing shallow underground structures in weak, unstable soils, it is often necessary to fix the surrounding area, both for the safety of work and to prevent subsidence of surrounding objects near construction. There are dozens of methods of fixing soils, each of which has its own disadvantages and advantages, but depending on technological, economic and hydrogeological conditions, each of them is more or less appropriate.

During the operation of interstation tunnels of underground constructed from solid-section frames in difficult hydrogeological conditions, deformations may occur due to uneven subsidence caused by vibrodynamic loads from the movement of underground trains. Significant funds are being spent on the repair and maintenance of such tunnels, which could be used to build new underground stations. Foreign experience and the introduction of the latest geotechnologies allows us to state that the issue of subsidence and deformation of tunnels can be solved using modern technology, design methods and work.

The study [1] describes a series of tests of centrifuge models aimed at studying the effect of sequential construction of two-level tunnels on an existing pile group under load in dry sand. Laying a tunnel of two levels was modeled in two stages: the first tunnel was laid at half the

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012048 doi:10.1088/1755-1315/1049/1/012048

depth of the pile, and the second - at the depth of the pile or below the depth of the pile. There were also two tests of different sequence and construction of two-level tunnels. The first tunnel was laid at or below the pile-laying depth, and the second tunnel was laid at the middle of the pile-laying depth. The tests were performed by the method of finite element analysis, which takes into account the strength of the soil from deformation. The results of measurements and calculations showed that changing the sequence of construction of two-level tunnels significantly affects the subsidence, slope and displacement in the cross-section of the pile group. No significant effect on bending moment and load transfer mechanism in piles was found.

The authors in their work [2], created a model of a test system that simulates horizontal freezing of the soil and shows the temperature distribution and displacement of frost heaving based on a real project of freezing of the Shanghai underground double tunnel. The results of model tests showed that soil displacement during frost heaving is closely related to time.

In this test, a successive freezing mode was adopted, the displacement during frost heaving during the freezing period of the downlink tunnel was less than during the freezing period of the uplink tunnel under the action of water displacement. The authors conducted numerical simulations of horizontal soil freezing of double tunnels with successive freezing and simultaneous freezing of tunnels on the ascending and descending lines. successive freezing of the soil reduces the displacement of frost heaving to a greater extent than simultaneous freezing. It can be used as a reference material in the design and construction of double tunnels by artificial freezing of the soil.

The article [3] substantiates the influence of the initial tunnel design on the level of soil vibration during the operation of the underground line in the future. This is important because the construction of the tunnel leads to soil disturbance, which indicates a high level of soil deformation near the tunnel. As a result, soil stiffness worsens, which affects ground vibrations and their propagation to foundations near buildings, and this requires research. To solve this problem, a new hybrid modeling approach was developed, consisting of a model construction and an elastodynamic model.

Underground transport infrastructure has an impact on increasing urban population [4]. These tunnels are built next to a tall building that rests on a fuel yard, which reduces differential saggings in structures.

In this study, three-dimensional numerical simulations were performed using an improved hypoplastic soil model to study the response of an existing pile yard to the passage of two-level tunnels at different depths. In the simulation, the first tunnel was laid at a depth of mid-depth of the piles, the second tunnel was built either at the depth of the piles, or below. In addition, three more analyses were performed to study the impact of changes in the sequence of construction of two-level tunnels in the pile yard. The greatest subsidence, but at the same time the smallest bending moment of the pile yard caused a variant below the depth of the passage of a two-level tunnel. The greatest slope of the pile yard occurred in the case below the depth of the pile yard. The first tunnel in each case caused the load to be transferred from the base to the piles. However, the second tunneling caused an increase in the load on the base due to its penetration into the soil. The diverse sequence of construction of two-level tunnels significantly affected the subsidence and formation of the slope of the pile yard.

Very often in urban conditions there are difficult geological conditions for tunneling, insufficient rock pressure to ensure the safety of tunnel work, which can lead to damage to neighboring buildings. The publication [5] obtained the maximum reference pressure at the tunnel boundaries, also analyzed the effect of internal friction angle, adhesion to the ground, the angle of friction at the interface, the thickness of the coating layer and the structure of the tunnel. The soil is presented as a hard plastic material. In addition, a mathematical model of static equilibrium with an extended boundary equilibrium limit has been developed. The distribution of pressure and mechanisms of destruction of the beginning of the tunnel is obtained by the finite element method. It was found that the pressure decreases with increasing angle of internal friction. When comparing the results obtained with the results found from the relevant links, it should be noted that the sliding line method for calculating the reference pressure at the beginning of the tunnel is reliable. In addition, it is extremely convenient when it is necessary to take into account the angle of internal friction and the slope line of the structure.

In weathered rocks in the first section of the arc tunnel, cracking and crushing were observed [6]. This happened during the construction of the second tunnel. Therefore, for almost one year, distributed monitoring was performed using opto-fiber to study the deformation and stress of the damaged lining of the first tunnel. Optical fibers were attached on opposite sides of the temporary support of the arch. The development of cracks was detected on the concrete lining and vertical ovality. Over time, compression deformation began to develop. With the help of opto-fiber, the radial displacement of the concrete cladding, which was caused by the bending moment, was calculated.

Comparing the results obtained with the help of total stations revealed obvious errors. A more precise method for determining the deformation regime of arched structures based on fiber-optic deformation data was proposed.

In concrete tunnels, segmental joints are the most vulnerable parts of the cladding. In most existing models of segmented joints, it is not possible to assess the damage and destruction due to elastic deformation. Segmental damage to tunnels may occur in the field. The study [7] presents full-scale tests of the segment connection of the gas tunnel. The segment hinge is constantly loaded to the maximum value of effort. The internal forces, deflection and fracture characteristics of the segmental joint during loading were calculated, and a comparison was made with previous studies on flat segments.

Prefabricated reinforced concrete segments in most cases are loaded with traction jacks at the stage of installation [8]. Then it is necessary at this stage to prevent the formation of cracks and damage to the segments to ensure their integrity. Using fiber admixtures in the form of fibers can reduce the number of cracks, in addition, the fibers help prevent local damage, such as chipping edges and corners of segments.

In a segmented underground tunnel, cracks, water leaks and other structural defects usually occur at the segmental joint, which has less rigidity than the section of the main segment of the tunnel. In this study [9], a model of a typical concrete segment joint was modeled using 3D-continuous elements. The simulation was performed using shear springs: the stiffness of conventional springs is mainly determined by the bolt itself, and shear springs take into account the friction of the bolt segment, the interaction and shear resistance of the bolt. Meanwhile, the interaction between two adjacent tunnel segments is modeled using elements in contact with each other.

The study [10] presents the results of laboratory tests, which allows to characterize the two-component filler during the curing period. A detailed study of the effect of the presence of filler material on the behavior of the support system of the tunnel was conducted. The filler in concrete increases the modulus of elasticity of the segmental lining of the tunnel. Using the method of Einstein and Schwartz, you can determine the bending moments and normal forces acting on the supporting structure of the tunnel, having the parameters of stiffness only overlays of the tunnel segment.

The mechanical behavior of sealing gaskets for district connections in the Z2 tunnel of the Tianjin Metro Line was investigated using an experiment [11]. To do this, a new device was developed to measure the mechanical properties of the gaskets of the joints. Four types of EPDM profiles and composite cross-section profiles with different hole combinations were tested. Water pressure and joint opening coefficient were used to study the mechanical characteristics of the gaskets.

The test results of the two gasket profiles were compared and the effect of the gasket hole area was discussed. To correlate the mechanical behavior of the gasket and the sealant, it was proposed to adopt the ratio of water resistance to average contact pressure. The results showed that the opening and shear of the gasket seam had a great influence on the water resistance. A relatively small change in the area of the gasket hole can lead to a significant change in mechanical and waterproof characteristics. Leak analysis has shown that bolt holes, wheel joints and concrete cracks are common leaks during tunnel construction and operation.

In loess soils, the subsidence of the tunnel depends on the angle of installation of the reinforcement bolt.

In [12] a mechanical calculation model was developed, which coordinates the deformation and displacement of the arch leg between the steel frame and the FRB. The influence of the anchor tube angle on the subsidence of the tunnel arc was investigated using finite element modeling. It was found that the maximum anti-slip force is at an angle of FRB 47 degrees.

In [13] it is argued that the pile-beam-arch method is suitable for the construction of shallow urban metro stations with heavy ground traffic. The main construction process consists of four stages: construction of pilot tunnels, installation of piles and beams, installation of arches and excavation of rocks inside the metro station. This study uses numerical calculations to study the patterns of loads during the development of the earth's surface. Empirically identified key steps to control subsidence of the surface.

The results show a linear relationship between the distance between the columns and the subsidence of the surface, with a smaller interval between the columns decreases the subsidence. The nonlinear dependence of the cross-sectional area of the column on the surface deposition is obtained. Surface deposition is stable at cross-sectional dimensions of 1.5×1.5 m. The results of this study make it possible to predict the subsidence of the surface during the construction of tunnels.

To improve the corrosion resistance of underground arches in the embankment structure, steel rods have been replaced by rods with basalt fibers and hybrid steel rods [14]. The study was conducted on eight arches. Quasi-static compression was performed to assess the structural characteristics of the arches. Concrete arches reinforced with composite rods have elastic-plastic deformation.

Arches have a typical bending mode, where the destruction is determined by the crushing of compressed concrete. Arches reinforced with composite rods have ductility and higher load capacity than arches reinforced with steel bars.

The publication proposed a method of analytical design for predicting load-bearing capacity. This method has tolerable errors.

This article [15] proposed a method for recognizing cracks in paved tunnels. The technique consists of three stages: pre-processing and image improvement, selection of signs and characteristics of cracks. To highlight the cracks, the images are improved using special algorithms. This paper proposes differential noise filtering and an improved segmentation method that detects crack boundaries. A self-regulating calibration method is used to characterize cracks. Experiments confirm the stability and reliability of the technique.

The main attention in solving the problem of reducing the intensity of subsidence is paid to strengthening the base, which takes loads through structural elements, and therefore the primary step to prevent further deformations is to perform work on strengthening the soil of the tunnel base.

2. Aim/tasks

Evaluate different options for fixing soils depending on the angle and depth of fixing the elements of underground tunnels. The use of computer simulation will make it possible to predict the positive effect of fixation

3. Research methods

The aim of the work is to study and substantiate an alternative method of fixing the soils of the base of the underground interstation tunnel at a high intensity of subsidence during operation.

When designing foundations and principles, it is necessary to exclude the possibility of deformations that can cause the destruction of the foundation or structure, and when calculating deformations of the foundation with complex engineering and geological conditions, or if the load-bearing capacity of the foundation is insufficient, it is necessary to provide measures to reduce the negative impact of these deformations. To improve the properties of soils, compaction (mechanical or physical) and fixing (mechanical or chemical) are used at the site of their occurrence.

When using jet injection technology, jet grouting piles with a diameter of up to 1000 mm are arranged, the parameters of the jet, the speed of its rotation and sliding movement up, the type, brand and amount of cement introduced into the soil are determined in the project based on research work performed at the design site.

In tunnels and substructures of the underground, it is necessary to provide for the installation of control and measuring equipment for uninterrupted observations (monitoring) of the condition of frames, structures of underground structures, engineering networks and the surrounding ground environment.

When comparing the methods of fixing the base, the most appropriate ones at the stage of design and operation of the interstation tunnel of the underground are chemical fixing of soils and the method of jet injection. Studying the experience of using these methods close to the specified conditions, we can conclude that chemical soil consolidation requires improvement or replacement as the main method for fixing the soils of interstation tunnels of the underground in water-saturated sands.

Analyzing the previous experience in reducing the intensity of subsidence, by fixing soils by two soluble silicatization, in areas from station “Vydubychi” to station “Kharkivska” failed to achieve significant results. As a result, the necessity appears to reduce the speed of trains to prevent further development of deformations.

The research area is the stage between stations “Pozniyaki” (SC232 + 92) - “Kharkivska” (SC245+50) belongs to the Syretsko–Pecherska line of the Kyiv Metro. The interstation tunnels were built by PJSC “Kyivmetrobud” cut-and-cover with the opening of the pit to a full profile, in sandy water-saturated soils with artificial lowering of the ground water level by deep wells. The stage length is 1258 m. The customer was PUC “Kyiv Metro”. Commissioning was carried out on December 28, 1994.

The geological structure to the explored depth is composed of a series of alluvial quaternary deposits of different ages in the Dnieper river valley, lying on the eroded surface of the Buchak layerof the Paleogene, covered from the surface by a soil-vegetation layer, partially bulk soil and alluvial sand. The thickness of the alluvial layer is about 5 meters. The thickness of alluvial quaternary deposits is represented by small, medium and large sands, sometimes with the inclusion of gravel and pebbles of crystalline rocks.

The interstation tunnels are constructed from blocks of solid-section frames (see figure 1), on a separate monolithic reinforced concrete slab, 300 mm thick, which is laid on a layer of crushed stone rammed into the ground.

To reduce the ground water level to 1-2 meters below the level of pit excavation, the project provided for the simultaneous operation of 10 water-lowering wells for each section with a length of 100 m. Water reduction was performed with needle filters. To absorb deformations of building structures, the device of compensatory expansion joints was provided, which are located in places where the type of structure or soil layers in the base change.

The survey of the technical condition of the tunnel frame made it possible to assess the damage and defects that occurred during the period of operation due to natural factors, design

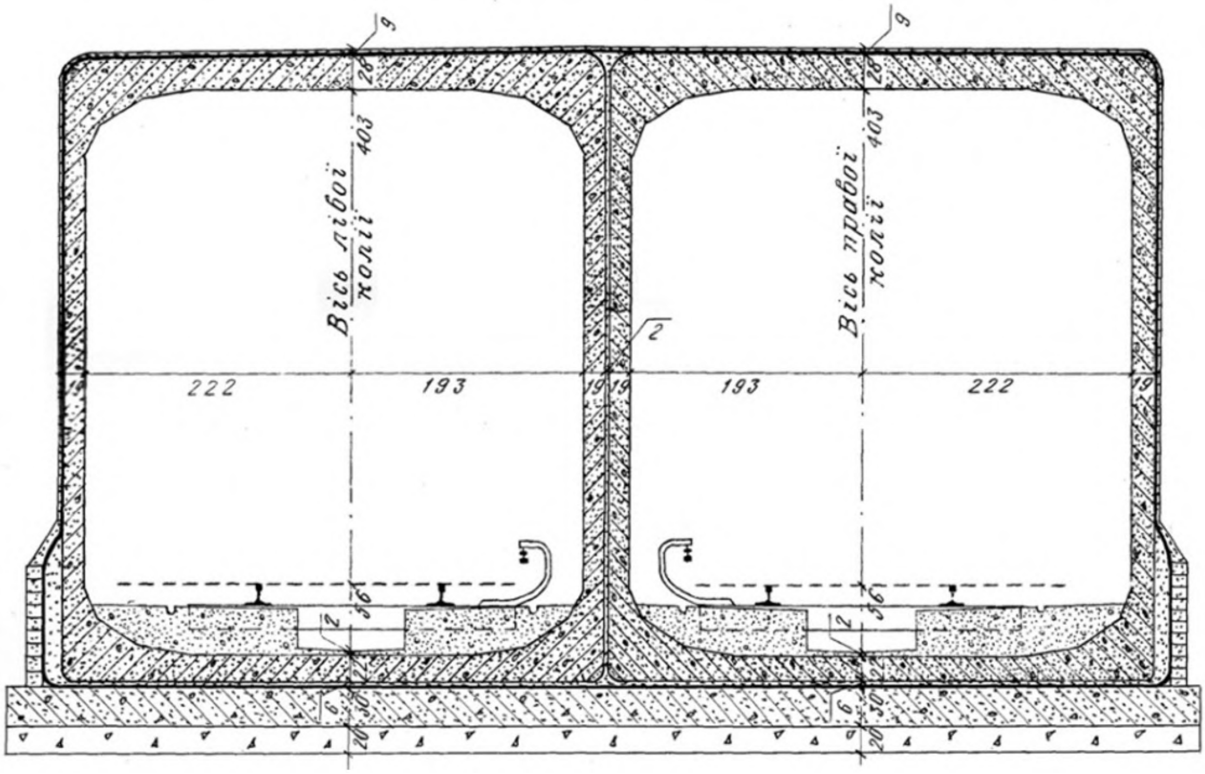

Figure 1. Construction of WCA blocks.

errors and construction technology violations. The complex of examinations included visual and instrumental inspections. The technical condition of separate structures was determined as a result of a general analysis of defects and damages identified by the results of the survey. According to the load-bearing capacity and operational properties, the technical condition of the structure is classified as one of the categories.

Most of the observations are made up of instrumental measurements of subsidence or deformation values, which are performed mainly by geodetic methods.

Geodetic observations of subsidence or deformations of artificial structures of the underground are carried out in order to determine the degree of deformation and assess the stability of the structure, take timely measures, study the causes of deformations of the underground structures, check calculated data and develop a methodology for predicting them [16].

Inspection of the technical condition of the tunnel frame was carried out along the I and II tracks on the section within SC235+80 ÷ SC243+80 of the stage between stations "Pozniyaki" - "Kharkivska" of the Syretsko–Pecherska line. Additionally, the surface above the tunnels was inspected for sinkholes and subsidence.

So the main detected defects and damages are:

- transverse and longitudinal cracks with an opening of up to 5 mm in track concrete;
- cracks with an opening of up to 5 mm in the locations of embedded parts in the WCA blocks;
- slots up to 10 mm at the junction of WCA blocks;
- chips of the protective layer of concrete with exposure of corroding reinforcement in the WCA blocks;
- filtration of ground water with sand removal through the joints of WCA blocks.

The active zone of propagation of power vibration loads in watered sands is located within a radius of 4.0-4.5 m [17].

The presence of filtration of ground water indicates a violation of the tightness and integrity of waterproofing [18].

4. Results and discussion

According to the results of periodic instrumental geodetic and survey observations of the high-altitude position of tunnels on the surveyed stretch, the maximum values of subsidence, counting from the time of commissioning, reached (as of September 2018):

- on I track on SC242+29 – -345 mm (see figure 2);
- on II track on SC236+00 – -321 mm.

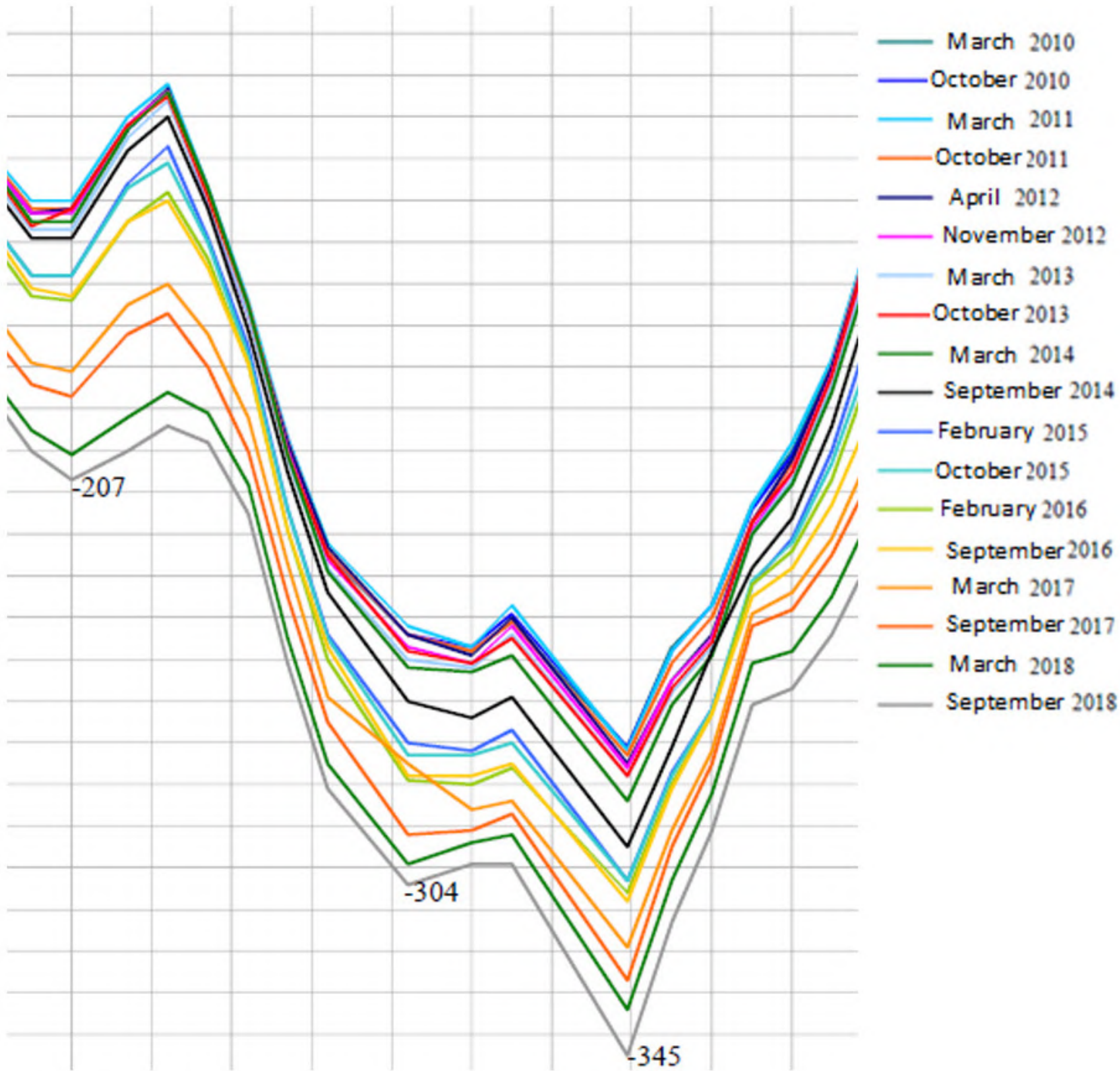

Figure 2. Subsidence of tunnel structures on SC242+29 along 1 track.

As can be seen from the subsidence graph, its propagation along the length occurs unevenly. During the visual inspection of the tunnel frame sections, cracks with an opening of up to 5 mm in the WCA blocks and track concrete were found in the area of individual upper peak points, as well as cracks of up to 10 mm in the joints between the blocks. The greatest opening width of the slits was observed in the arch of the tunnel frame.

Insufficient thickness of the protective layer of concrete in reinforced concrete blocks of a solid-section frame leads to corrosion of the reinforcement. Corrosion products, increasing in volume, lead to the creation of excessive internal pressure, which in turn causes cracking, peeling and chipping of the protective layer of concrete.

The presence of filtration of ground water indicates a violation of the tightness and integrity of waterproofing.

Based on the results of survey data for March 2019 (table 1) it was found that the maximum subsidence rates of interstation tunnels on individual pickets during the last half-year and for the year reached the following values:

Table 1. Tunnel subsidence values for March 2019.

I - track				**II - track**			
SC	maximum amount of subsidence	within six months	within a year	SC	maximum amount of subsidence	within six months	within a year
240+00	-301	-18	-30	**239+51**	-237	-7	-15
240+77	-319	-10	-18	**240+00**	-270	-11	-23
240+97	-331	-13	-20	**240+39**	-220	-12	-27
241+67	-214	-14	-22	**241+80**	-237	-11	-25
242+29	-353	-8	-19	**242+74**	-125	-13	-26
243+45	-204	-13	-22	**243+19**	-192	-23	-37

Over the past five years, there has been a tendency to continue increasing the intensity of subsidence. So in the following years, the amount of subsidence on 1 track SC242+29 (table 2) was as follows:

Table 2. The amount of subsidence on 1 track SC242+29 in the following years.

Date	Subsidence
02.2015	-303 mm
02.2016	-306 mm
03.2017	-319 mm
03.2018	-334 mm
03.2019	-353 mm

Analyzing the results obtained, it should be noted that on this stage there is a continuation and increase in the intensity of subsidence of the tunnel frame with the appearance of characteristic deformations (cracks, chips, expansion of joints).

Based on the above and taking into account the presence of damage in reinforced concrete structures, it is necessary to perform work on fixing the ground of the base to prevent further deformations of the tunnels.

Let's consider the simulated options for fixing the ground base of the underground intersatation tunnel using jet injection technology.

In the process of modeling, the properties of the soil cement material and the geometric dimensions of soil cement piles were selected as the most optimal for the specified conditions.

Ground-cement piles built using jet-grouting technology with a diameter of 0.8 m in increments of 1.8 m from the center of the axis and a calculated deformation modulus of 3000 MPa are used as fixing elements of the array [17–19].

The essence of the calculation is to determine the values of subsidence before and after fixing the soil by jet injection. For the modeling process, 3 variants of fasteners with angles of inclination of 30 (see figure 3), 35 and 40 degrees relative to the surface were selected. The expected result is a reduction in the subsidence of the tunnel structures (distribution plate) after the device is fixed with jet grouting piles.

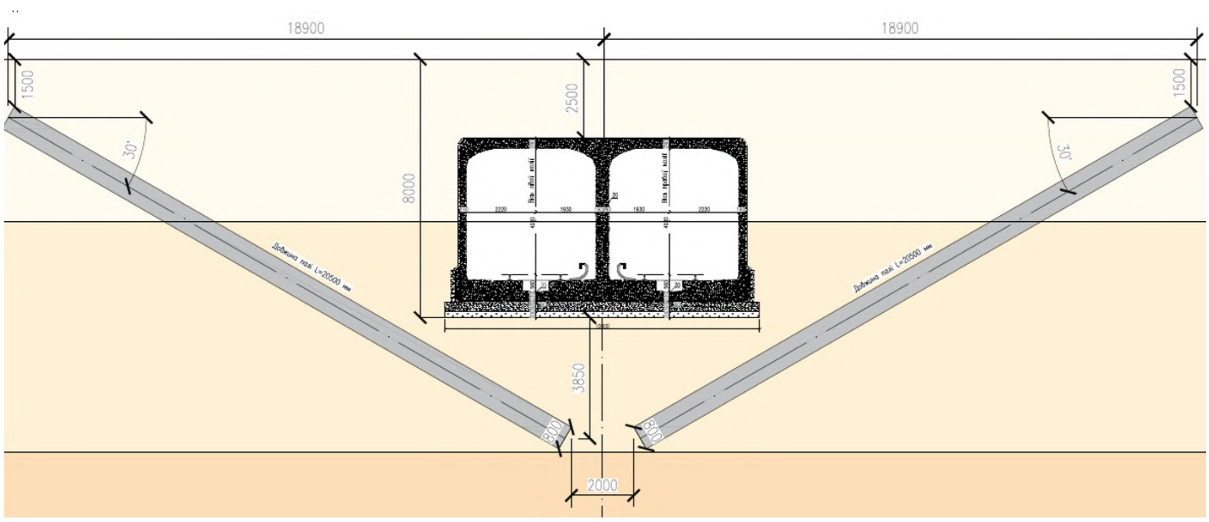

Figure 3. Calculated model for 30 degrees E_{cp}=41.42 MPa.

The total load of rolling stock and vibrodynamic impact from train traffic is assumed to be 200 kN/m in the left and right tunnels.

The calculation of subsidence is performed according to the method, the essence of which is that jet grouting piles and soil are considered as a soil array with a cellular deformation modulus E_{cp}.

Based on the calculation results, the following is established:

1. The amount of subsidence of tunnel structures, namely the distribution plate on which the WCA blocks are supported, without the use of fixing elements is – 25.55 mm (see figure 4);
2. When fixed at an angle of 30 degrees, the subsidence - 7.8 mm (see figure 5), at 35 degrees – 8.19 mm, and at 40 – 8.82 mm.

In order to save material and the total cost of construction work, the option of fixing soils with jet grouting piles of reduced length (10 m) at an angle of inclination of 30 degrees was additionally developed and calculated (see figure 6).

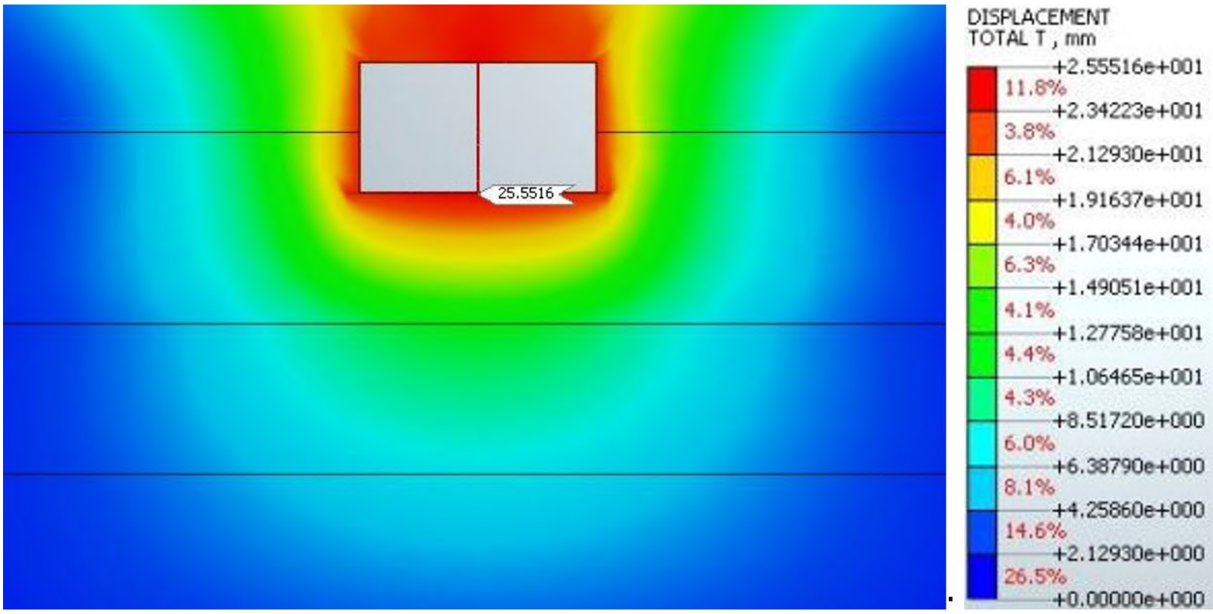

Figure 4. The subsidence of the slab before fixing the soil.

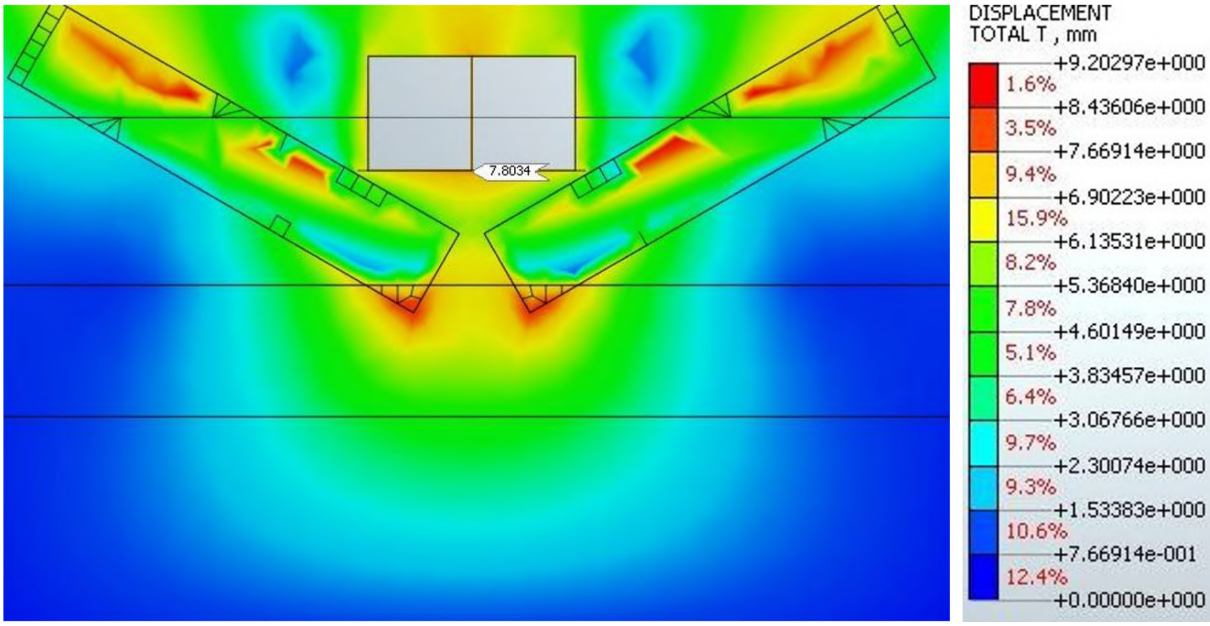

Figure 5. The subsidence of the slab after fixing the soil with jet grouting piles at an angle of 30 degrees.

5. Conclusions

Analyzing the results of mathematical modeling, the most effective was the option of fixing at an angle of 30 degrees, which allowed to reduce the subsidence by 70%. Computer-mathematical modeling has shown that as the angle of the soil-cement piles increases, the amount of subsidence of the tunnel increases. When installing soil-cement piles at an angle of 30 degrees, it is possible to reduce the length of the pile by half, reducing material consumption by 40-45%, which will lead to a slight increase in tunnel subsidence by 2.6% compared to 20.5 m and angle 30 degrees.

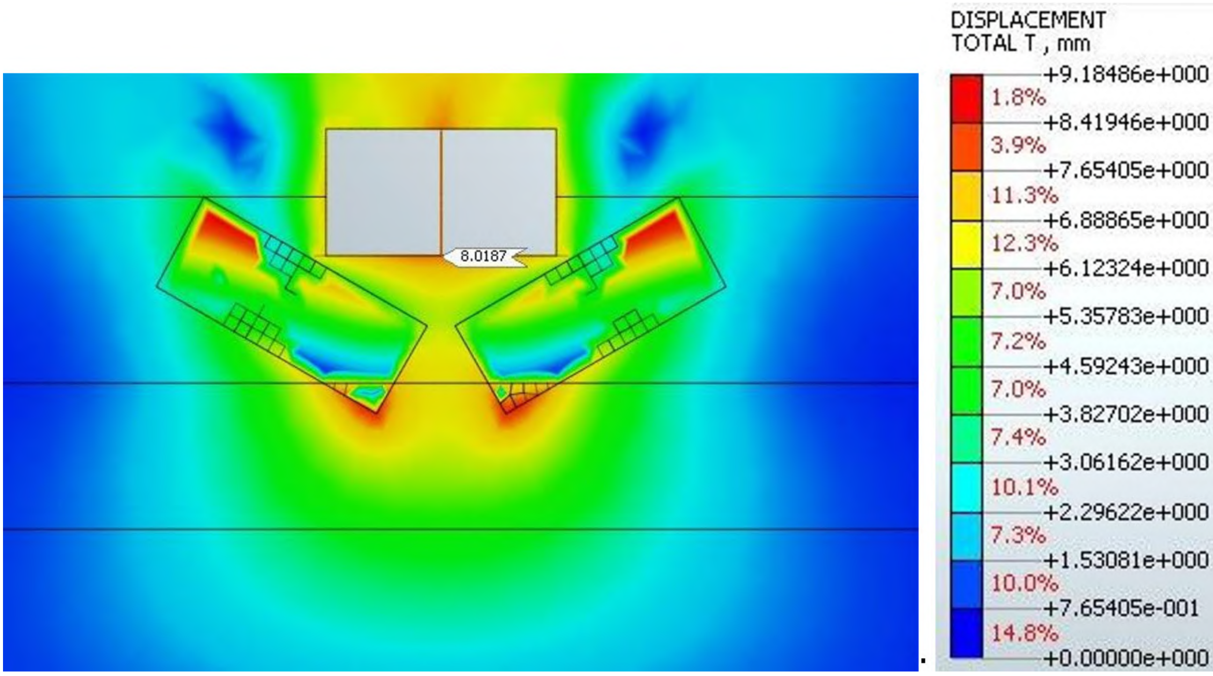

Figure 6. The subsidence of the slab after fixing the soil with jet grouting piles at an angle of 30 degrees.

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IOP Conference Series: Earth and Environmental Science

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To cite this article: A A Butenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012049

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012049 doi:10.1088/1755-1315/1049/1/012049

Increasing of strength-rigidity parameters of bases of metallic silos

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Abstract. To date, effective codes of Ukraine limit settlement of foundations of metallic silos to 15 cm. To provide normative settlement of foundation with diameter up to 40 m and more is not always possible without additional essential measures for strengthening or changing base soils. Taking into account high levels of loads, soils of bases in natural condition can not carry stress under the base of foundation and require strengthening. Execution of works on change of soils of bases or installation of soil cushions is not always possible taking into account underflooding of territory, building development that exist near at hand, or other complicating factors. Soil cement after Deep Soil Mixing (DSM) technology, Jet Grouting, injection and micropiles were considered for different types of strengthening taking into account application in great volumes. From analysis of the obtained results, it was determined that soil cement after Deep Soil Mixing technology is the most economically justified method. Application of Jet Grouting is justified during strengthening of soil thicknesses locally separated by depth. Injection and micropiles are used appropriately only in conditions of reconstruction under absence of direct access to the base.

1. Introduction

Ensuring of reliability and safety of operation of metallic silos with the goal of decreasing of foundation settlements is topical both for new building and for objects already brought into operation [1–5] . Taking into account requirements of effective land legislation to efficient land management, new building is planned on plots unsuitable for agriculture. Therefore, topical is the need of using development sites characterized by complicated geotechnical conditions. At present a considerable part of metallic silos for storing of grain crops in Ukraine is built in such conditions [6–8]. Now, effective codes of Ukraine limit foundation settlements of metallic silos up to 15 cm. To ensure normative settlement of foundation with diameter up to 40 m and more is not always possible without additional substantial measures for strengthening or replacement of soils [8, 9].

2. Aim
Application of "parametric" strengthening of soil for foundations of big dimensions, which makes it possible to optimize stress-deformed state of foundation, its settlement and to increase reliability of operation of foundation and structure as a whole by way of examples of application of soil cement by Deep Soil Mixing technology (DSM), Jet Grouting, injection and micropiles.

3. Tasks
On the basis of analysis of practically realized methods of strengthening of soils of base of metallic silos from the viewpoint of technology of execution of big volumes of work (equipment, materials, method of arrangement), to calculate and compare indicators of their economy, to present generalized indicators for application in engineering methods during selection of rational methods of strengthening of soils of bases characterized by complex geotechnical conditions.

4. Methodology
Building of agro-industrial objects in Ukraine most frequently occurs in complicated geological and hydro-geological conditions. Considering high levels of loading, base soils in natural state are not capable to take up stresses under foundation foot and require strengthening. Territories on collapsible, filled, silted or peat soils most frequently belong to building sites that require strengthening.

Execution of works to replace base soils or to arrange soil cushions is not always possible taking into account high level of ground water, existing development or other complicating factors.

Strengthening parameters are determined from conditions of given settlement of building or structure in particular soil conditions under given level of loading [10].

Plate foundations on natural and artificial bases and plate-pile foundations are most widespread as foundations of granaries of silo type on soft soils. Long-term experience of operation of such silos [11, 12] and numerous examples of observation of built silos performed by the authors of this investigation indicate inevitability of essential risk when using soft soils as foundation base. In the process of designing it is necessary to consider also essential mutual influence of neighboring silos on settlement of their bases. A peculiarity of stressed state of silo bases is in cyclic influence of pressure from periodic loading and unloading of grain into silos, so this requires obligatory precise geodesic observations of such structures. Way out of this situation is increasing of load-carrying capacity of soils by reinforcing of base under structures.

By reinforcement of base is meant improvement of physical-mechanical properties of soil mass by arrangement of more strong and rigid elements that work in common with soil but are not connected structurally with foundation (figure 1). Strengthening of base by reinforcement is based on interaction of soil with inclusions in the form of elements of increased rigidity from stabilized or compacted soil or other materials. The necessary parameters of rigidity and strength of bases are achieved through arrangement of more rigid and strong elements in soil, that have good bond and friction with natural soil. Depth of reinforcement and step of arrangement are calculated and taken depending on necessary strength-rigidity parameters of reinforced soil. The placement of reinforcement elements depends on technology of their fabrication [13, 14].

To reinforce base it is possible to use different kinds of piles – precast-concrete, auger cast, grout-injected and soil cement elements.

One efficient trend in decreasing of cost of pile foundations is the use of soils that lie in the base of buildings and structures. For this purpose vertical reinforcement is arranged, which is carried out with the use of base soils strengthened by cement mortar – soil cement elements (SCE).

Reinforcing of bases by soil cement elements is reasonable in cases of high depth of soft soils and deep arrangement of bearing soil layer. Application of piles in such soil conditions requires substantial length of piles to rest on bearing layer of soil.

Method of strengthening of soft soil by soil cement elements makes it possible to ensure bearing capacity of foundation and to maintain normative settlements without substantial penetration along the depth of geologic section. The depth of compressible thickness of soil under silo foundations usually does not exceed 15 m. Thus, if the depth of soft soils of building site exceeds the mentioned value, then it is reasonable to use soil strengthening for arrangement of foundation base instead of pile base.

Otherwise there arises the necessity to use augercast or grout-injected piles, or components of precast concrete piles to reach the depth of bedding of bearing soil layer. In such conditions deadlines and cost of building increase substantially.

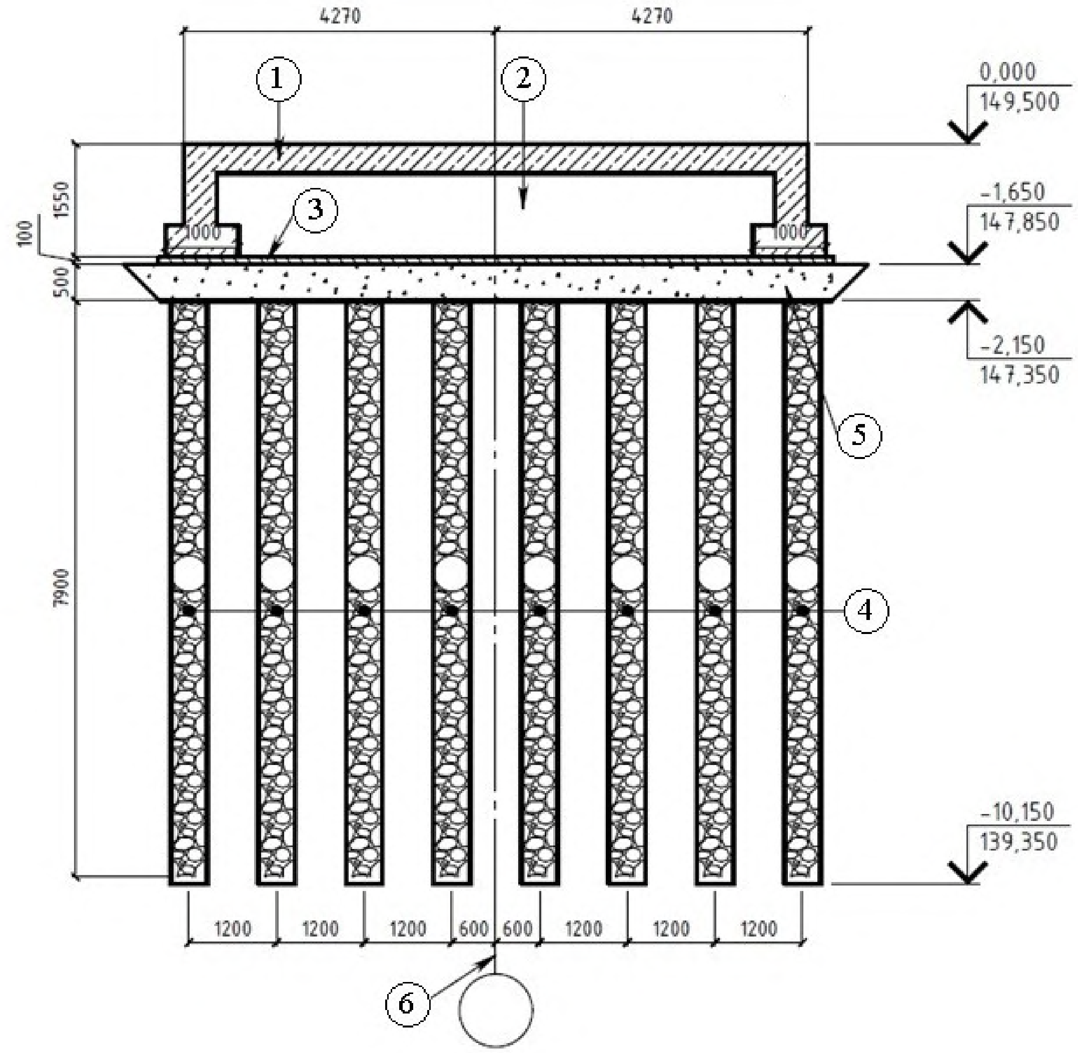

Figure 1. Strengthening of the base by vertical elements of the silo base in urbanized settlement uts. Dniprovs'ke of Dnipropetrovc'k region: 1 – silo foundation, 2 – sand from riddlings of crushing of igneous rocks, 3 – foundation mat, 4 – soil cement elements 505 mm in diameter, 8 m in length, 5 – damper layer from crushed rock size fraction 20-40 mm, 6 – silo axis.

Soil cement bored piles have all advantages of bored piles, but technology of their arrangement completely excludes the necessity for additional provision of stability of bore walls in any geotechnical building conditions including complicated ones [15, 16].

One of the most important characteristics of soil cement from the viewpoint of its structural operation is mechanical strength and its increase with time. Investigations show that strength of soil cement increases with time, and such process can continue for years [17]. Increase in temperature and humidity of environment substantially accelerates the process of solidification of soil cement. When soil cement is in water, more intensive increase in strength is observed. This undoubtedly indicates that being in water-saturated soils is the most favorable for solidification of soil cement [18].

Placement of reinforcement elements depends on technology of their fabrication. Soil cement elements can be obtained by using Deep Soil Mixing technology (DSM), Jet Grouting. Deep Soil Mixing technology is the most widespread in the Ukraine's territory.

Efficiency of this technology consists in low consumption of materials, machines, and energy. In reinforcing of soils by Deep Soil Mixing technology only 15-20% of cement are used, the other 80-85% fall on soil that is strengthened. Strengthening of soil by Deep Soil Mixing technology is used in different directions – vertical, at an angle, and horizontal depending on drilling rigs that are used. Vertical reinforcement is used most frequently for preparation of bases of buildings and structures [19].

Deep Soil Mixing technology of arrangement of soil cement most frequently is performed with diameters up to 650 mm and depth up to 10 meters. This is connected with the present-day technical possibilities of soil mixing with necessary rate of rotation and the number of passes in the borehole. Also, the limitations of Deep Soil Mixing technology are arrangement of soil cement in the whole borehole from the surface of pit to the bottom of the borehole. Unlike Deep Soil Mixing technology, soil cement elements in Jet Grouting technology have larger diameters, and diameters less than 700 mm are even difficult to arrange. Jet Grouting technology makes it possible to arrange soil cement elements from any depth from the surface (most frequently to arrange horizontal grout curtains). Thus, with the help of Jet Grouting technology it is possible to strengthen interlayers of soft soils that lie deep (up to 100 m). Advantage of soil cement is the possibility to fabricate reinforcement elements in water-saturated soils.

Jet Grouting technology makes it possible to create soil cements elements of various diameters depending on the kind of soil (from 0.7 to 5 m). But presence of different layers of soils when drilling vertical borehole does not make it possible to maintain the same diameter of the pile along the length. And if stones or hard inclusions are encountered, "shade" in the form of unfilled soil arises behind them.

One more disadvantage of Jet Grouting is increased leakage of soil cement in the process of formation of soil cement piles compared to Deep Soil Mixing technology. During leakage, loss of cement mortar takes place, which correspondingly raises the cost of production of soil cement.

5. Results

Indicators of examples of projects on strengthening of bases under metallic silos realized in Ukraine are presented in tables 1-4 and figures 1-7.

Analysis of constructional designs for strengthening of silo bases indicates dominant use, as a means for strengthening of bases, of piles fabricated by Deep Soil Mixing technology for new building (figure 8).

Analysis of parametrical indicators for different objects of building is presented in table 4. One can see essential dependence of consumption of stregthening material on geological conditions and inessential – on loads and dimensions of foundation (figure 9, figure 10).

To substantiate economically appropriateness of application is possible after comparing variants of arrangement of base by strengthening of soil or by use of piles taking into account indicator of cost.

Table 1. Parameters of foundations of silos and artificial bases.

Object number	Object name	Silo diameter (m)	Depth of laying (m)	Constructional design of foundation	Silo height H (m)
1	Sumy region, Krolevetsky distr., t. Krolevets' (figure 2, 3)	27.5	1.2	Reinforced concrete, with under-silo storey	29.7
2	Sumy region, Krolevetsky distr.	22.5	1.6	Reinforced concrete, with underground gallery	24.0
3	Chernigiv region, Bakhmatsky distr.	27.5	2.5	Reinforced concrete, with underground gallery	29.7
4	Chernigiv region, Borznyans'ky distr., v. Velyka Doch (figure 4, 5)	24.0	2.6	Reinforced concrete, with underground gallery	24.0
5	Dnipropetrovs'k region, Verkhn'odniprovs'ky distr., uts. Dniprovs'ke, Kyivs'ka str., 1 (figure 1)	9.2	1.5	Reinforced concrete, with underground gallery	19.25
6	Kharkiv region, Novovodolaz'ky distr., v. Palatky	22.5	1.6	Reinforced concrete, with underground gallery	24.0
7	Kharkiv region, Krasnograds'ky distr., v. Dobren'ka	27.5	2.4	Reinforced concrete, with underground gallery	17.5
8[a]	t. Zaporizhzhya	27.5	1.6	Reinforced concrete, with underground gallery	29.7
9[a]	t. Zaporizhzhya, Zaporizhien OEP	22.0	1.6	Reinforced concrete, with underground gallery	30.7
10	Sumy region, t. Shostka (figure 6)	27.5	2.4	Reinforced concrete, with underground gallery	29.7
11	Lugansk region, t. Svatove	32.0	2.6	Reinforced concrete plate grillage	37.4
12	Kharkiv region, Valkivc'ky distr., uts. Kov'yagy (figure 7)	22.5	1.1	Reinforced concrete plate grillage	24.0

[a] Objects already built, where strengthening of the base was necessary in connection with above-normative settlements.

Figure 2. Water lowering before performing works on exploitation of pit and reinforcing silo base in t. Krolevets' of Sumy region.

Figure 3. Arrangement of silo foundations on the base of strengthened soil in t. Krolevets', Sumy region.

Figure 4. Strengthening of silo base by vertical soil cement elements in v. Velyka Doch, Chernigiv region.

Figure 5. Arrangement of damper layer over reinforced base of silo by vertical soil cement elements in v. Velyka Doch, Chernigiv region.

Figure 6. Arrangement of crushed rock cushion on sand soils under silo foundation in t. Shostka of Sumy region.

Figure 7. Strengthening of base by built-up reinforced concrete piles under foundation of silo with underground gallery in uts. Kov'yagy of Kharkiv region.

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Table 2. Geotechnical conditions, mechanical and deformation characteristics of bases.

Object number	Object name	Average pressure under foundation foot p(MPa)	Average modulus of deformation $\bar{E}$(MPa)	Average settlement S(cm)	Type of geological conditions
1	Sumy region, Krolevets'ky distr., t. Krolovets'	0.24	14.3	11.8	Soft soils in the higher zone and buried vegetable soil layer at depth 15 m
2	Sumy region, Krolevets'ky distr.	0.22	12	27	Soft interlayer of soil
3	Chernigiv region, Bakhmats'ky distr.	0.23	14	14	Soft soils in the higher zone and buried vegetable soil layer at depth 5 m
4	Chernigiv region, Borznyans'ky distr., v. Velyka Doch	0.22	12	13	Soft soils in the higher zone and buried vegetable soil layer at depth 16 m
5	Dnipropetrovs'k region, Verkhn'odniprovs'ky distr., uts. Dniprovs'ke, Kyivs'ka str. 1	0.15	14	9.7	High thickness of soft soils
6	Kharkiv region, Novovodolaz'ky distr., v. Palatky	0.22	12	22	High thickness of soft soils
7	Kharkiv region, Krasnograds'ky distr., v. Dobren'ka	0.18	15	9.1	High thickness of soft soils with laying of sands at depth 6 m
8	t. Zaporizhzhya	0.22	14	12	High thickness of soft collapsible soils with laying of sands at depth 18 m
9	t. Zaporizhzhya, Zaporizhien OEP	0.22	16	4	High thickness of soft collapsible soils with laying of sands at depth 24 m
10	Sumy region, t. Shostka	0.23	23	8	Sand soils with soft loose sands in the higher zone
11	Lugans'k region, t. Svatove	0.16	28	6	High thickness of soft soils with sand laying at depth 8 m
12	Kharkiv region, Valkivs'ky distr., uts. Kov'yagy	0.22	18	5	High thickness of soft soils with laying of semi-hard clay at depth 12 m

Table 3. Constructional design for strengthening of base and parametrical indicators.

Object number	Object name	Type of artificial base	Volume of material (m^3)	Silo capacity (ths. m^3)	Specific consumption (m^3/ths. m^3)
1	Sumy region, Krovelets'ky distr., t. Krovelets'	Soil cement elements 500 mm in diameter, 4 m in length (SCE-0.5-4.0), step of SCE in both directions 1150x1150 mm	512.8	12.5	41
2	Sumy region, Krovelets'ky distr.	Jet Grouting of soft layer of soil at depth 3.5 m	379.94	6.25	60.8
3	Chernigiv region, Bakhmats'ky distr.	Soil cement elements 505 mm in diameter, 8.0 m in length, (SCE-0.505-8.0), step of SCE in both directions 1200×1200 mm	856	12.5	68.5
4	Chernigiv region, Borznyans'ky distr., v. Veluka Doch	Soil cement elements 650 mm in diameter, 3.5 m in length, (SCE-0.65-3.5), step of SCE in both directions 1500×1500 mm	295.68	7.5	39.4
5	Dnipropetrovs'k region, Verkhn'odniprovs'ky distr, uts. Dniprovs'ke, Kyivs'ka str. 1	Soil cement elements 505 mm in diameter, 8.0 m in length, (SCE-0.505-8.0), step of SCE in both directions 1200×1200 mm	83.2	0.9	92.4
6	Kharkiv region, Novovodolaz'ky distr., v. Palatky	Injection down to depth 4.5 m is required	-	-	-
7	Kharkiv region, Krasnograds'ky distr., v. Dobren'ka	Soil cement elements 500 mm in diameter, 5 m in length, (SCE-0.5-5.0), step of SCE in both directions 1400×1400 mm	410	7.5	54.7
8	t. Zaporizhzhya	Soil cement elements 650 mm in diameter, 5.0-15.0 m in length, (SCE-0.650-5.0…15), step of SCE in both directions 1200×1200 mm	1730.4	12.5	138.4
9	t. Zaporizhzhya, Zaporizhien OEP	Soil cement elements 505 mm in diameter, 10.0 m in length, (SCE-0.505-10), step of SCE in both directions 1000×1000 mm	850	7.5	113.3
10	Sumy region, t. Shostka	Crushed rock cushion			
11	Lugansk region, t. Svatove	Piles C 10.0-40-11, 277 in number.	443.2	25	17.7
12	Kharkiv region, Valkivs'ky distr., uts. Kov'yagy	Piles C 14.0-35-9, 107 in number.	183.505	6.25	29.4

Table 4. Reduced parametric indicators.

Object number	Object name	Depth of reinforcement/strengthening of base (m)	k_l[a] (m^2/ths. m^3)	Indirect step of SCE (m)	k_{ls}[b] (m/ths. m^3)	k_{lsp}[c] (m/(ths. $m^3\times$MPa))
1	Sumy region, Krovets'ky distr., t. Krovelets'	4	10.26	1.15	8.92	37.16
2	Sumy region, Krovelets'ky distr.	3.5	17.37	2.0	8.68	39.47
3	Chernigiv region, Bakhmats'ky distr.	8	8.56	1.2	7.13	31.01
4	Chernigiv region, Borznyans'ky distr., v. Velyka Doch	3.5	11.26	1.5	7.51	34.13
5	Dnipropetrovs'k region, Verkhn'odniprovs'ky distr., uts. Dniprovs'ke, Kyivs'ka str. 1	8	11.56	1.2	9.63	64.20
7	Kharkiv region, Krasnograds'ky distr., v. Dobren'ka	5	10.93	1.4	7.81	43.39
8	t. Zaporizhzhya	13	10.65	1.2	8.87	40.34
9	t. Zaporizhzhya, Zaporizhien OEP	10	11.33	1.0	11.33	51.52
11	Lugans'k region, t. Svatove	10	1.77	1.7	1.04	6.5
12	Kharkiv region, Valkivs'ky distr., uts. Kov'yagy	14	2.1	1.93	1.09	4.95

[a]Specific consumption of material of strengthening per unit length of reinforcement element.
[b]Specific consumption of material of strengthening per unit length of reinforcement element and indirect step of elements.
[c]Ratio of specific consumption of strengthening material to loading on unit length of reinforcement element and indirect step of elements.

Reduced indicators of specific consumption of strengthening material per unit length of element show likeness of specific consumptions in arrangement of piles. Reduced indicator k_l gives possibility to predict material consumption for reinforcement of soil having results of geological explorations.

Choice of step of arrangement of soil cement elements influences the value of minimal thickness of damper layer. Usually thickness of damper layer is from 400 mm to 700 mm. Increase of thickness of damper layer caused by increase of step of reinforcement elements causes increase of cost and time of building. Reduced indicator k_{ls} allows predicting material consumption for strengthening of soil taking into account indirect step of elements.

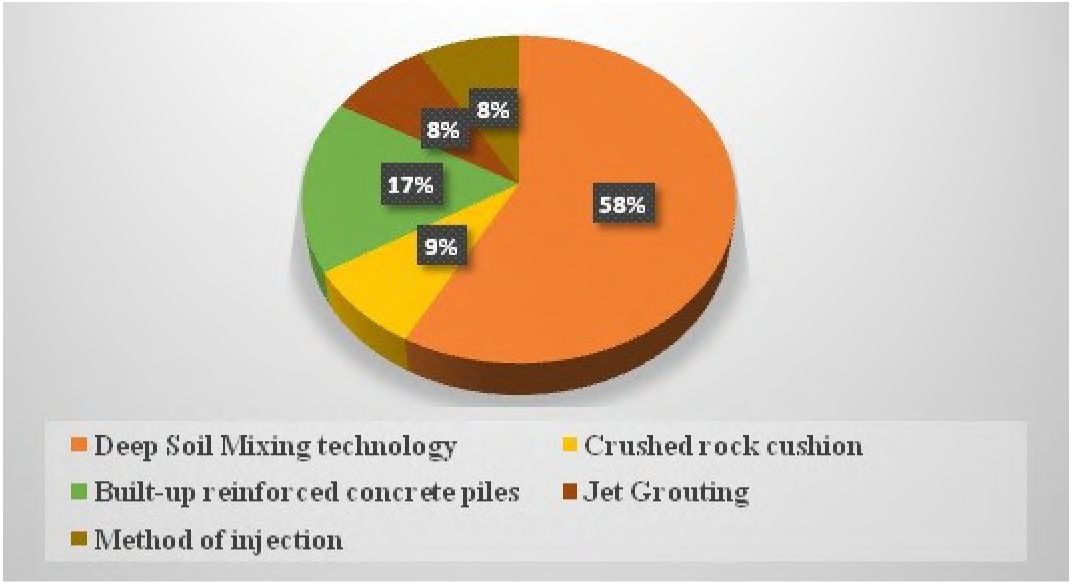

Figure 8. Comparison of different kinds of strengthening of silo bases.

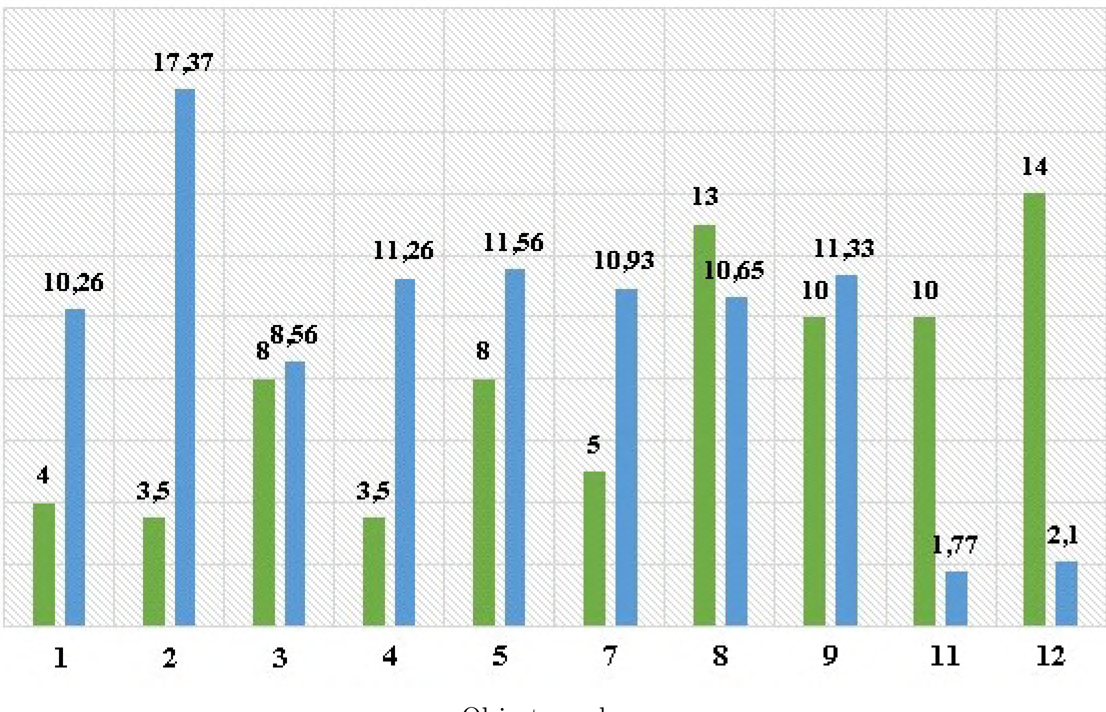

Figure 9. Reduced indicators of consumption of material on length of elements: – Depth of reinforcement, (m); – specific consumption of material of strengthening per unit length of strengthening element, k_l (m^2/ths m^3).

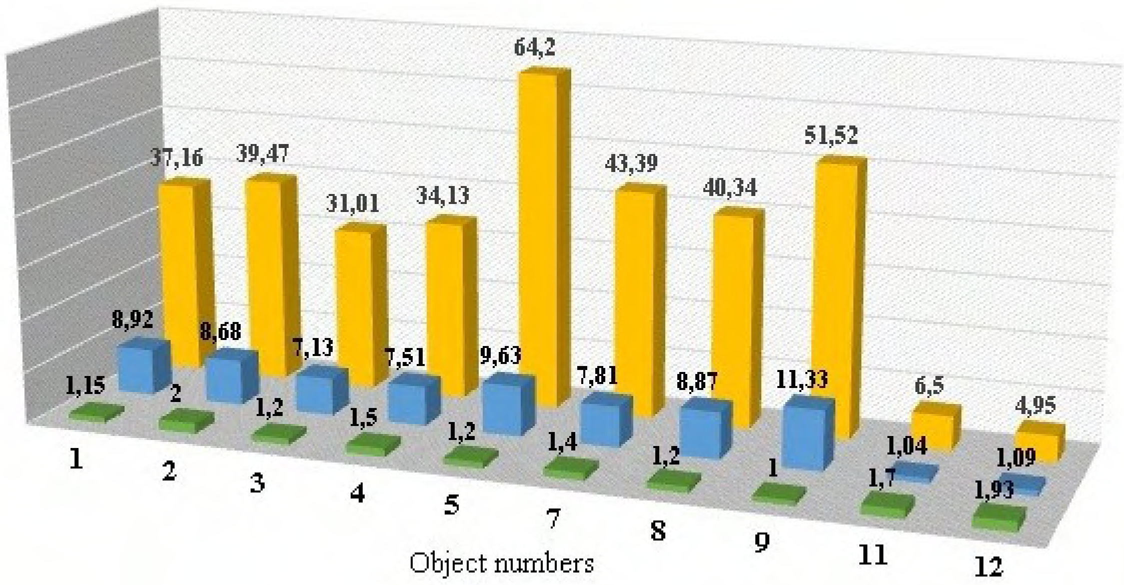

Figure 10. Reduced parametric indicators of consumption of material taking into account step of elements and load on base: – Step of soil cement elements, (m); – specific consumption of material of strengthening per unit length of reinforcement element and indirect step of elements, k_{ls} (m/ths. m^3); – ratio of specific consumption of strengthening material to load on unit length of reinforcement element and indirect step of elements, k_{lsp} (m/(ths. $m^3\times$MPa)).

Reduced coefficient k_{lsp} determines ratio of specific consumption of material used to strengthen base to load on unit length of element taking into account indirect step of elements. The coefficient can be used in designing silos of decreased height or silos of core enterprises for grain crops that are smaller in specific consumption than standard (wheat). Noteworthy is universality of Deep Soil Mixing technology of arrangement of SCE to strengthen bases. Thus, by changing distance between soil cement elements and their dimensions it is possible to make strengthening of soils in any geotechnical conditions (table 2). Experience in soil strengthening proved its competitiveness for filled, collapsible, soft soils and also for sand soils under various levels of ground water. The following may be thought of as general advantages of Deep Soil Mixing technology of fabrication of soil cement elements: low level of vibration and noise during their arrangement, possibility of fabrication and efficient operation in water-saturated, collapsible soils and in limited working space, easy changing of pile diameter by way of increasing diameter of cutting tools, high mobility of set of necessary machines and mechanisms to make piles, which will satisfy tough schedules of present-day building. Also, there is no necessity for regular supplying of fillers for mixture [20]. To increase strength of soil cement it is reasonable to perform operation of vibration compaction by way of vibration of soil cement mixture in borehole. In the process of vibration there takes place elimination of air bubbles, which in its turn causes increase in compactness of SCE. If necessary it is possible also to make reinforcement of soil cement piles. Cost of arrangement of 1 m^3 of soil cement by Deep Soil Mixing technology is smaller by a factor of 3-4 than by method of Jet Grouting.

6. Conclusions

From the presented indicators for different objects of building it can be seen that consumption of material for strengthening essentially depends on geological conditions, and on loads and dimensions of foundation – not essentially. To substantiate economically appropriateness of application is possible after comparing variants of arrangement of base by strengthening of soil or by application of piles taking into account indicator of cost. Thus, it can be noted that consumption of soil cement is 1.5-4.5 times greater than consumption of piles, but cost of material of piles and works on their arrangement is 10 times greater than soil cement.

The main advantage of arrangement of foundations on bases from strengthened soil is the possibility of realization in conditions of high thickness of soft soils and placement of support horizon for piles at essential depth, for example deeper than 15 m. In conditions of essential depths there arises necessity to use augercast or grout-injected piles, or components of built-up piles. Deadlines of building and cost in such conditions increase essentially.

Also the advantage of use of soil cement is the possibility to use it in saturated soils without additional measures, as distinct from augercast piles.

Quickness is also an essential advantage of soil cement. Compared to driven and augercast piles quickness of arrangement of soil cement by Deep Soil Mixing method is 3-5 times higher and 2-3 times higher than when arranging piles by method of driving or jacking. Jet Grouting is justified in strengthening of thicknesses of soils locally separated along depth, but, compared to Deep Soil Mixing technology (DSM), is more consuming by materials, energy, and cost. Application of Jet Grouting is widespread in arrangement of soil cement elements of large diameters for enclosing sheeting, arrangement of waterproof layer, grout curtains, and soil cement piles with essential load capacity.

Such types of strengthening of bases as injection and micropiles are justified more frequently in conditions of reconstruction in the absence of immediate access to the base. Their application is determined by necessity to perform works in reconstruction or overhaul in conditions of tight development and limited access to foundations. It is justified to use them on the basis of injections to stabilize existing foundations of silos with symptoms of loss of bearing capacity or above-normative deformations of settlement.

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To cite this article: S I Sakhno *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012050

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012050 doi:10.1088/1755-1315/1049/1/012050

Investigation of the influence of technological factors and compositions of binders on the strength characteristics of blast–furnace cement with magnetized ferromagnetic additives

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Abstract. Cement production is a significant source of carbon dioxide emissions. One of the ways to reduce emissions is to reduce the proportion of clinker in cement by introducing active mineral additives into its composition, particularly granulated blast-furnace slag. One of the ways to increase the activity of such cement is the effect of magnetic fields on the spin multiplicity of the substances involved in the hardening reaction. In this case, the maximum effect is ensured by introducing a magnetized finely dispersed ferromagnetic substance into the cement composition. The activation effect depends on the additive's adding method to the cement's composition, the components ratio in the cement, and the cement hardening mode. This work aims to identify the influence of the adding method of the additive, the slag and additive proportion in cement, and the steam curing temperature on the activity effect of the binder. Three groups of studies were carried out to determine the strength characteristics of laboratory samples hardened both in natural conditions and during steaming. In the first group, cement samples have tested containing 40% slag obtained by joint grinding and joint mixing of the additive with cement for 0.5, 1, 2, 4 and 8 minutes. In the second group, samples have tested with the additive amount varied from 0 to 2.5%, and slag amount from 0 to 80%. Finally, cement samples were tested in the third group containing 50% slag and from 0 to 2.5% additive. The samples were steam cured at temperatures ranging from 50 to 90° C and tested one day, 28 and 90 days after steam curing. As a result of the research, it has revealed that to obtain the maximum effect, the additive must be introduced into the cement composition by joint grinding. The factors influencing the activity have been determined. At the same time, the time of joint grinding should ensure uniform mixing of the components and the formation of new surfaces of cement grains in the presence of magnetic fields. Too long joint grinding leads to the loss of the magnetic properties of the addition. It was found that the activation effect from the additive addition increases with an increase in the proportion of slag. In cement without slag, an increase in the additive content leads to a drop in strength. It was revealed that the introduction of magnetized ferromagnetic dust additives into the composition of the SPC makes it possible to reduce the steam curing temperature of products by 20-25° C. Studies have shown that using a finely dispersed ferromagnetic substance as an activating additive can save energy resources and reduce emissions.

1. The problem formulation and its relationship with scientific and practical tasks

For the foreseeable future, cement will remain one of the primary materials used in construction. Yearly more than 4,100,000 tons of cement are produced in the world [1] . Cement production is highly energy-intensive and involves the release of significant amounts of carbon dioxide into the atmosphere. The amount of CO_2 emissions associated with cement production is 8% of the global emissions [2] has reached 2.2 gigatons of carbon dioxide per year [3] and continues to grow. About 50% of the emission from cement production occurs during the calcination of limestone during the production of portland cement. Another 40% of emissions occurs when fossil fuels are burned in clinker kilns [4]. Thus, in cement production, 90% of the emissions occur in the production of clinker.

Reducing the energy intensity of cement production and reducing the volume of CO_2 emissions into the atmosphere may be by improving the production technology [5, 6], using alternative fuels [7,8], and capturing and storing carbon [9,10]. However, the most effective way of emissions tumbling in cement production is to reduce the clinker proportion in cement [11, 12]. Reducing the balance of clinker in cement can decrease emissions by more than 60% [13].

2. Research and publications analysis

A decrease in the proportion of clinker is possible due to the introduction of active mineral additives into the cement composition. Industrial waste is most often used as such additives. In addition to reducing the consumption of fossil fuels and emissions, the introduction of active mineral additives in cement composition gives them additional favourable properties. For example, the introduction of granulated blast-furnace slag (from now on BFS) into the cement composition increases the corrosion resistance of the cement. National standards limit the share of active mineral additives introduced into cement composition since exceeding the maximum permissible value degrades cement's strength and other characteristics [14]. However, a further increase in the proportion of active mineral additives in cement without a drop in strength is possible using various activation methods.

We are investigating the mechanism of activating blast–furnace cement (from now on BFC) by introducing magnetized ferromagnetic dust additive (from now on MFDA) into their composition. The magnetic fields effect on chemical reactions has been well studied and, in particular, considered in works [15–18]. Magnetic fields affect spin dynamics and control the spin multiplicity of radical pairs of substances involved in a chemical reaction. Thus, even weak magnetic fields affect the chemical activity of reagents [19, 20]. Furthermore, the influence of magnetic fields on the hardening of binders is considered in works [21–27]. In research results [28, 29], it has been proved that both the magnetization of particles and their dispersed composition affect the strength characteristics of BFC.

The effect of the MFDA on the cement hardening mechanism and the structure of cement stone was studied in [30]. Our research has confirmed that the magnetic fields created by the dust-like additive can positively affect cement activity. Furthermore, during the investigation, nonlinear dependence's of the activation effect created by the MFDA on the technological parameters of cement hardening were revealed. In particular, studies have shown that heat and moisture treatment of hardening cement reduces the activation effect. We have conducted additional research studies to determine how the method of introduction and the duration of mixing of the MFDA, the proportion of BFS in the cement and the temperature of cement hardening affect the activity of the binder. This article presents the results of these studies.

3. Statement of material and results

3.1. Influence of the mixing method

Previous studies [29, 30] have significantly influenced the methods and time of mixing on the resulting activation effect.

The existing technology for cement production allows mixing the binder components either with the creation of tribochemical processes or without them. In the first case, mixing is carried out in ball mills; in the second, using mechanical mixers or aeromixers. Mixing components in a ball mill can be combined with grinding of clinker, gypsum and BFS or carried out after that.

Three series of experiments were comprised in the research to simulate different ways of mixing the MFDA with binders:

– clinker, blast furnace slag and gypsum were mixed into a laboratory ball mill in a ratio of 55.0:40.0:5.0 by weight. The mill was filled with MFDA in the amount of 2% by the weight of the binder components. Next, joint grinding was carried out to obtain cement with $S_{sp} = 3100^{cm^2}/_{g}$. Finally, an MFDA-free control binder was prepared similarly;
– a ready-made BFC (CEM III/A) containing 40% BFS and 5% gypsum were placed in a laboratory ball mill. The MFDA and CEM III/A were mixed in 2% of the total mass of cement into the mill. In different experiment series, dust and cement were mixed for 0.5; 1; 2; 4; 8; 16 minutes. Simultaneously, additional mixing of the control samples was carried out without an MFDA;
– the MFDA was introduced into the CEM III/A and mixed in a specially designed device for 0.5; 1; 2; 4; eight; 16 minutes.

This device has been designed to mix the binder with the MFDA without the influence of tribochemical factors. It contains a steel cylinder with 80 mm diameter and 200 mm length and a drive that rotates the cylinder at 250 r/pm. Five cylpebs weighing 100 g each were placed in the cylinder together with the cement to improve the mixing processes. Further tests were carried out following by DSTU EN 196-1:2007. The test results showed in table 1.

Mixing the MFDA with a binder by the first way does not create, and the third way creates a weak activation effect. However, when mixing the components according to the second method, with an increase in the mixing time, the activation effect first increases and then decreases again (figure 1, figure 2).

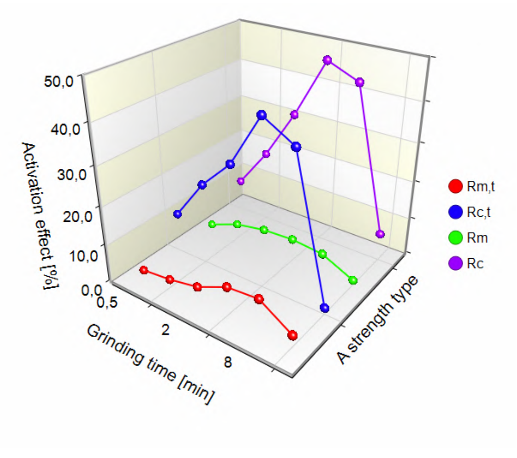


Figure 1. Influence of the grinding time of the components on the activation effect (A) created by the MFDA.

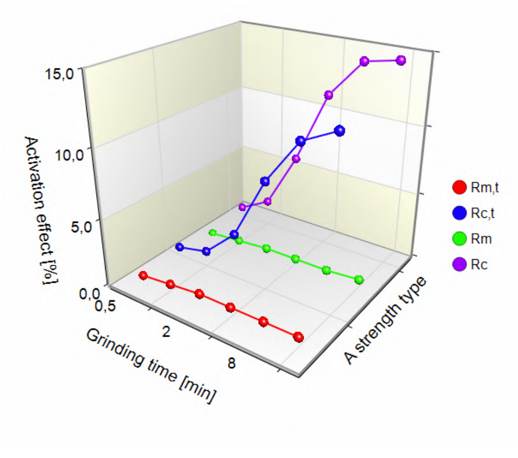


Figure 2. Influence of the mixing time of the components on the activation effect created by the MFDA.

The results show that the joint grinding time dependence of the activation effect with the MFDA has the form:

– natural hardening

Table 1. Influence of the method and time of mixing the MFDA with the binder on the strength characteristics of cement-sand mortars.

Mixing method	Type of binder	Mixing time [min]	Strength [MPa]			
			Steam curing		Natural hardening	
			$R_{m,t}$	$R_{c,t}$	R_m	R_c
1. Joint grinding	clinker+BFS+ +gypsum+MFDA	up to specific surfacearea 310 m^2/kg	3.9	18.92	5.02	23.90
2. Joint grinding	clinker+BFS+ +gypsum	up to specific surfacearea 310 m^2/kg	3.9	18.92	5.02	23.98
3. Grinding	BFC + MFDA	0.5	4.07	21.87	5.09	26.88
4. Grinding	BFC	0.5	4.02	19.81	5.04	24.82
5. Grinding	BFC + MFDA	1	4.16	24.54	5.30	30.14
6. Grinding	BFC	1	4.07	20.26	5.09	25.35
7. Grinding	BFC + MFDA	2	4.29	27.16	5.48	34.94
8. Grinding	BFC	2	4.13	21.07	5.19	26.50
9. Grinding	BFC + MFDA	4	4.52	31.6	5.62	42.34
10 Grinding	BFC	4	4.20	22.19	5.30	28.80
11 Grinding	BFC + MFDA	8	4.65	34.5	5.81	47.98
12. Grinding	BFC	8	4.29	25.04	5.52	33.41
13. Grinding	BFC + MFDA	16	4.62	31.52	5.81	45.04
14. Grinding	BFC	16	4.48	30.98	5.73	41.97
15. Mixing	BFC + MFDA	0.5	4.02	19.10	5.04	24.39
16. Mixing	BFC	0.5	4.01	18.98	5.04	24.24
17. Mixing	BFC + MFDA	1	4.03	19.32	5.05	24.77
18. Mixing	BFC	1	4.01	19.1	5.04	24.31
19. Mixing	BFC + MFDA	2	4.05	19.79	5.05	25.88
20. Mixing	BFC	2	4.02	19.15	5.03	24.38
21. Mixing	BFC + MFDA	4	4.05	20.65	5.03	27.06
22 Mixing	BFC	4	4.02	19.13	5.01	24.27
23. Mixing	BFC + MFDA	8	4.04	21.29	5.01	27.43
24. Mixing	BFC	8	4.01	19.14	4.99	24.01
25. Mixing	BFC + MFDA	16	4.04	21.52	5.01	27.54
26. Mixing	BFC	16	4.01	19.14	4.98	24.01

$$A_c = 0.672t^2 + 10.97t + 3.602;$$

$$A_m = -0.103t^2 + 1.404t + 1.617;$$

– steam curing

$$A_c = 0.645t^2 + 11.675t + 2.181;$$

$$A_m = -0.179t^2 + 3.124t - 0.834;$$

where A_c - is the activation effect (% increase in strength) for ultimate compressive strength;
A_m - ditto for ultimate strength in bending;
t - mixing time in minutes.

The revealed regularities show that a magnetized substance must participate in forming the binder's surface for the manifestation of activation properties. In this case, magnetic fields can influence the defectiveness of the binder structure and thus its activity. Consequently, the magnetic fields induced by the dust affect the tribochemical phenomena occurring during cement grinding.

The grinding of the MFDA with the binder has a tribochemical effect on cement and the dust itself. The grinding reduces the size of dust particles and causes them to heat up. With an increase in the grinding time, the temperature of the particles passes the Curie point and causes their demagnetization. Another feature is that the magnetic properties of particles manifest themselves only if their size exceeds the critical one [31, 32]. This leads to an activation effect decrease after a specific time of MFDA joint grinding with cement. Thus, long-term grinding completely neutralizes the impact of MFDA. According to the results of the experiments, the optimal time for grinding the MFDA with cement is 5-10 minutes.

3.2. Selection of optimal compositions of BFC with an MFDA

Studies of the strength characteristics of binders with different BFS/MFDA ratios were carried out to identify the optimal amount of MFDA in cement with different BFS content. Investigated binders, having in their composition in various series 0; 1.25; 2.5% MFDA, 0; 20; 40; 60; 80% BFS, 4.5% gypsum. The components of the BFS were ground in a ball mill to obtain $S_{sp} = 310^{m^2}/_{kg}$, then dust was added, and the grinding was performed for 8 minutes. Further tests were carried out according to the by DSTU EN 196-1:2007 method.

The test results showed in table 2, figure 3 and figure 4.

Table 2. Strength characteristics of cement with different BFS and MFDA content.

Slag fraction in BFC %	Natural hardening [MPa]						Steam curing [MPa]					
	MFDA amount [%]											
	0.00		1.25		2.50		0.00		1.25		2.50	
	R_m	R_c	R_m	R_c	R_m	R_c	R_m	R_c	R_m	R_c	R_m	R_c
0	6.40	45.55	5.59	35.53	5.59	34.57	4.55	26.34	4.53	26.40	3.78	17.62
20	6.06	40.58	5.65	42.28	6.10	42.23	4.46	26.77	4.56	30.39	4.51	24.92
40	5.52	33.24	5.70	50.75	6.20	48.02	4.28	25.05	4.62	29.23	4.78	32.50
60	5.11	27.16	5.62	49.88	6.15	48.14	4.12	22.27	4.53	26.95	4.78	32.78
80	4.58	20.51	5.52	34.10	5.51	34.87	3.61	16.05	4.45	21.28	4.58	25.52

The results show that the dependence of the strength R on the consumption of the MFDA and the BFS has the form:

– natural hardening

$$R_m = 6.47 - 1.21D + 0.35D^2 - 0.03S + 0.04SD - 0.01SD^2 - 0.0002S^2D$$

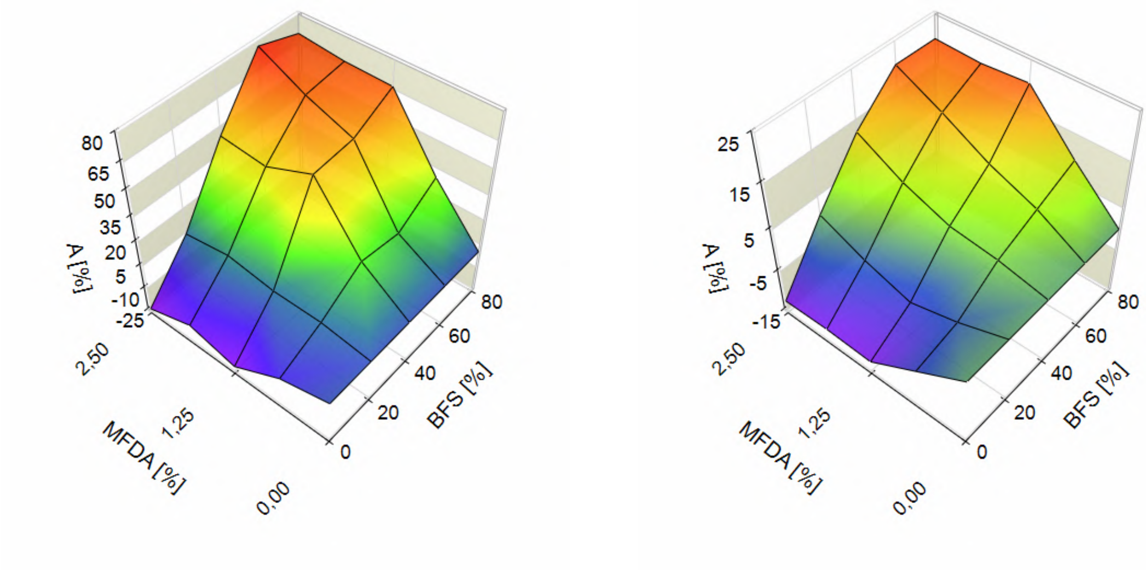
$$R_c = 45.79 - 14.28D + 3.74D^2 - 0.28 \cdot S + 1.34SD - 0.38SD^2 - 0.0004S^2 - 0.01S^2D + 0.003S^2D^2$$

– steam curing

$$R_{m,t} = 4.58 + 0.03D - 0.13D^2 - 0.005S + 0.02SD$$

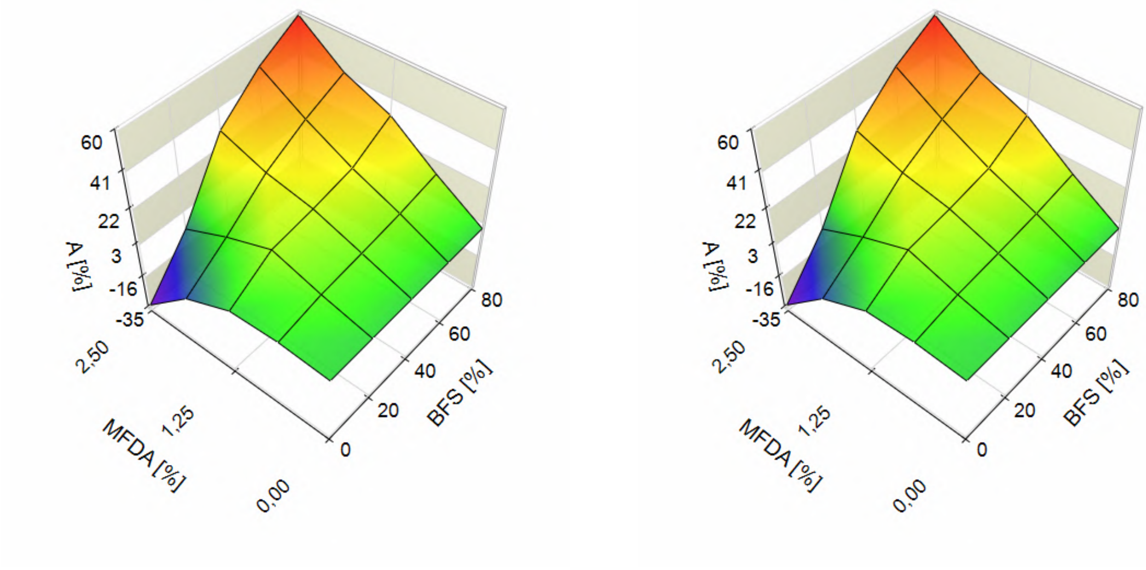
$$R_{c,t} = 26.26 + 4.45D - 3.31D^2 + 0.08S + 0.006SD + 0.09SD^2 - 0.003S^2 - 0.0002S^2D - 0.0006S^2D^2$$

where: D is the amount of MFDA, %;



(a) (b)

Figure 3. Activation effect A, achieved with the introduction of MFDA to the BFC of various compositions, (a) - compression, normal hardening, and (b) - bending, normal hardening.



(a) (b)

Figure 4. Activation effect A, achieved with the introduction of MFDA to the BFC of various compositions, (a) - compression, steam curing, and (b) - bending, steam curing.

S - the amount of BFS, %.

With an increase in the proportion of BFS, the need for MFDA increases, and the activation effect enlarges. At the same time, an increase in the amount of MFDA added to BFS - free cement causes a drop in the activity of the binder.

The described effects confirm the conclusions of [30]. Furthermore, the data obtained show that introducing an MFDA into the composition of the BFC makes it possible to obtain cement of equal strength with an increased BFS content against the usual range. The resulting decrease in the share of clinker makes it possible to significantly reduce the consumption of fossil fuels and emissions associated with cement production.

3.3. Optimization of hardening regimes of blast–furnace cement with MFDA

Earlier studies [33] showed that the introduction of activating additives into cement composition causes a decrease in the optimum steam curing temperature. Studies of the strength characteristics of cement steamed at different temperatures with different amounts of the added MFDA were carried out to clarify the optimal hardening regimes. The study used cement containing 50% BFS. First, the cement mixing with the MFDA was carried out in a ball mill for 8 minutes. Then, steam curing was carried out according to the mode 3 + 6 + 2 hours at temperatures 50°, 70° and 90°. Samples have tested 24 hours, 28 days and three months after steaming. The research results are summarized in table 3 and shown in figure 5, figure 6 and figure 7.

Table 3. Influence of the amount of MFDA and steam curing temperature on the strength characteristics of the BFC.

The amount of MFDA in the BFC, %	Steam curing temperature, ° C	Ultimate strength Rc [MPa], mortar samples 7.07×7.07×7.07 cm through		
		24 hours after steam curing	28 days after steam curing	90 days after steam curing
0	50	9.8	19.1	20.3
	70	12.8	19.9	20.7
	90	17.8	23.6	24.2
1.5	50	12.8	21.9	24.8
	70	17.1	29.2	30.5
	90	21.4	24.9	25.9
2.5	50	14.5	28.6	31.8
	70	20.9	35.8	36.2
	90	23.2	30.4	30.6

With an increase in the amount of MFDA in the binder, a more significant increase in strength is observed at lower temperatures. Thus, the combined action of the MFDA and temperature increases the destructive processes occurring during clinker hydration and, simultaneously, intensifies the process of binding hydrated lime and slag hardening.

The processing results showed that the samples strength dependence on the MFDA content and the steam curing temperature is as follows:

$$R_1 = 13.58 - 12.23D + 0.21D^2 - 0.23T + 0.42TD - 0.003TD^2 + 0.003T^2 - 0.003T^2D$$

$$R_{28} = -29.18 - 14.79D + 3.18D^2 + 1.49T + 0.39TD - 0.03TD^2 - 0.01T^2 - 0.002T^2D$$

$$R_{90} = -23.87 - 7.94D + 2.83D^2 + 1.36T + 0.247TD - 0.028TD^2 - 0.01T^2 - 0.001T^2D$$

where R_1, R_{28} and R_{90}, respectively, the strength of the samples after 1, 28, 90 days after steaming;

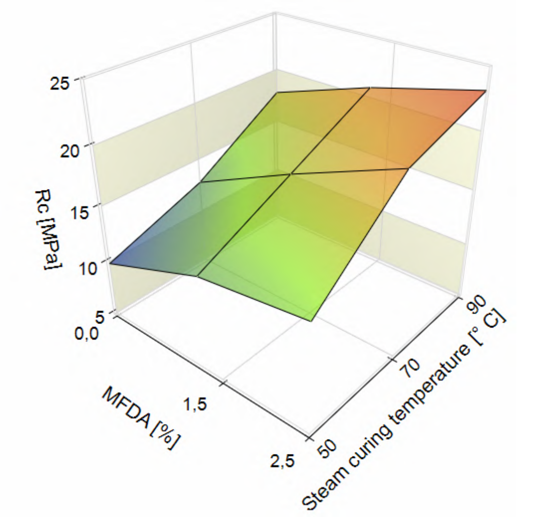


Figure 5. Influence of isothermal heating temperature on the MFDA activation effect created one day after steam curing.

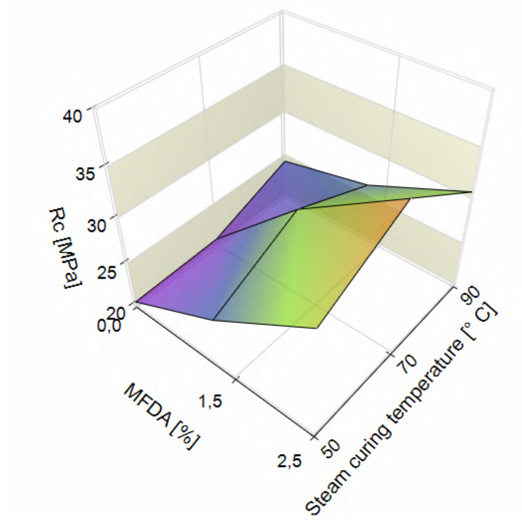


Figure 6. Influence of isothermal heating temperature on the MFDA activation effect created 28 days after steam curing.

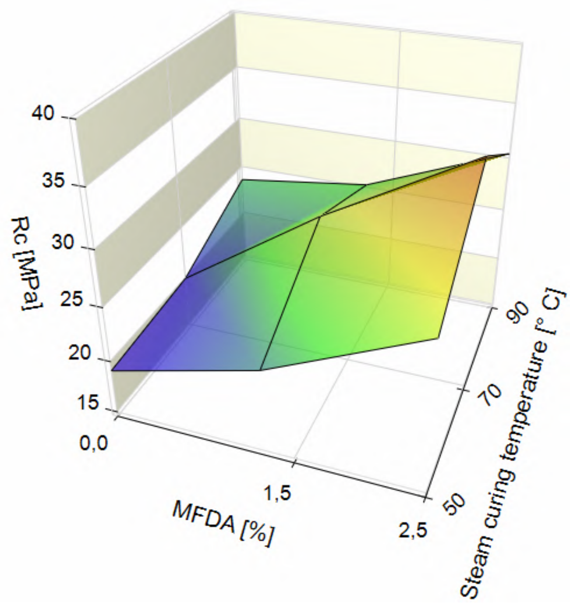


Figure 7. Influence of isothermal heating temperature on the MFDA activation effect created 90 days after steam curing.

T is the steam curing temperature in degrees Celsius;

D - MFDA consumption in %.

The research results show that the most significant increase in strength has been observed in samples steamed at 70°. The recommended steam curing temperature for ordinary BFC is 90-95° C. The introduction of MFDA into the composition of the BFC makes it possible to reduce the steam curing temperature of products by 20-25° C. Thus, the introduction of MFDA makes it possible to save energy resources on heat treatment prefabricated reinforced concrete significantly.

4. Conclusion

As a result of the research, it has revealed that the optimal method for introducing the MFDA into the binder is a method that ensures the simultaneous passage of tribochemical reactions in cement during the joint grinding of the components. Thus, the optimal time for joint grinding of ingredients is substantiated.

A relationship has been established between the activation effect: the consumption of BFS and MFDA. Furthermore, it has revealed that the MFDA addition activation effect increases with an increase in the proportion of BFS in the binder from 0 to 80%.

It has been determined that the introduction of the MFDA into the binder composition allows one to lower the optimum steam curing temperature by 20-25°, which significantly reduces energy consumption.

Thus, introducing an MFDA into the composition of BFC allows reducing energy consumption and emission by reducing the proportion of clinker in cement and reducing the temperature of heat and moisture treatment of products on this cement.

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PAPER • OPEN ACCESS

Investigation of energy-power parameters of thin sheets rolling to improve energy efficiency

To cite this article: V A Chubenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012051

Investigation of energy-power parameters of thin sheets rolling to improve energy efficiency

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Abstract. In order to study processes occurring during manufacturing of thin steel sheet by cold rolling and change of energy-power parameters, simulation was performed using engineering software DEFORM 3D, which allows to reflect rolling technology accurately. Model of treatment process was created, output data, modes and temperature of treatment, motion parameters of rolls and sheets were set, material of workpiece was selected and its properties were determined. During simulation of sheets cold rolling process, Lagrange analysis was used, number of simulation steps was 100. Process of plastic deformation of metal along curved grid was investigated, vector displacement field was determined, and it was found that maximum movement of metal occurs under effect of top roll. Distribution of stress-strain state was investigated and maximum stress in strain zone was determined. Distribution of rolling forces and torque was investigated, which allowed to determine their maximum values. Maximum rolling forces and torque were observed at $7-9^{th}$ second of treatment, and in future they were reduced due to the fact that pushing force disappeared and steady process began.

1. Introduction

Cold rolling technologies are widely used for thin sheets manufacturing, which allows to obtain products of exact size and high quality. Process of metal treatment by pressure is quite labor intensive and energy consuming. Cold rolling leads to significant changes in the metal structure. Distribution of strains and stress during reduction during cold rolling is difficult to investigate in production conditions, because of very high cost of such experiments.

Currently direction, connected with computer designing of metal treatment by pressure processes has been formed in science at sufficiently high level. Computer programs allow to create models that accurately reflect treatment parameters, where you can track all transformations that occur during reduction.

Investigation of cold rolling with help of DEFORM 3D engineering software is relevant, because it allows to significantly reduce time for conducting experiments, accelerate determination of rational modes of reduction during thin sheet cold rolling, which reduce energy consumption costs, improve product quality, increase efficiency and decrease self-cost of process.

Task to improve rolling technology using rational reduction modes, which provide required quality of products with minimum energy consumption is relevant.

For this purpose, it is necessary to carry out research of metal treatment using DEFORM 3D computer software, which significantly speeds up treatment process improvement.

Purpose of this work is to study cold rolling of thin sheets using DEFORM computer software to determine rational energy-power parameters.

2. Analysis of literature data and problem definition

Within framework of stable metallurgy development program, team of scientists from Ferrous metals metallurgy and foundry Department of Kryvyi Rih National University deals with following important tasks: improvement of sheet rolling technology and improving quality of manufactured products [1]. Another area of research is development of recommendations for improving energy efficiency of cold rolling technologies.

Thin sheets manufactured by rolling are widely used in vehicle manufacturing industry and engineering industry. Thin steel sheets are mainly produced on cold rolling mills. This process allows to obtain sheet thickness of $0.15 - 1.8mm$ and width of $700 - 2300mm$, tin plate and stripes with thickness of $0.0015mm$. Starting material for cold rolling is steel having thickness of $1.6 - 6mm$ [2]. This steel is obtained by hot rolling in a rolling mill in hot rolling shops.

Production of cold-rolled sheets manufactured in cold rolling workshops involves large number of stages and requires usage of various and sophisticated equipment [3].

Cold-rolled sheets are produced on continuous or semi-continuous rolling mills. They have a large number of work stands, which shall be adjusted. Cold-rolled sheet steel shall have high strength. Its surface shall be matt in some cases and polished in other cases.

Cold rolling significantly changes metals properties: as value of reduction increases, yield strength of metal and deformation resistance increase, elongation of strip decreases. This is due to the change of grains size during cold deformation, which leads to change of metal structure.

There is non-uniform distribution of friction forces [4], which affects deformation process. All these factors affect change of energy consumption during rolling, which affects cost of rolling production. Cold rolling processes require further investigation, research and refinement to improve product quality, reduce power costs and cost of production.

Volumetric displacements occurring in strain zone during rolling are not available for direct study, and experiments cannot cover the whole set of interaction of reduction technological factors, that's why many results have individual characteristics and can only be used for conditions in which they were obtained [5].

It is known that during rolling a strain zone is formed, which consumes a lot of energy and creates complex stress-strain state of metal [6–8].

Studies [9, 10] use large number of numerical one-dimensional models, which enable to take into account nature of geometric parameters distribution, mechanical properties and conditions of contact friction in strain zone of rolling process of thin sheets and steel strips.

Mathematical models [11, 12] show cold rolling processes and power calculations, but do not take into account dynamic nature of process.

Dynamic models [13–15] do not account for foreseen stresses and strains during cold rolling. The work [16] does not take into consideration contact interaction between material and rolls. Computer simulation methods offer great opportunities for solving problems of metal treatment by pressure [17]. Finite element methods, finite difference methods, boundary element method and finite volume method [18] have become very popular in theory of metal treatment by pressure.

A large number of studies using finite element methods [19, 20] were devoted to problem of metal flow during deformation. But it shall be noted that in these works process of thin sheets cold rolling was not investigated. In article [21] engineering software complex DEFORM 3D was used to study processes of sheets hot rolling, where nature of metal form changing, forming of

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products microstructure, energy costs for process were carefully studied, but characteristics of cold rolling of thin sheets were not investigated.

Therefore, authors consider it necessary to pay attention to energy consumption during cold rolling of thin sheets using DEFORM 3D software.

3. Purpose and tasks of research

Purpose of work: to investigate cold rolling process of thin steel sheet using DEFORM 3D software to determine energy-power parameters of process. In order to reach this goal, following tasks were set:

- to create model of cold rolling of thin sheet in DEFORM 3D software;
- determine forces and torques that arise during deformation process and their distribution in strain zone during cold processing.

4. Research Methodology

Sheet with length of $l = 1000mm$, width of $b = 1000mm$ and height of $h = 5mm$ was used to simulate cold rolling. Rolling was carried out in cylindrical rolls. Roll diameter is $200mm$, length is $1200mm$. Initial temperature of rolling process was $20°C$. Research is aimed to investigate change of stress in strain zone, which occurs during rolling (figure 1). Change of stress value leads to change of force and energy consumption.

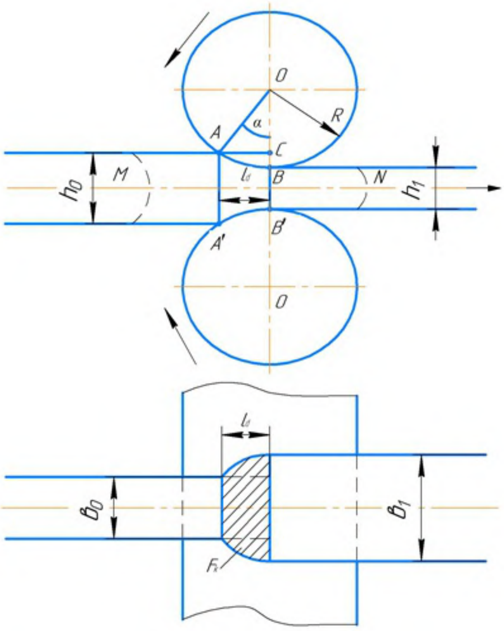

Figure 1. Deformation scheme: $ABB'A'$ is strain zone; h_0 is sheet thickness before rolling; h_1 is sheet thickness after rolling; b_0 is strip width before rolling; b_1 is strip width after rolling; α is capture angle during rolling; R is roll radius; F_k is contact area of the sheet with the rolls; l_d is length of the strain zone; M is metal flow before entering the strain zone; N is metal flow when leaving the strain zone.

Uneven stresses that occur in the metal cause uneven deformations that affect surface quality of sheet. Deformation degree during study varied from 10 to 80%. Deformation degree was determined by the formula (2):

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$$\varepsilon = \Delta h / h_0, \tag{1}$$

where Δh is absolute reduction,

$$\Delta h = h_0 - h_1, \tag{2}$$

where h_0, h_1 – initial and final thickness of strip accordingly.

Software DEFORM 3D simulated original workpiece, placed it in space, determined parameters of interaction between roll and workpiece, friction conditions and nature of heat exchange, positioned rolls relative to workpiece, as shown in figure 2. Diagram shows metal clamping process by rolls, which occurs at initial stage of rolling (first step of simulation).

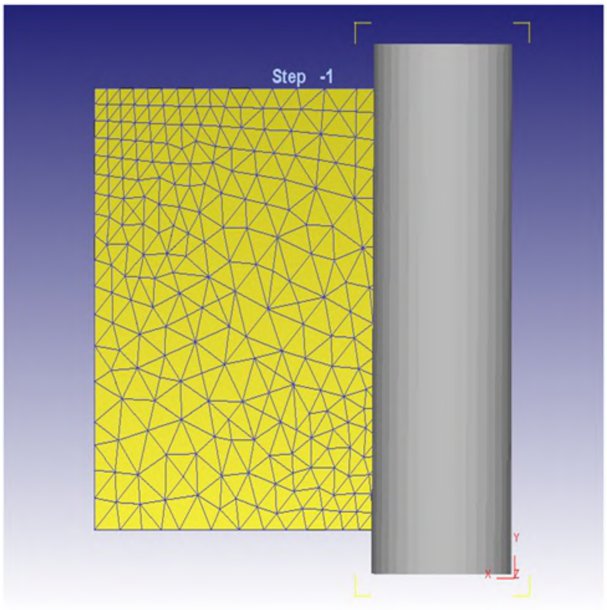

Figure 2. Positioning of roll relative to workpiece.

The diagram (figure 2) shows how the interaction of the rolls and the processed material occurs (top view). Rolls reduce rolled material, rotate, strip moves gradually towards rolls rotation direction. Grid of finite elements on workpiece, number of which is 2051, was constructed. It was adjusted that main roll is top one, that reduces metal along height. Material of treated workpiece was determined from computer software library. Carbon steel sheet AISI-1015_(20-1200C) was used in research. Figure 3 presents diagram "Stress-Strain", which shows value of stress at which plastic deformation of material begins. Yield strength of material was determined according to the energy law [17]:

$$\sigma = \varepsilon^n * u^m + y, \tag{3}$$

where σ is effective stress of plastic material flow, ε is material deformation, u is material deformation speed; n is deformation degree indicator, m is indicator of deformation degree speed, and y is material constant.

Selected elastic properties of material are characterized by Young‘s modulus and Poisson‘s ratio. These coefficients are constant and are 0.3 and $1.5 * 10^5$ respectively. Heat capacity of investigated material, which depends on treatment temperature, was determined (figure 4).

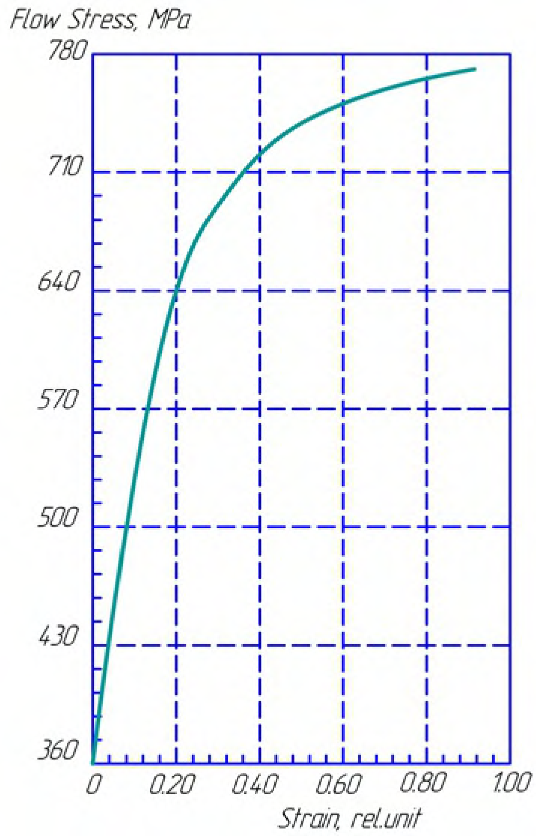

Figure 3. Diagram "Stress-Strain".

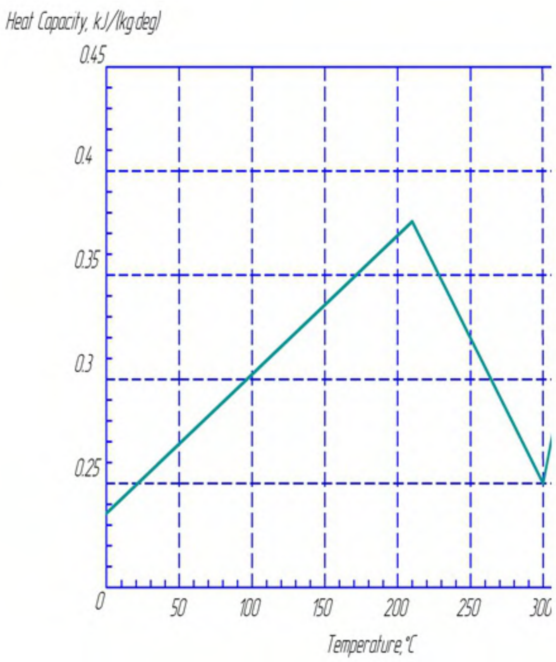

Figure 4. Dependence of heat capacity of steel on temperature.

Graph shows that heat capacity of treated steel increases with increasing of temperature and takes maximum values at treatment temperature of $210°C$. This increase occurs under influence of plastic deformation. After this temperature heat capacity decreases. During simulation Perzyna‘s model was used [17]:

$$e` = \gamma(\varepsilon`/\sigma - 1) * m, \tag{4}$$

where γ is fluidity; $\varepsilon`$ is effective stress; $\sigma$ is flow stress; $m$ is material parameter; $e`$ is effective strain speed.

To study cold rolling process, one object was carefully positioned relative to others. Positioning accuracy was selected. Coefficient of friction during cold rolling was assumed to be 0.1. It was assumed that force of friction varies according to law of Siebel. Contact between workpiece and top and bottom rolls was generated. For simulation, it was assumed that workpiece is plastic type of object, for which analysis was performed based on specified values of metal yield strength, and roll is rigid, which means that it is not deformable object. Parameters of rolls (speed of rotation) and workpiece (linear speed of strip displacement) were specified. During simulation of sheets cold rolling process, Lagrange analysis was used, number of simulation steps was 100. Calculations were performed using the SI unit system. Simulation mode was deformation. Number of steps was determined by the formulas [17]:

$$n = x/(v\Delta t), \tag{5}$$

where n is number of steps, x is summary movement of main roll, v - main roll speed, Δt is time increment for one step. Theoretical study of rolling force was carried out according to the formula (2):

$$P = \sigma n_\sigma b\sqrt{\Delta h R}, \tag{6}$$

where n_σ is stress coefficient (2), b is sheet width. Selected parameters of database allowed us to simulate cold rolling process, to determine its main characteristics, changes in forces and torques of deformation during treatment and to study transformation in strain zone formed during rolling.

5. Discussion of energypower parameters investigation results and identification of rational reduction modes

As result of simulation, process of metal flow along curved coordinate grid was investigated and vector displacement field was determined, which is shown in figure 5. Figure 5 shows that maximum displacement vector appears under press of upper roll at beginning of treatment. Bottom roll has less intense impact on metal because top roll is the main tool. Strain distribution in volume of treated material during cold rolling is shown in figure 6.

Stress-strain state of metal at point of its clamping by rolls was identified; maximum strain values in strain zone reach $0.309mm$ per $1mm$ of workpiece height. Change in rolling force during cold rolling in strain zone with time was investigated (figure 7), and results show that rolling force increases during the first 9 seconds and reaches 5.5 MN.

In real conditions, for these modes, the rolling force reaches 5.3 MN [8], which corresponds to a high simulation accuracy, where the error is 5.5%. Formula (6) was used to check adequacy of model. A further sharp decrease in the rolling force is explained by the fact that the process of clamping the billet with the rolls is over and a stable rolling motion has begun, when the pushing forces are removed and the metal moves without significant efforts. As result of simulation, graph of torque change over time, formed by top roll, was obtained (figure 8). Graph (figure 8) shows that torque from beginning of cold rolling of sheet steel changes periodically, reaching maximum values at 7^{th} second from process beginning. Studies show that power consumption

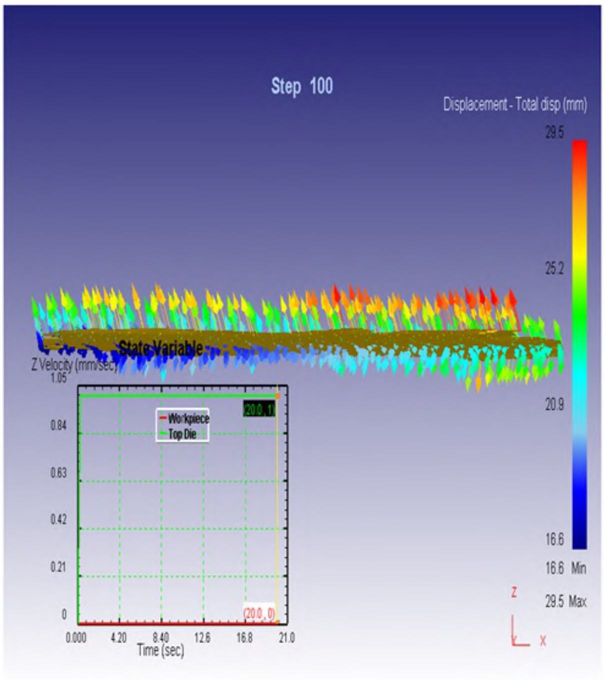

Figure 5. Vector displacement field of metal during rolling.

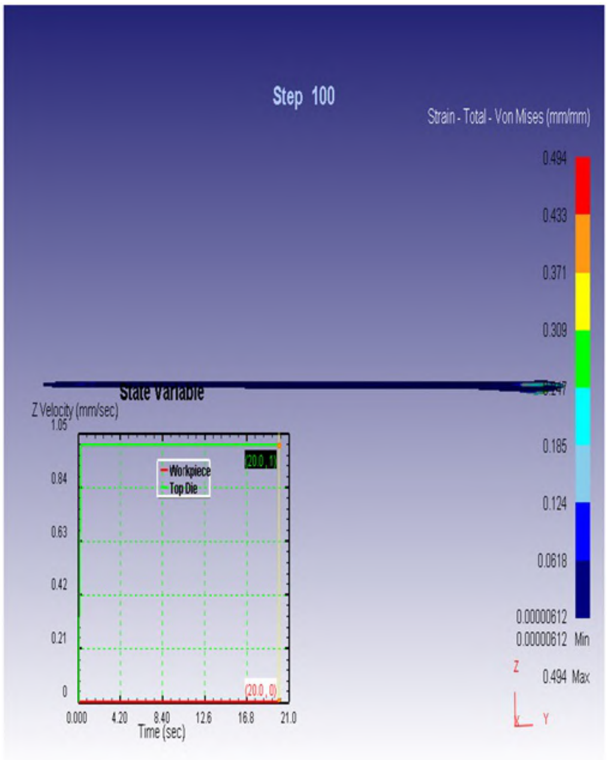

Figure 6. Strain distribution during cold rolling.

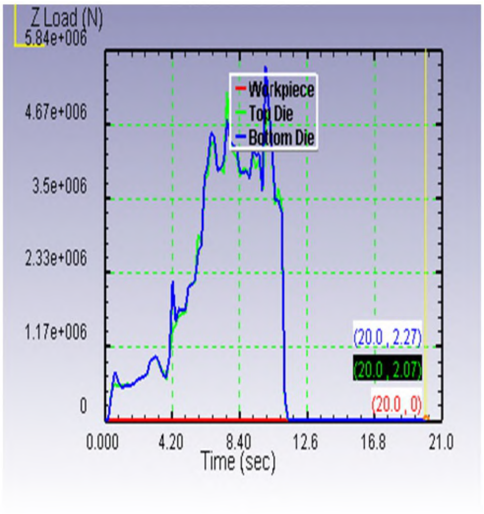

Figure 7. Change of rolling load over time.

at beginning of cold rolling process increases rapidly and reaches maximum values at $7-9^{th}$ second under effect of upper roll and subsequently decreases. Checking of investigation results regarding torque during cold rolling was carried out according to the formula:

$$M = P\psi\sqrt{R\Delta h}, \tag{7}$$

where ψ is moment arm ratio.

Rolling force was applied to the center of strain zone. Torque arm was calculated by the following formula:

$$\psi = \frac{1}{2}R\sin\alpha, \tag{8}$$

Capture angle was calculated by the formula:

$$\alpha = \sqrt{\frac{\Delta h}{R}}, \tag{9}$$

Parameters obtained during simulation were used for further theoretical calculations of work applied for rolling process and process capacity. Rolling work was determined taking into account symmetrical rolling process according to the formula:

$$A = \frac{2Ml_d}{R(1+S)}, \tag{10}$$

$$S = \frac{R}{h_1}\gamma^2, \tag{11}$$

where γ is angle of neutral plane, where speed of rolls is equal to speed of metal. Angle of neutral plane depends on capture angle and friction coefficient. It is calculated by the formula:

$$\gamma = \frac{\alpha}{2}(1-\frac{\alpha}{2\beta}), \tag{12}$$

where β is friction angle. Cold rolling enables treatment in case if friction angle is $\beta = 0.1$. Capacity that was used on cylindrical part of roll was determined by the formula:

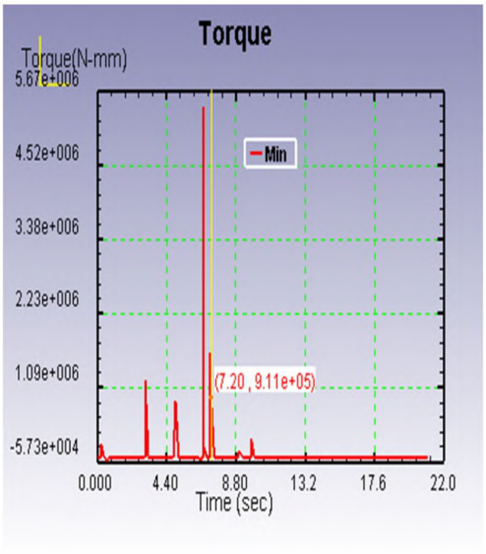

Figure 8. Torque change.

$$W = \frac{2Ml_d}{R(1+s)\tau}, \tag{13}$$

where τ is time of rolling.

Research enabled to choose rational treatment modes for cold rolling: efficient degree of deformation ε of 70% is accepted. This degree of deformation enables to obtain sheets with maximum hardness, and they can deform plastically. Increase of deformation degree requires increase of energy consumption. Increasing of deformation degree leads to elastic displacement of rolls, which makes quality of sheet surface worse. With increase of deformation degree, stress of metal surface layer increases, as well as rolling force and torque, and process defects may appear: microcracks, microfiber on sheets and rolling tools. Reduction of deformation degree up to 45% leads to decrease of strength and hardness of metal. Sheet is able to deform plastically under load during operation. Investigation results are shown in table 1. Executed research enabled to use efficient modes of reduction (table 1) when developing new technological process for manufacturing thin sheets by cold rolling, which ensures sustainable development of cold rolling technologies.

Table 1. Results of the study power parameters cold rolling

σ, MPa	b, mm	h_0, mm	h_1, mm	$\varepsilon, \%$	P, MN	M, MNm
740	1000	5	1,5	70	5,3	0,198

Such modes will make it possible to obtain cold-rolled sheets with high strength characteristics at a minimum cost.

6. Conclusions

As result of investigation of cold rolling of thin steel sheets was executed following:

- model of cold rolling of thin sheets in DEFORM 3D software was created and research methodology was developed, which allowed to determine changes of energy-power parameters that occur in strain zone during treatment; vector field of metal movement and its stress-strain state during cold rolling of thin sheets were determined;
- there were determined forces and torques that arise during deformation process, and there was investigated their distribution in strain zone during cold treatment, which made it possible to determine rational energy consumption during cold rolling;
- simulation showed that stress reaches its maximum during 9th second of treatment $5.5MN$ during cold rolling, and accuracy of simulation is 5.5%.

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To cite this article: V I Dmytrenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012052

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012052 doi:10.1088/1755-1315/1049/1/012052

The use of bischofite in the gas industry as an inhibitor of hydrate formation

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Abstract. The article considers the possibility of using natural, environmentally friendly, cheap raw materials as the basis of a complex inhibitor of hydration and corrosion. It is proposed to use bischofite solutions with mass fraction of 24% $MgCl_2$ as a carrier of a complex inhibitor. A set of laboratory studies was carried out in order to eliminate the main shortcomings of bischofite solution. Such disadvantages are that highly concentrated solutions of bischofite, untreated from sulfate ions and iron compounds, without a corrosion inhibitor cause corrosion of equipment and salt deposits. According to the results of laboratory studies, the composition of a complex inhibitor of hydroformation and corrosion based on bischofite was proposed. Based on the results of laboratory studies, suitable reagents were selected for preparing a bischofite solution for use in the processes of production and preparation of gas for transport, and the mechanisms of reagents action were proposed.The results of industrial tests show the effectiveness of a new complex inhibitor. The achieved properties of the complex inhibitor have led to the improvement of technical, economic and environmental performance of gas production enterprises of Ukraine.

1. Introduction

In modern conditions, when structural changes are carried out in our country and new economic conditions are introduced, gas and oil industries, as before, are the main industries in the fuel and energy complex of Ukraine. The development of technology for the operation of gas and gas condensate fields in the conditions of carbon dioxide corrosion and hydration requires a special approach that opens new directions in science and industry.

Extraction and preparation of gas for transportation is complicated by hydration and corrosion of metal equipment [1–6]. Carrying out work to eliminate these complications dramatically increases the cost of operating wells and hydrocarbon collection systems. Neglecting corrosion protection leads to frequent interruptions, and in some cases when the tubing is broken – stops the production of hydrocarbons. The main indirect losses from hydroformation and corrosion are the underproduction due to emergency and repair shutdowns, environmental sanctions.

The introduction of advanced technologies for the protection of operating equipment helps to reduce labor costs and material consumption, reduce the duration and cost of repair and restoration work carried out at industrial enterprises [2, 4]. These measures will ensure sustainable development in the future during the operation of oil and gas fields in the conditions of hydrate formation and carbon dioxide corrosion.

2. Problem statement

World and domestic practice shows that one of the simplest, most effective and in many cases cost-effective methods of combating the processes of hydrate formation and corrosion is the use of inhibitors. [7, 8]. According to the data of the feasibility study on the use of reagents, technologies based on the use of complex inhibitors are more efficient.

Inhibitors for industrial piping systems must have certain technological and protective properties. For example, hydration inhibitors should lower the hydration temperature by more than 25 ℃, corrosion inhibitors should have high protective properties in the water and vapor phases (not less than 85% of total corrosion), not to have a negative impact on technological processes [7].

Nowadays, some experience has been gained in the use of inhibitors to prevent hydration and corrosion. Methanol, glycols and calcium chloride are mainly used as inhibitors of hydrate formation [8–11]. These solutions in their properties meet the requirements for inhibitors of hydration, but have significant disadvantages.

The main disadvantage of methanol is its high toxicity, explosion and fire hazard. In addition, low boiling point and high volatility cause significant losses of methanol in the industrial gas treatment system. The use of methanol is the source of environmental pollution [8, 9].

Compared to methanol and calcium chloride, glycols are less effective in reducing the temperature of hydration, are quite expensive, cause technological difficulties in separating the emulsion, have high viscosity and relatively high crystallization temperature [10].

The main disadvantage of calcium chloride is high corrosion activity, deposition during interaction with carbon dioxide, which is always contained in natural gas [11].

Therefore, in some cases it is advisable to use other antihydrate reagents.

In connection with the above, the current problem is the choice of process fluid, which would ensure quality and trouble-free operation of gas wells, systems for collection and preparation of hydrocarbons and at the same time would have minimal negative impact on the environment.

The authors have conducted laboratory studies on the selection of the composition of environmentally friendly complex inhibitor of hydration and corrosion (CIHC), which meets the requirements for inhibitors of hydration and corrosion.

Bischofite solution is proposed as an environmentally friendly basis for the CIHC formulation. When using thermodynamic inhibitors of hydrate formation, including bischofite, there is a change in the structural parameters of water, reducing the vapor pressure of water, which causes changes in hydration conditions [8, 12, 13], helps prevent the formation and destruction of hydrate deposits.

Bischofite solutions have better antihydrate activity than calcium chloride and not worse than methanol [2] (reduce the equilibrium temperature of hydration by ≈27–29 ℃), as well as significantly lower corrosion aggressiveness compared to calcium chloride. Bischofite is an inexpensive, non-volatile, safe reagent [12, 13]. The inhibitory effect is achieved due to ions Mg^{2+}, Ca^{2+} and Cl^{-}, which attract water dipoles. Bischofite solutions have a freezing point ≈ -30 ℃ [12–15]. Therefore, the use of bischofite is acceptable in temperate climate deposits. Particularly rational from the economic point of view is the use of this effective inhibitor of hydration in the case of its direct extraction on the territory of gas fields or bischofite fields in the surrounding areas. In deposits characterized by high cryolithozone capacity (up to 700 m) and low geothermal gradient (1.5–2.5 ℃ per 100 m), the use of bischofite may be appropriate in hydrocarbon collection systems.

In Ukraine, large deposits of bischofite have been explored in Poltava and Chernihiv regions. In Russia – in Saratov, Volgograd and other regions. These bischofite reserves are almost inexhaustible.

The use of bischofite in gas production companies is often limited due to its irrational use. Highly concentrated solutions of bischofite, untreated from sulfate ions and iron compounds, without corrosion inhibitor cause corrosion of equipment and salt deposits.

Research on these issues and the development of economic technologies for the use of complex reagents based on bischofite will improve the environmental performance and performance of gas collection and treatment systems.

The purpose of the study: prevention of hydration and carbon dioxide corrosion during the operation of gas condensate fields by the use of domestic, available, inexpensive raw materials instead of expensive methanol and corrosion inhibitors.

3. Materials and methods

Bischofite solutions with a mass fraction of $MgCl_2$ 24% from well №1 of Zaturyn area were used as a carrier of the complex inhibitor.

Primary selection of reagents was performed. Analysis of the technical and economic characteristics of more than one hundred surfactants allowed to identify the following reagents for further experiments: KI-1M, sulforocanol (SRK), emily (EM), cocamide propylbetaine (CAPB) and stentex (St). The following acids and complexes were selected as stabilizers of iron ions: hydrochloric acid, acetic acid, formic acid, citric acid, oxalic acid, sodium salt of ethylenediaminetetraacetic acid (EDTA).

The process of hydrate deposition was studied under dynamic conditions on an experimental setup (figure 1).

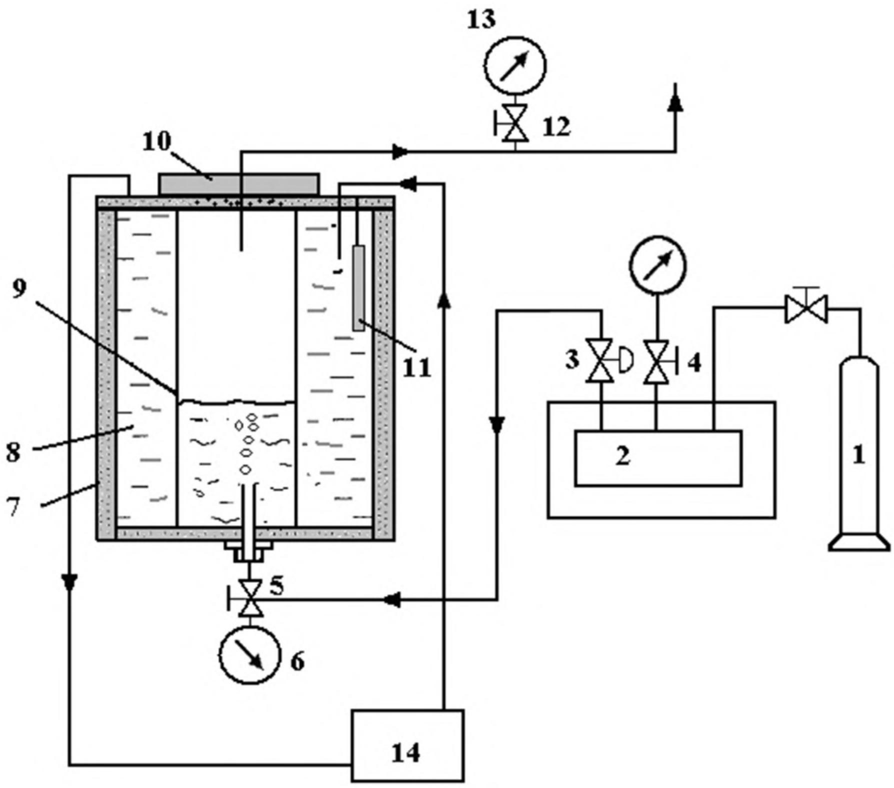

Figure 1. The scheme of the experimental installation for the study of hydrate formation processes:
1 – gas cylinder; 2 – buffer tank with gas (thermostated); 3, 4 – gas reducer; 5 – inlet valve; 6, 13 – manometer; 7 – housing; 8 – cooling chamber; 9 – reactor; 10 – cover; 11 – thermometer; 12 – outlet valve; 14 – refrigerator.

Technical propane and surfactant solutions in double-distilled water and bischofite were used to obtain hydrates. The main element of the installation is a sealed reactor, which has the shape of a cylindrical glass with a useful volume of 300 cm^3, made of organic glass. The reactor was filled with thawed cooled test liquid with solid phase crystals. Gas from the cylinder through the outlet valve at a pressure of 0.4 MPa was fed to the reactor and released under a pressure of 0.35 MPa at a given temperature. The temperature in the chamber was created and regulated by the coolant supplied to the reactor jacket. The experiment ended when all the liquid in the reactor turned into a solid phase, the conditions and time of hydration were recorded.

Bischofite solution with a mass fraction of 24% $MgCl_2 + 3\,g/dm^3\,CH_3COOH$ was used to study effectiveness of the corrosion inhibitors. Concentration of acetic acid was chosen bacause of the maximum content of low molecular weight carboxylic acids in the formation waters of wells of Northeastern Ukraine. Lighted condensate was used as hydrocarbon phase, as it has neutral reaction of medium and constant fractional composition and carbon dioxide as gaseous medium.

One of the main parameters influencing the corrosion rate is the ionic composition of the aqueous phase [4]. The main component of formation waters of North-Eastern Ukraine is sodium chloride NaCl [7]. Therefore, a solution of 0.5 M $NaCl + 3\,g/dm^3\,CH_3COOH$ in distilled water was chosen as the model medium for model formation water.

Corrosion studies were carried out in a thermostatic installation (figure 2) The installation is designed at the All-Union Scientific Research Institute of Natural Gases and Gas Technologies (VNIIGAZ) for determination of corrosion rate in the simulated conditions of industrial pipelines [7]. It is a glass vessel in which the test solution was poured and a fluoroplastic cylinder with witness samples and a propeller stirrer was placed.

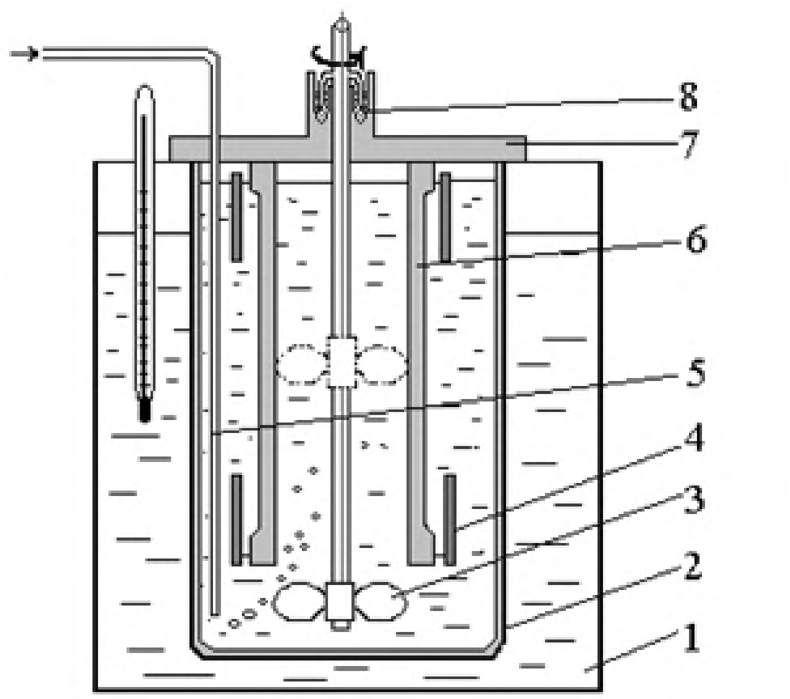

Figure 2. Figure 2. Installation diagram for corrosion research:
1 – thermostat; 2 – glass chamber; 3 – mixer; 4 – metal piece; 5 – gas supply tube; 6 – fluoroplastic cylinder; 7 – cap; 8 – hydraulic seal.

The cell was attached to an electric motor that rotated the stirrer. During rotation of the stirrer, circular fluid motions in the laminar mode were created in the fluoroplast cylinder with a flow rate of 0.3–0.5 m/s. When the propeller was mounted below the bottom of the cylinder, it was rotated at a speed of 1400 revolutions per second. There was a circular motion of the fluid in turbulent mode. The speed of stream flow in the area of placement of metal piece was 7–8 m/s. In addition to circular motion, fluid was also circulated through the small cylinder by creating irritation during rotation of the stirrer.

The corrosion rate of the metal was calculated by the equation (1) [7]:

$$v = \frac{\Delta m}{S\tau} \tag{1}$$

where v – the corrosion rate g/(m^2·h); Δm – the loss of the metal piece, g; S – the surface area of the coupon, m^2; τ – the test duration, h.

Protective effect of test reagents in bischofite solution (Z) was calculated by the equation (2) [7]:

$$Z = \frac{v_0 - v_1}{v_0} 100 \tag{2}$$

where, v_0 – corrosion rate of the metal piece without the corrosion inhibitor e, g/(m^2·h); v_1 – corrosion rate of the metal piece with the corrosion inhibitor, g/m^2·h.

The stability of soluble forms of iron under the action of reagents was determined by colorimetric method in accordance with GND 211.1.4.040-95. The effect of surfactants on the rate and completeness of calcium sulfate deposition was performed in accordance with the standards for determining the content of sulfates in the sediment and solution by gravimetric method according to GOST 7759-73. Based on the results obtained, the degree of precipitation of calcium sulfate relative to the initial amount of sulfate ions in solution was calculated. Phase equilibria in the studied systems were studied by the isothermal solubility method, which allows to establish the exact molecular ratio of the components.

The quantitative indicators obtained in the experiments were analyzed using the methods of mathematical statistics.

4. Experimental laboratory results

It is known that surfactant additives with a concentration of 0.1% do not change the equilibrium conditions of gases hydration [8, 16]. The conclusion follows from the fact that surfactants in low concentrations can not significantly affect the chemical potential of water in solution, which is defined as the equation (3):

$$\mu = \mu_0 + RT \ln(1 - x) \tag{3}$$

where, μ_0 – chemical potential of pure water, x – is the molar fraction of surfactants in the solution.

To elucidate the nature of the hydroformation process in the processes of gas production and treatment, the temperature of hydrate formation (p = const) was determined under dynamic conditions under the action of distilled water, aqueous solutions of surfactants 0.1% wt., bischofite solution 10% wt. and a mixture of bischofite 10 wt%. with surfactant 0.1% wt.

It was found that the introduction of a complex inhibitor based on bischofite as an anti-agglomerate inhibitor of hydration of cationic surfactants CAPB and KI-1M, mass fraction of which in solution is 0.1%, the temperature of deposition of hydrates decreases by 6 ℃, hydrate

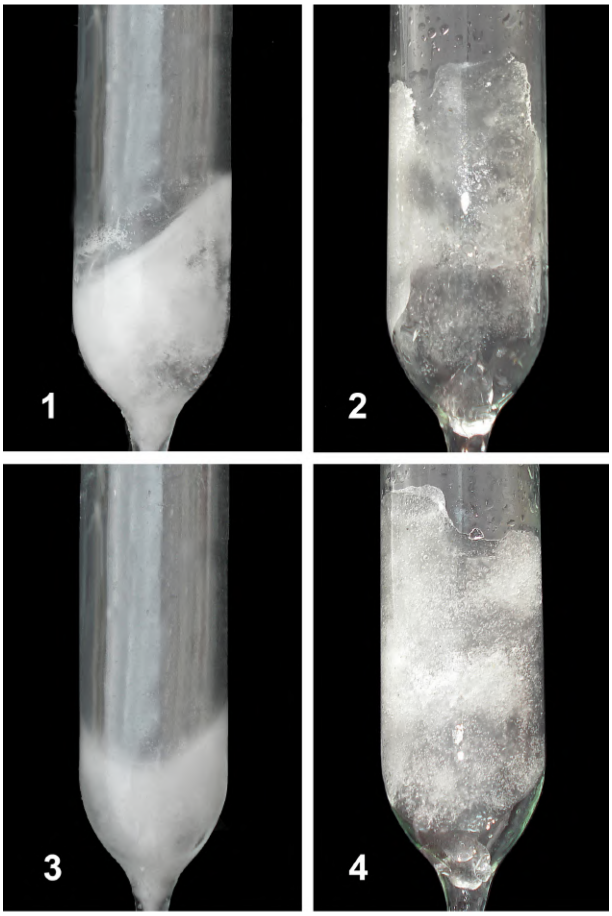

Figure 3. Hydrate in the surfactant system – bischofite/water – propane:
1 – propane hydrate obtained from water; 2 – propane hydrate obtained from a surfactant solution of 0,1% wt.; 3 – propane hydrate obtained from bischofite 10% wt.; 4 – propane hydrate obtained from a solution of bischofite 10% wt. with the addition of surfactants 0,1% wt.

is formed on the solution surface and on the walls of the reactor (figure 3). The adhesion of such hydrates to the reactor walls is negligible. In a distilled water control experiment, the hydrate is formed as a solid throughout the volume of the liquid-filled reactor. A similar hydrate was obtained from bischofite. Our data are confirmed by studies of the authors [16–18], who determined the effect of surfactants on the kinetics of hydrate formation.

In order to eliminate the main technological shortcomings of bischofite, a number of laboratory studies were carried out.

The results of studies on the protective effect of surfactants showed that in the complex inhibitor of hydration and corrosion instead of high-quality imported corrosion inhibitors it is possible to use surfactants of domestic production, which significantly reduce the cost of inhibitor and do not impair its technological properties. It was found that all surfactants studied in the model environment of formation waters show a protective effect of more than 90% with a dosage of 1 g/dm^3 (figure 4a), which satisfies the requirements of regulatory documents for corrosion inhibitors.

It is established that the protective properties of surfactants in bischofite solution are 1.01–2.50 times less effective than in the model environment of formation waters. The degree of surfactant protection of SRK, EM and CAPB is reduced by 2.45–2.50 times. The degree of

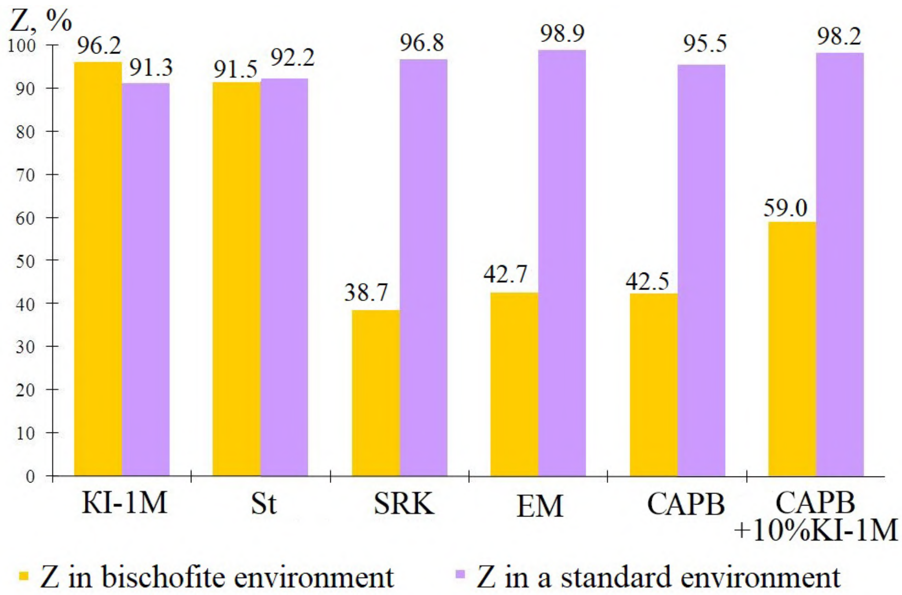

Figure 4a. The degree of protection against corrosion of steel P-110 in the presence of surfactants in bischofite solution and model environment of formation waters [7].

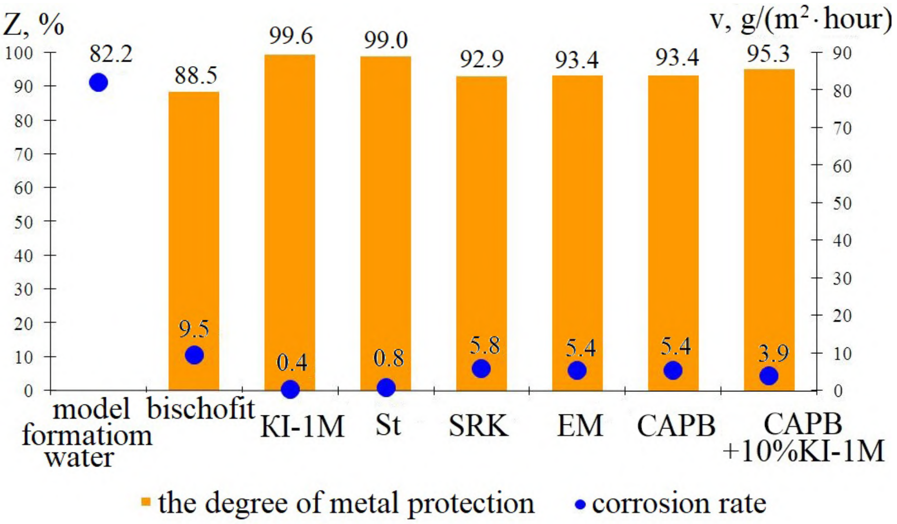

Figure 4b. The degree of protection against corrosion of steel P-110 in the presence of surfactants in the solutions of complex inhibitors of hydrate formation and corrosion on bischofite basis relatively to the model environment of formation waters [7].

protection of more than 90% was detected in the presence of St and KI-1M. Reagent KI-1M in bischofite solutions practically does not change its efficiency (increases by 1.05 times). All studied complex systems provide a degree of protection of the metal more than 90 ℃ (figure 4b). The most effective corrosion inhibitor is a complex inhibitor containing $MgCl_2$ 24% and KI-1M 0.1%, which showed a degree of protection of the metal of 99.57% relative to the model environment of formation waters.

When choosing an iron stabilizer, a number of organic and inorganic acids has been studied. The study found that the most effective reagents are EDTA, oxalic and citric acids, which form

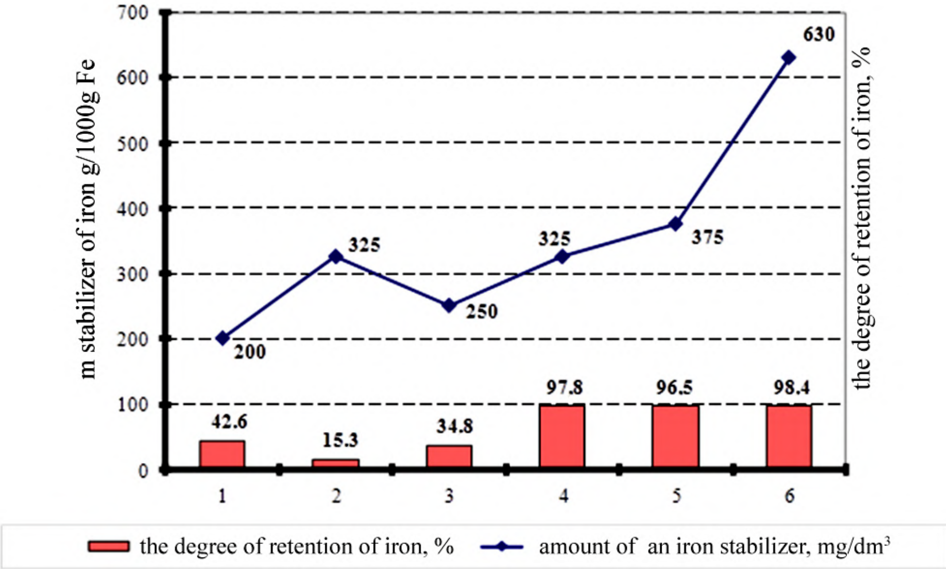

Figure 5. Characteristics of iron stabilizers: 1 – hydrochloric acid; 2 – acetic acid; 3 – formic acid; 4 – oxalic acid; 5 – citric acid; 6 – ETDA.

stable soluble forms of iron, provide a degree of iron ions retention in the soluble state of 96.5–98.4% for 30 days (figure 5). Based on the calculation results of the effective concentration of stabilizers shown in figure 5, citric and oxalic acids were isolated, so much so that to maintain the same amount of iron ions requires 1.68 citric acid, and oxalic acid – 1.94 times less than EDTA.

For the final choice, corrosion studies of reagents at a temperature of 106 °C. As a result of the study, data were obtained that allowed to choose citric acid, which causes 1.81 times less corrosion than oxalic acid, as a stabilizer of iron ions for bischofite solutions.

Table 1. The degree of calcium silfate precipitation in the presence of surfactants and stabilizers of iron ions, T=20 °C.

Enviro-nment	Stabilizer of iron ions (w=0.5%)	Degree of precipitation $CaSO_4$, %					
		Surfactant (w=0.1%)					
		–	KI-1M	St	SRK	EM	CAPB
Bischofite ($w(MgCl_2)=24\%$)	–	12.10	3.60	10.30	48.20	68.20	88.96
	Hydrochloric acid	12.00	2.30	8.40	7.80	8.30	8.50
	Acetic acid	11.30	3.20	9.60	7.90	9.30	9.60
	Formic acid	10.80	2.50	8.35	7.81	8.29	8.75
	Citric acid	11.20	4.50	11.20	20.21	55.52	78.91
	Oxalic acid	83.09	70.85	78.67	68.60	88.95	97.62
	EDTA	94.94	30.50	75.29	76.35	98.56	99.69

Further research was aimed at removing sulfates from bischofite solutions. For this purpose, the effect of surfactants on the crystallization of calcium sulfate in an aqueous solution of bischofite – 24 mass % solution, was studied. Determined the degree of precipitation, phase distribution rate and the effect of reagents on the precipitation of chlorides. It was found that during bisulfite desulfation, EM, CAPB and SRK reagents effectively improve calcium sulfate precipitation and prevent chloride salting.

The mutual influence of iron ion stabilizers and surfactants on the process of desulfation of bischofite solutions has been studied. Based on research, it has been determined (table 1) that surfactants EM, SRK and CAPB have a complexing effect on alkaline earth metal ions. This is confirmed by the fact that in the presence of strong acids, the degree of precipitation of calcium sulfate decreases sharply due to the destruction of complex compounds, supersaturation of $CaCl_2$ solution and precipitation of chlorides.

The results were taken into account when developing the technology of a complex inhibitor preparation. The use of amphoteric surfactant CAPB with a mass fraction of 0.1% in the preparation of bischofite as a catalyst for sulfate precipitation and a chloride precipitation inhibitor allows to increase the degree of $CaSO_4$ precipitation by 76.86% and reduce the volume of precipitate formed by 9.4 times. According to the results of laboratory studies, the following component composition of the complex inhibitor of hydration and corrosion OV-07 (mass fraction, %): magnesium chloride – 23–25, amphoteric surfactant CAPB – 0.1–0.2, cationic surfactant KI-1M – 0.1–0.2 and citric acid – 0.2–0.5.

The composition is designed simultaneously to prevent hydration and corrosion in the conditions of well removal of formation waters with an initial high content of iron ions <600 mg/dm^3.

5. Industrial tests

Industrial tests of the complex inhibitor of hydration and corrosion OV-07, which is proposed by the author to increase the reliability of gas wells operation in the conditions of hydration and corrosion, conducted at Kaverdynske gas condensate field. Methanol was previously used as an inhibitor of hydrate formation at this field. Well operating parameters: gas flow rate – 206 thous. m^3/day, water quantity 1.5 m^3/day, volume fraction of CO_2 – 5.3%, organic acid content – 167 mg per liter of water products. According to the calculations, the equilibrium temperature of hydration formation for C-1 conditions at a pressure of 120 kg/cm^2 is 20 ℃, the corrosion rate is 6.3 g/(m^2·h). The supply of the inhibitor was carried out centrally at the wellhead and in front of the heat exchanger of gas delivery station through the inhibitor lines dosing pumps ND/63/400 with a capacity of 0.063 m^3/h; the average supply of OV-07 to the wellhead was about 0.055 m^3/h, in front of the heat exchanger – 0.06 m^3/h.

The effectiveness of the complex inhibitor in preventing hydrate formation was determined by controlling the operation of well №2 in hydrate mode without the supply of inhibitor. The dewpoint of the gas was determined by a moisture meter «Kharkiv-2M», the intensity of corrosion – by witness samples, which were installed in the samplers at the mouth of the well.

The results of industrial tests confirmed the effectiveness of the technology of corrosion prevention and hydration with the use of a complex inhibitor based on bischofite:

1) the rate of uniform corrosion with constant circulation of the inhibitor in the system did not exceed 0.01 mm/year. The OV-07 inhibitor effectively inhibits corrosion of tubular steel;
2) formation of hydrates in the well and at gas delivery station was not found. The use of the complex inhibitor OV-07 instead of methanol makes it possible to prevent hydrates formation and obtain a treated gas dew point corresponding to the use of methanol.

There is also a significant environmental effect due to the prevention of pollution of petroleum products and disposal of used reagents.

6. Conclusions

1. Laboratory studies of the effect of surfactants on antihydrate, corrosion and technological properties of bischofite solutions. It was found that the introduction into the solution of bischofite amphoteric surfactant CAPB provides a decrease in the temperature of deposition of hydrates by 6 °C and increase the degree of precipitation of $CaSO_4$ by 76.86%; cationic surfactant KI-1M – a high degree (99.6%) of metal protection against corrosion; citric acid – the degree of retention of iron ions 96.5%.

2. Based on bischofite solutions, a new formulation of a complex inhibitor of hydrates formation and corrosion OV-07 was developed, including (mass fraction, %): magnesium chloride – 23-25, amphoteric surfactant CAPB – 0.1–0.2, cationic surfactant KI 1M – 0.1–0.2 and citric acid – 0.2–0.5.

3. Industrial tests show that the introduction of technological schemes for the use of complex inhibitors based on bischofite allowed to obtain an annual economic effect of 356.1 thous. UAH/year due to the use of cheap raw materials (bischofite, surfactants) instead of expensive methanol and inhibitors corrosion, reduction of the number of injections of two inhibitors and a significant environmental effect due to the prevention of pollution of petroleum products and disposal of used reagents.

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Statistical evaluation of fuel values

To cite this article: A Walter *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012053

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012053 doi:10.1088/1755-1315/1049/1/012053

Statistical evaluation of fuel values

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Abstract. Aviation emissions, domestic and international, account for approximately 2 % of total global CO_2 emissions. Fuel consumption for a given route, excluding other factors such as wind, depends largely on the weight of the aircraft. To minimise fuel consumption, it is often most economical to carry only the minimum weight required for the sector. Within the framework of a dissertation, possibilities to reduce the final reserve fuel and thus the amount of fuel required are being researched and evaluated. This paper shows part of the results, as reliability and accuracy of flight planning and actual operations are a necessary basis for a possible reduction. The level of safety in aviation must always be taken into account. To prove this, fuel values are recorded and statistically evaluated, based on real flight and fuel data provided. Analysis, systematization and generalization were used to conduct the study. As a statistical background, extensive fuel data of an airline from a period of about five years were examined. The focus of this paper is on the results for taxi and trip fuel. The result shows that the current requirements for flight planning and the subsequent execution of flights are very reliable and highly accurate today. The results of the study can be used as a basis for a performance-based approach to reduce the final reserve fuel while maintaining the necessary safety level. Reducing the final reserve has a significant impact on reducing overall fuel consumption and emissions. Further research and studies are needed to determine performance indicators.

1. Introduction

Fuel, which is required for the daily operation of thousands of flights worldwide, is one of the most important cost factors in the airline business. The associated emissions of air traffic have an impact on the climate that is increasingly coming into focus. In 2020, almost every commercial aircraft is still equipped with a fossil fuel-based propulsion system. Emissions from aircraft are greenhouse gases and noise. Main emissions from aviation published by IPCC [1] are CO_2 emissions, which account for approximately 2 per cent of the global man-made CO_2 emissions. They are expected to increase by 3 to 4 per cent annually. Besides CO_2, water vapor H_2O is another products of jet fuel combustion. Their emission indices are 3.15 kg/kg fuel burned and 1.26 kg/kg fuel respectively [1]. NO_x constitutes the next most abundant engine emission [1]. Mitigation of emissions from the aviation sector potentially can come from improved fuel efficiency. This is although in the financial interest of the operators, see e.g. in the documents published by Airbus [2] or IATA [3]. However, such improvements are expected to only in part offset the growth of aviation CO_2 emissions [4]. For this reason, correspondingly great efforts are being made in various areas to reduce emission.

As the area of fuel economy and emissions reduction becomes more prominent, a wide range of research is being conducted. Singh and Sharma have found that the number of articles published has increased since 2000 compared to three decades before [5]. Here are a few examples, representing the broad spectrum: Kaiser et el. presented a jet performance model for prediction of optimized four-dimensional aircraft trajectories to allow better prediction of fuel flow and thus give a base for airborne and ground flight optimisation [6]. Trajectory optimization, in regard of better use of Flight Management Systems, was done by Patrón, Berrou and Botez. They presented an algorithm for a complete trajectory optimization, from climb to descent using real flight information [7]. Benefits of improved cruise speed and altitude profiles were investigated by Lovegren and Hansman [8]. Ryerson, Hansen and Bonn highlighted the role of the air traffic management in fuel saving improvements [9]. These examples represent only a small part of the comprehensive optimisation efforts.

Aircraft manufactures try to improve their respective models in terms of efficiency. Weight saving is a crucial point here [2]. Capoccitti, Khare and Mildenberger [10] show that a saving of just 1 % in fuel consumption for a medium-sized aircraft could offer savings of around 100 tonnes of fuel per year, resulting in an annual cost reduction of around EUR 38 000 per aircraft [11].

Opportunities to reduce costs and emissions are often associated with newer aircraft, which are claimed to perform better. Efforts have already been made in recent decades to introduce new aircraft models. To further reduce fuel consumption in the long term, revolutionary aircraft technologies are needed, such as the double-bubble fuselage, blended wing body or the box-wing aircraft. The development of evolutionary and revolutionary aircraft technologies is a medium to long-term task.

Regulators are also taking into account the development of emissions reduction and fuel economy. ICAO published document 10013 - Operational Opportunities to Reduce Fuel Burn and Emissions. It provides civil aviation stakeholders with operational opportunities and techniques to reduce fuel burn and therefore emissions. Doc 10013 assumes that the most effective way to minimise emissions is through the amount of fuel consumed [4].

Many efforts are being made in the area of research and development to make aviation more efficient. Weight reduction, engine consumption and aerodynamics are the fundamental pillars here. An instant reduction of weight through saved transported fuel promises quick results. For a given route, fuel consumption under constant environmental conditions such as weather or routing depends on the weight of the aircraft. The specific range at given altitude, temperature and speed depends on the mass of the aircraft. The heavier the aircraft, the higher the fuel consumption. To minimise fuel consumption, it is most economical to carry only as much fuel as is required for the sector in question. Lighter aircraft have performance advantages during take-off and landing and reduced wear, e.g. on the brakes. In addition, fuel can be saved in climb, as the lighter aircraft reaches its optimum flight altitude earlier [12]. The primary focus was to explore and evaluate ways to reduce the final reserve fuel (FRF) carried by aircraft with turbine engines and thus the amount of fuel needed. Final reserve fuel is the fuel required for a 30-minute flight at holding speed at an altitude of 1500 feet (450 m) above the aerodrome under standard conditions, calculated with the estimated mass on arrival at the destination alternate aerodrome or the destination aerodrome if no destination alternate aerodrome is required. Normally, this proportion of fuel is not required as a landing had already taken place beforehand. This paper specifies a relevant part and a step towards achieving a possible reduction in FRF: the correlation between flight planning fuel figures and actual in-flight fuel consumption as a basis for assessing the reliability of fuel planning and flight execution.

The European Union Aviation Safety Agency (EASA) has published Notice of Proposed Amendment (NPA) 2016-06, which takes a performance-based approach by updating regulatory requirements for fuel planning, selection of aerodromes and in-flight fuel management to improve operational efficiency and deliver cost and environmental benefits [13]. The NPA 2016-06 also introduces the concept of individual fuel schemes, which is already included in Regulation (EU) No 965/2012 with the flight time specification schemes. Those operators who demonstrate certain capabilities will be able to use individual fuel schemes in the future. Recently, the associated new EASA fuel management rules were published as part of the regulatory package consisting of Regulation (EU) 2021/1296 and Decision 2022/005/R of the European Parliament and Council - applicable from autumn 2022.

However, due to the special nature of air traffic, considerations regarding fuel planning and the execution of flights are always linked to corresponding safety considerations. A corresponding safety level, which must be demonstrated by the operator, is the prerequisite for the approval of the individual fuel schemes. In order to achieve a certain safety level, Drees et al. therefore recommend on the other hand a higher final reserve fuel value [14]. In the same context, Gregor also researched the probability of landing at the airport with less than final reserve fuel or running out of usable fuel, along with corresponding risk assessments for today's commercial turbine aircraft operations. The safety assessment focused on the risk of attaining low usable fuel levels during flight due to insufficient planning, loss of fuel or inability to use remaining fuel [15]. Based on Gregor's work, Mazaris went on to estimate the probabilities of rare events for several operational scenarios related to the issue of fuel planning and management, together with quantification of risks. Landing below FRF probability and fuel exhaustion were simulated [16]. The 60 million simulated flights represent almost twice the actual number of flights worldwide [17]. As a result, Mazaris obtained probabilities in the range of 10^{-6} for the different below FRF scenarios investigated. For fuel exhaustion the probabilities were significantly lower [16].

The EASA Member States accident rate for the year 2011-2014 had an average value of 0.0235 accidents per 10 000 flight hours, or $2.35 * 10^{-6}$. The 4-year period (2011-2014) fatal accident rate was as low as 0.0004 per 10 000 flight hours, or $4 * 10^{-8}$ [18]. This high level of safety forms the basis for the introduction of performance-based regulations.

2. Methods

The possible adjustment of the different fuel values is to be done according to a performance-based approach. A risk assessment is part of the process. In order to obtain the necessary information, among other things, the statistical evaluation of fuel data has to be taken into account. To explore a statistical background, the fuel data of an airline were examined for a period of about five years, from March 2016 to the end of December 2020. The airline operates Boeing B777-200 aircraft in a freighter version. The route network it operates includes both major airports and some local airports. The route network offers a mix of short-, medium- and long-haul flights.

For the data period provided, multiple flight information, available via various reports, is fed back into the airline data management system used. The system collects and provides a variety of facts in different areas of interest, such as aircraft information, airport statistics, cosmic radiation, crew details, on-time performance and so on. Flight information such as tracking of auto lands, city pair information, de-icing reports, delay reports, etc. are also available. The information from the data system is used, among other things, to provide fuel planning information and statistics to the flight crew via an Electronic Flight Back (EFB) application. Thus, specific fuel and flight information is available via 5 different reports:

- Fuel Data Validation, contained 40 166 flights
- Dynamic Flight List, 43 113 flights
- Fuel Analyzer Reference List, contains information for 31 315 flights

- Fuel Analyzer App Data
- Flight List Uld Detail Load

Examination of the 5 reports revealed that they contain different amounts of data records or information for the same period - as the first three entries above illustrate. Missing data, incorrect data or erroneous entries lead to differences in the reports. Missing data can lead to a flight not being included in one report, while the same flight is still included in another report that has a different focus or filter. Missing or incorrect data may result from connectivity problems of the Aircraft Communications Addressing and Reporting System (ACARS) used, miscalculations, e.g. due to missing data, accidental operation of the ACARS system, diversion of an associated flight or simply missing information. Missing information that may lead to the rejection of a record may include: previous fuel, fuel uplift, density, off or on block time, shutdown fuel. The varying number of records in the reports did not allow the information to be combined into a single report.

Various reports were evaluated to verify the information, depending on the information needed and available in each case. Presented here is mainly the Fuel Data Validation Report. It contains planned (p), actual (a) and corrected (c) information. While planned figures are self-explanatory, such as a planned departure time, actual figures are the reality figures, such as the actual departure time. Actual numbers describe the numbers returned by the aircraft. The report also contains corrected figures. The corrected figures describe the difference between the planned figures and the figures returned, based on the true fuel decision and payload of the flight.

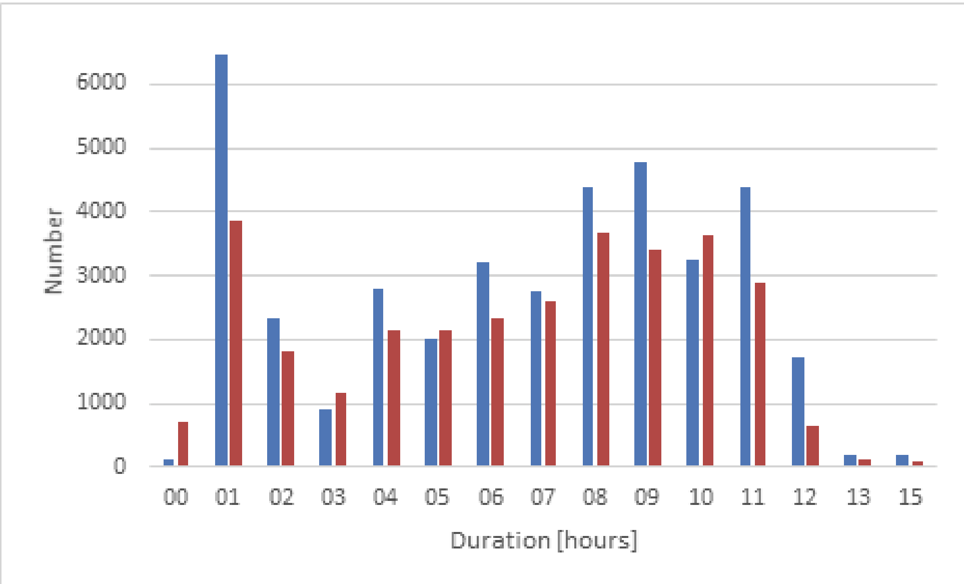

Figure 1. Distribution of flight times.

To start a flight, here with the push-back at the gate, the so-called off-block fuel is on board. The off-block fuel could be evaluated in the fuel data validation report. For 39 928 flights, the average was 61 650 kg, with a minimum of 8 200 kg and a maximum of 142 300 kg. The mean was 63 800 kg, the deviation 28 800.6 kg and the variance 829 474 303.09 kg. The 25 percent quantile is 38 500 kg and the 75 percent quantile is 85 300 kg. The ratio of mean value and deviation together with the quantile limits shows the broad distribution of the discrete off-block fuel values. This reflects the distribution of flight times, as shown in figure 1, different routings, different payload and consideration of weather for the sectors flown.

For the evaluation of planned and real figures, within the framework of the overall consideration for the dissertation, all parts of the required fuel quantity were evaluated. As an example, only the results for taxi fuel and travel fuel are presented below. Figure 4 shows information on average values of other fuel information.

2.1. Taxi Fuel

Taxi fuel could be analysed in the Fuel Analyzer App Reference List report as planned (p) and actual (a) value. For the 31 315 flights, the average taxi out fuel was 724 kg (a) and 670 kg (p). The maximum values where 64 000 kg (a) and 2 000 kg (p). The minima where -98 700 kg (a) and, for 16 cases, 0 kg (p). These values are considered unrealistic or erroneous, as they may be due to incorrect inputs or calculations. Mean values are 700 kg (a) and 600 kg (p), the standard error of the mean is 4.97 (a) and 0.78 (p). The 25 percent quantiles are 500 kg (a) and 600 kg (p), the 75 percent quantiles are 900 kg (a) and 733 kg (p), respectively. As shown above, the actual taxi fuel required was on average 54 kg higher than planned. On the other hand, this corresponds to a deviation of only 0.08 % in relations to the average 61 500 kg off-block fuel. It should be noted that the deviation in taxi fuel was calculated from 31 315 flights. The average off-block fuel was calculated from 39 928 flights.

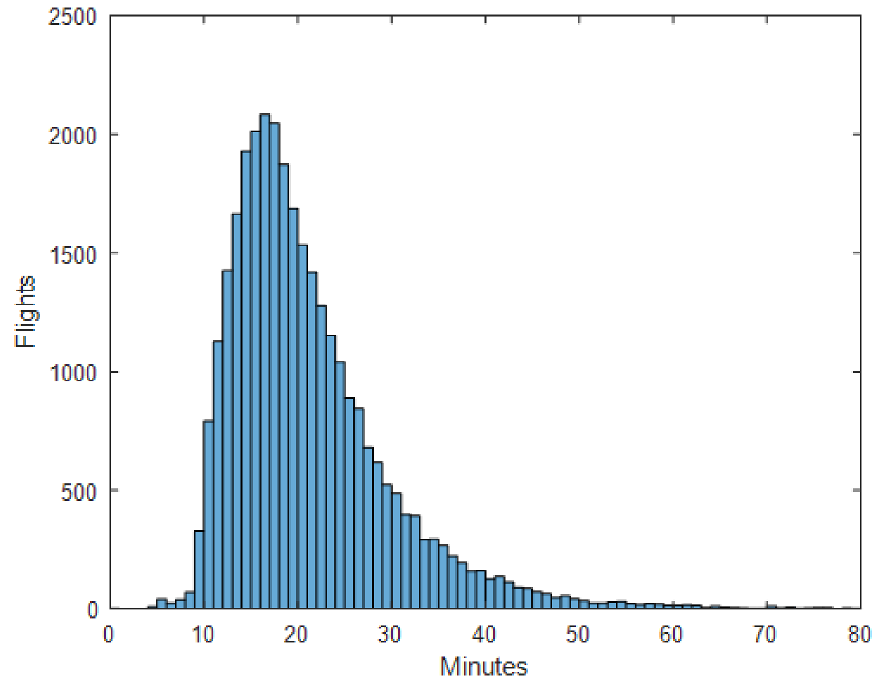

Figure 2. Taxi out times.

As can be seen in figure 2, the upward deviations of taxi fuel are explained by taxi times of 30 minutes and more.

2.2. Trip Fuel

Trip fuel* values are tracked in the Fuel Analyzer App Reference List. As described above, planned, actual and corrected values are available. All of these values are close to each other, as shown in the overview for the average Trip Fuel* value:

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- Actual trip fuel* 50.382,00 kg
- Trip fuel* corrected 50.442,96 kg
- Trip fuel* planned 50.353,70 kg
- Trip fuel* planned corrected 50.414,66

It is worth mentioning that the definition of trip fuel* in the Fuel Analyzer App and the Fuel Analyzer App Reference List includes taxi out fuel. This differs from the definition according to Regulation (EU) No 965/2012 [19].Therefore, the marking with a * was chosen. However, it is possible to calculate the actual trip fuel as trip fuel* minus actual and planned taxi fuel to obtain the value that complies with Regulation (EU) No 965/2012. The trip fuel planned (trip fuel* planned – taxi out fuel planned) is the value listed in the operational flight plan (OFP) for that flight. The actual trip fuel (trip fuel* – actual taxi out fuel) is the value reported back via the aircraft system.

The average planned trip fuel for 31 315 flights in the Fuel Analyzer App Reference List report was 49 683 kg. The actual average was 49 658 kg. The 25 percent quantiles are 23 895 kg (p) and 24 300 kg (a), the 75 percent quantiles are 73.431 kg (p) and 73.600 kg (a), respectively. This shows that the planned and actual fuel consumption correspond to a large extent.

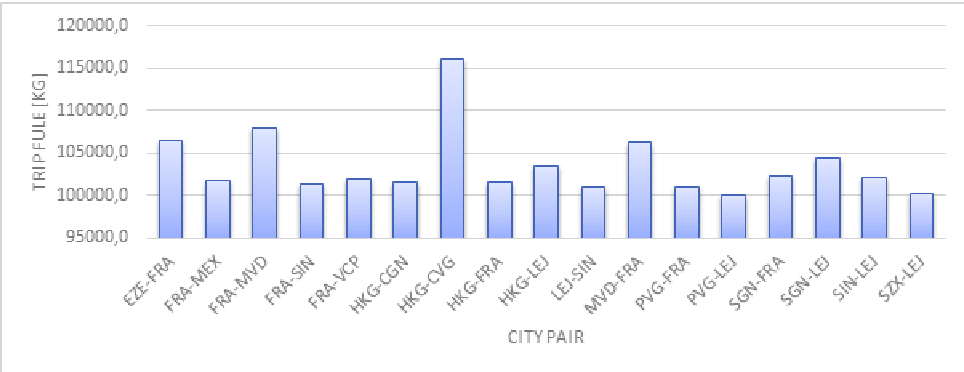

Figure 3. Trip Fuel more than 100 tonnes.

Most trip fuel was consumed on the Hong Kong – Cincinnati route, compare figure 3. Due to the long distance, long flight time and high load, the largest amounts of fuel were refuelled and consumed on this route. This pair of cities was flown to 177 times. In an exceptional flight, 123 400 kg of travel fuel was consumed, compared to 124 131 kg planned. About 300 kg more fuel was consumed on this flight, which in this case corresponds to a difference of 0.24 %. However, such differences between planned and actual circumstances are covered through contingency fuel. A total of 344 flights with a planned en-route fuel of more than 100 tonnes could be identified. This correspond to 1 % of 31 315 flights. These are therefore relatively rare cases of high cruise fuel volumes, with correspondingly little buffer for additional extra fuel.

The comparison between the average planned 50 353 kg and the actual fuel quantity of 50 382 kg showed that in fact slightly more fuel was needed than planned. In the corrected figures, the values were 50 414 kg and 50 442 kg respectively. The difference determined was less than 30 kg in both cases. On the one hand, this indicates exact planning, and on the other hand, it can be explained by the fact that the fuel consumption was slightly higher than planned due to extra fuel added by the crew. At this point it should be mentioned that extra fuel that is not planned but added by the crew during flight preparation leads to extra consumption due to the fuel penalty factor. As can be seen in figure 4, the average value of the additional fuel required by the commander over all flights from the Fuel Analyser reports is about 900 kg - this leads to additional consumption.

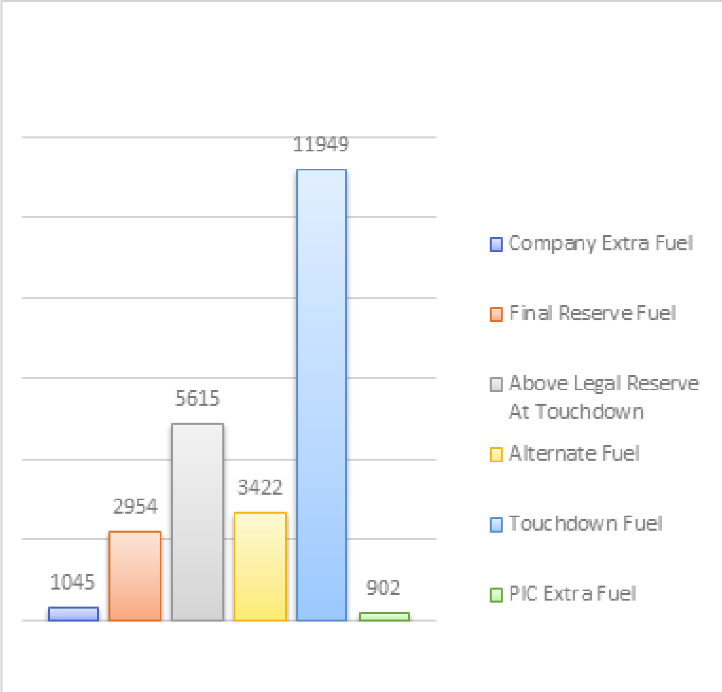

Figure 4. Average Fuel values.

Figure 4 also shows other fuel components and values that could be evaluated from the various reports, e.g. alternate fuel. These components are not evaluated in depth in this paper. The investigated components taxi and trip fuel are deliberately not shown in the figure, as they are significantly smaller and significantly larger, respectively.

3. Results

The above assessment was carried out on the basis of statistical data for a period of almost five years. The analysis of the fuel data has shown that the planned and actual figures for taxi and trip fuel are very close. The planning and in-flight management processes are mature. Even extraordinary events, such as the eruption of a volcano, did not result in a situation where fuel values, as required per legal regulations, where not meet or in danger. Planned figures and real consumption were close together. The planning process thus proves to be very reliable. By checking the reliability of the planning and execution of the flights, a first step was taken towards a performance-based approach to fuel planning. As a result, a reduction of the fuel portions not needed in normal cases can be considered. The conclusion of the single value observation of all fuel values showed that planned and actual consumption are on a high and reliable level. It can therefore be assumed that the planned and actual fuel values on board can be considered reliable and almost consistent.

It was determined that an adjustment of the Final reserve fuel figures in terms of reduction is possible. A reduction in fuel (weight) has an impact on overall fuel and emissions. Between 3 and 4 % difference in fuel consumption per kg and flight hour for additional weight can be taken as a basis for the savings potential.

A reduction in transported fuel by a value equivalent to 5 minutes of flight time corresponds to e.g. to $\sim 600kg$ less fuel carried, corresponding to the examined aircraft type B777-200. Based on the average 16 flight hours, this would mean a daily saving of $\sim$ 270 kg less fuel consumed. This in turn would save approx. 850 kg CO_2 and 340 kg H_2O per aircraft per day for this aircraft type and operation. The potential savings for a fleet of 20 Boeing B 777 aircraft amount to 6 209 000 kg CO_2 and 1 973 000 kg fuel per year – corresponding to the average daily flight hours of 16 hours or more. On this basis, airline operators are recommended to evaluate their operational procedures, management and safety systems in preparation for the introduction of reduced fuel.

4. Discussion

For evaluation, the actual development of fuel consumption and supply over real flights is recommended. In particular, extreme values should be taken into account. Inaccuracies in displays and systems are also low today compared to the early days of aviation and are at a high and reliable level in modern aircraft. Nevertheless, investigation of this area should be carried out to avoid inaccuracies, even if only in a small range.

Further research is needed to identify performance indicators. The above assessment has focused only on two fuel components. A more in-depth assessment of total fuel numbers is recommended, as well as consideration of other factors such as aircraft system reliability, the influence of weather or airfield processes. Based on these investigations, a risk assessment can be made to further consider the reduction of the fuel.

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Modified three-stage model for forecasting the demand for energy resources at various hierarchy levels of the economy

To cite this article: V V Horskyi *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012054

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012054 doi:10.1088/1755-1315/1049/1/012054

Modified three-stage model for forecasting the demand for energy resources at various hierarchy levels of the economy

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Abstract. Forecasting of the demand for energy resources is a very important scientific area when determining adequacy of energy resources in the country, compiling the country's energy balance, determining need for import of some energy resources for the country's economy for types of economic activity (TEA) and regions. The pace of development and proportions in the country's and the region's economy may affect their levels of energy consumption, and the latter determine the extent of energy industry's impact on the environment, i.e. these indicators are interdependent. The relevance of the work is related to creation of a mathematical model and tools for forecasting the demand for energy resources and determining the amount of emissions of harmful substances into the atmosphere as a result of fossil fuels combustion. The methods and tools for forecasting the demand for energy resources for various types of economic activity or regions take into account the following factors: impact of changes in the structure of the economy on fuel and energy consumption as well as on technological re-equipment of industries that together form the overall energy saving capacity and structures of electricity production sources and heat energy supply sources to ensure their production. The authors propose a three-level model for forecasting the demand for energy resources (electricity, heat, fuel in total and its types: coal, natural gas and other fuels). This model uses a double agreement of forecasts: between the third (types of economic activity in regions), the second (regions) levels, and the subsequent agreement with the top (country) level. The calculations performed using this model demonstrate the feasibility of this approach. This model was tested on retrospective data with an error of less than 5%. Calculations under this model show a forecast of savings of 8.7 million tons of coal by 2040 due to structural and technological changes (2.272 million tons and 6.428 million tons, respectively). Reduction of coal consumption will reduce emissions of pollutants into the atmosphere (thousand tons): nitrogen oxides – 19.671; sulfur oxides – 295.06; carbon monoxide – 393.414; solid dispersed particles – 104.255; carbon dioxide – 5271.75.

1. Introduction

Many Ukrainian and foreign scientists are engaged in forecasting of energy consumption in the world [1–17]. For example, in [1], it is proposed a deterministic-stochastic model for forecasting the demand for electricity based on the detection of dependences in electricity consumption for the retrospective period. A comprehensive model for estimating energy consumption in regions was proposed in [2,3], but this model clearly does not determine the impact of structural changes in the economy on the volume and structure of energy consumption, although development of energy-intensive types of economic activity (metallurgy, chemistry, etc.) promotes increase in the industry's energy consumption. The method of exponential smoothing is proposed in [4] as the best method for predicting electricity consumption in the food industry. Methods of regression analysis in combination with the use of neural networks are proposed in [5–7] for prediction of electricity consumption based on the history of energy use. These models require very accurate history of observations of energy consumption for various groups of consumers in retrospect and are developed taking into account the specificities of certain consumers. Some other models, such as Gray-specific models [8] for forecasting of electricity consumption in cities of China and STL-model [9] for monthly campus electricity consumption that takes into account seasonal and trend-based components are focused on specific facility as well. Most of existing works are focused on short-term forecasting methods for individual sectors of the economy [5, 6, 8, 10–14]. Long-term forecasts of energy consumption are developed for some sectors of the world economy and for individual regions of the world [7, 9, 15–17]. The Institute of General Energy at the National Academy of Sciences of Ukraine has proposed a comprehensive method for forecasting energy consumption based on the two-stage method [17] and its development based on the three-stage method [18].

2. Description of the mathematical model

This paper describes a model that combines two structures of the economy: regional structure and structure for types of economic activity, which is presented for the first time.

The studied hierarchical levels of the economy are as follows: Level I (macro level) – the country; Level II (meso level 1) - types of economic activity in the country, Level III (meso level 2)- economy of a region. Accordingly, key parameters are as follows: Country's gross value added (GVA_T), energy intensity of GVA ($eGVA_T$); gross value added of the type of economic activity - TEA (GVA_i), energy intensity ($_eGVA_i$). For regions – Region's gross value added (GVA_r), energy intensity of the Region's GVA ($eGVA_r$).

A modified three-stage model has been developed. Its structure is shown in figure 1.

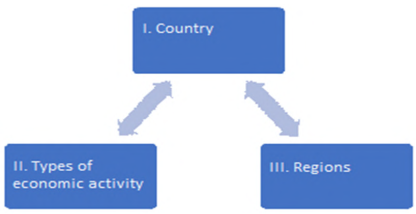

Figure 1. Structure of the three-stage model for forecasting the demand for energy resources for types of economic activity and regions.

Thus, the presented structure of the mathematical model allows moving from energy consumption for the country to energy consumption by types of economic activity in the country and to regional levels and vice versa. The model is flexible and convenient for obtaining forecasts. For various configurations of economic structures and volumes of technological energy savings, level I is compared with two other levels (II and III). In reality, they are not the same even for the base year (the difference between energy consumption statistics for the country and the total for all types of economic activity and the total for all the regions is about 5%). In the long run, this difference additionally grows.

When modeling energy consumption by types of energy resources, the scenario method is used. It considers two or three scenarios of the economy's development: the existing structure for the base year, which is determined as a percentage of energy consumption by a particular

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sector of the economy (by group of economic activity types) to energy consumption by the whole country, prospective (taking into account retrospective trends and/or global trends taking into account technical and raw material bases). The index s is variable. For each $s (s = 1, 2, ..., n)$, it is set the ratio of sectorial gross value added (GVA) for the economic sector to the country's GVA [17]. Moreover, the scenarios are used for calculating the volume of possible implementation of technological energy saving. All components in formulas (1)-(10), which depend on the variable t^{th}, are calculated for tth year depending on the structure of the economy s and probable reduction in the energy intensity of GVA at given volumes of technological energy saving implementation for appropriate scenarios [17, 18]. For the purpose of forecasting by regions, it is also taken into account structure of their economies within the country's economy and typical energy saving measures.

The novelty of the presented model consists in the determining of reconciled forecasted levels of energy consumption both by sectors of the economy and by regions, taking into account their regional economic structure. The reconciliation of the received forecasts and the number of these reconciliations are determined by parameters of the base year and by discrepancy between the consumption for the country as a whole, total by types of economic activities and total by regions. In examples provided, it is expedient to do reconciliation between the total forecast in the regions and the country level with further distribution of reconciled results between regions (using consumption structure coefficients in regions for forecasted years determined by changes in energy consumption structure of regions) and coefficients of forecasted structure of the country's economy TEA sectors. Both parts of the model (see figure 1) have been tested on retrospective data and showed acceptable accuracy of forecasts (error did not exceed 5%).

For Level I - country (Top-level) forecasted energy consumption shall be determined by the formula [17]:

$$P^t_{sTOP} = e^b_{GVAs} V^t_{GVAs} - \sum \Delta E^t_i + P^t_{pop}, \tag{1}$$

where e^b_{GVAs} is the energy intensity of country's GVA in the base year for s^{th} structure of the economy: $e^b_{GVAs} = \frac{\sum E^b_i}{\sum e^b_{GVA_i}}$;

E^b_i is energy consumption for i^{th} type of economic activity (TEA) in accordance with KVED-2010 classifier in the base year;

$V^b_{GVA_i}$ – Gross Value Added of ith TEA of the economy in the base year;

V^t_{GVAs} – forecasted county's Gross Value Added (total by all TEAs) in t^{th} year for s^{th} structure of the economy;

$\sum \Delta E^t_i$ – scope of reduction in energy consumption due to structural and technological changes (energy saving capacities) in the t^{th} year;

P^t_{pop} – forecasted energy resources consumption by the population to be determined using a special methodology set forth in [17].

For Level II - types of economic activity (DOWN1). Forecasted demand for types of economic activity shall be determined as follows:

$$\sum P^t_i = \sum e^b_{GVA_i} V^t_{GVA_i} - \sum \Delta E^t_i, \tag{2}$$

where $e^b_{GVA_i}$ – GVA energy intensity for i^{th} type of economic activity under KVED-2010 classifier in the base year for s^{th} structure of the country's GVA;

$V^t_{GVA_i}$ – forecasted GVA of i^{th} type of economic activity under KVED-2010 classifier in t^{th} year for sth structure of the country's GVA;

$\sum \Delta E^t_i$ – scope of reduce in energy resources consumption if structural (ΔE^{b-t}_s) and technology (ΔE^t_T) changes (energy saving capacity) takes place in t^{th} year for s^{th} structure of the country's GVA taking into account the package of technology-related energy saving activities:

$$\sum \Delta E_i^t = \Delta E_s^{b-t} + \Delta E_T^t, \tag{3}$$

To move from the type of economic activity level to the country's level, the equation (2) needs to be appended with the following component: P_{pop}^t. This sum will be the country's demand when calculating it bottom-to-top:

$$P_{sDOWN}^t = \sum P_i^t + P_{pop}^t, \tag{4}$$

Depending on the type of energy resource, an indicator of specific consumption of fuel or electricity per capita, or specific consumption of thermal energy for heating and ventilation of residential and office premises (per $1sqm$ or $1cbm$) may be used when forecasting energy consumption. Consumption of hot water by the population is calculated per 1 person. The methodology of calculating the forecasted demand for the population is described in [17].

At Level III (DOWN2), the forecasted regional demand is determined using equation [18]:

$$P_{sDOWN}^t = \sum_r P_r^t + P_{pop}^t, \tag{5}$$

where P_r^t is forecasted demand for the energy resource in tth year for rth region of Ukraine. Forecasted demand for energy resources for regional economies shall be determined as follows [18]:

$$\sum_r P_r^t = \sum_r e_{GVA_r}^b + V_{GVA_r}^t - \sum_r \Delta E_r^t, \tag{6}$$

where $e_{GVA_r}^b$ is GVA's energy intensity for the base year for economy of r^{th} region of Ukraine;

$V_{GVA_r}^t$ is the forecasted GVA in t^{th} year for economy of r^{th} region of Ukraine, it is determined by pace of changes of the indicator in retrospect and by estimations of international economic organizations;

$\sum_r \Delta E_r^t$ is the total forecasted energy saving capacity in t^{th} year for economies of all r^{th} regions in the forecasted year t. It is determined by the sum of energy resources savings as a result of energy saving activities typical for all the regions. With this, reduction of energy intensity shall be chosen taking into account existing examples of new technology implementation and results that can actually be achieved.

The structural energy saving capacity for regional energy consumption shall be determined by the following formula:

$$\Delta E_r^{b-t} = e_{GVA_r}^b (V_{GVA_r}^b - V_{GVA_r}^t), \tag{7}$$

where $e_{GVA_r}^b$ is GVA's energy intensity for r^{th} region in the base year;

$V_{GVA_r}^b$ is the volume of GVA in r^{th} region for structure of the base year (region's GVA to country's GVA ratio as in the base yeari) at forecasted value of GDP in t^{th} year;

$V_{GVA_r}^t$is the volume of GVA for r^{th} region for structure of forecasted t^{th} year with the same value of the forecasted GDP.

The structural energy saving capacity for energy consumption by types of economic activity shall be is determined by the following formula [17]:

$$\Delta E_{TEA_i}^{b-t} = e_{GVA_i}^b (V_{GVA_i}^b - V_{GVA_i}^t), \tag{8}$$

where $e_{GVA_i}^b$ is GVA's energy intensity for i^{th} type of economic activity in the base year;

$V^b_{GVA_i}$ is volume of GVA for i^{th} type of economic activity under KVED-2010 classifier for the structure of the base year (GVA to GDP ratio as in the base year) with forecasted value of GDP in t^{th} year;

$V^t_{GVA_i}$ is volume of GVA in i^{th} sector with the structure of forecasted t^{th} year with the same value of forecasted GDP.

For the three-stage model of economy, the technological energy saving capacity (ESC) shall be determined using the following algorithm:

– at the country's level:

$$\Delta E_j^{b-t} = (e^b_{GVA_i} - e^t_{GVA_i})V^t_{GVA_i}, \tag{9}$$

where E_j^{b-t} is energy saving capacity of j^{th} type of energy resource in the country in t^{th} year;

$e^b_{GVA_i}$ is the country's GVA energy intensity for j^{th} type of energy resource in the base year;

$e^t_{GVA_i}$ is the forecasted energy intensity of the country's GVA for j^{th} type of energy resource in t^{th} year, taking into account energy saving activities by types of economic activity, regional-wide and national activities;

$V^t_{GVA_i}$ is the forecasted volume of the country's GVA in t^{th} year;

– at the level of types of economic activity:

$$\Delta E_{TEA_i}^{b-t} = (e^b_{GVA_i} - e^t_{GVA_i})V^t_{GVA_i}, \tag{10}$$

where $\Delta E_{TEA_i}^{b-t}$ is the energy saving capacity for i^{th} TEA in t^{th} year;

$e^b_{GVA_i}$ is the GVA's energy intensity for i^{th} TEA in the base year;

$e^t_{GVA_i}$ – forecasted energy intensity of GVA for i^{th} TEA in t^{th} year taking into account energy saving activities;

$V^t_{GVA_i}$ – forecasted volume of GVA for i^{th} TEA in t^{th} year;

– at the level of rth region, technology-based ESC is determined as decrease in energy resource consumption in t^{th} year as compared with the base year and is calculated as follows:

$$\Delta E_{TEA_r i}^{b-t} = (e^b_{GVA_r} - e^t_{GVA_r})V^t_{GVA_r}, \tag{11}$$

where $\Delta E_{TEA_r}^{b-t}$ is the energy saving capacity for r^{th} region in t^{th} year;

$e^b_{GVA_r}$ is the GVA's energy intensity in r^{th} region in the base year;

$e^t_{GVA_r}$ is the forecasted GVA's energy intensity for r^{th} region in t^{th} year, taking into account energy saving activities;

$V^t_{GVA_r}$ – forecasted volume of GVA for r^{th} region in t^{th} year.

3. The results of the calculation and their analysis

The technology-based energy saving capacity for Ukrainian economy until 2040 is estimated in [17, 18] and more precisely determined in this work when forecasting volume of coal required to meet the electricity and heat generation needs.

Examples of calculated forecasts for individual components of the model are provided in tables 1 and 2.

As it can be seen from tables 1 and 2, there is a discrepancy in the forecasted figures obtained for various levels: country, as a whole, types of economic activity and the regional level. This means that there is a need for further improvement of forecasting methods and reconciliation of forecasts. As compared with the model described in [18], the presented three-stage model allows solving of two problems: forecasting of energy consumption at two DOWN levels, which may vary depending on the task. The improved three-stage model provides the same energy efficiency indicators at different hierarchical levels - GVA's energy intensity at corresponding

Table 1. Forecasted demand for electricity for scenario-based economic structure and technology-based energy saving capacity identified at various hierarchical levels of the economy under pessimistic (structure of 2017) and conservative (structural changes happen) scenarios.

No	**Forecast indicators for scenarios I and II**	**2030 (I*)**	**2030 (II**)**	**2040 (I*)**	**2040 (II**)**
1	GDP forecast in 2015 prices, UAH billion	2904	2904	4298	4298
2	The country's GVA forecast in 2015 prices according to economic development scenarios, UAH billion	2451	2549	3627	3821
3	Electricity saving of from structural changes, billion kWh	0	8.9	0	19.1
4	Electricity savings from technological changes, billion kWh	0	11.0	0	18.5
5	**Electricity consumption by country with population (TOP), billion kWh**	**148.0**	**128.1**	**219.1**	**181.4**
6	Electricity consumption by the amount of consumption by type of economic activity (excluding population), billion kWh	107.4	87.4	159.0	119.3
7	Electricity consumption by the population, billion kWh	32.2	32.4	32.0	34.0
8	**Electricity consumption by the amount of consumption by type of economic activity and for the population (DOWNi), billion kWh**	**139.6**	**119.7**	**191.0**	**153.3**
9	Electricity consumption by amount of consumption by regions, billion kWh	113.2	104.3	186.9	164.3
10	**Electricity consumption by the sum of consumption by regions and for the population (DOWNr), billion kWh**	**145.4**	**136.7**	**218.9**	**198.3**

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Table 2. Forecasted demand for thermal energy for scenario-based economic structure and technology-based energy saving capacity identified at various hierarchical levels of the economy under pessimistic (structure of 2017) and conservative (structural changes happen) scenarios.

No	**Forecast indicators for scenarios I and II**	**2030 (I*)**	**2030 (II**)**	**2040 (I*)**	**2040 (II**)**
1	GDP forecast in 2015 prices, UAH billion	2904	2904	4298	4298
2	The country's GVA forecast in 2015 prices according to economic development scenarios, UAH billion	2451	2549	3627	3821
3	Thermal energy saving from structural changes, PJ	0	40.6	0	63.6
4	Thermal energy saving from technological changes, PJ	0	17.6	0	41.8
5	**Thermal energy consumption by country with population (TOP), PJ**	**919.3**	**1081.4**	**1155.6**	**1404.9**
6	Thermal energy consumption by the amount of consumption by type of economic activity (excluding population), PJ	245.5	288.7	331.8	432.8
7	Thermal energy consumption by the population, PJ	673.7	757.9	760.5	874.0
8	**Thermal energy consumption by the amount of consumption by type of economic activity and for the population (DOWNi), PJ**	**919.2**	**1046.6**	**1092.3**	**1306.8**
9	Thermal energy consumption by amount of consumption by regions, PJ	246.8	328.0	402.2	557.3
10	**Thermal energy consumption by the sum of consumption by regions and for the population (DOWNr), PJ**	**920.1**	**1085.9**	**1162.7**	**1431.3**

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levels that per se already reduces the error in forecasts when using various indicators: energy intensity of GDP at TOP (national) level, GVA's energy intensity for economic activities and energy intensity GRP for the regional level – that are traditionally used by economists.

Estimation of reliability of forecasts of heat energy consumption for 2020 in relation to 2017, obtained by the two-stage method, is presented in table 3 [19].

Table 3. Estimation of reliability of forecasts of heat energy consumption for 2020 in relation to 2017, obtained by the two-stage method, million Gcal.

Type of economic activity (TEA)	2017 (fact)	2020 (forecast) [20]	2020 (fact)	Error forecast,%
Agriculture, forestry and fisheries	2.18	2.4 – 2.7	1.74	27.5 – 35
Mining and quarrying	2.17	2.4 – 2.3	1.75	27 – 23.9
Manufacturing industry	36.0	39.8 – 37.1	38.0	5 – 2
Supply of electricity, gas, steam and air conditioning. Water supply; sewerage, waste management	3.2	3.6 – 3.7	2.1	41.6 – 30
Transport, warehousing, postal and courier activities	1.4	1.59 – 1.68	1.29	19 – 23
Other TEA	13.6	15.0 – 14.4	11.62	22.5 – 19.3
Together for TEA	59.1	64.8 – 61.9	56.5	12.8 – 8.7
Population (calculation)	160.8	170.0	170.0	0
Total	219.9	234.8 – 231.9	226.5	3.5 – 2.3

Data on heat energy consumption in 2021 on the website of the State Statistics Service of Ukraine are currently missing.

To assess the reliability of electricity forecasts in 2020, we used the comparison of forecasts and actual consumption for 2020, which is given in table 4 [19].

Thus, the model for forecasting the demand for energy resources by the two-stage method for heat gives very close forecasts for the country as a whole (error 2.3–3.5%), for economic activities together (error 8.7 – 12.8%)) and large sections of the economy, in particular "Manufacturing" (2 – 5%). For small sections, the forecast error averages between 23 – 27%. For electricity, the situation is different: for large consumers, which include sectors of the economy "Mining and quarrying, Manufacturing, Population", the calculation error is small and acceptable, as these sectors were able to withstand the worst corona crisis, for "Agriculture and Transport" it has significant the value explained by the extraordinary conditions of their operation at this time (almost complete cessation of passenger traffic and partial - freight), for the sectors of electricity, gas, steam and air conditioning, water supply; sewerage, waste management and other activities; In the country as a whole, the error is within acceptable limits. Thus, the forecasting model needs further development, but it shows a fairly acceptable level of forecast values, given the fact that in 2019-2020 there was a coronavirus pandemic that collapsed the economies of all

Table 4. Estimation of reliability of forecasts of electricity consumption for 2020 in relation to 2017, obtained by the two-stage method, million kWh.

Type of economic activity (TEA)	2017 (fact)	2020 (forecast) [20]	2020 (fact)	Error forecast,%
Agriculture, forestry and fisheries	2424.7	2918.9	2111.4	38.3
Mining and quarrying	12121.4	12571.3	12299.5	2.2
Manufacturing industry	36268.0	38311.3	35137	9.0
Supply of electricity, gas, steam and air conditioning. Water supply; sewerage, waste management	18975.9	22360.3	18219.7	22.7
Transport, warehousing, postal and courier activities	7060.8	7756.9	5432.0	42.8
Other TEA	12717.7	13679.7	10689.4	28.0
Together for TEA	89568.4	97598.3	83888.6	16.4
Population (calculation)	35019.9	34189.5	36436.0	6.2
Total	124588.3	131787.9	120324.6	9.5

countries and could not predict any organization in the world. Therefore, our forecasts are quite reliable.

According to [21], the volumes of electricity consumption in 2021 were analyzed (table 5).

Preliminary data provided in the table 5. The actual data may differ up to + 10% (will be published in the Statistical Collection of Ukraine for 2021). There is also a discrepancy between the content of certain indicators by areas of use provided by Ukrenergo and indicators by TEA.

According to the calculations on the model ”country-types of economic activity” (left branch of the model structure presented in Fig. 1), the calculated electricity forecast for 2021 by country (TOP level) relative to energy efficiency indicators in 2017 gave a very good coincidence of results – 1.9%.

The forecast of electricity consumption by DOWN-level - together by TEA with the population shows a brilliant coincidence of the forecast with the fact - 0.14%! The total amount of forecast of electricity consumption by TEA as a whole differs from the actual consumption by foreign trade by 5.5%, which is a good result.

The forecast of electricity consumption by the population was lower by 11.8% than the actual one, which is most likely due to the reduction of natural gas consumption by the population and the transition to using of electric stoves and electric heaters and insufficient consideration of corona-crisis restrictions in the forecast. This value is acceptable for the forecast. We can also talk about an acceptable error in forecasting of industrial production (mining and processing industries together) - 11.6% and the transport sector - 12.5%. More significant errors in the forecasting of electricity by agriculture and “Other TEA”.

Agriculture consumed 1.5 times more electricity, which is due to savings in fuel consumption: primarily natural gas. The share of electricity consumption in agriculture from the actual electricity consumption of Ukraine in 2021 is 2.9%. Even an error of 46.9% to 2.9% is not significant in the overall forecast.

Table 5. Estimation of reliability of forecasts of electricity consumption (net) for 2021, calculated according to the forecast of GVA in the prices of 2016, obtained by the two-stage method, thousand kWh.

Type of economic activity (TEA)	2021 (forecast)	2020 (fact)*	Error forecast,%
Agriculture, forestry and fisheries	1961.5	3695.4	21.0/46.9
Industry, total **	46326.5	52392.0	11.6
Transport	6926.8	6159.4	12.5
Other TEA (Supply of electricity, gas, steam and air conditioning. Water supply; sewerage, waste management. Trade, construction, financial, insurance, social services, education, health, public administration and defense)	36431.0	24629.5	47.9
Together for TEA	91645.8	86876.3	5.5
Population	34189.5	38778.5	11.8
Together with the population (DOWN-level)	125835.3	125654.8	0.14
Country with population (TOP-level)	127991.0	125654.8	1.9

* - preliminary data for January 2022 [21]
** - included data on industry only (excluding TEA “Supply of electricity, gas, steam and air conditioning, Water supply; sewerage, waste management”)

Electricity consumption of group “Other TEA” in 2021 amounted to 19.6% of the actual electricity consumption of the country. We forecast higher electricity consumption by 47.9%, but energy saving measures reduced electricity consumption primarily for lighting (most of the replaced light sources for more energy efficient) and additional electric heating due to thermal modernization of state and municipal buildings.

The largest GVA is created by group “Industry”, which is also the largest consumer of electricity. As shown above, the forecast of electricity consumption for this group is acceptable. From all the above we can conclude that the presented model in the country as a whole gives almost close to the fact forecasts of electricity consumption.

For the sections with high GVA and electricity consumption, the calculated forecasts are acceptable (up to 12.5%). For small GVA and electricity consumption sections and the group “Other TEA”, the difference with the forecast is up to 50%, but it should be noted that this error applies to electricity consumption of 22.5% (agriculture 2.9% + Other TEA 19.6%). That is, the assessment of the adequacy of the model speaks of its relevance. The authors will continue to work on improving the forecasting model and improving its accuracy for all components.

Using the two-level model “country-types of economic activity”, it was estimated forecasted required volumes of coal by 2040, in particular, the coal needs for thermal power plants and CHP plants under condition of intensive development of renewable sources of energy (optimistic scenario).

Table 6 shows results of assessing probable coal savings if the optimistic scenario takes place as compared with the pessimistic scenario (development of Ukrainian economy with the structure of 2017).

Table 6. Forecasted decrease in the coal consumption and pollutant emissions in Ukraine by 2040, thousand t.

Indicators	2017 – act	2021-est.	2025	2030	2035	2040
Coal consumption for the country (structure of 2017; consumption by the population is included)	42664.6	40004.6	39059.5	41850.6	44472.4	44163.8
Coal consumption for the country, taking into account structural and technological changes (consumption by the population is included)	42664.6	38947	36583	37704.4	37741.2	36348.1
Decrease in coal consumption as a result of structural changes (forecasted for the structure of economy 2017).	0	364.6	794.6	1338.0	1921.4	2272.1
Decrease in coal consumption as a result of technological changes (forecasted for the structure of economy 2017, consumption by the population is included)	0	693.0	1681.9	2808.2	4809.9	5543.7
Total coal savings with structural and technological changes happen	0	1057.6	2476.5	4146.2	6731.3	7815.8
Decrease in pullutant emissions as a result of decrease in coal consumption						
- nitrogen oxides (NOx)		2.7	6.4	10.6	16.8	19.7
- sulfur oxides (SOx)		39.7	96.6	159.2	251.7	295.1
- carbon oxide (CO)		52.9	128.8	212.2	335.7	393.4
- particulate matter (PM10)		14.0	34.1	56.2	88.9	104.3
- carbon dioxide (CO2)		709.1	1725.9	2843.7	4497.9	5271.8

As calculations show, the forecasted reduction in coal consumption may amount to 7.8 million tons by 2040 due to structural and technological changes (2.272 million tons and 5.544 million tons, appropriately). The reduction in coal consumption will reduce emissions of pollutants into the atmosphere, which were calculated in accordance with the guidelines [20, 22] (thousand tons): nitrogen oxides - 19.7; sulfur oxides 295.1; carbon monoxide - 393.4; particulate matter - 104.3; carbon dioxide - 5271.8.

The authors' article [23], published in 2021, provides the expected forecast of coal consumption in Ukraine in 2021 in relation to energy efficiency indicators in 2017 and the projected GVA of the country. According to the presented data [23], coal consumption in 2021 was expected in the amount of 38, 947.0 (TOP level) – 38, 504.8 thousand tons (DOWN level) in the baseline scenario. According to the State Statistics Service of Ukraine [24], the consumption of coal in Ukraine in the amount of consumption by months for January-December 2021 actually amounted to 39, 164.5 thousand tons of coal. Thus, the forecast of coal differed by $0.5 - 1.7\%$ from actual consumption. This confirms the relevance of the results of the forecasting model to the actual data.

4. Conclusions

Solving the problem of forecasting is a necessary condition for drawing up any development programs: for the country, regions and types of economic activity (economic sectors). This necessitates further development and improvement of methods for forecasting and reconciliation of the forecasts. The presented three-stage model allows solving of two tasks: forecasting energy consumption at the TOP- level (for the country level) and forecasting of energy consumption at two lower levels, which may be changed depending on the task: types of economic activity or regions. The three-stage model ensures the same energy efficiency indicators at different hierarchical levels - energy intensity of gross value added at the appropriate level (country, region and type of economic activity), which reduces the error of forecasts when using various indicators. The proposed model allows forecasting of changes in energy consumption due to structural and technological changes in the country's economy, which makes it possible to determine forecasted changes in emissions of pollutants into the atmosphere related to combustion of fossil fuels, including coal.

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Economic aspects of introducing pumped-storage hydroelectric power plants into the mine dewatering system for distributed power generation

To cite this article: O Mykhailenko and K Budnikov 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012055

Economic aspects of introducing pumped-storage hydroelectric power plants into the mine dewatering system for distributed power generation

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Abstract. The paper examines the pumped hydroelectric energy storage potential of mine dewatering system for power generation in a distributed power system. Based on the water inflows that can be used to fill the drainage basins, the following options for pumped-storage hydroelectric power plants (PSHPP) are considered: when groundwater is discharged from only one mine, one hydraulic turbine is installed on the horizon below the surface; with additional discharge of groundwater from neighboring mines – installation of two or four hydraulic turbines at the drainage stages closest to the surface. Comparison was made with grid only system. It is based on net present value (NPV) and levelized cost of energy (LCOE) criteria. Variable parameters were hydraulic turbine water flow and mine power consumption. Also, for a certain combination of parameters, the optimal mine power system was determined. The area of use of the PSHS is estimated. It was found that the smallest economic effect is achieved when the power generation of one hydraulic turbine is close to the power consumption. The area of expedient use of the PSHPP within the limits of parameter variation is 17.2%, 19.6% (base and peak costs of power). This is because power generation drops when the water flow decreases. It does not cover the needs of the mine and there is a power shortage. Thus, the mine power system autonomy is very low. With an increase in water inflow and the number of hydraulic turbines, first up to two and then up to four units, the area of expedient use of PSHPP increases to 51.5%, 55.9% and 50.6%, 72.8%, respectively. However, with low energy consumption and a low water flow, it is still rational to receive electricity from the grid. This is due to a sharp drop in the efficiency of hydraulic turbines and high costs for maintenance and repair of PSHPP equipment, which are not comparable to the cost of purchasing power. So it was noted that with the base cost of electricity and an increase in the number of hydro turbines from two to four, the area of conditions under which the use of PSHPP is justified even decreased by 0.9%. At peak cost, the area increases by 16.9%. The mine power system autonomy is not achieved. In general, the efficiency of using PSHPP for mine dewatering systems is high, but the feasibility of their use should be studied for specific conditions of use.

1. Introduction

Improvement of energy efficiency in mining production aims to enhance competitiveness of Ukrainian enterprises on global and domestic markets. This can be done either by optimizing operational modes of available equipment or replacing, where possible, obsolete power machines with up-to-date, more energy efficient ones. On the other hand, introduction of additional generation facilities into the enterprise power system is able to reduce costs when purchasing electric power from external distribution operators. In this respect, wind and solar power is the most promising energy resources for creating local power plants. However, their use is constrained by peculiarities of technological processes at ore underground ore mines, namely location of main consumers underground, as well as availability and location of areas purchased for installing power generation equipment. Location of alternative energy generation plants at dumps is currently one of the options under study [1].

Yet, considering their distance from consumers of the main production facility and a low level of initial voltage, power supply from helio- and wind power plants will cause significant power losses. We also emphasize a high level of possible contamination of the surface of photoelectric panels, this reducing their initial power and making location of powerful wind generation equipment at dumps impossible because of their instability.

All of the above makes feasibility of introducing these generation facilities into the power system of a mining enterprise disputable. Technological facilities located directly in or next to mine workings can be viewed as an alternative method of producing power. The mine water drainage system is one of such facilities and its energy potential is not currently used to the fullest. It is mainly used as a load regulator in the enterprise power system [2].

With this approach applied, either under the maximum load or during peak hours with tariffs differentiated at intervals when the power cost is the highest, drainage pumps are disconnected from the grid, so mine water is not pumped. In other conditions, especially with minimal power consumption, pumps are in operation and perform their function. This results in balancing power loads by adjusting drainage capacities of consumers. At the same time, this approach requires sufficient pumped-storage capacity which is three or even four times higher than the daily water inflow. Also, to observe safety conditions, pumps cannot be turned off with a significant increase in the mine water level. On the other hand, treating mine water drainage as a set of reservoirs located at different heights relative to each other, it can be stated that there are appropriate preconditions for creating a pumped-storage hydroelectric power plant (PSHPP) on this basis.

2. Literature review

Implementation of a PSHPP in the power system of mining enterprises is the subject of research in a number of works [3–13].

[3–5] consider application of the PSHPP to water drainage during open pit mining operations; [6–13] look into pumped-storage equipment use at water intake facilities of underground mine workings.

[6–12] are mostly devoted to studying the impact of water drainage design elements, in particular, intake facilities, hydraulic systems and technological modes of PSHPP operation at underground mines.

[6] analyzes geomechanical characteristics of the water intake facility used with PSHPP hydroturbines and studies the influence of the material of reservoir gallery supports on their mechanical strength.

[7] investigates into the influence of the water intake design on PSHPP operation and considers the use of interconnected tunnels and galleries as a lower reservoir of the network. The research determines atmospheric pressure and the rate of mixing mine water in intake compartments for water discharge and inflow.

[8] deals with atmospheric pressure changes in the underground intake facility during the water drainage mode of the PSHPP, i.e. the pump station mode, and its impact on design elements of the reservoir.

[9] analyzes waves occurring in underground water intakes during PSHPP operation and their possible impact on mechanical strength of reservoir structures (walls and supports).

[10] focuses on the impact of water inflows on PSHPP efficiency.

[11] evaluates PSHPP operation, namely the influence of water discharge and drainage on inflows, i.e. the nature of ground water inflows. In particular, the intake level and hydraulic

pressure are analyzed for different PSHPP modes. When modelling the required generation volumes of PSHPPs that affect intensity of water discharge and drainage, data on power costs for 14 days in winter, spring and summer is used.

[12] investigates into the intake level during PSHPP operation under different modes.

However, economic aspects of PSHPP implementation for mine water drainage are somewhat ignored. [13] looks into economic indices of PSHPP operation with power being sold to external consumers. Dependences of economic indices, in particular power costs, the NPV, the IRR, the payback period on investments and turbine cycles are built.

At the same time, the main approach to developing state-of-the-art power supply systems involves efficient design of distributed generation systems with PSHPPs and improvement of power flows considering economic terms [14–16].

[14] deals with optimization of power system design for wind farms and PSHPPs according to criteria of power production cost and the level of carbon dioxide emissions. The number of storage pumps and wind turbines to reduce these indices is determined as well.

[15] determines efficient designs of the power supply system for wind, photoelectric, biomass and pumped-storage power plants guided by the criterion of minimal power production costs.

[16] suggests a multi-staged method of adjusting active power production in the power system with wind, photoelectric, thermal and pumped-storage power plants and power storage devices installed. The power system is planned and optimized on a daily, hourly and real time basis. This approach reduces power fluctuations caused by a changeable nature of renewable energy sources. The cost of power production is also used as an optimization criterion.

[17] determines the power generation level of the PSHPP depending on the water level in the upper reservoir as in the case of the pumped-storage facility located on the Sebeș River (Gâlceag, Romania).

Efficiency of the distributed generation system in mine conditions can be improved by introducing either wind generators with modern control systems [18] or power storage systems [19] to reduce generation fluctuations caused by a changeable nature of renewable energy sources.

3. Materials and methods

3.1. Description of iron ore mines power systems configurations

To increase efficiently of an energy resource, a mini pumped-storage hydroelectric power plants (mini-PSHPPs) are suggested to be installed in sections of mine water drainage. Thus, mine waters can be discharged backward either from upper horizons or the surface to lower horizons, thus generating power via hydroturbines. It is assumed that pumps will not be turned off to avoid overflow of reservoirs. Constant water discharge for generating power eliminates the need to expand reservoirs for mine waters.

Different designs of the distributed generation system can be applied to building PSHPPs for underground mines. Installation of a hydroturbine next to a reservoir on a separate level is the simplest option when using only one target mine for producing power from water resources. Advantages of this approach include autonomous application of power generated and control of balancing the enterprise power system, low investments and easy engineering implementation. Yet, power production constrained by mine inflows can be considered a disadvantage. Alternatively, an option that involves accumulation of water from several underground mines in surface intakes of a target mine followed by its discharge to a lower level can be suggested. Thus, the energy potential of water drainage increases enhancing the level of power generation. Simultaneously, this option requires installation of additional hydroturbines that increases required investments for their purchase and installation. In addition, it is necessary to determine how to distribute the economic effect from mini-PSHPPs among underground mines supplying water.

To increase power generation, multi-staged water discharge from higher to lower levels can be performed with mini-PSHPPs installed next to a reservoir at each level mark.

Because of the above disadvantages, there is a need for coordinated control over individual mini-PSHPPs on different levels, which significantly complicates engineering implementation of the system. Yet, among all the options considered, the outlined design provides the highest power production and, therefore, it is the most economically feasible.

Efficiency of introduction of mini-PSHPPs for combined power supply of mine consumers is considered by taking water drainage of Rodina mine as an example (figure 1). Main drainage facilities including pumps and reservoirs are located on the 500m, 940m, 1240m, 1315m, 1465m and 1540m levels. When conducting computational experiments, installation of 1 MW hydrogenerators of CJ A237-W-90/1x5.5 type is envisaged (table 1).

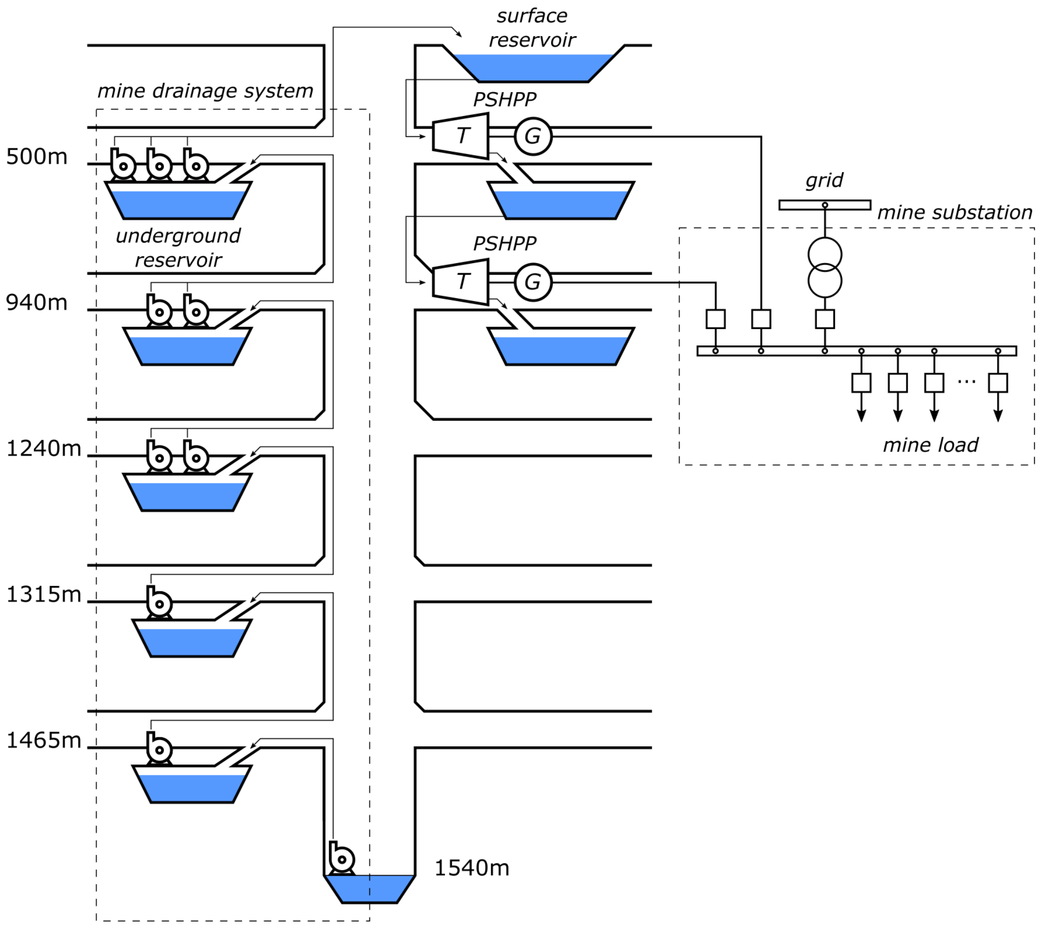

Figure 1. Scheme of mine pumped-storage hydroelectric power plant: T – water turbine; G – generator.

Table 1. Nominal parameters of the hydroturbine CJA 237.

h, m	$Q, m^3/sec$	P, kW	n, rpm	$Generator$	P_n, kW	U, kV
540	0.23	1075	1000	SFW 1000-6/1180	1000	6300

Let us evaluate the energy potential of each water drainage stage by calculating the power generation level of a hydroturbine at the maximum allowable water consumption [20]:

$$P = \eta \rho g h Q, \tag{1}$$

where:
η is the hydroturbine efficiency factor;
ρ is the water density, kg/m^3;
g is the gravitational acceleration, m/s^2;
h is head, m;
Q is water flow rate, m^3/s.

For multi-staged water discharge on the 0m, 500m, 940m, 1240m, 1315m levels, power production makes 1015.3 kWh, 893.49 kWh, 609.2 kWh and 152.3 kWh respectively. Therefore, it is advisable to consider options for placing hydroturbines on the 500m and 940m levels. Power generation for 940m-1240m and 1240m-1315m levels makes 60 % and 1.5 % of the nominal capacity of a storage pump, this indicating its inefficient load.

When conducting the research, three designs of the distributed generation system via mini-PSHPPs are considered:

- a single hydroturbine ($N_{HT} = 1$) on the 500m level using water from one mine;
- two hydroturbines ($N_{HT} = 2$) on the 500m level using water from several mines;
- four hydraulic turbines ($N_{HT} = 4$) – two on the 500m level and two on the 940m level using water from several mines.

For each system design, a comparative analysis is performed with two options of power consumption considered:

- from the industrial power grid supplied by the external power system;
- combined power supply of the grid and the mini-PSHPP.

The first option involves purchasing power from the power supplying company at current tariffs to fully satisfy the facility's needs. The second one provides power supply of drainage pumps from both mini-PSHPP hydrogenerators and the enterprise grid in case of power shortage due to either increased power consumption because of additional pumps installed when increasing water inflow to the mine or reducing water consumption of a storage pump.

The net present value (NPV) of the system is used as a criterion for comparing efficiency of the above two options [21]:

$$NPV = \sum_{i=1}^{N} \frac{R_i}{(1+d)^i}, \tag{2}$$

where:
R_i is the difference between profits and expenses during system operation, UAH;
d is the discount rate;
N is the number of years of system operation.

The economic index is used for modelling to take into account the cost of purchasing and maintaining generation equipment of mini-PSHPPs. The power obtained from the external power system and paid for at current tariffs of the power supplying company can be an obvious criterion of the system efficiency. Yet, this criterion is unrepresentative as any additional power supply source reduces the level of power supplied by the external grid.

Additionally, the value of levelized cost of energy (LCOE) for the combined power system was calculated.

3.2. Description of modeling conditions
Computational experiments are conducted by using MATLAB.

When modelling, the nominal power load seems to be uniformly distributed during 24 hours of operation with average and peak capacities of 900 kW and average daily consumption of 21600 kWh. There are calculations for cases with additional power equipment installed, when average daily consumption increases up to 43200 kWh and decreases to 10800 kWh.

Calculations of the mini-PSHPP option consider investments for purchasing a hydroturbine (540 000 UAH) and various expenses for scheduled and preventive repair and maintenance works amounting to 80 000 UAH per year. Power generation of mini-PSHPPs is performed at the nominal hydrostatic pressure of 500m (0m–500m) and 440m (500m–940m) and losses in the hydraulic system of 15%. When modelling, the amount of water passing through the hydroturbine tends to decrease compared to the nominal value and makes 0.23 m^3/sec; 0.15 m^3/sec, and 0.07 m^3/sec. The hydroturbine efficiency is 90%. The cost of power received from the power supplying company is 93.38 UAH/MWh for first-category industrial (non-household) power consumers. Besides, power costs during peak hours are also modelled and make 140.07 UAH/MWh. The service life of the system makes 25 years with the nominal discount rate of 8%.

4. Results and discussion

4.1. Economic performance of the distributed generation power system based on pumped-storage hydroelectric power plant, containing one hydroturbine located on the underground horizon of 500 meters

4.1.1. Basic power tariff case. The computational experiment results are given in table 2 and table 3.

Table 2. NPV (UAH) and $LCOE$ (UAH/kWh) when introducing the distributed generation system with the mini-PSHPP at the 500m level with the tariff of $\alpha_{base} = 93.38 UAH/MWh$, $N_{HT} = 1$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	3929427.39	0.09338	4744160.92	0.112742
	0.15			2095383.12	0.049795
	0.23			1820973.14	0.043274
21600	0.07	7858854.77		8673588.3	0.103061
	0.15			6024810.51	0.071588
	0.23			2727270.31	0.032406
43200	0.07	15717709.55		16532443.08	0.09822
	0.15			13883665.28	0.082484
	0.23			10586125.09	0.062893

In figure 2 and figure 3, there are discounted operating costs and NPVs of the power supply system for individual consumers of the mine when introducing an additional generation facility – a mini-PSHPP containing a single hydroturbine with the tariff of $\alpha_{base} = 93.38$ UAH/MWh. The graphs specify economic indices for the enterprise power grid and mini-PSHPPs as well as total indices of the distributed generation system.

The graphs indicate that at low power consumption and hydroturbine water consumption close to the nominal value when $Q = 0.23$ m^3/sec and $E = 10800$ kWh, the NPV of the

Table 3. NPV (UAH) and $LCOE$ (UAH/kWh) when introducing the distributed generation system with the mini-PSHPP at the 500m level with the tariff of $\alpha_{peak} = 140.07$ UAH/MWh, $N_{HT} = 1$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	5894141.08	0.14007	6205754.8	0.147475
	0.15			2232588.11	0.053056
	0.23			1820973.14	0.043274
21600	0.07	11788282.16		12099895.89	0.143773
	0.15			8126729.19	0.096563
	0.23			3180418.9	0.037790
43200	0.07	23576564.32		23888178.05	0.141921
	0.15			19915011.36	0.118316
	0.23			14968701.06	0.08893

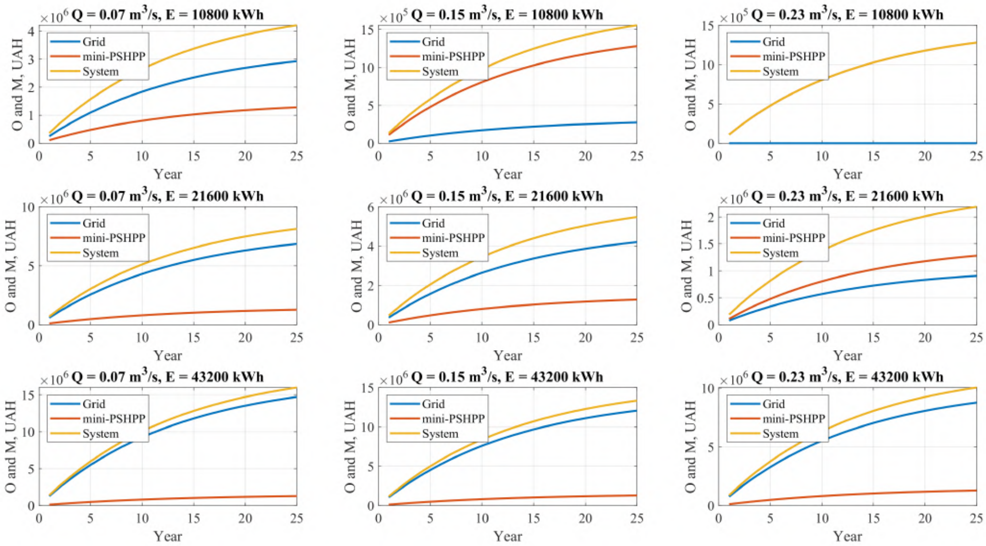

Figure 2. Operating costs of the power supply system with the mini-PSHPP for different values of hydroturbine water consumption and average daily power consumption with the power cost of 93.38 UAH/MWh.

system is determined by operating costs of the mini-PSHPP. This is due to the fact that power generation of the hydroturbine fully satisfies the current power consumption, so the purchase of power from the external power grid of the distribution operator is not carried out. The distributed generation power system operates autonomously.

Under typical operation conditions with $Q = 0.23$ m^3/sec and $E = 21600$ kWh as well as $Q = 0.15$ m^3/sec and $E = 10800$ kWh, the NPV of the system is actually conditioned by the NPV of the mini-PSHPP. Thus, the fraction of the NPV resulted from power generation via hydroturbines makes 86.9% with $Q = 0.15$ m^3/sec and $E = 10800kWh$ and 66.76% with $Q = 0.23$ m^3/sec and $E = 21600$ kWh.

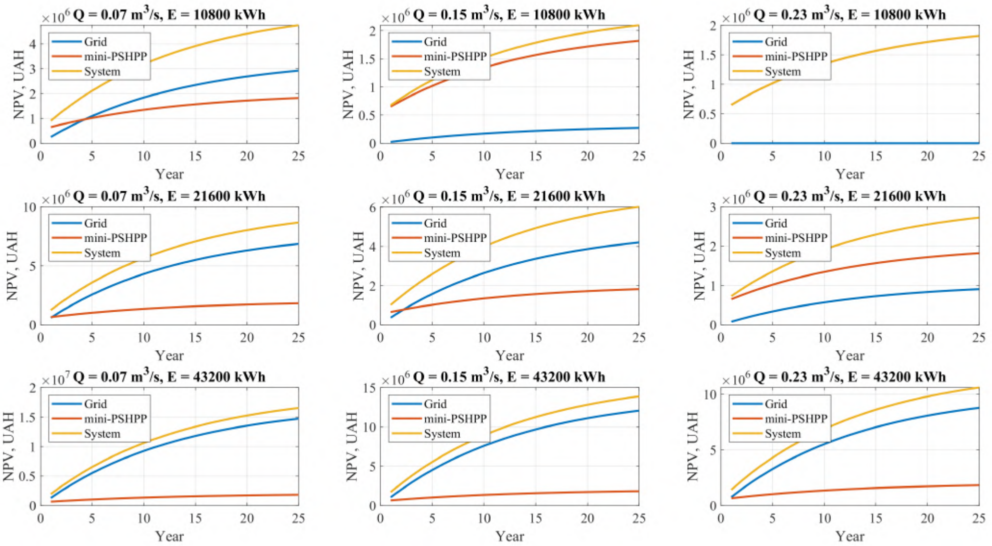

Figure 3. NPV of the power supply system with the mini-PSHPP for different values of hydroturbine water consumption and average daily power consumption with the power cost of 93.38 UAH/MWh.

With an increase in power consumption, the capacity shortage of the mini-PSHPP begins to be covered by external power supply. With $Q = 0.07\ m^3/sec$ and $E = 21600\ kWh$; $Q = 0.07\ m^3/sec$ and $E = 43200\ kWh$; $Q = 0.15\ m^3/sec$ and $E = 43200\ kWh$; $Q = 0.23\ m^3/sec$ and $E = 43200\ kWh$, the NPV of the system almost entirely depends on the cost of power purchased from the distribution operator which is explained by the low generation level of the mini-PSHPP.

Thus, the fraction of the NPV from hydroturbine operation in the total structure of the NPV system is only 11.01% with $Q = 0.07\ m^3/sec$ and $E = 43200\ kWh$, 13.12% with $Q = 0.15\ m^3/sec$ and $E = 43200\ kWh$, 20.99% with $Q = 0.07\ m^3/sec$ and $E = 21600\ kWh$, and 17.2% with $Q = 0.07\ m^3/sec$ and $E = 43200\ kWh$ respectively. In these cases, it is inefficient to use the system design in question.

Comparing economic indices of the two suggested options of power supply – only from the grid and from the combined power supply system with the mini-PSHPP (see table 2) – it is established that with the increased Q to the nominal value of the hydrogenerator (0.23 m^3/sec), the NPV for the mini-PSHPP system decreases. Thus, during the operation of power equipment with $E = 21600\ kWh/day$ and $Q = 0.15\ m^3/sec$, the NPV of the mini-PSHPP system is 23.34% smaller as compared to the system without the mini-PSHPP, and with $Q = 0.23\ m^3/sec$ it is 65.3% smaller (41.96% greater than with $Q = 0.15\ m^3/sec$).

In case of introducing two pumps, i.e. with increased power consumption up to $E = 43200\ kWh/day$ with $Q = 0.15\ m^3/sec$ for the mini-PSHPP system, the NPV is 11.67% smaller and with $Q = 0.23\ m^3/sec$ – 32.65% smaller (20.98% greater as compared to $Q = 0.15\ m^3/sec$). So, with increased capacity of water drainage consumers, efficiency of the mini-PSHPP system is not growing so intensively. This is due to the fact that for some reason a hydroturbine cannot fully meet the needs of the facility, this causing capacity shortages.

Table 2 contains calculated data on power costs of the combined power supply system for different operation conditions.

The results of calculations reveal that at low intensity of the water flow passing through the mini-PSHPP hydroturbine during mine water discharge, in particular with $Q = 0.07\ m^3/sec$ and power consumption of the nominal value and higher, the power cost exceeds the tariff set by the distribution operator. This is due to maintenance and repair costs of hydroturbines exceeding the economic effect of additional generation leading to a great difference between the volume of power produced and consumed.

Additionally, there is a dependence of the NPV of the combined power supply system on hydroturbine water consumption and power consumption. There are also determined application areas of parameters within which it is advisable to use a particular design. Graphical interpretation of optimal applications of a certain power supply option is similar to the Optimal System Plot of the Homer Pro application package [22]. To perform calculations, intervals of changing independent parameters (hydroturbine water consumption and power consumption) are reduced. Thus, Q changes within $[0.07\ m^3/sec;\ 0.23\ m^3/sec]$ in increments of $1\cdot10^{-4}\ m^3/sec$; average daily capacity – within [450 kW, 180 kW] in increments of 10 kW.

In figure 5 and further in yellow, the area of the power supply system efficiency is indicated, which provides for power supply from the grid without the mini-PSHPP, in blue – distributed generation systems with mini-PSHPPs.

Analysis of the obtained results (figure 4, figure 5) shows that with the current power tariff of $\alpha_{base} = 93.38\ UAH/MWh$, the combined power supply system with a hydrogenerator should be used for water flow intensity above 0.1339 m^3/sec and average daily power consumption of 10800 kWh/day; 0.1899 m^3/sec – with 21600 kWh/day and 0.23 m^3/sec – with 29520 kWh/day. Reduced water consumption leads to the increased NPV for systems without mini-PSHPPs as compared to the option without it, which indicates inefficiency of the combined power supply system. Power consumption over 29520 kWh makes application of the mini-PSHPP system inefficient.

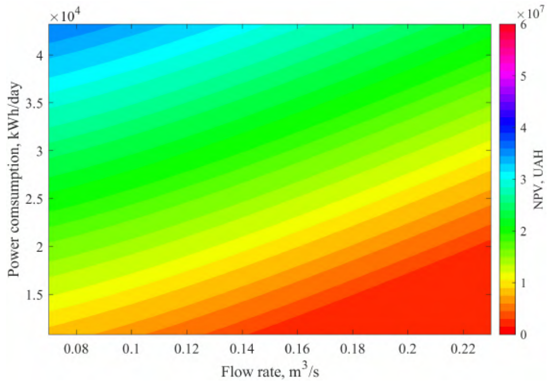

Figure 4. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption $NPV = f(Q, E)$ with a single hydroturbine introduced on the 500m level with the tariff of 93.38 UAH/MWh.

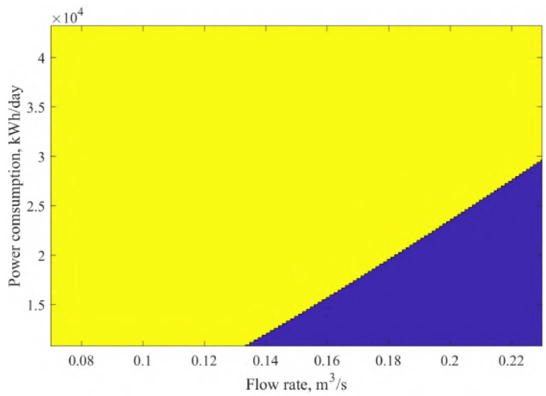

Figure 5. Power supply system of the 500m level with a single turbine introduced which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of 93.38 UAH/MWh.

The area of effective application of the combined power supply system with its own distributed generation facilities within the considered change of parameters ($\alpha_{base} = 93.38\ UAH/MWh$) is 17.2%. These are the most unfavourable conditions for modernization of the power system, as their totality indicates the lowest area of distributed generation applied making it inefficient.

4.1.2. Peak power tariff case. Application of the tariff for peak hours (α_{peak} = 140.07 UAH/MWh – table 3, figure 6, figure 7) is expected to increase efficiency of the combined power supply system, with the single hydroturbine-based mini-PSHPP on the 500 m level.

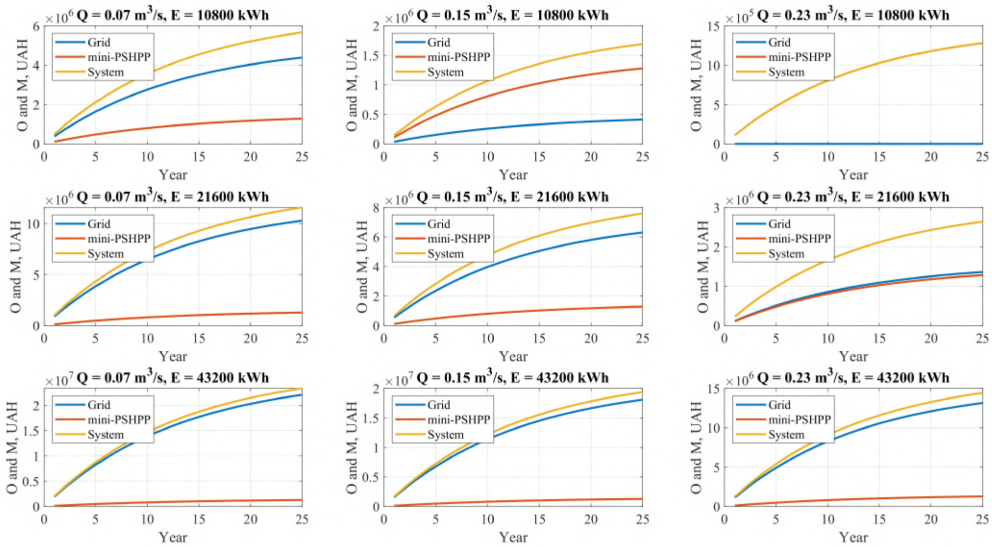

Figure 6. Operating costs of the power supply system with mini-PSHPPs during the operation period for different values of hydroturbine water consumption and average daily power consumption with the power cost of 140.07 UAH/MWh.

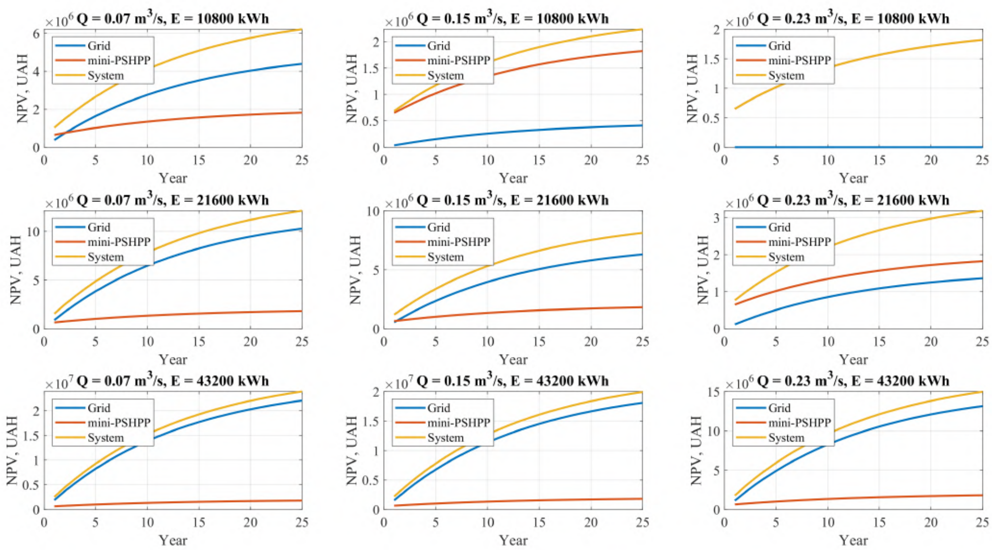

Figure 7. NPV of the power supply system with mini-PSHPPs during the operation period for different values of hydroturbine water consumption and average daily power consumption with the power cost of 140.07 UAH/MWh.

This is due to increased costs for power purchased from the external power grid at higher prices. At the same time, expenses for purchasing, maintaining and repairing a hydrogenerator remain unchanged as compared to the basic tariff.

Thus, in the most unfavourable operating conditions, the fraction of the NPV of mini-PSHPPs for the peak tariff in the total structure of the system NPV decreases as compared to the basic tariff ($\alpha_{base} = 93.38\ UAH/MWh$). For example, it makes 7.62% with $Q = 0.07\ m^3/sec$ and $E = 43200\ kWh$; 9.14% with $Q = 0.15\ m^3/sec$ and $E = 43200\ kWh$; 12.17% with $Q = 0.23\ m^3/sec$ and $E = 43200\ kWh$; 15.05% with $Q = 0.07\ m^3/sec$ and $E = 21600\ kWh$. For the basic tariff, the fraction is 11.01%, 13.12%, 20.99% and 17.2% respectively.

It is also worth mentioning that the fraction of the NPV of mini-PSHPPs decreases greatly for such conditions as $Q = 0.07\ m^3/sec$, $E = 10800\ kWh$ and $Q = 0.15\ m^3/sec$, $E = 21600\ kWh$ and amounts to 29.34% and 22.41% (38.38% and 30.22% with $\alpha_{base} = 93.38\ UAH/MWh$) respectively. This is due to increased costs for power purchased from the external grid.

Under nominal conditions of $Q = 0.23\ m^3/sec$ and $E = 21600\ kWh$ as well as $Q = 0.15\ m^3/sec$, $E = 10800\ kWh$, the NPV is conditioned by the power purchased from the external power grid and still remains lower than the NPV of the mini-PSHPP.

The NPV of mini-PSHPP systems increases more significantly with increased water consumption up to the nominal value as compared to the basic tariff. For example, with $E = 21600\ kWh/day$ corresponding to the consumer's capacity of 900 kW, the NPV with $Q = 0.15\ m^3/sec$ is 31.06% lower for the combined power supply system as compared to power supply only from the external power system (it is decreased by 23.34% for the basic tariff), while with $Q = 0.23\ m^3/sec$, it is 73.02% lower (65.3% for the basic tariff).

In case of simultaneous operation of two consumers with the capacity of 900 kW, i.e. $E = 43200\ kWh/day$, the NPV of the mini-PSHPP system is 15.53% lower with $Q = 0.15\ m^3/sec$ (11.67% for the basic tariff) and 36.51% lower with $Q = 0.23\ m^3/sec$ (32.65% for the basic tariff).

In other words, with the increased hydroturbine water consumption up to the nominal value, the fraction of the NPV reduction for the system with mini-PSHPPs is almost comparable – 73.02% vs. 65.3% for $E = 21600\ kWh/day$ and 36.51% vs. 32.65% for $E = 43200\ kWh/day$.

Also, when increasing the established capacity, a difference of the reduced NPV is not so significant for the two considered options of power costs (basic and peak).

The reduced power cost in the mini-PSHPP system (table 3) exceeds the peak tariff with $Q = 0.07\ m^3/sec$ for all considered options of power consumption, which indicates low efficiency of the distributed generation system with low water consumption via a storage pump. Power costs in combined power supply systems are close to the peak tariff with $Q = 0.15\ m^3/sec$ and $E = 43200\ kWh/day$ and lower by only 15.53%.

In figure 8, the dependence graph shows a more intensive increase in the NPV with increased power consumption and reduced hydroturbine water consumption.

The graph (figure 9) reveals that the system without mini-PSHPPs should be used with water flow intensity below 0.1264 m3/sec for $E = 10800\ kWh/day$, 0.1839 m^3/sec – for $E = 21600\ kWh/day$ and 0.23 m^3/sec – for $E = 30960\ kWh/day$. That is, the application area of the distributed generation system with mini-PSHPPs increases to 19.6% compared to the tariff of $\alpha_{base} = 93.38\ UAH/MWh$, yet not significantly – only by 2.4%. With the level of power consumption above 30960 kWh/day, the use of the mini-PSHPP system is inefficient.

4.2. Economic performance of the distributed generation power system based on pumped-storage hydroelectric power plant, containing two hydro turbines, which are located on the underground horizon of 500 meters

4.2.1. Basic power tariff case. At the next stage of the research, calculations are made for the option with two hydroturbines installed on the 500m level of Rodina mine.

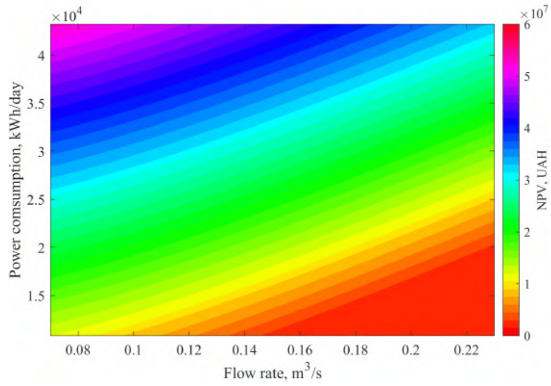

Figure 8. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and power consumption $NPV = f(Q, E)$ with a single hydroturbine introduced on the 500m level with the tariff of 140.07 UAH/MWh.

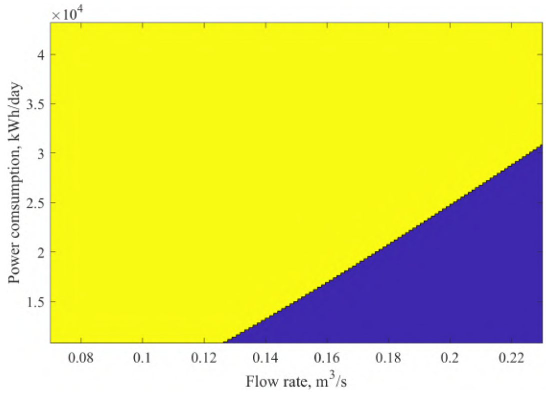

Figure 9. Power supply system of the 500m level with a single turbine introduced which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of 140.07 UAH/MWh.

Computational experiment results for the basic tariff of α_{base} = 93.38 UAH/MWh are summarized in table 4 and table 5.

Table 4. NPV (UAH) and $LCOE$ (UAH/kWh) for the distributed generation system with the mini-PSHPP (two hydroturbines) introduced on the 500 m level with the tariff of 93.38 UAH/MWh, $N_{HT} = 2$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	3929427.39	0.09338	5558894.45	0.132103
	0.15			3641946.29	0.086548
	0.23			3641946.29	0.086548
21600	0.07	7858854.77		9488321.83	0.112742
	0.15			4190766.25	0.049795
	0.23			3641946.29	0.043274
43200	0.07	15717709.55		17347176.61	0.103061
	0.15			12049621.02	0.071588
	0.23			5454540.63	0.032406

The data obtained reveals an increase in the fraction of the NPV of mini-PSHPPs in the structure of the system NPV. This is due to increased volumes of power generation by storage pumps and reduction of power shortages. As a result, expenses for power purchased from the external distribution operator are reduced.

However, comparing the results are in table 2 and table 4, it can be seen that the reduced power cost in the mini-PSHPP system with two hydroturbines is growing. This is due to double capital expenses for purchasing generation equipment and annual expenses for maintenance and repairs.

4.2.2. Peak power tariff case. When applying the peak power tariff (table 5) compared with the option with the basic tariff (table 4), it can be seen that the NPV criterion indicates increased efficiency of distributed generation systems because the difference between NPVs becomes more significant.

Table 5. NPV (UAH) and $LCOE$ (UAH/kWh) for the distributed generation system with two hydroturbines introduced on the 500m level with the tariff of 140.07 UAH/MWh, $N_{HT} = 2$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	5894141.08	0.14007	6517368.53	0.154881
	0.15			3641946.29	0.086548
	0.23			3641946.29	0.086548
21600	0.07	11788282.16		12411509.61	0.147475
	0.15			4465176.23	0.053056
	0.23			3641946.29	0.043274
43200	0.07	23576564.32		24199791.77	0.143773
	0.15			16253458.39	0.096563
	0.23			6360837.8	0.03779

Data on the calculated reduced power cost in the system with two storage pumps (table 5) operating with the peak tariff shows that compared to the option where the power shortage is covered by purchasing power at the basic tariff (table 4), its cost increases.

4.3. Economic performance of the distributed generation power system based on pumped-storage hydroelectric power plant, containing four hydro turbines, which are located on the underground horizons of 500 and 940 meters (two on each)

4.3.1. Basic power tariff case. At the final stage, efficiency of introducing the distributed generation system with mini-PSHPPs on the 500m and 940m levels of Rodina mine is considered. As this option has the energy potential of water discharge from several mines, four storage pumps are envisaged – two on each level.

The obtained data (table 6) indicates that the NPV of the mine power supply system with the mini-PSHPP is growing significantly. It remains lower than the NPV when consumers are supplied from the external power grid only in four cases: $Q = 0.15$ m^3/sec and $E = 21600$ kWh/day (7.32% less), $Q = 0.23$ m^3/sec and $E = 21600$ kWh/day (7.32% less), $Q = 0.15$ m^3/sec and $E = 43200$ kWh/day (46.67% less), and $Q = 0.23$ m^3/sec and $E = 43200$ kWh/day (53.66% less).

In general, the NPV of the mini-PSHPP system consisting of four hydroturbines with the basic tariff under nominal operating conditions ($Q = 0.23$ m^3/sec and $E = 21600$ kWh/day) increases compared to the use of one or two storage pumps by a factor of 2.67 and 1.99 respectively.

Analysis of the components of the NPV system with combined power supply (figure 10, figure 11) indicates a greater increase in the fraction of the NPV of mini-PSHPPs in the NPV system compared to the option in which power is generated by two storage pumps installed next to the water intake of the 500m level. In this case, the level of power generation sufficient for autonomous power supply is provided in all the cases except for $Q = 0.07$ m^3/sec and $E = 21600$ kWh/day, $Q = 0.07$ m^3/sec and $E = 43200$ kWh/day and $Q = 0.15$ m^3/sec and $E = 43200$ kWh/day. Yet, with $Q = 0.07$ m^3/sec and $E = 21600$ kWh/day and $Q = 0.15$ m^3/sec and $E = 43200$ kWh/day, the NPV of the system mainly depends on the

Table 6. NPV (UAH) and $LCOE$ (UAH/kWh) for distributed generation systems with mini-PSHPPs introduced on the 500m and 940m levels with the tariff of 93.38 UAH/MWh, $N_{HT} = 4$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	3929427.39	0.09338	7283892.57	0.173096
	0.15			7283892.57	0.173096
	0.23			7283892.57	0.173096
21600	0.07	7858854.77		11117788.9	0.132103
	0.15			7283892.57	0.086548
	0.23			7283892.57	0.086548
43200	0.07	15717709.55		18976643.67	0.112742
	0.15			8381532.49	0.049795
	0.23			7283892.57	0.043274

NPV of the mini-PSHPP the fraction of which makes 65.52% and 86.9%. It means that with $Q = 0.07\ m^3/sec$ and $E = 21600\ kWh/day$, the NPV of the system and that of the mini-PSHPP are actually equal.

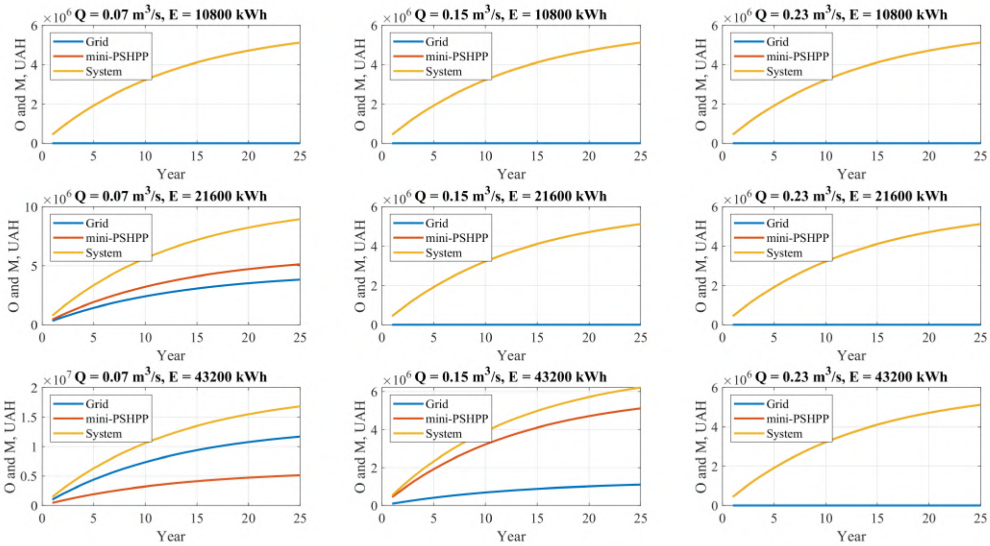

Figure 10. Operating costs of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 93.38 UAH/MWh.

As a result, only with $Q = 0.07\ m^3/sec$ and $E = 43200\ kWh/day$, the NPV of the system is conditioned by the power purchased from external companies, its fraction making 61.62%.

A significant increase in the costs of generation equipment (four hydroturbines) and its further maintenance leads to exceeding the tariff of $\alpha_{base} = 93.38\ UAH/MWh$ by the reduced power cost

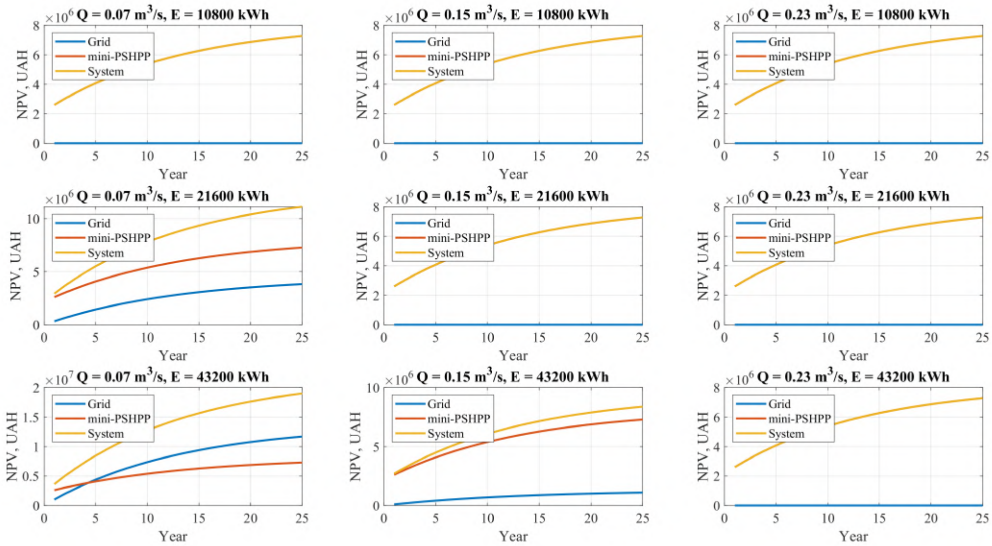

Figure 11. NPV of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 93.38 UAH/MWh.

in the distributed generation system except for $E = 21600\ kWh/day$ and $E = 43200\ kWh/day$ with water consumption $Q = 0.15\ m^3/sec$ and $Q = 0.23\ m^3/sec$. With low power consumption and water flow intensity, it is favourable to supply power only from the grid and purchase power from the distribution operator. Modernization of the mine power grid by building a mini-PSHPP is not feasible because the economic effect of power generation for 25 years does not cover capital investments and operating costs. To make the energy potential of mini-PSHPPs on the 500m and 940m levels more efficient, it is necessary to supply power to more consumers.

The dependence graph $NPV = f(E, Q)$ in figure 12 shows an increase in the system NPV in the area of increasing power consumption from $E = 10800\ kWh/day$ to $E = 32100\ kWh/day$ and water consumption from $Q = 0.12\ m^3/sec$ to $Q = 0.23\ m^3/sec$ (indicated in orange).

The graph (figure 13) shows that the system without mini-PSHPPs should be used for water flow intensity below 0.1011 m^3/sec with $E = 21600\ kWh/day$ and 0.1336 m^3/sec – with $E = 43200\ kWh/day$. The peculiarity of this case is that with power consumption below $E = 20160\ kWh/day$ mini-PSHPPs in the power supply system are inefficient for any value of hydroturbine water consumption. As a result, the area of parameters change of the distributed generation system slightly decreases (by 0.93% to 50.64%) compared to the case with the basic tariff in action and two hydroturbines installed on the 500m level.

4.3.2. Peak power tariff case. With the peak tariff of $\alpha_{peak} = 140.07\ UAH/MWh$ in action, the NPV of the proposed power supply system with the mini-PSHPP is lower than the NPV of the system in which consumers are supplied only from the external power grid with power consumption $E = 21600\ kWh/day$ and $E = 43200\ kWh/day$ and water consumption $Q = 0.15\ m^3/sec$ and $Q = 0.23\ m^3/sec$ (table 7). Thus, with $Q = 0.15\ m^3/sec$, $E = 21600\ kWh/day$ and $Q = 0.23\ m^3/sec$, $E = 21600\ kWh/day$, it reduces by 62.12%, while with $Q = 0.23\ m^3/sec$, $E = 43200\ kWh/day$ – by 69.11%. At the basic tariff, these percentages for similar conditions make 7.32%, 7.32%, 46.67% and 53.66%. The increased difference of NPVs is explained by increased costs of purchasing power from the power supplying company due to the peak tariff

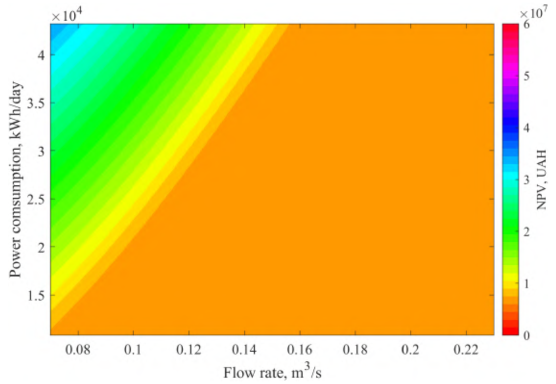

Figure 12. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption $NPV = f(Q, E)$ with two hydroturbines introduced on the 500m level and two hydroturbines introduced on the 940m level with the tariff of 93.38 UAH/MWh.

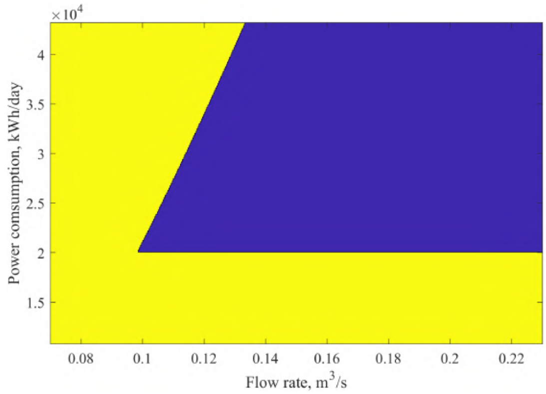

Figure 13. Power supply system with four hydroturbines introduced on the 500m and 940m levels which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of 93.38 UAH/MWh.

while maintaining the level of power generation via their own storage pumps as well as capital and operating costs and those for scheduled and preventive repairs.

Table 7. NPV (UAH) and $LCOE$ (UAH/kWh) for distributed generation systems with mini-PSHPPs introduced on the 500m and 940m levels with the tariff of 140.07 UAH/MWh, $N_{HT} = 4$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	5894141.08	0.14007	7283892.57	0.173096
	0.15			7283892.57	0.173096
	0.23			7283892.57	0.173096
21600	0.07	11788282.16		13034737.06	0.154881
	0.15			7283892.57	0.086548
	0.23			7283892.57	0.086548
43200	0.07	23576564.32		24823019.22	0.147475
	0.15			8930352.45	0.053056
	0.23			7283892.57	0.043274

Analysis of the NPV components of the combined power supply system (figure 14 and figure 15) shows that with parameters $Q = 0.07$ m^3/sec, $E = 43200$ kWh/day, the NPV of the system is conditioned by the discounted power cost the fraction of which is 70.66%, which is 9.04% higher than with $\alpha_{base} = 93.38$ UAH/MWh.

In such conditions as $Q = 0.15$ m^3/sec and $E = 43200$ kWh/day, the fraction of the NPV of the mini-PSHPP exceeds the NPV of the enterprise grid by 63.12% and is 81.56% vs. 18.44% respectively (figure 14, figure 15). With $Q = 0.07$ m^3/sec and $E = 21600$ kWh/day, they take

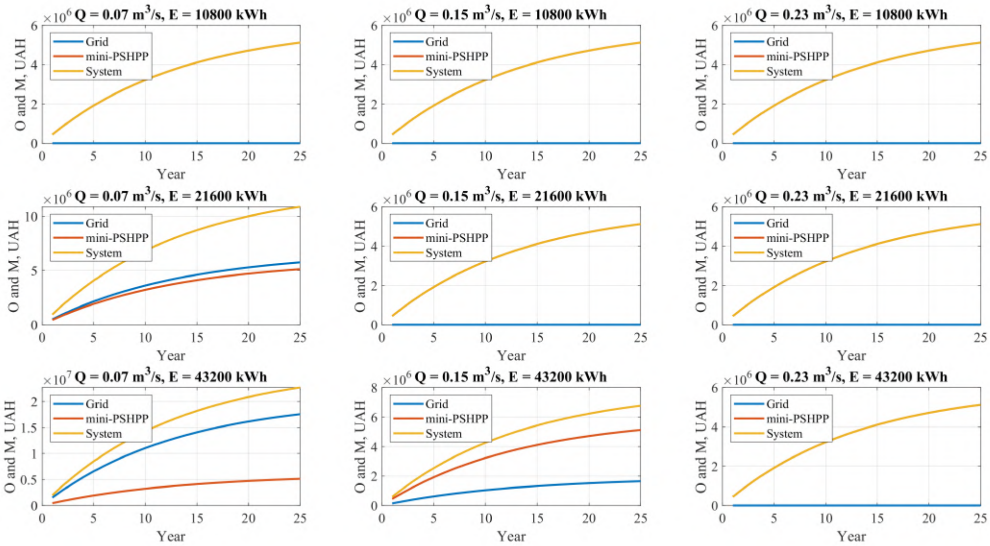

Figure 14. Operating costs of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 140.07 UAH/MWh.

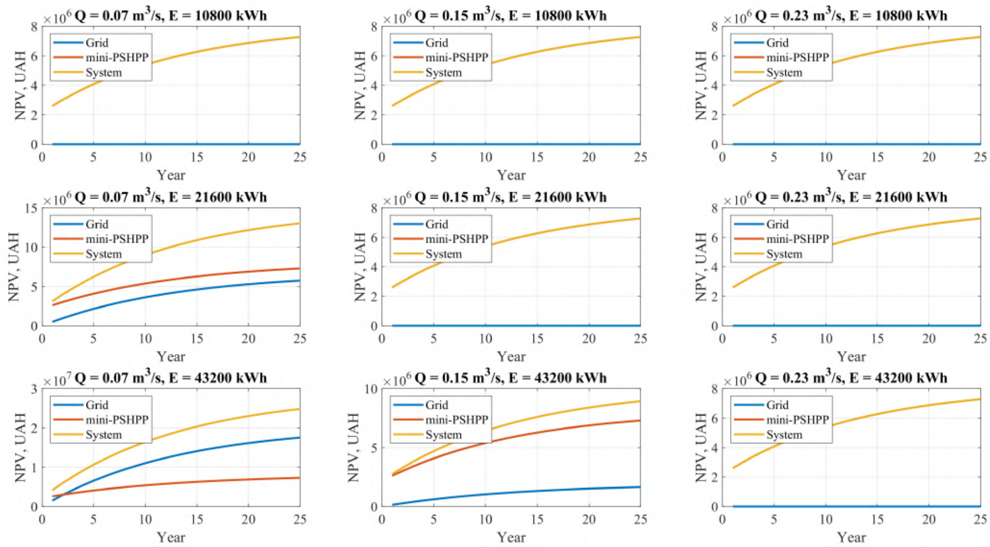

Figure 15. NPV of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 140.07 UAH/MWh.

almost the same values – the NPV of the grid exceeds that of the mini-PSHPP by only 2.75%.

In all other conditions, except those mentioned, the NPV of the system is completely determined by the NPV of the mini-PSHPP as the generated power is sufficient for autonomous power supply of water drainage consumers.

Given that in this case the power tariff increases by a factor of 1.5 up to $\alpha_{peak} = 140.07\ UAH/MWh$ and, accordingly, the cost of its purchase from the distribution operator increases, the reduced power cost of the distributed generation system with the mini-PSHPP (table 7) becomes lower than the current tariff not only with $Q = 0.23\ m^3/sec$ as for $\alpha_{base} = 93.38\ UAH/MWh$, but also with $Q = 0.15\ m^3/sec$, i.e. the energy potential of water drainage is used more efficiently.

The dependence graph $NPV = f\,(Q, E)$ in figure 16 shows a more intensive increase in the NPV with increased power consumption and reduced hydroturbine water consumption.

The graph (figure 17) shows that the system without mini-PSHPPs should be used for water flow intensity below $0.0926\ m^3/sec$ with $E = 21600\ kWh/day$ and $0.1259\ m^3/sec$ with $E = 43200\ kWh/day$. In this case, in contrast to the basic tariff, the mini-PSHPP system should not be applied to reduced power consumption below E=13400 kW*h/day (for $\alpha_{base} = 93.38\ UAH/MWh$ this limit is $E = 20160\ kWh/day$ as in figure 13). This significantly expands the application area of the distributed generation power supply system compared to the previous case. It is worth noting that comparing the efficiency area of the system with four storage pumps with the corresponding areas with one or two hydroturbines installed, this one appears to be the largest and makes 72.84%.

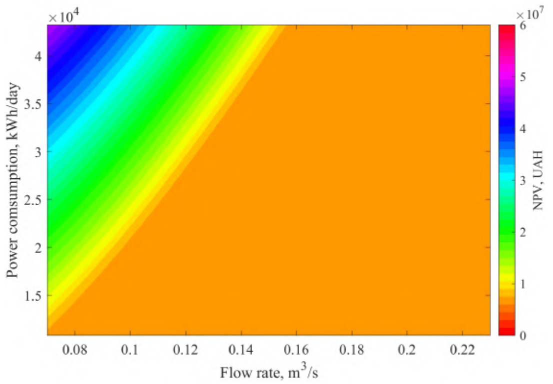

Figure 16. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption $NPV = f\,(Q, E)$ with two hydroturbines introduced on the 500m level and two hydroturbines introduced on the 940m level with the tariff of $140.07\ UAH/MWh$.

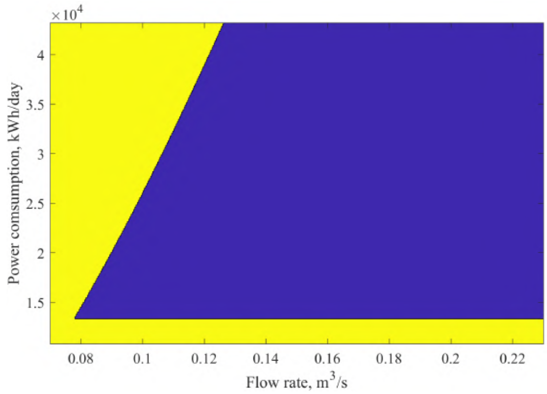

Figure 17. Power supply system with four hydroturbines introduced on the 500m and 940m levels which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of $140.07\ UAH/MWh$.

It means that despite high capital costs for purchasing generation equipment and its subsequent maintenance, this option is the best in terms of power supply with varied power consumption or hydroturbine water consumption.

5. Conclusions

Application of mining enterprises' drainage systems with hydroturbine-based mini-PSHPPs of various capacity to producing additional power enables increasing efficiency of power supply to consumers by reducing the cost of purchasing power from external grids. This also reduces the cost of final products and increases their competitiveness.

However, in order to provide the proper level of power generation, it is necessary to maintain intensity of the water flow passing through the hydroturbine above a certain limit. Also, when the installed capacity of consumers of a production facility increases, efficiency of the combined power supply system decreases because of the shortage of power generated by a storage pump. Therefore, feasibility of using mini-PSHPPs should be specified in each case.

Analysis of different designs of mine power supply systems, in particular installation of one or two hydroturbines on the 500 m level and four hydroturbines (two and two) on the 500m and 940m levels of Rodina mine of the JSC Kryvbaszalizrudkom reveals that mini-PSHPPs are efficient when generated capacity is close to the installed capacity of consumers. Application of different criteria to determining the most efficient design of the power supply system indicates opposite results. For example, in terms of power costs, the distributed generation system with a single hydroturbine installed on the 500m level is the most effective option.

In this case, the reduced power cost exceeds the current tariff for almost all the considered operating conditions, except for cases with very low water consumption via a storage pump. This is due to the optimal ratio between investments in the purchase of mini-PSHPP equipment, the cost of its maintenance and scheduled repairs and, on the other hand, the level of coverage of consumer needs in generated power. The system with mini-PSHPPs (four storage pumps on the 500m and 940m levels) appears to be the best option for the peak tariff as it reveals the lowest value of the NPV in conditions close to nominal and the highest application area.

However, the analysis of the NPV indicates that under conditions close to nominal, the use of mini-PSHPPs with a single hydroturbine has the highest reduced cost due to low generation, thus making it inexpedient to use compared to other designs.

With the basic tariff, it is advisable to use the distributed generation system with only two storage pumps installed on the 500m level as it has the highest efficiency among all studied designs.

Thus, the greatest economic effect can be achieved by introducing the mini-PSHPP system consisting of four hydroturbines, two of which are used during the basic tariff hours and when the peak tariff is used, all units are involved. Such balancing should be introduced by means of the power supply control system of mine consumers [23].

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Spatial variation of soil temperature fields in a urban park

To cite this article: T Kulish 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012056

Spatial variation of soil temperature fields in a urban park

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Abstract. Soil temperature is the most important factor that regulates the rate of physical, chemical and biological processes in the soil. A peculiarity of the urban environment is the occurrence of "heat islands". The increased temperature of urban environment significantly changes environmental conditions and contributes to the activation of phenomena that lead to the acceleration of global climate change. The aim of the work is to reveal the patterns of spatial variation of soil temperature in a city park at the different scale levels. Soil temperature was measured on a regular grid with different lags between measurement points. The measurement results were processed using geostatistical methods to quantify the spatial process at different scales. The results obtained allowed to quantify the patterns of spatial variability of temperature fields at different hierarchical levels. Scale-dependent effects of soil temperature variation were identified. The role of stand density, litter depth, and soil moisture on soil temperature variation was found. The results of the study are the basis for developing an optimal soil temperature measurement plan for environmental monitoring purposes. Suggestions were also made for the management of park stands in order to reduce the temperature load. The spatial variation in soil temperature demonstrates the occurrence of scale-dependent patterns. The spatial organization of temperature fields must be taken into account for optimal environmental monitoring and urban environmental management strategies. The soil temperature regime is characterised by a significant level of stability compared to air temperature. The soil temperature fields in an artificial park plantation are characterized by spatial patterns of a complex nature. The temperature field presents a spatial component that is invariant to time. It is most likely that the spatial variability of soil properties induced by natural factors and recreation are the cause of the generation of this pattern. Also in the soil temperature field there is a spatial pattern, which reflects the different sensitivity of the soil to the seasonal trend of temperature change. The generation of this pattern is due to the different insulating capacity of the forest litter in the park plantation. The results obtained point to the important role of leaf litter as a factor in the dynamics of the soil temperature regime. It is hypothesized that leaf litter in the park contributes to the enhancement of carbon sequestration during winter time.

1. Introduction

Soil temperature is one of the key factors determining the functioning of ecological systems [1,2] and affects both the vegetation and animal communities of soils [3]. The temperature regime strongly influences the intensity of soil processes, both mechanical and geochemical as well as biological [4,5]. Soil temperature is one of the important factors affecting soil properties and the processes involved in plant growth and regulates the physical, chemical and biological processes in the soil [6–8]. Soil temperature affects interspheric gas exchange processes between the atmosphere and the soil [9, 10]. The soil temperature plays an important role in plant nutrition [11, 12]. Soil temperature affects the activity of soil micro-organisms and root architecture, which modulates mutualistic and pathogenic interactions between plants and soil biota [13, 14]. According to the Van't Hoff rule, the speed of chemical reactions is accelerated by a factor of 2 to 3 when the temperature rises by 10°C. Soil warming can change the relationship between some plant species and soil animals [15, 16]. An increase in soil temperature leads to a decrease in α-diversity of plant and invertebrate communities, which was caused by a decrease in plant species richness and an increase in the dominance of some invertebrate species in warmer habitats [3,17]. Such soil processes as sorption and desorption [18], gas solubility [19], the ratio of solid and liquid phases in the soil [20], peptization and coagulation of colloids [21] depend on temperature.

Soil temperature is influenced by factors from two groups: these are factors that determine the amount of heat reaching the soil surface and factors that influence the amount of heat transferred along the soil profile [22, 23]. The factors that influence the amount of heat that reaches the soil surface are the colour of the soil surface [24], mulching [25], the amount of solar radiation [1,26,27] the slope of the soil surface [28,29], the vegetation cover [30,31], the organic matter content of the soil [32] and the intensity of evaporation from the soil surface [33, 34]. The amount of radiation received by the soil affects soil temperature, biological processes such as: seed germination, seedling emergence, plant root growth and nutrient availability. Factors influencing the amount of heat dissipated from the soil down the profile are moisture content and bulk density [35]. Soil temperature changes the decomposition rate of organic matter and mineralization of various organic materials in the soil. Soil temperature also affects the retention, transmission and availability of soil water to plants. There was no effect of temperature on vegetation projective cover at the community level, which was due to contrasting effects at the population level [3]. Soil thermal regime is one of the most important factors in soil formations [36] and living conditions for terrestrial biota [37, 38]. A significant horizontal variation in the temperature of the upper soil horizons was found, which in forest ecosystems is related to the spatial heterogeneity of the tree stand and the understorey [39, 40]. The studies of temperature fields with long time series began with the advent of programmable sensors. Most of these studies are related to the task of determining the properties of agricultural land [41], or accompany a study of soil processes, e.g. salinity [42]. The spatial variability of the soil temperature regime of natural communities is related to the thinness of the forest cover [43] and shrub canopy, with local soil properties. There are also studies devoted to the problem of spatial variation of soil temperature [44] and analysis of spatial and spatio-temporal temperature fields [45]. However, such studies are rare, and the nature of spatial variation in soil temperature for many areas and terrestrial ecosystems remains unknown.

2. Research aim and objectives

Parkland has important ecological functions in the urban environment [46–48]. The degree of transformation of ecological systems under the influence of anthropogenic pressure is characterised by the concept of hemeroby [49, 50]. In addition to factors influencing the urban environment, park areas are also influenced by the recreational function [51–53]. To some extent, the function of recreation and other ecological functions of urban parks are antagonistic [54, 55]. Obviously, in the management of parkland it is necessary to look for the optimal solutions, as a result of which the parks can effectively perform both ecological functions and be an area for recreation. In this aspect, the role of the soil temperature regime of park plantations is a key one, but one that has been little researched.

The aim of the work is to reveal the patterns of spatial variation of soil temperature in a city park at the different scale levels.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012056 doi:10.1088/1755-1315/1049/1/012056

3. Material and methods

The research was conducted from 18 November 2021 to 3 January 2022 in Oak Grove Park (Zaporozhye, Ukraine). The park (47°48´C 35°10´B) was founded on 1 May 1959. In the park, apart from the oaks, there is a variety of flora. The total area of the park is 57 hectares of forest, of which five hectares are classified as natural reserves. The soil temperature was measured within the polygon, which consisted of 10 transects of 20 measuring points each. The distance between the measuring points in the transect was 2 metres. The distance between the transects was 2 metres. Thus, the experimental polygon was a regular grid with 2×2 meter cells of 10×20 meters in size. The temperature measurements were taken during the day between 12pm and 1pm, at a time when the change in daytime temperature was the smallest. The measurements were made in the soil at the depth of 3-4 cm with an electronic thermometer on November 18 and 28, December 7, 12, and 20, 2021 and January 3, 2022.

The descriptive statistics and principal component analysis were performed using Statsoft 12.0 software. The variogram parameters were calculated and mapping was performed in Surfer 15.0 software.

4. Results

During the study period, precipitation fell on 47.8% of days. Daily precipitation ranged from 0.1 to 13 mm (figure 1, A). Air temperature varied from -16.3 to +17.6°C. Mean daily temperature ranged from –9.15 to +12.3°C (figure 1, B). The general trend of temperature change was a seasonal temperature decrease with significant temperature variations over a short period of time. Thus, drops in mean daily temperatures of 12–15°C occurred in 3–4 days in some cases. Clear skies occurred 11.3% of the time. Fog occurred 4.9% of the time. Cloudiness range of 3–6 was 14.7% of the time, while cloudiness of 8 was 10.7% of the time, cloudiness of 9 was 34.0% and cloudiness of 10 was 24.4% of the time.

Soil temperature varied within a much narrower range than air temperature (table 1). There was no correlation between soil temperature and air temperature measured with a lag of one day to 7. The lowest soil temperature was recorded on November 18 and it was 1.99±0.06°C. The highest soil temperature was recorded on December 7 and was 3.16±0.04°C. The range of variability of soil temperature within the polygon was 2.5–4.3°C. The distribution of soil temperature indices within the polygon was symmetrical, except for December 20, when the distribution was shifted to the left (figure 2). The distribution was kurtosis-free on 18 November, while on the other dates the distribution was negative kurtosis, indicating bimodality.

Table 1. Descriptive statistics of soil temperature variability and results of principal component analysis.

Date	Mean ±st.error	Minimum	Maximum	CV, %	Skewness ±st.error	Kurtosis ±st.error	PC1 λ=2.8, 47.6%	PC2 λ=1.8, 30.2%
18.11.2021	1.99±0.06	0.10	4.20	40.13	0.21±0.17	0.08±0.34	–0.58	–0.68
28.11.2021	2.81±0.05	1.40	4.50	26.07	0.21±0.17	–0.65±0.34	–0.36	–0.78
07.12.2021	3.16±0.04	1.90	4.40	19.92	0.02±0.17	–0.73±0.34	–0.74	–0.43
12.12.2021	2.93±0.05	1.20	4.50	24.75	0.05±0.17	–0.66±0.34	–0.73	0.42
20.12.2021	2.52±0.05	0.90	4.20	30.13	0.32±0.17	–0.47±0.34	–0.84	0.36
03.01.2022	2.17±0.07	0.00	4.30	46.45	–0.20±0.17	–0.80±0.34	–0.78	0.49

The principal component analysis allowed the extraction of two components whose eigenvalues exceeded unity.

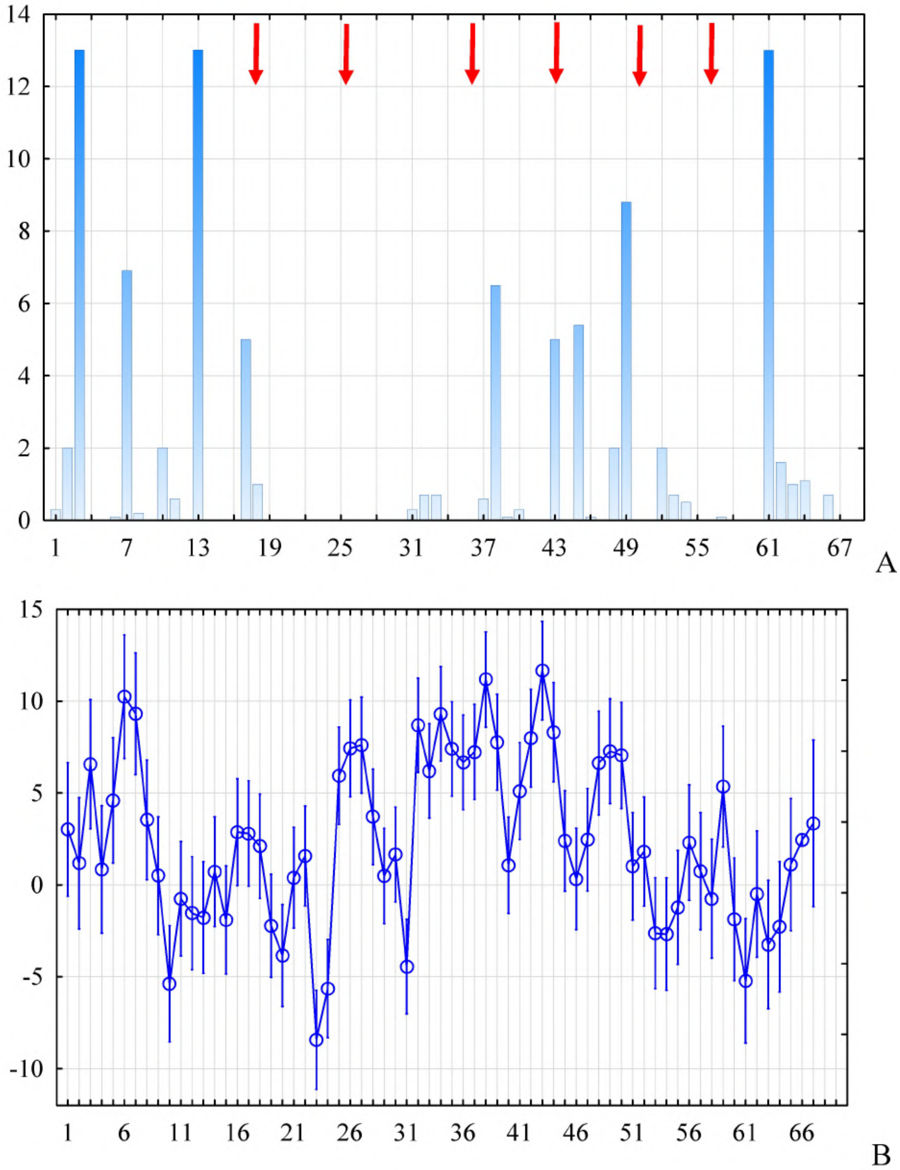

Figure 1. Dynamics of mean precipitation and mean daily temperature in the study area. Abscissa 1 shows November 1, 2021; 2 and following are subsequent dates; axis of ordinates are daily precipitation, mm (A) and mean daily temperature, °C (B). Arrows show soil temperature dates: November 18 and 28, December 7, 12, and 20, 2021 and January 3, 2022.

The principal component 1 described 47.6% of the variation in soil temperatures. The temperature values for all survey dates had a high correlation with this principal component of the same sign. Thus, the principal component 1 reflects a time invariant pattern of soil temperature variability. The principal component 2 describes 30.2% of the variation in temperature indices. The correlation coefficients with this principal component show a stable trend of variability over time. In the initial stages, the measurements showed negative correlation coefficients with PC2. The correlation coefficients changed to positive over time.Thus, the principal component 2 reflected the temporal aspect of this soil temperature variability.

The variograms showed the presence of a spatial component of soil temperature variation (figure 3). The variogram parameter range decreased consistently with time from 27.1 to 18.6 m (table 2). The spatial dependence level (SDL) decreased with time from 77.6 to 57.4%. The general pattern of soil temperature variability was very stable over time (figure 4). The PC1 variation pattern was characterised by a range which was 14.8 m and the SDL was 74.7%. The spatial variation of PC1 displayed a time invariant pattern of soil temperature (figure 5).

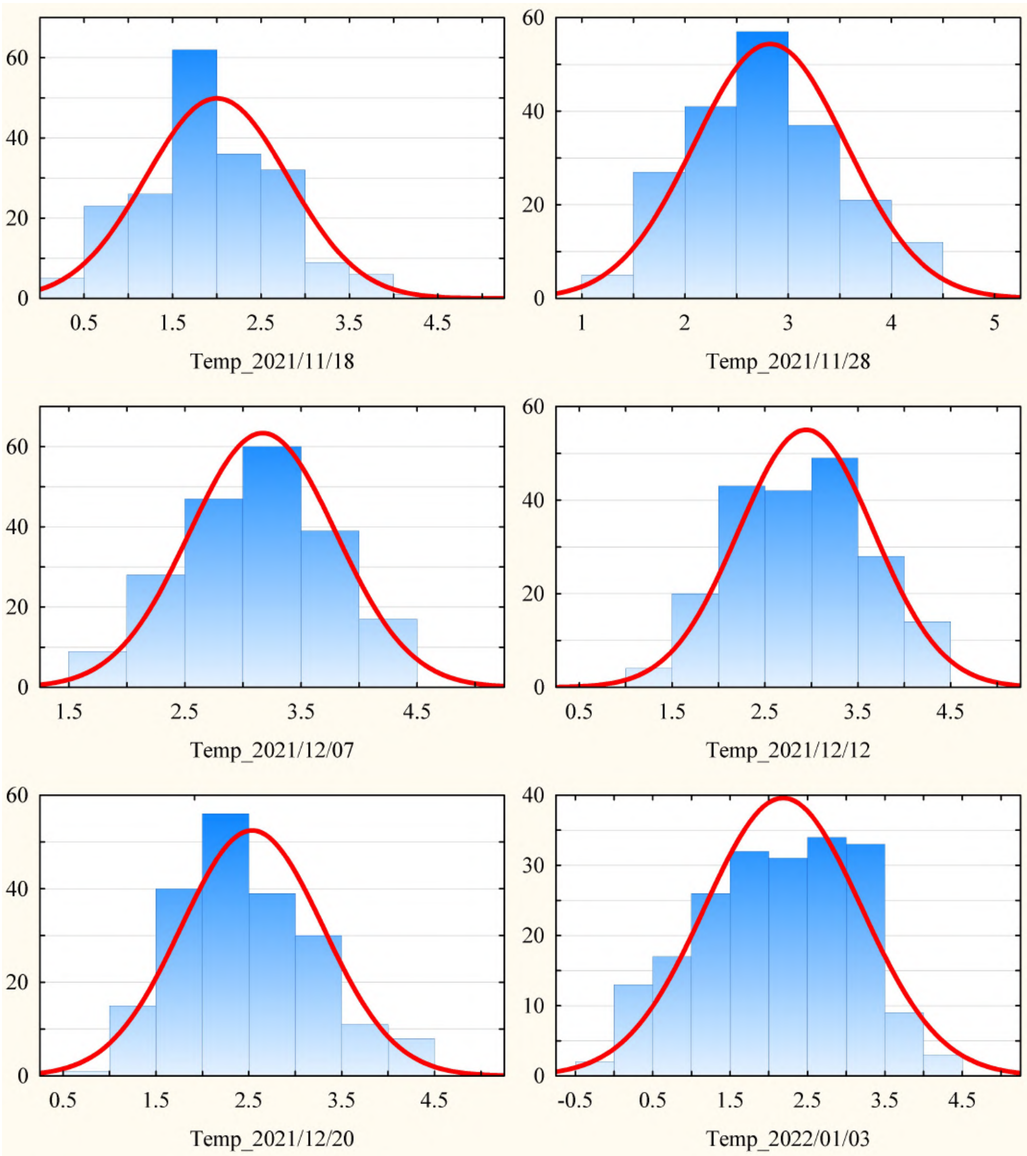

Figure 2. Histograms of the distribution of soil temperature indicators on different dates.

The PC2 variogram was characterised by a Range that was 12.7 metres and the SDL was 66.3%. The spatial variation of PC2 displayed a time-variant soil temperature pattern.

5. Discussion

During the study period, air temperature showed considerable variability, whereas soil temperature was subject to much less variability. The coefficient of variation of air temperature was 237%, while the level of variation of the soil temperature was much less and ranged between

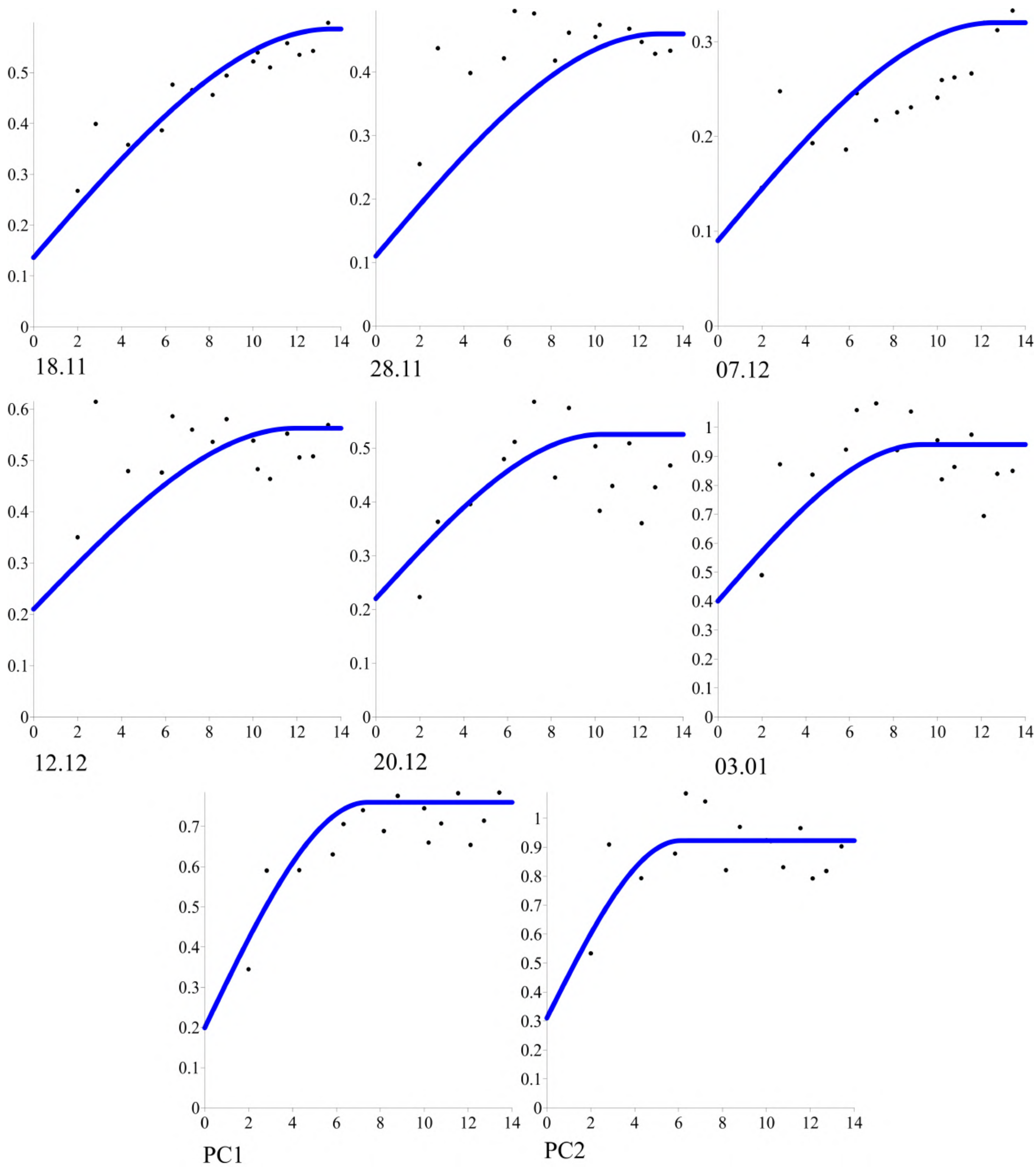

Figure 3. Variograms of the soil temperature indicators on different dates (November 18 and 28, December 7, 12, and 20, 2021, and January 3, 2022) and the values of the principal components 1 and 2. Abscissa axis is lag (m), ordinate axis is semivariation. Spherical model.

19.9–46.5%. No correlation between the soil and air temperature was found. This is due to the fact that the studies were conducted in the cold period of the year, when the seasonal trend of air temperature change was stabilized and the main aspect of variability of meteorological conditions were significant temperature fluctuations, when short-term periods of warming alternated with periods of abrupt cooling.

Table 2. Parameters of variogram of spatial variation of soil temperature and principal components 1 and 2. SDL – spatial dependence level calculated as ratio of Partial sill to the sum of Partial sill and Nagget (in %).

Parameter	18.11	28.11	7.12	12.12	20.12	03.01	PC1	PC2
Nagget	0.13	0.11	0.09	0.21	0.22	0.40	0.19	0.31
Partial sill	0.45	0.35	0.23	0.35	0.31	0.54	0.56	0.61
Range, m	27.1	25.8	25.1	23.8	20.5	18.6	14.8	12.7
SDL, %	77.6	76.1	71.9	62.5	58.5	57.4	74.7	66.3

The soil should be noted to have a high heat capacity, which provides considerable stability over time of the soil temperature regime. Soil is a powerful heat reservoir, acting as an energy store during the day and a source of heat through surface radiation at night During the warm season the soil accumulates energy and during the cold season the soil radiates it to the atmosphere [56]. The soil temperature depends on the ratio of energy absorbed and energy lost from the soil [57,58]. Soil temperature oscillates over the course of the year and every day due to fluctuations in air temperature and solar radiation [56,59]. The overall trend of soil temperature variability corresponds to the seasonal climate variability: the soil temperature is generally decreasing, but the rate of this decrease is very low and much less than the air temperature variability. The decline is not monotonic, but deviations from the decreasing temperature trend are much smaller than large variations in air temperature. Urban green spaces are regarded as a suitable way of reducing the urban heat island effect and providing comfort for residents. In addition to cooling the actual space, urban green spaces are also capable of affecting the surrounding area, a phenomenon called the urban green space cooling effect [60]. Our results provide a broader perspective on the influence of parkland on the temperature regime of urban environments. Our results indicate that the soil of the park plantation acts as a stabiliser of the temperature regime of the urban environment. The positive soil temperature preserves the possibility of biological processes in the soil. Previous findings indicate that winter climate change will be a key driver of nitrogen dynamics in forest ecosystems over the next 50–100 years, with important consequences for ecosystem productivity [61]. The diversity of soil macrofauna in winter is strongly correlated with soil temperature and microbial biomass, and the abundance of soil macrofauna correlates significantly with the water content of the soil. Vegetation type and soil microbial dynamics have a strong influence on the diversity of soil macrofauna communities in winter, which further influences soil nutrient cycling and ecological processes [62]. The biological processes in winter in the conditions of the steppe zone of Ukraine occur at a sufficient level of moisture due to both the seasonal maximum of precipitation and a much lower level of water evaporation from the soil surface, which is proportional to the soil temperature. The favourable moisture conditions create a combination of aerobic and anaerobic conditions in the soil, which is most likely to promote the activity of humification and carbon sequestration processes in the soil.

The soil temperature field in the park plantation is not uniform and has a spatial regularity that results from the superposition of two components: the spatial component, which is invariant in time, and the spatial component, which indicates the varying intensity of temperature variability processes over time. This result is of particular importance because an increase in paired soil temperature difference between sites stimulates greater species turnover in plant and invertebrate communities [3]. The overall trend of decreasing temperature coincides with the trend of decreasing spatial component of soil temperature variability. When explaining the

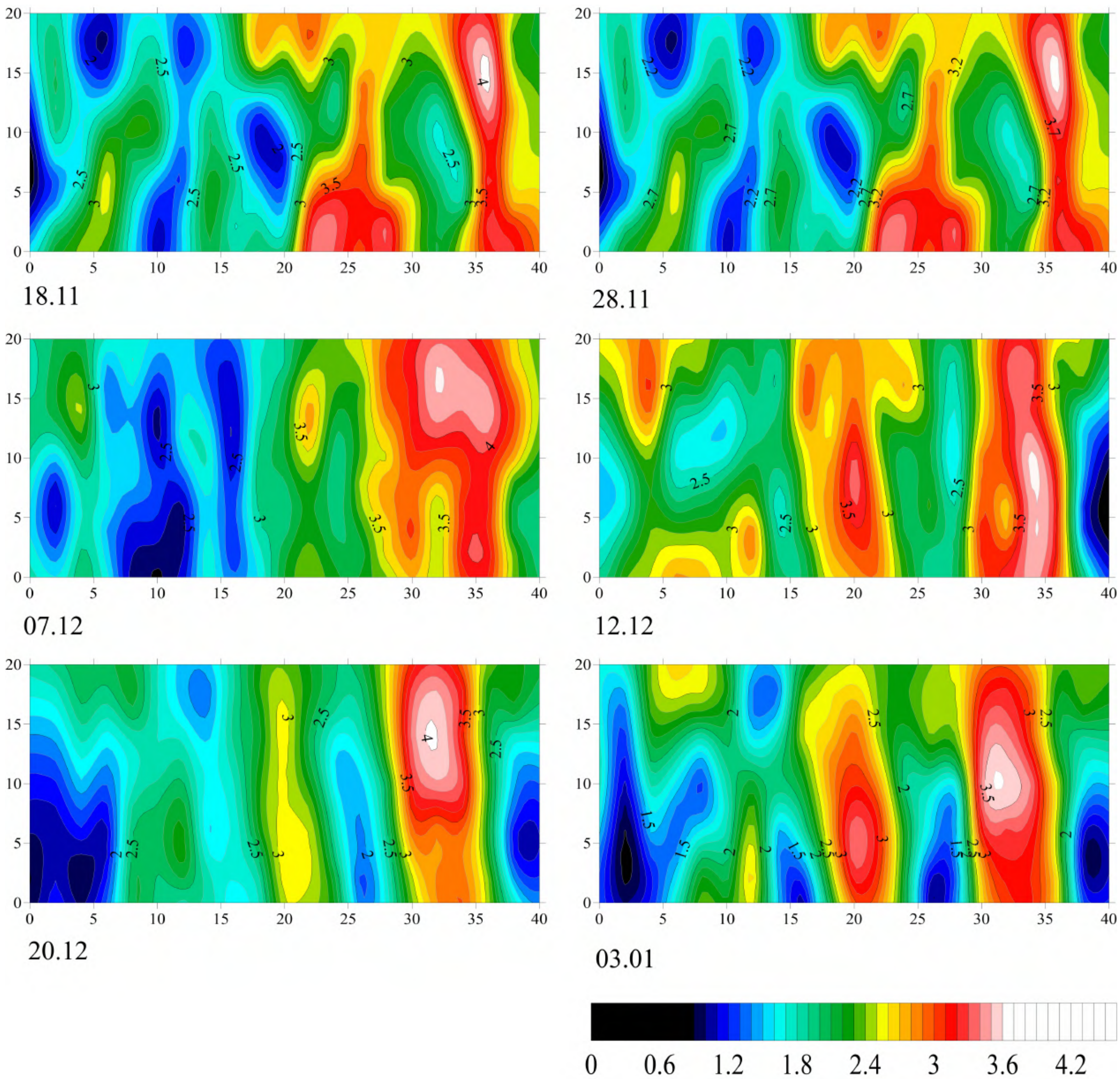

Figure 4. Spatial variation in temperature within polygons.

spatial heterogeneity of the soil temperature field, the factors of soil properties heterogeneity come to the fore. In warm seasons, the factors that redistribute solar energy to the soil surface are crucial. These include the structure of tree crowns, shrub and grass cover, and forest litter. In late autumn and winter, the role of solar radiation as a factor of soil thermal regime is greatly reduced. We found that fog and cloud cover of 8-10 points were observed 74.1% of the time. Moreover, it should be noted that in deciduous forest stands, the role of tree crowns as a factor distributing solar energy strongly decreases after the fall of leaves. An increase in soil temperature resulted in a decrease in the mean body mass of invertebrates and an increase in the total invertebrate community, which did not result in an overall change in community biomass [3]. Thus, the study of soil spatial heterogeneity in late autumn and winter allows us to evaluate the role of soil factors in forming spatial temperature patterns.

The soil thermal conductivity depends on the ratio of solid, liquid and gaseous soil phases.

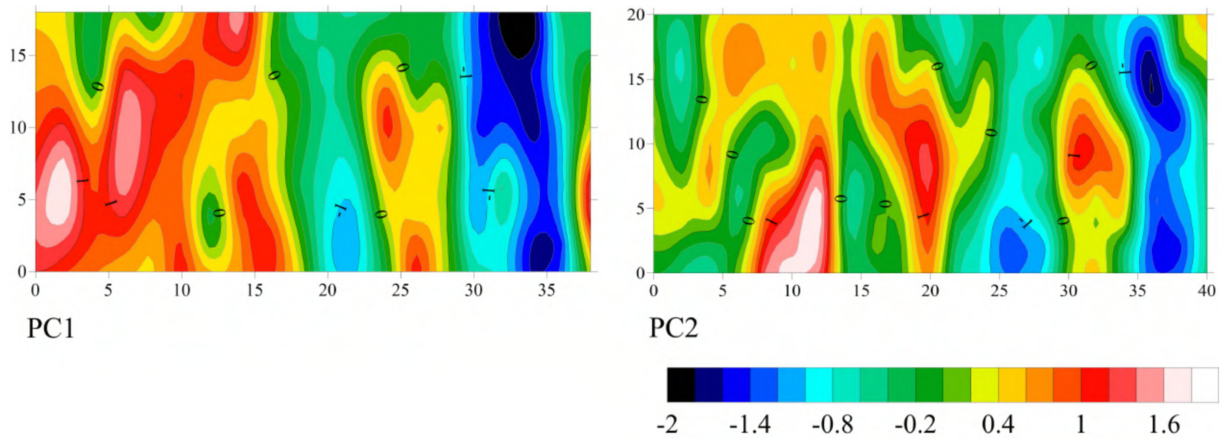

Figure 5. Spatial variation in the invariant component of temperature variability (principal component 1) and temporal component (principal component 2).

Accordingly, we can explain the spatial patterns of soil temperature by the heterogeneity of the soil phase ratio, which is reflected in soil indices such as density, compactness and moisture content. The recreational load and technological processes in the park plantation are significant factors that influence the physical condition of the soil cover. Also important is the relaxation potential of the soil after recreational load, which depends on the granulometric and aggregate structure of the soil, the organic matter content and the activity of the soil biota. Also drivers of soil property variability are trees, which transmit wind energy through trunk oscillation to the root system, and oscillation attenuation energy causes changes in physical properties as the trees move away from the trunk. A positive stable soil temperature maintains conditions for active soil animals, which change soil properties as they burrow and involve dead organic matter in the soil profile. The activity of terrestrial biota decays after the onset of late autumn, but the activity of soil animals in the soil continues into winter, all the more so as the observed soil temperatures were positive.

Anthropogenic and natural factors in the park can alter the microrelief of the soil [63], which affects the redistribution of moisture [64,65]. The role of water increases considerably in the arid zone in winter, when rainfall is much higher than in summer. As a rule, the intensity of rain at this time is low, but drops of light rain have a greater destructive power than drops of intense rain, because in the latter case, intense rainfall results in a thin layer of water covering the soil, which has a protective function. In low-intensity rainfall, no protective layer of water is formed, the soil aggregates are destroyed and the soil is crusted due to colmatation [66]. The soil crust has a poor capacity for water infiltration, so it activates the lateral runoff [67], which greatly increases the role of microrelief as a factor regulating the distribution of moisture in space [68]. The role of recreational load, which leads to an increase in compactness and deterioration of the water-physical properties of the soil, should also be noted. The above-mentioned processes can explain formation of spatial temperature variability stable in time, which are described by PC1.

The occurrence of the principal component 2 reflects the existence of soil zones that differ in their cooling/heating dynamics over time. It is most likely that this difference can be explained by the unequal thickness of the leaf litter, which has a considerable thermal isolating capacity and affects the thermal regime of the soil [69]. Obviously, areas with a higher litter thickness will change their temperature more slowly, while areas with less or no litter thickness will cool more quickly or heat up more quickly [70]. The litter thickness depends on its redistribution within the space. Generally, the litter thickness is higher in the micro-depressions where the leaf litter accumulates. Also the thermal isolating capacity of the litter depends on its degree of compactness and moisture content. The compactness changes under the influence of recreation and as a result of trophic activity of soil animals. Soil animals also regulate the litter storage, as they constantly macerate the litter or involve it in the soil profile [71]. The results allow us to determine the prospects for further research. Obtaining information about the spatial variability of the soil temperature fields of the park plantation during the whole year is undoubtedly necessary. We surveyed only a fragment of the end of autumn and beginning of winter. The observation of temperature dynamics under different meteorological conditions and at different phenological stages of living cover dynamics is important. It is necessary to clarify the role of the stand in the formation of temperature fields in different seasons of the year. In this regard, it is advisable to map the location of trees on the trial polygon and measure crown density and passing solar energy. It is also necessary to measure spatial variability of forest litter thickness and use the data obtained to explain spatial patterns of soil temperature. Information on soil properties such as moisture, density, soil penetration resistance, soil conductivity and aggregate structure can be expected to provide a better understanding of soil temperature variability processes.

6. Conclusion

The soil temperature regime is characterised by a significant level of stability compared to air temperature. The soil temperature fields in an artificial park plantation are characterized by spatial patterns of a complex nature. The temperature field presents a spatial component that is invariant to time. It is most likely that the spatial variability of soil properties induced by natural factors and recreation are the cause of the generation of this pattern. Also in the soil temperature field there is a spatial pattern, which reflects the different sensitivity of the soil to the seasonal trend of temperature change. The generation of this pattern is due to the different insulating capacity of the forest litter in the park plantation. The results obtained point to the important role of leaf litter as a factor in the dynamics of the soil temperature regime. It is hypothesized that leaf litter in the park contributes to the enhancement of carbon sequestration during winter time.

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To cite this article: O O Khromysheva and O V Yakoviichuk 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012057

Influence of organic and inorganic precipitators on the efficiency of surfactants extraction from wastewater by flotation

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Abstract. The chemical structure of surfactants causes their accumulation on the surface of water sources and leads to the formation of stable foam, which prevents the access of oxygen to the water and leads to the death of hydrobionts and deterioration in water quality. Therefore, the extraction of surfactants from wastewater is an urgent task. Increase the efficiency of flotation extraction of cationic surfactants, namely hexadecyl pyridinium chloride $[C_{16}H_{33}NC_5H_5]Cl$ (CHDP) and surfactants based on it - cetazol, by introducing organic – (sodium alkyl sulfate (SAS), $C_nH_{2n+1}OSO_3Na$, n=10-16), and inorganic - potassium hexacyanoferrate (II, III) precipitators. The solubility of the products of interaction of cationic surfactants with SAS (sublates) was determined, which are extracted from solutions at different temperatures and impurities of electrolytes. The Gibbs free energy (ΔG^0_{ads}), enthalpy (ΔH^0_{dis}), and entropy (ΔS^0_{dis}), which take place in the process of dissolution, are calculated. The low value of the heat of dissolution (2.1-16.6 *kJ/mol*) indicates a small effect of temperature on the solubility of sublates. The thermodynamic analysis of the process of formation of sublates allows determining the optimal length of the hydrocarbon radical of the precipitator. It is established that the extraction of the studied cationic surfactants should be extracted from water solutions and wastewater by the method of precipitation flotation using organic and inorganic precipitators. The presence of electrolytes and an increase in temperature leads to an increase in the degree of extraction hexadecyl pyridinium alkyl sulphonates sublates.

1. Introduction

Currently, water quality and safety have become one of the most troubling environmental issues. A third of the world's drinking water demand is provided by surface sources: lakes, rivers, and canals [1, 2]. At the same time, these sources of freshwater also serve as a reservoir for domestic and industrial wastes. At the same time, surface water is used as a source of drinking and domestic water [3]. In developing countries, wastewater is treated and reused for agricultural irrigation, surface water recharge, and even as drinking water [1, 4]. Therefore, surface water must be cleaned of contaminants before use, and water reuse requires higher quality wastewater to ensure water safety, especially for the control of microbiological pollutants, surfactants, metals, and other harmful substances [2, 5].

The main sources of water pollution are untreated and incompletely treated wastewater. Emissions of industrial wastewater contaminated with technical surfactants (surfactants) have led to a critical state of surface water sources in Ukraine, which has been formed for a long time due to neglect of objective laws of development and reproduction of natural resources of Ukraine. When entering the water, the most widespread surfactants interfere with biologic oxidation processes and inhibit their self-purification. As a result, sanitary and chemical indicators of water quality deteriorate - dry matter increases, oxidation, and chemical oxygen demand increase. In addition, the water acquires an unpleasant taste and odor if it contains surfactants [6,7]. Surface water is one of the most impacted ecosystems on Earth, and its changes have led to extensive environmental degradation, such as reduced water quality and availability, species extinction, waterlogging, reduced biodiversity [8].

According to current international standards, a lot of surfactants are classified as the third and fourth class of hazard and therefore their content in open water and wastewater, which are used for biological treatment, is regulated. There is a need for improvement of existing and development of new methods of wastewater treatment of technical wastewater, which is quite a complex technological task. The flotation method deserves special attention, as it is notable for its simplicity, cost-effectiveness, high productivity and widely implemented in practice [9]. Flotation is known as a separation process based on the introduction of gas bubbles as a transport medium. The suspended particles, being hydrophobic or hydrophobic conditioned, then attach themselves to the bubbles and move toward the surface of the aqueous solution [8, 10]. This method has a number of modifications both by the type of bubble formation and by the presence of additional components (reagent and nonreagent). Initially, this method was used in the mining industry, but later the method has found wide application in other industries and demonstrates high results of wastewater treatment from various pollutants [8]. n this regard, the development of ideas about the patterns of flotation removal of technical ionic surfactants is relevant from both scientific and practical points of view and allows to expand basic knowledge and provide a scientific basis for improving wastewater treatment technology contaminated with harmful substances.

The aim of the work is to improve the flotation extraction of cationic surfactants based on N-hexadecyl pyridinium from aqueous solutions and wastewater, by introducing inorganic and organic reagents, and thermodynamic justification of their choice.

2. Research methods and materials

2.1. Object of research and staging of the experiment

The objects of research are N-hexadecylpyridinium chloride $[C_{16}H_{33}NC_5H_5]Cl$ (CHDP) and technical surfactants based on it - cetazole, which is widely used in industry. Sodium alkylsulfates (SAS) with the formula $C_nH_{2n+1}OSO_3Na$ (where n=10-16), were used as precipitators. Model surfactant solutions were prepared by dilution in bidistilled water. The solubility of sparingly soluble products of the interaction of cationic surfactants with sodium alkyl sulfates (sublates) was determined by the turbidimetric method. Below are the results of the research aimed at determining the basic regularities of the flotation separation process of hexadecyl pyridinium chloride (1.5-5)*10^{-4} mol/dm^3) and cetazole (50 mg/dm^3) precipitated by sodium alkyl sulfates at a concentration below the critical concentration of myceloid formation. Their choice was conditioned by their availability and biological quality [9]. To determine the effect of electrolytes on the solubility of sublates, a salt ($NaCl$) solution with a concentration of 5,0*10^{-4} mol/dm^3 was used as an electrolyte. SAS solutions were injected into CHDP and cetazol solutions at continuous mixing in the quantity required for the formation of sparingly soluble substances (hexadecylpyridinium alkyl sulfate - HDPAS) 1-2 minutes before the start of flotation. The interaction of SAS and CHDP solutions proceeded rapidly for 1-2 minutes and was accompanied by the formation of sparingly soluble HDPAS colloidal and semi-colloidal degree of dysfunction in accordance with $C_{16}H_{33}C_5H_5NOSO_3R^1$, where -$R^1$ is a hydrocarbon radical (CH_3-CH_2-).

2.2. Flotation extraction parameters and evaluation of its efficiency
Flotation treatment of surfactant solutions was performed on the unit, the main element of which was a 0.140 *m* high glass column of 0.045 m diameter. The bottom of the column and air disperser was a glassy crusty plate. The air was supplied to the column at a speed of 2.5-5.8*10^{-7} m^3/s. The volume of surfactant solution poured into the column was 3*10^{-2} dm^3, flotation time 600 *s*. The efficiency of the flotation separation process of surfactants was evaluated by the degree of their separation from the solution (α).

$$\alpha = [(c_p^0 - c_p)/c_p^0] * 100 \tag{1}$$

where c_p^0 and c_p - surfactant concentration in the solution, before and after flotation.

Each measurement was repeated 5-6 times to obtain statistically significant results. The measurement error of the degree of flotation purification of HDP and cetazole α did not exceed 5 %.

2.3. Determination method of surfactant content in solution
The surfactant content in the solution was performed by photometric method which is based on the interaction of cationic surfactants with methyl orange and the formation of a chloroform-soluble yellow complex. The color intensity of the chloroform solution is proportional to the concentration of the methyl orange-cationic surfactant complex and is measured photometrically. To determine the surfactant concentration, aliquots of the test solution are placed in a separatory funnel and diluted with distilled water to 50 *ml*. Add 1 *ml* of methyl orange (0.1 %), 5 *ml* of citrate-phosphate buffer solution (pH = 3.0) and 25 *ml* of chloroform. Close the separating funnel with a stopper and shake it for 30 seconds. Allow the sample to stand for 20 minutes. The chloroform layer is separated from the water and is at the bottom. Place the filter funnel over a clean cuvette (thickness of the absorbed layer 5 *sm*) and filter the chloroform layer through fiberglass to remove water from it. Collect chloroform extract in a cuvette. Determine the optical density of the chloroform solution at λ = 415 *nm* relative to pure chloroform. The equivalent surfactant content is determined by a calibration curve constructed for cetyldimethylbenzylammonium chloride [11].

3. Results and discussion
The solubility of mixed micelles sublates is low (table 1), and is determined by the length of the SAS hydrocarbon radical which is involved in their formation. And much less solubility of the compounds formed by the deposition of alkylpyridinium ions by inorganic precipitants [9] and with increasing temperature in the range of 20-40 ^oC decreases slightly, and then with increasing to 60 ^oC practically does not change. This can be explained by an increase in sublate particles formed by the interaction of hexadecylpyridinium chloride and cetazole with sodium alkyl sulfates, which dehydration of the particles causes [12]. At all temperatures from the solutions by flotation can be removed that part of the surfactant, which when introduced into the precipitator solution becomes part of the dispersed phase of the colloidal solution formed. With increasing temperature from 20 to 40 ^oC, solubility decreases slightly, then, with increasing to 60 ^{O}C practically does not change. The values of the free Gibbs dissolution energy (ΔG^0_{dis}), calculated according to the equation:

$$\Delta G^0_{dis} = -RTlnSP \tag{2}$$

are in the range 48.3-67.5 *kJ/mol* and increase with increasing temperature and the length of the SAS carbohydrate radical; entalpy

$$\Delta H^0_{dis} - lnS = -\Delta H^0_{dis}/(RT) + const \tag{3}$$

in the range - (2.1-16.6) *kJ/mol*; entropy

$$\Delta S^0_{dis} - \Delta S_{dis} = (\Delta H^0_{dis} - \Delta S^0_{dis})/T \tag{4}$$

in the range -140.2 - 165.3 *J/mol*K* and decrease with increasing temperature.

Table 1. Values of S (solubility), ΔG^0_{dis}, H^0_{dis} and ΔS^0_{dis} for the process of dissolving the products of the interaction of hexadecylpyridinium chloride and cetazole with sodium alkyl sulfates. **Note.** *-: SOS - sodium octyl sulfate; SS - sodium decyl sulfate; SDS - sodium dodecyl sulfate; STS - sodium tetradecyl sulfate; SHS - sodium hexadecyl sulfate; CZ - cetazole

Sublate	T,K	$S * 10^{-5}, mol/dm^3$	$\Delta G^0_{dis}, kJ/mol$	$\Delta H^0_{dis}, kJ/mol$	$-\Delta S^0_{dis}, J/mol * K$
*SOS	293	5.0	48.3	2.1	157.8
	303	4.8	50.1	2.1	158.5
	313	4.7	51.8	2.1	158.8
	323	4.6	53.6	2.1	159.5
	333	4.5	55.4	2.1	160.2
	293	3.0	50.7	2.1	144.7
	303	2.9	52.6	2.1	146.1
*SS	313	2.7	54.7	8.3	148.2
	323	2.7	56.5	8.3	149.2
	333	2.7	58.2	8.3	149.8
*SDS	293	2.7	51.5	9.7	142.6
	303	2.6	53.2	9.7	143.5
	313	2.5	55.4	9.7	145.9
	323	2.5	56.9	9.7	146.0
	333	2.5	58.7	9.7	147.1
*STS	293	0.9	56.5	16.6	136.1
	303	0.8	59.1	16.6	140.2
	313	0.7	61.8	16.6	144.6
	323	0.7	63.7	16.6	145.7
	333	0.7	65.7	16.6	147.5
*SHS	293	0.7	57.9	12.5	155.1
	303	0.6	60.6	12.5	158.5
	313	0.5	63.5	12.5	158.5
	323	0.5	65.5	12.5	158.5
	333	0.5	67.5	12.5	158.5
*SDS+CZ	293	1.2	55.2	8.3	160.0
	303	1.2	57.2	8.3	161.3
	313	1.1	58.9	8.3	161.6
	323	1.2	60.8	8.3	162.5
	333	1.3	62.3	8.3	162.1

The dependence of the solubility of the sublimate on the number of atoms (n) of carbon in the carbohydrate radical SAS is described by the equation:

$$lnS = A - (16 + n)B \tag{5}$$

Numerical values of coefficients A and B were determined experimentally and calculated theoretically:

$$A = (\Delta G_p^{0'} + \Delta G_p^{0''})/(2RT), B = -\Delta G_{CH_2}^0/2RT \quad (6)$$

(where $\Delta G_p^{0'}$, $\Delta G_p^{0''}$ - the contribution to the Ghibbs energy of the polar atom group of sublate formation; $\Delta G_{CH_2}^0$ - contribution to the methylene group of sublate formation), the values of 1.84 and 0.32 are well matched and equal, respectively. The obtained results indicate that SAS are quite effective precipitators and at the same time flotation collectors of the studied surfactants, which allows them to be used as precipitators and at the same time flotation collectors of cationic surfactants [9]. For all members of the SAS homologous series $|\Delta G_{form.subl.}^0| > |\Delta G_{form.collec.}^0|$ (therefore, they are able to interact with surfactants with the formation of sublates – mixed micelles), then $|G_{form.subl.}^0| > |\Delta G_{ads.}^0|$ (as a result, their flotation extraction takes place in the mode of foam flotation).

The point of intersection of the lines that describe the dependence of the intrinsic Ghibs energy of the SAS creation ($\Delta G_{form.collec.}^0$) and the intrinsic Ghibbs energy of adsorption ($\Delta G_{ads.}^0$) of SAS, depending on the length of the carbohydrate radical, which corresponds to sodium tetradecyl sulfate (n=14), coincides with the maximum point on the curve of the dependence of the degree of flotation isolation of HDPAS on the length of the carbohydrate radical SAS (figure 1).

This can be explained based on the notion of adsorption-mechanical energy ratio (AMER) of surfactants, which is described by the ratio of Gibbs free energy of surfactant adsorption at the solution-air interface to Gibbs free energy of their micelle formation in solution (AMER = $\Delta G_{ads.}^0$ / $\Delta G_{micel.}^0$), according to which the efficiency of the collecting action of the SAS is maximal at AMER=1 [13].

It should be noted that for the first time flotation purification of water from surfactants using molecular analogues (potassium alkylcarboxylates) of SAS as precipitators and flotation collectors of surfactants, was presented in Skrilov et al., 1998 [14]. His method allows to achieve the highest surfactant recovery in the foam fraction and reduce flotation time. Comparison of the obtained experimental values of using SAS with the prototype Skrylov et al. shows higher efficiency (up to 95 %) than the prototype using potassium alkylcarboxylates (80-90 %). In addition, the alkyl carboxylates used by the Skrylev group have higher biological rigidity, cost and low biodegradation. They also do not describe the effect of the presence of electrolytes on α [14].

Introduction to surfactant solutions containing HGDP sublates a small amount (1,0-3,5*10^{-4} mol/dm^3) of electrolytes into sublate solutions, somewhat reduces their solubility. The solubility of HDPAS is affected by both the concentration of the counterion (Na^+ - ions) and the nature of the electrolyte, which is associated with varying degrees of their dissociation (table 2).

One of the advantages of flotation extraction of surfactants in the form of sparingly soluble compounds, in contrast to their extraction in ionic or molecular form, is the ability to expand the range of pH values optimal for their flotation extraction, namely its displacement into the neutral area, which is always technologically feasible. The degree of flotation extraction of CHDP and cetazole in the form of sparingly soluble compounds practically does not change with pH varying, because the pH shift to strongly acidic or alkaline area does not significantly affect the solubility of compounds that are practically not hydrolyzed [12], and only changes in the colloid-chemical properties of sublates are observed.

The use of SAS as precipitators and at the same time flotation collectors, makes it possible to reduce the flotation time up to 5-6 minutes instead of 10 minutes, which on an industrial scale can save material resources. The Skrylev method with co-authors also involves reducing the flotation time to these values (5-6 *min*) [14]. The speed constants of the flotation extraction

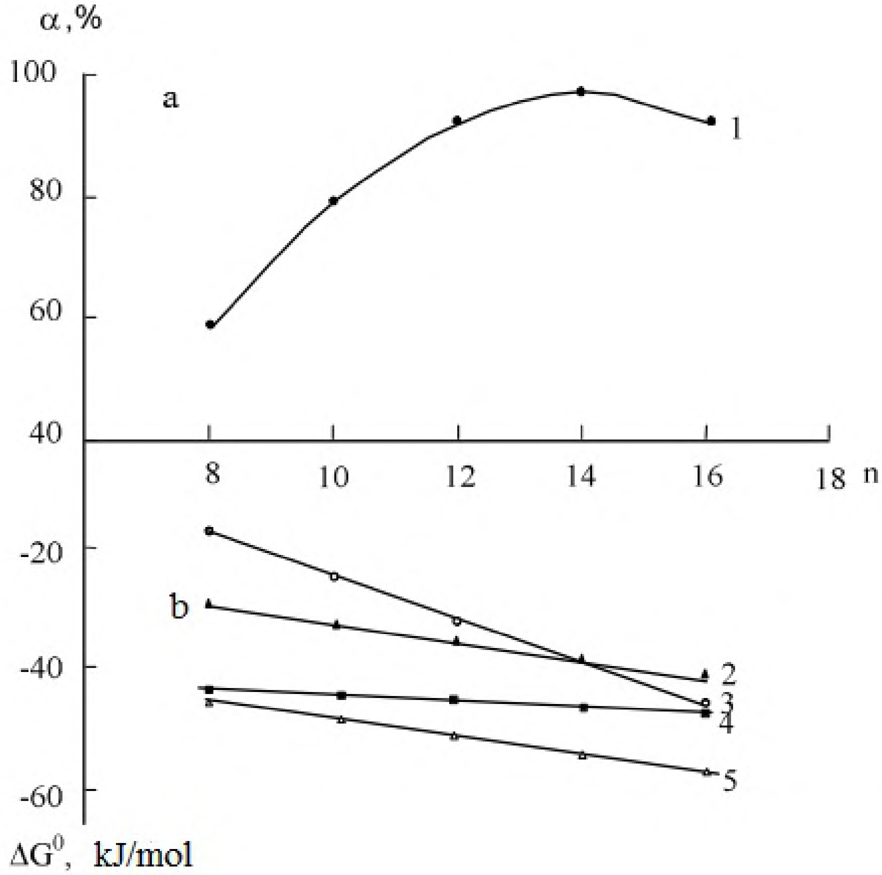

Figure 1. Influence of the number of carbon atoms (n) in the SAS carbohydrate radical on: – degree of flotation extraction (a) CHDP (1) and b - the Gibbs volatile energy of the SAS adsorption at the interface of the fluid-air phase $\Delta G^0_{ads.}$ (2), the Gibbs volatile energy of the SAS formation $\Delta G^0_{form.colec.}$ (3), free Gibbs energy adsorption sublate at the interface phase solution-air $\Delta G^0_{ads.subl}$ (4) and the free Gibbs energy of substrate formation $\Delta G^0_{form.subl.}$ (5).

of CHDP by SDS, STS, SHD and cetazole by SDS are large (table 3).

Based on the first obtained values of solubility of products of interaction of hexadecylpyridinium chloride with sodium alkyl sulfates without and in the presence of electrolytes in solution, we concluded that the process of flotation extraction of cationic surfactants from aqueous solutions using organic precipitants (sodium alkyl sulfates) is effective because: the degree of flotation extraction of hexadecylpyridinium chloride is maximum when introduced into a solution of sodium tetradecyl sulfate, the AMER of which is equal to one; reducing the solubility of hexadecylpyridinium-alkyl sulfates leads to an increase in the degree of flotation extraction of HDP^+ ions. n particular, it is established that the obtained laws allowed to move to scientifically sound methods of wastewater treatment from surfactants, as well as to identify and establish such methods of flotation that provide the greatest efficiency of the treatment process.

The efficiency of flotation extraction of the studied technical cationic surfactants can be increased by switching from foam fractionation to precipitating flotation, by introducing inorganic precipitators. Thus, the introduction into the surfactant solutions of electrolytes (potassium hexacyanoferrates III and II) (table 4), which form sparingly soluble compounds

Table 2. The effect of electrolyte solution (NaCl) additives on the solubility (S) of the interaction products (sublates) of alkyl sulfates (SAS) and cetazole (50 mg/dm^3).

Sublate	$C, mg/dm^3$	$S * 10^{-5}, mol/dm^3$
SOS + cetazole	0	4.3
	100	4.0
	200	3.8
	300	3.5
	400	3.3
	500	3.0
SS + cetazole	0	2.6
	100	2.2
	200	2.0
	300	1.8
	400	1.6
	500	1.4
SDS + cetazole	0	1.2
	100	1.0
	200	0.8
	300	0.6
	400	0.5
	500	0.4
STS + cetazole	0	0.4
	100	0.4
	200	0.3
	300	0.3
	400	0.3
	500	0.3
SHD + cetazole	0	0.3
	100	0.2
	200	0.2
	300	0.2
	400	0.1
	500	0.1

Table 3. Values of rate constants of extraction of hexadecylpyridinium chloride and cetazole with sodium alkyl sulfates

Sublate	SS	SDS	STS	SHS	CHDP	SDS+cetazole
Speed constants,*10 min^{-1}	4.6	5.8	6.3	6.9	4.2	5.2

with surfactants, intensifies the process of their removal by precipitation flotation (the degree of flotation recovery increases to 90 %, the volume of foam switched to solution, decreases to 1-5 % of the total volume of the solution, reduces the flotation time for technical cationic surfactants to 5 minutes, the range of pH values favorable for flotation extraction expands.

Table 4. The effect of potassium hexacyanoferrates III and II content on the degree of flotation extraction of cetazole. **Note.** Flotation time - 5 minutes.

Electrolyte	$C * 10^{-2}, mol/dm^3$	$\alpha, \%$
$K_3[Fe(CN)_6]$	0	75.0
	0.5	93.0
	1.0	92.0
	2.0	100.0
	3.0	100.0
	4.0	100.0
	5.0	100.0
$K_4[Fe(CN)_6]$	0	75.0
	0.5	94.0
	1.0	97.0
	2.0	98.0
	3.0	98.0
	4.0	100.0
	5.0	100.0

Elucidation of physicochemical regularities of the process of extraction of the studied cationic surfactants and thermodynamic analysis showed that they should be removed from aqueous solutions and wastewater by precipitation flotation using organic (SAS) and inorganic (potassium hexacyanoferrates III and II) precipitators. The presence of electrolyte ($NaCl$) and an increase in temperature leads to an increase in the degree of extraction of HDPAS sublates. The advantages of using precipitation flotation can also include a large pH range of purified water.

Thus, the method of precipitation flotation can be recommended for wastewater treatment containing both cationic surfactants and anionic after mixing, which does not require additional costs.

4. Conclusions

The solubility of the products of the interaction of cationic surfactants with sodium alkyl sulfates (sublates), which are extracted from solutions at different temperatures and impurities of electrolytes, has been established; the Gibbs free energy ($\Delta G^0_{ads.}$), enthalpy ($\Delta H^0_{dis.}$) and entropy ($\Delta S^0_{dis.}$), which take place in the process of dissolution, are calculated. The low value of dissolution heat (2.1-16.6 *kJ/mol*) indicates a small effect of temperature on the solubility of sublates. The thermodynamic analysis of the process of formation of sublates allows to determine the optimal length of the hydrocarbon radical of the precipitator. The high efficiency of the method for extracting surfactants from model solutions 75 – 100 % has been established, which in combination with the low cost of equipment, allows to recommend it for wastewater treatment from this type of pollutants.

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Capabilities of the WEBBIRDS system in the process of assessing the impact of wind farms on seasonal bird complexes on the example of spring migrants at the Botiieve wind farm in 2013-2021

To cite this article: V D Siokhin *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012058

Capabilities of the WEBBIRDS system in the process of assessing the impact of wind farms on seasonal bird complexes on the example of spring migrants at the Botiieve wind farm in 2013-2021

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Abstract. This paper contains the analyzed results of field observations of the spring migration of birds on the territory of the Botiieve wind farm in 2013-2021. The work was carried out as part of the planned monitoring of the ornithological situation in the area of the Botiieve wind farm (Pryazovskyi district, Zaporizhzhia region) and also covered the Tubal Estuary formed by the confluence of the Velyka and Mala Domuzla and Akchokrak Rivers and in the mouth of the Korsak River. During each trip, up to 70% of the wind farm area was covered. There were given characteristics of the taxonomic composition of the ornithocomplex, flight phenology, height and direction of migration by seasons and months. In the spring period of 2013-2021, 156,910 individuals of 125 species were recorded in the project area. 52,575 individuals of 92 species of these birds (33.5%) were observed directly within the Botiieve wind farm and buffer zones and there were recorded 104,335 individuals of 99 species (66.5%) at the adjacent wetlands - the Botiieve Ponds and the Tubal Estuary. New methods for collecting, storing and processing information, including mapping, server storage and data processing using two web applications, have been proposed. In order to describe in detail the migration processes in the local area, methods of vector mathematics, as well as computer vision algorithms, were used. The result of the analysis was a gradient map of seasonal bird migration concentration, which allows a differentiated approach to assessing the threats to birds from operating wind turbines. The impact of the Botiieve wind farm on birds during the period of seasonal migrations is estimated to be low.

1. Introduction

The need to adapt traditional methods of ornithological observations is due to the peculiarities of the behaviour of birds and their reactions in different phases of the annual cycle to the infrastructure of wind farms at the stages of planning, construction and operation of wind farms [1]. The ambiguous attitude to the development of wind energy, which is especially discussed among ornithologists [2–20], makes it necessary to critically study the versatile aspects of the interaction between operating wind turbines and birds [21]. The research, the result of which should be a conclusion obtained on the basis of personal experience, is improved by using software systems for statistical data processing. This requires taking into account modern analysis tools, such as multivariate correlation and regression analyses, construction and analysis of OLAP models, automatic expert systems, systems based on heuristic analysis algorithms, etc. [22–24]. Therefore, an independent software system was developed, which not only provides the user with the opportunity to receive versatile monitoring data, both in tabular and cartographic formats, but also contains tools for assessing the impact of the construction and operation of wind farms on birds.

The idea of creating a mechanism for automatic assessment of possible negative impact of wind turbine generators (WTGs) on birds with the developed author's method became the basis of the WEBBIRDS Computer Programme with the multithreaded Web-portal, which provides the process of transmission, storage, multilevel access and processing of information on the state of the seasonal ornithocomplexes on the research territories [25–27].

The WEBBIRDS system is designed as a web application that creates a single information network for all participants in the study of ornithological complexes, and which can be used simultaneously with a browser by several users using a mobile device with GPS capable to automatically determine the coordinates of observations. The system allows to quickly obtain up-to-date information about observations, both new and those recorded in the programme earlier, to work with data on bird species, changes in their numbers, flight altitude, types of migrations.

The main purpose of the study is to assess the impact of wind farms on the ornithological situation of a given territory through the element of the WEBBIRDS system called concentration gradient.

2. Materials and methods

Monitoring studies of the ornithological situation were carried out at the Botiieve wind farm in 2013-2021 according to generally accepted methods by carrying out special expeditionary trips using vehicle and pedestrian methods of bird census. During each trip, up to 70% of the wind farm territory was covered. Studies were also carried out on the Tubal Estuary, formed by the confluence of the Velyka and Mala Domuzla and Akchokrak Rivers and in the mouth of the Korsak River (figure 1). Until recently, ornithological research in the area between the Domuzla and Korsak Rivers was practically absent. The first report on the birds of the Korsak River was published by Chernichko I. and Falko A. [28]. In connection with the plans to build the Botiieve wind farm, the authors organize preliminary studies since 2010, and after the start of construction and commissioning of the wind farm (2012-2013), seasonal ornithological observations.

The research paper is based on the results of observations of spring migration as the most massive movement of birds against the background of maximum species diversity.

Using the tools of the WEBBIRDS mobile WEB-application with the saved data based on the results of field studies, tables and maps were generated to conduct a detailed analysis of the seasonal migrations at the Botiieve wind farm. The analysis of the presented results was carried out for certain seasons, using the necessary filters in the date format. The numerical, altitude and rhumb characteristics of the behaviour of the species recorded in the study area were obtained by choosing a specific species from the proposed list of birds from the wind farm site.

Data on migrations were entered into the WEBBIRDS application using the Birds Fly programme (author's development, certificate APS/9126-18122018 [25, 26]) through the active page, which made it possible to obtain in addition to distribution maps of recorded migrations, tables and graphs with migration directions, the ratio of the number of individuals to heights, as well as to analyze the impact of wind farms on migratory birds using a concentration gradient.

Data obtained during monitoring studies in 2013-2021 at the Botiieve wind farm were entered into the programme database and processed by the WEBBIRDS using the concentration gradient

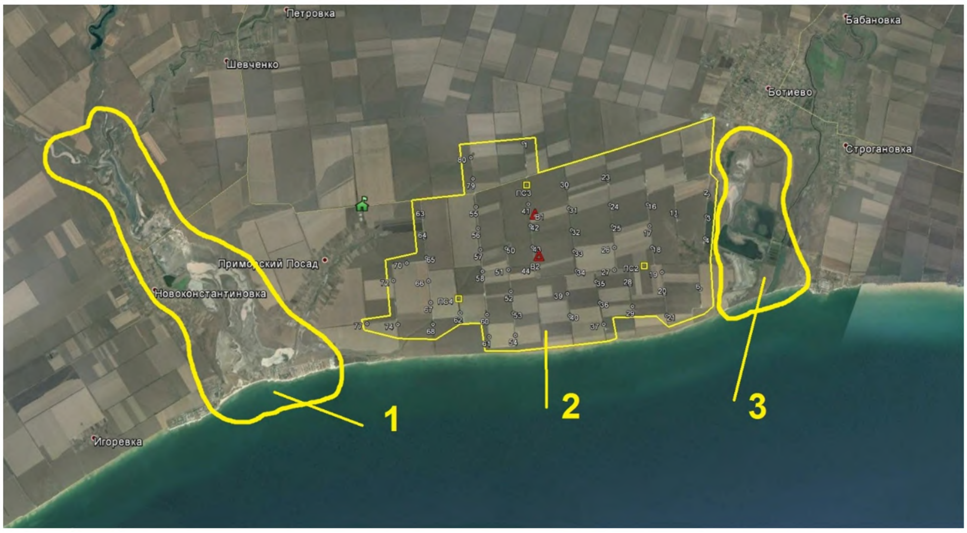


Figure 1. Area of research (1 – the Tubal Estuary; 2 – the Botiieve wind farm; 3 – the mouth of the Korsak River; ◯17 – wind turbines; △ – a meteorological mast).

analysis method. The method of analysis used in the work can be presented as a study of the concentration gradients of migration flows to assess their safety, which was done by the authors in previous studies [27].

Migration studies, assessment of their intensity, safety and impact on them, were carried out using the basic methods of vector mathematics, as well as algorithms used in computer vision. Since the migration process is directly related to the map data and is also being explored in a certain geographic area, computer vision tools such as image convolution, image filtering, and gradient delimitation allow analysis of critical areas of the map. If we define the geometric content of the vector, then this is a straight line segment for which limit points and a direction corresponding to the concept of bird migration are given. Vector analysis provides tools for the study of vectors, their features and allows you to perform operations on them.

Based on the results of research on the monitoring site of the Botiieve wind farm, included in the programme, a map is generated with vectors (figure 2) indicating the direction of the nearest migration in relation to a certain point on the ground, taking into account the influence of other, less numerous migrations. If the vector field showing the direction of growth of a certain value ϕ – gradient, then this is a concentration gradient, and having a map of the gradients of each field (figure 3), it is possible to determine the concentration gradients, which allow us to assess the impact of various factors on the migration flow.

Statistical processing of the material was carried out in Microsoft Office Excel 2007.

In addition, we adapted the generally accepted methods for specific areas of the wind farm, where studies are necessary to assess the degree of impact of operating wind turbines on birds [27, 29].

The accumulation and storage of the field data was carried out in a specially designed database of a server created for this purpose [30].

The algorithm of the model, designed as a web application, can be defined as follows:

(i) Representation of a set of observations of a bird or a flock migration as a set of vectors.
(ii) The calculation of the bases of the obtained vectors and determination of the weight coefficients.
(iii) The construction of concentration gradients for each vector.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012058 doi:10.1088/1755-1315/1049/1/012058

Figure 2. The working page of the WEBBIRDS programme in the BirdsFly application with a map with a three-dimensional representation of migrations recorded during the monitoring of the ornithocomplexes at the Botiieve wind farm in 2021.

(iv) The convolution of a geographical map.
(v) Overlaying the obtained gradients on the map with subsequent accumulation of values.
(vi) Filtering out insignificant gradient values.
(vii) Determination of areas of increased concentration of vector gradients.
(viii) Carrying out a differential analysis of each zone to identify its weight characteristics.
(ix) Interpretation of the weight characteristics on bird migrations passing in this zone.

Thus, the combination of classical field observations and server accumulation of long-term ornithological monitoring data in a specific area with the capabilities of two web applications not only characterize in detail the state of birds during migration periods, but also objectively assess the impact of the wind farm on ornithicomplexes [30].

3. Results and discussion

To compare the ornithological situation at the Botiieve wind farm, its buffer zones and adjacent areas of increased biodiversity (the Botiieve Ponds and the Tubal Estuary) during 2013-2021 (wind farm operation period), the spring period was chosen because in this region it is more significant than the period of autumn migration.

In general, the picture is clear: most of the birds, both sitting on the ground and flying in the air, were observed outside the territory of the wind farm. This trend is observed throughout all 9 monitoring years, with slight modifications, as shown in figures 4-7.

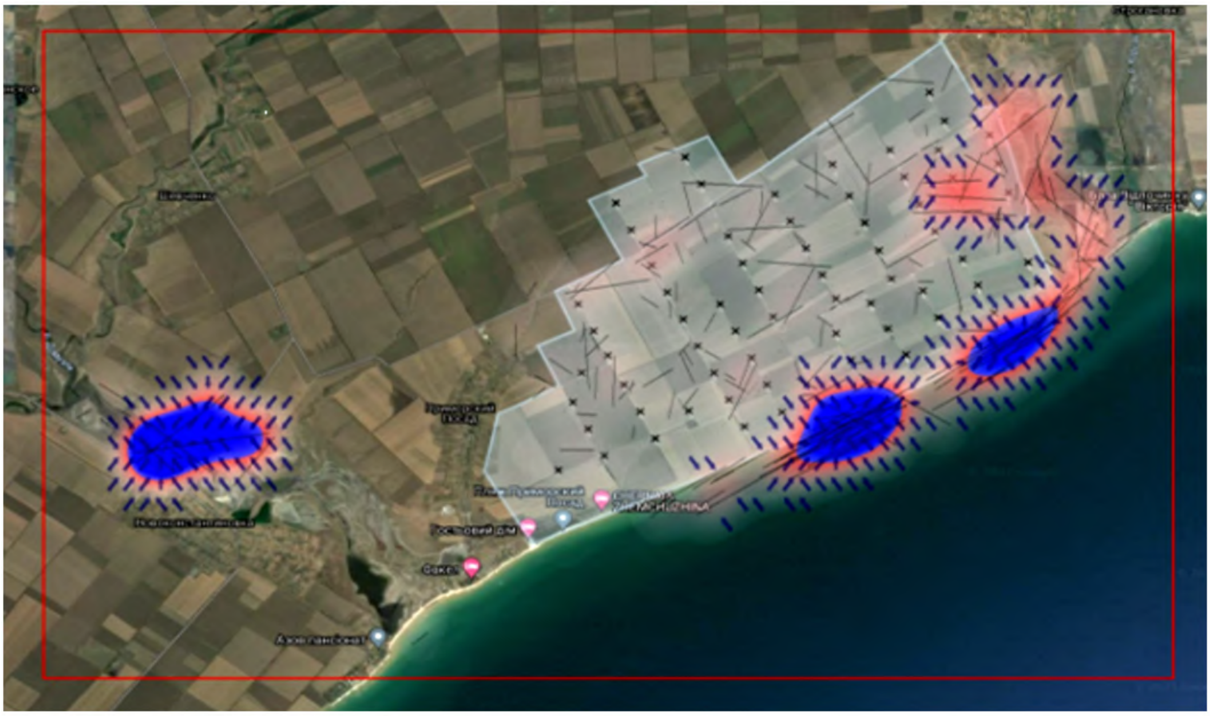


Figure 3. The map with the gradient vectors of each field in accordance with the concentration gradients according to the analysis of bird migrations at the Botiieve wind farm in 2021.

In 2013, the main concentrations of birds were observed on the Tubal Estuary, the Botiieve Ponds were in second place. Migrations were recorded mainly over the Azov Sea, at a distance of up to 2-2.5 km.

In 2014, the number of birds was significantly less (10,572 individuals against 19,741 individuals in 2013), and due to the fact that the period of existence of the water surface on the Tubal Estuary was much shorter and at the end of spring there was almost no water in most of the estuary, significant gatherings of birds were not formed here (unlike the Botiieve Ponds). However, we observe the growth of number of birds in the northern part of the wind farm site, near the WTG No 50. In spring 2014, 2 colonies of *Corvus frugilegus* were formed here, which in May consisted of 420 and 120 nests. Migratory movements of birds were carried out mainly outside the wind farm site, along the coastline of the sea, as well as in the area of the mouth of the Korsak River and the lower Botiieve Pond.

The weather conditions in spring 2015 led to the fact that the water level in the adjacent wetlands increased, and was the highest for the previous 3 monitoring years, which led to an increase in the total number of birds (24,862 individuals). Among the migratory birds, the most numerous was *Phalacrocorax carbo*, 7,625 individuals (or 63.1% of the migrants), which was noted southeast of the village of Prymorskyi Posad. In the second place among the migratory birds was *Corvus frugilegus*, 2,238 individuals, 18.5%. It is interesting that one flock of this species numbering 1,250 individuals flew in transit to the northeast at altitudes of more than 200 m along the coast of the Sea of Azov.

The following year, the number of birds was even greater (39,724 individuals), also due to the adjacent areas. On the territory of the wind farm birds did not form significant gatherings at all. 3,000 individuals of *Phalacrocorax carbo* were recorded in the sea on March 11, 2016 at a distance of up to 1.5 km from the wind farm site. On this day, *Phalacrocorax carbo* dominated among the migratory birds: 3 flocks with a total number of 1,104 individuals headed to the colony on the Obytichna Spit in the eastern direction.

In 2017, a total of 18,472 individuals were registered (15,879 individuals of them, 86.0%, were observed outside the wind farm site and buffer zones). As in 2016, no numerous concentrations of birds were observed on the territory of the wind farm, migratory movements were not intensive (1,075 individuals, 5.8% of the total number of birds).

In 2018, the picture was similar, although the number of birds decreased to 7,097 individuals. And only 873 of them (12.3%) were recorded in flight. We observe several places where the number of flying birds was higher. One of them was noted in the southern part of the wind farm, in the area of the WTGs No 53, 54, 60 and 61, and coincides with the registration of flocks of *Sturnus vulgaris*, which made forage and transit flights at altitudes outside the zone of risk collision with wind turbines. Another situation is observed in the northeastern part of the wind farm near the WTGs No 9 and 10 and is explained by the foraging flights of Corvus frugilegus from the colony located in the forest near the Botiieve Ponds to neighboring agrocenoses.

Observations in 2019 showed a continuation of the trend in the last 3 years. In total, 6,928 individuals were recorded, 1,034 individuals of them (14.9%) were registered as migrants. Gatherings of perched birds, except for the adjacent wetlands, were observed only in the waters of the Sea of Azov southeast of WTG No 37 (these were waterfowl birds - *Podiceps cristatus, Larus cachinnans, Anas querquedula, Aythya marila*), and also partially, in the area of the WTGs No 9 and 10 (*Corvus frugilegus*). Among the migrants, the most numerous were Larus melanocephalus, the flight of which was observed on April 24, 2019 east of the WTG No 37 over the coastline of the Sea of Azov, as well as the *Corvus frugilegus* and *Sturnus vulgaris* (in total, these 3 species accounted for 41.8% of migratory birds in spring 2019).

In 2020, the trend of previous years continued. In general, 14,638 individuals were recorded, only 8.7% (1,277 individuals) of them made flights. Traditionally, gatherings of mainly waterfowl birds were recorded in adjacent wetlands (mainly on the Botiieve Ponds), including the lower part of the Tubal Estuary, which is located between the villages of Prymorskyi Posad and Novokonstiantynivka, and a small number of them were observed in the the Sea of Azov near the WTGs No 37 and 21. *Corvus frugilegus, Larus ridibundus* and *Oenanthe isabellina* dominated among migrants, subdominants were *Hirundo rustica, Phalacrocorax carbo* and *Sturnus vulgaris* (these 6 species accounted for 73.9% of the total spring migratory birds). The most intensive flights were in the area of artificial afforestation at the Botiieve Ponds, as well as in the southern part of the wind farm.

And, finally, in 2021, 14,876 individuals were registered, a quarter of them 25.6% (3,808 individuals) were observed during flights. The vast majority of birds, 12,264 individuals, 82.4%, were recorded outside the territory of the wind farm (at the same time, the role of the adjacent territories was not the same - about 60% of birds were recorded on the Tubal Estuary, and only 40% on the Botiieve Ponds; unlike last year when the situation was the opposite). Among the migrants, *Anser albofrons* dominanted, and the subdominant was *Philomachus pugnax* (these 2 species accounted for 64.8% of the total number of spring migrants). The most intensive flights were in the southern and eastern parts of the wind farm.

Thus, in the spring period of 2013-2021, 156,910 individuals of 125 species were recorded in the project area. Of these, 52,575 individuals of 92 species (33.5%) were observed directly within the Botiieve wind farm and buffer zones. 104,335 individuals of 99 species (66.5%) were recorded on the adjacent wetlands, the Botiieve Ponds and the Tubal Estuary.

The role of different functional zones was not the same, although in almost all years (except 2014-2015) the adjacent territories dominated in terms of the number of birds recorded there (figures 4-7).

Migration movements were carried out by 34,297 individuals of birds (or 21.86% of the total number of recorded birds). At the same time, the number of migrants varied over the years (figures 4-7). In the first 3 monitoring years, the number of migrants was growing (30.3, 35.1

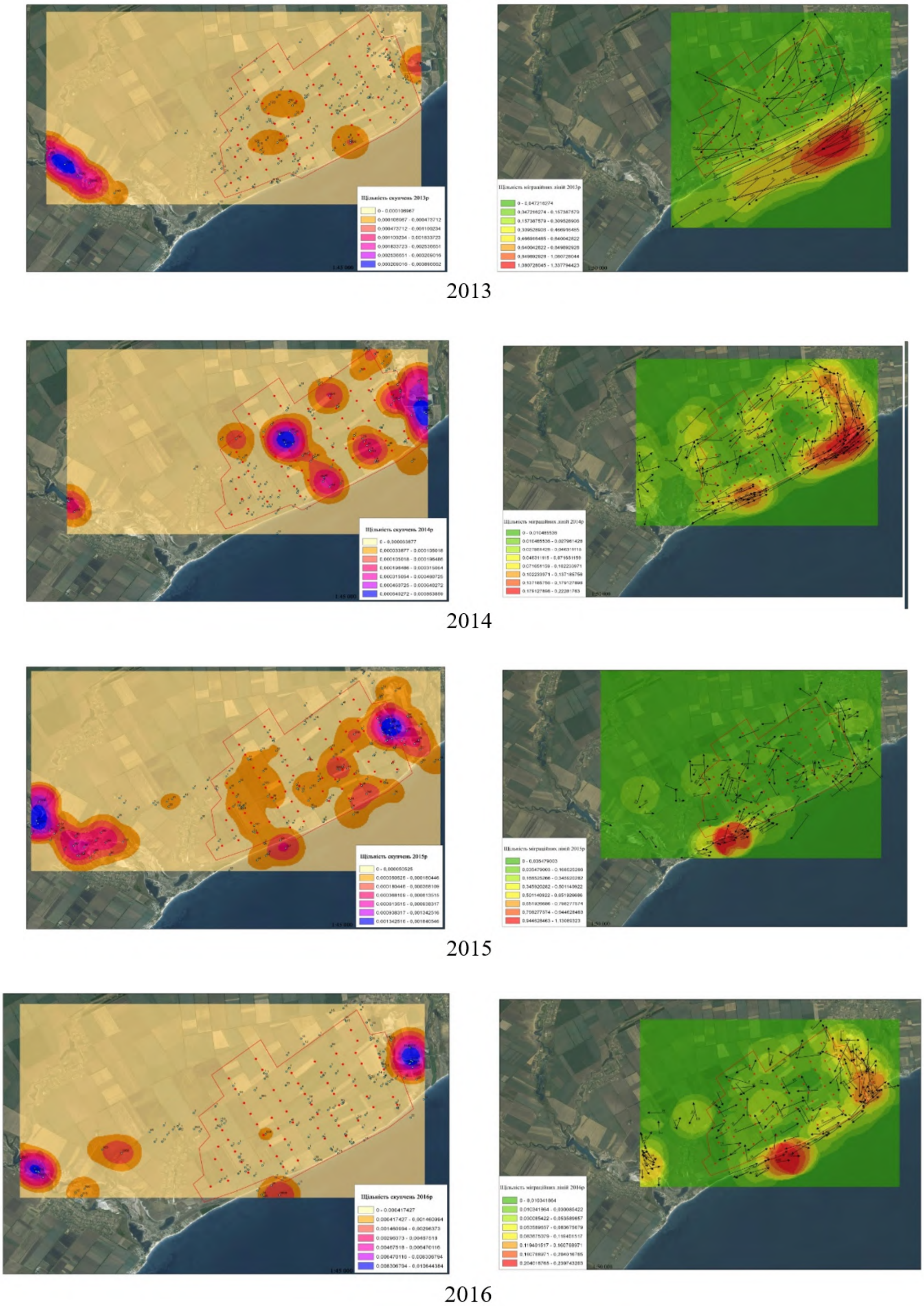


Figure 4. Ornithological situation at the Botiieve wind farm and adjacent territories in the spring period of 2013-2016. On the left are recorded birds (not in flight), on the right are migratory movements.

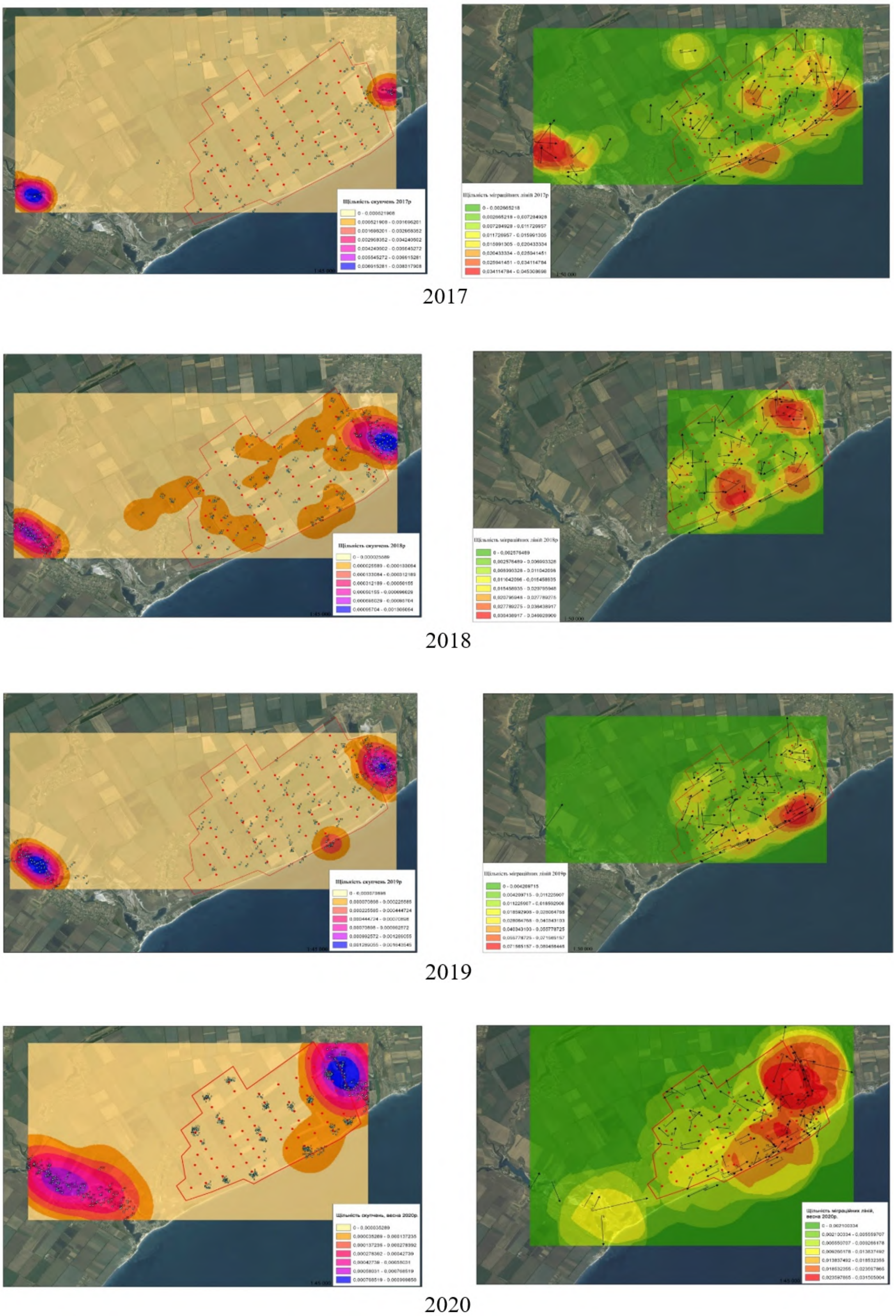
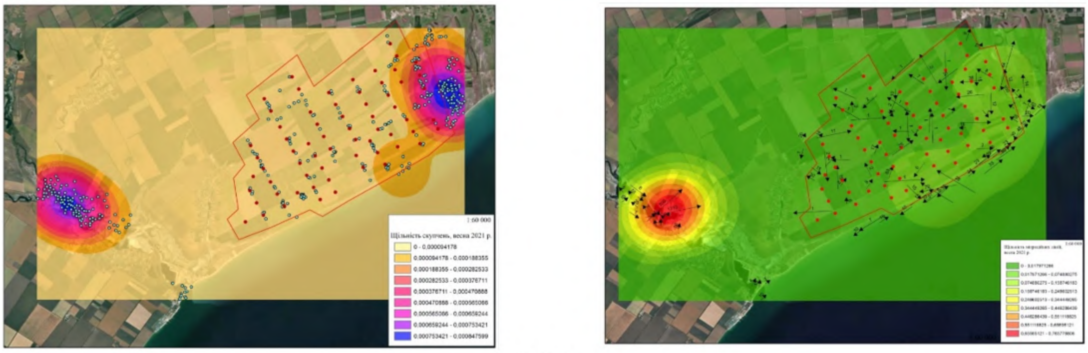
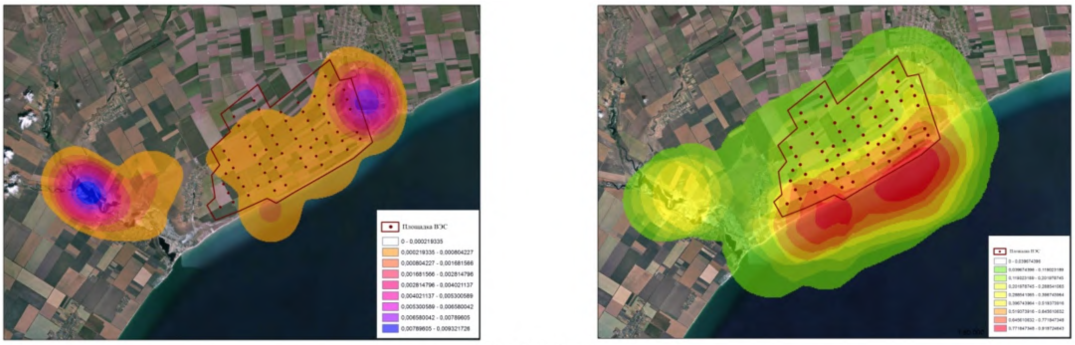


Figure 5. Ornithological situation at the Botiieve wind farm and adjacent territories in the spring period of 2017-2020. On the left are recorded birds (not in flight), on the right are migratory movements.



2021

Figure 6. Ornithological situation at the Botiieve wind farm and adjacent territories in the spring period of 2021. On the left are recorded birds (not in flight), on the right are migratory movements.



2013-2021

Figure 7. Ornithological situation at the Botiieve wind farm and adjacent territories in the spring period of 2013-2021. On the left are recorded birds (not in flight), on the right are migratory movements.

and 48.6% of migrants against 69.7, 64.9 and 51.4% of the recorded perched birds), but starting from 2016 it was decreasing. However, in 2021, the number of migrants increased again and accounted for almost a quarter (25.6%) of all birds, while the number of recorded perched birds, on the contrary, decreased (74.4%).

If we extrapolate the obtained data for the whole spring period, we can expect about 380 thousand birds to fly through the project area in 9 years (2 months of spring migration per year). However, it should be noted that migration is divided into transit and forage. The peculiarity of bird transit flight is the massive process involving a large number of birds and species, purposeful active type of flight (swinging and soaring) in the appropriate direction, long single flight distance (over 500-600 km), with no delays and stops on the migration route.

At the same time, foraging migrants reveal a slightly different type of behaviour, characterized by a long stay of birds within the region, daily foraging flights from roosting places to feeding places, the entire spectrum of migration directions determined only by the search for food, the formation of gatherings of various sizes, and short distances of flights.

The number of forage and transit migrants was almost the same (16,422 individuals, or 47.88% of forage migrants and 17,875 individuals, or 52.12% of transit migrants). But if we exclude 2015 from the calculations (when there was a massive anomalous transit passage of

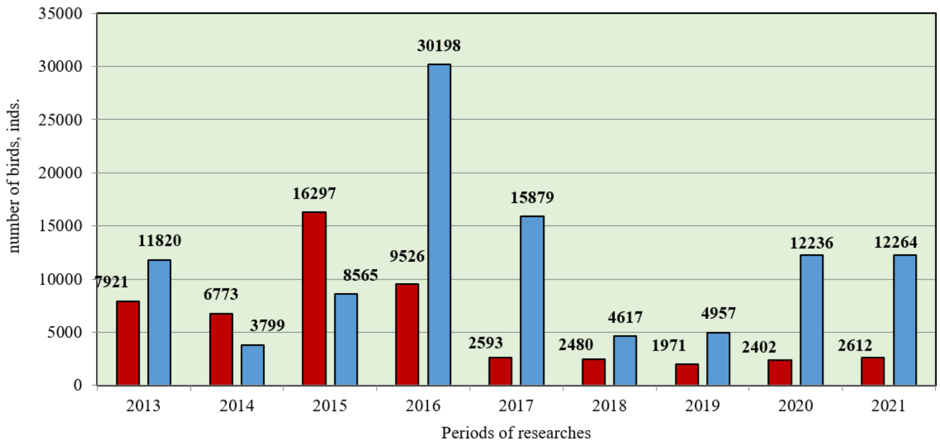


Figure 8. Distribution of birds recorded in 2013-2021 on the territory of the Botiieve wind farm and buffer zones (red column) and adjacent territories (blue column).

Phalacrocorax carbo across the project area to the colony of the species on the Obitochna Spit, which accounted for 63.1% of all recorded migrants in spring 2015), then the situation will be different (65,82% of forage migrants vs. 34.18% of transit ones).

Landscape and biotope conditions have a significant impact on the abundance and species composition of the ornithocomplex in the project area. If within the Botiieve wind farm the state of biotopes (which are mainly represented by an anthropogenic landscape - farmland and artificial forest plantations-forest belts) remained more or less stable for 9 monitoring years, then in the adjacent areas of increased biodiversity, the Tubal Estuary and the Botiieve Ponds, it can vary dramatically over the years. For example, in 2014 the water level was the lowest compared to previous years, and the gatherings of waterfowl birds there were few. A completely opposite picture was observed in 2016 when the high water level remained throughout the spring and almost the entire summer, which led to an increase in both the number and species diversity of birds. Another significant factor influencing birds in adjacent areas is hunting, primarily for game birds, which lasts from early August to late December (although a greater impact from hunting as a disturbance factor is observed in the post-breeding and autumn phenological periods).

In 2018-2019 the lowest number of birds was observed in the project area, approximately the same situation was in 2014, which is not related to the operation of the wind farm. The most probable reason for this phenomenon is periodic fluctuations in the abundance in the populations of recorded bird species, as well as less favourable conditions in adjacent areas. However, today (2020-2021) the situation has changed somewhat, and bird numbers have begun to grow again. But if we consider only the territory of the Botiieve wind farm, then over the past 5 years (2017-2021), the number of birds here has been consistently low.

The presence of areas of increased biodiversity near the Botiieve wind farm leads to a relatively high total number of birds in the project area. 66.49% of the total number of birds in the spring period have been recorded in the Tubal Estuary and the Botiieve Ponds in 9 years. In 7 years, out of 9, the part of the adjacent territories was larger (59.88% in 2013, 76.02% in 2016, 85.96% in 2017, 65.06% in 2018, 71.55% in 2019, 83.59% in 2020 and 82.44% in 2021). Only in 2014 and 2015, the wind farm site and buffer zones dominated, and part of the adjacent territories accounted for only a third of the total (35.94 and 34.45%, respectively).

Observations showed that only 21.86% of the total number of birds carried out forage and transit movements through the project area (34,297 individuals). If we extrapolate the obtained data for the whole spring period, we can expect about 380 thousand birds to fly through the project area. At the same time, the number of transit migrants is smaller than the number of foraging migrants, as most of the recorded birds that moved through the project area flew during feeding (*Sturnus vulgaris, Corvus frugilegus, Larus cachinnans*, etc.).

Of all migrants registered during 9 years, only a small part moved in the potentially dangerous altitude range of 51-150 m. There were less than 1% of such birds (285 individuals). If a part of migrants is at risk zone, the number of individuals and frequency of such cases is small. The bulk of migrants is accounted for either under the rotor-swept area (85.88%) or above the rotor-swept area (13.28%). Since a significant part of migrants were *Passeriformes*, more than 40% of migrants were observed at ground altitudes up to 10 m.

For migratory birds, a significant factor of disturbance is the anthropogenic factor - agricultural work during the year. However, it can affect birds that are long-term associated with the project area, i. e. forage migrants and those birds that remain breeding at the end of the spring migration. For transit migrants, the territory of the Botiieve wind farm is not a place for them to stop due to the unattractiveness of its habitats. On the other hand, recently there has been a change in transcontinental migrations, when most geese and Eurasian Cranes and others fly through the territory of Ukraine in transit. The disturbance factors existing at the wind farm, such as the presence of wind turbines and routine work on the territory of the wind farm, do not practically impact on these birds.

4. Conclusions

As a result of the work performed with the help of the BirdsFly programme and the WEBBIRDS web application, there were created maps (figures 4-7), which reflect the ornithological situation at the Botiieve wind farm and adjacent areas in the spring period in 2013-2021. Thanks to the “concentration gradient” tool, the maps clearly trace the functional areas with the largest bird concentration. These areas all lie outside the wind farm. We note the low theoretical and no real negative impact of the Botiieve wind farm on bird populations during the spring migrations in 2013-2021, both in the short and long term.

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Morphological response of lagoon cockle *Cerastoderma glaucum* (Poiret, 1789) to eutrophication in the Sea of Azov

To cite this article: A T Mirzoeva and N A Demchenko 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012059

Morphological response of lagoon cockle *Cerastoderma glaucum* (Poiret, 1789) to eutrophication in the Sea of Azov

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Abstract. The bivalve species *Cerastoderma glaucum* (Poiret, 1789) was studied in this study. This species is allochthonous and belongs to the Mediterranean zoogeographic complex and was introduced in the Holocene. The *C. glaucum* is the dominant species among the bivalves in the Sea of Azov and has a wide range of distribution. The species is distributed in the coastal zone within 100-300 m from the shore, and it is also found in desalinated water bodies such as estuaries. The *C. glaucum* is fairly resistant to hypoxia. It is euryhaline with respect to salinity and eurybiontic with respect to soil. The species can settle on sandy, muddy or sandy-silty substrate. The aim of the study was to investigate the morphology of shells of this species in order to find out the reasons of morphological features change of *Cerastoderma glaucum* in different biotopes of the Sea of Azov. The study was conducted in early June 2021 on the northwestern coast of the Azov Sea. A total of 20 stations were investigated. *Cerastoderma glaucum* was found at all stations. The morphological variability of the bivalve *Cerastoderma glaucum* was investigated using the method of discriminant analysis. A notable morphological feature was the external alteration of the mollusc shell. A displacement of the apex to the anterior edge of the shell, lengthening of the posterior edge, and deformation of the shell shape, indicating the ecological characteristics of the study area and its inhabitants. Also, there is a difference in the ratio of shell height to shell length, indicating an increased level of siltation in the ground. Shell thickness varies in all survey areas, indicating different levels of salinity. The overall abundance of molluscs from the different biotopes indicates the factors determining the shape of cockle shells. In turn, morphological parameters indicate the general condition of the Sea of Azov. So, it can be assumed that siltation of the substrate on which benthic communities are located has increased as a consequence of massive deposition of phytoorganic residues. In addition, the hydrolytic regime has changed as a result of anthropogenic factors. As a consequence, salinity, oxygen levels are changing, etc.

1. Introduction

The current state of the ecosystem of the Azov Sea is in "ecological crisis" due to the process of eutrophication [1]. The depressed state of the reservoir has become as a consequence of the mass multiplication of microalgae of cyanobacteria *Nodularia spumigena*, dinophyte alga *Lingulodinium polyedra* and *Centric diatoms* called "water blooms" and decreased water transparency [2–4]. The process of "water blooms" was the result of intensive anthropogenic impact through nutrient inputs, radioactive and chemical contamination of water, dumping, and sand mining in the sea [5–8]. The long–term suppression led to the death of most marine organisms [9–12]. Changes in the marine ecosystem have disturbed the sustainability of inhabitants supporting the marine environment [13–15]. There are numerical reductions in populations of most shelf dwellers due to a decline in the number of dominant organisms of benthic communities such as bivalve molluscs [16, 17]. In Bivalvia populations, the visible morphological changes have manifested as a result of the process of metabolism in the body, leading to changes in growth rate, abundance, and distribution in the marine environment [18].

The marine bivalve is *Cerastoderma glaucum* (Poiret 1789) or lagoon cockle [19–21]. A representative of the infauna of shallow sand sediments of the European coast. It belongs to the family Cardiidea; its closest relative is *C. edule*, originally inhabiting the Mediterranean Sea [22]. The diversion of *C. glaucum* from its nearest relative, *C. edule*, and its distribution along the European coast took place at the end of the Miocene and the beginning of the Pliocene [23]. It entered the Sea of Azov in the Holocene after the connection of the Black Sea with the Mediterranean. The physiology and evolutionary development of the species allows *C. glaucum* to be tolerant to physical factors of different marine ecosystems. The cockle's euryhalinity of 5–38‰ and eurythermicity (0–25°C) allows the species to expand and diversify its habitat [23]. The cockleshell is found in lagoons, estuaries, deltas with partially saline areas, or in coastal marine shallows. In most cases, high occurrence is observed in the Mediterranean Sea and southern Europe and has been recorded off the coast of Egypt, Tunisia, Turkey, Sardinia, Italy, Greece, Portugal, Spain, France (Atlantic and Mediterranean coast), Netherlands, British Isles, Denmark, Finland, Norway, Baltic Sea, Mediterranean Sea, Adriatic Sea, Red Sea, Aegean Sea and Caspian Sea [19, 24–35]. This species is an inhabitant of shallow waters. The maximum depth of *C. glaucum* survival does not exceed 0.5–1 m. The depth of submergence depends on friability, tidal fluctuations of water, and hydrolytic regime. Silted sands and shells are characteristic of the Sea of Azov. The submergence of the cockleshell is 3/1 of the total body area [36]. Life expectancy depends entirely on habitat. In most of the experimental work done, the age exceeds 6 years for some populations. In conditions with increased mortality and poor growth, the figure can often be reduced to 2–3 years maximum [37–39].

2. Research aim and objectives

The stability of *C. glaucum* to these water body habitats allows it to play a dominant role in the most benthic communities of the northeastern coast. This species is often found in a community with *Abra nitida* (Müller, 1776), *Capitella capitata*, *Alitta succinea*, *Spio filicornis*, *Tubificoides* sp. [40,41]. Or as a subdominant in a community with an allochthonous, fairly recently colonized species, *A. kagoshimensis* [42].

In this connection, the purpose of this work was to study the morphological variability of the lagoon cockle *Cerastoderma glaucum* in different areas of the Azov Sea.

3. Material and methods

An analysis of morphometric traits was performed to reveal the patterns of morphological adaptations in *C. glaucum* populations in the different areas of the Sea of Azov. Mollusc shells sampling was conducted in early June 2021 on the coast of the Sea of Azov. The average water temperature was 18.5°C. The material was collected at 5 sites (table 1).

In the past century, the benthic communities of the study areas have been exposed to commercial fishing and baitfish digging, including fisheries based on manual rake. In this study, we need to find out what are the impacts now experienced by modern benthic communities at the head of the lagoon cockle. To do this, fourteen morphometric features were selected for each *C. glaucum*, by which the condition of the species inhabiting the Sea of Azov will be evaluated. Measurements of the shell were made to an accuracy of 0.01 mm using a caliper. Was measured H – shell height, mm; B/2 – shell width, mm; L – shell length, mm; a – ligament length, mm; b – length of the upper edge of the shell, mm; c – length from anterior edge of the ligament to

Table 1. Geographic data of the sample collection site.

Location of collection	Latitude	Longitude
Station 1	46°13’00.0”N	35°14’00.0”E
Station 2	45°59’34.7”N	34°49’40.8”E
Station 3	45°59’33.3”N	34°49’29.8”E
Station 4	45°59’33.3”N	34°49’29.8”E
Station 5	46°00’00.3”N	34°49’25.2”E

the apex, mm; d – length from anterior edge of the shell to the apex, mm; e – distance between the anterior end of the shell and the apex, mm; f – distance from the mantle edge to the shell edge, mm; h – width of the posterior adductor scar, mm; i – width of the anterior adductor scar, mm; j – height of umbo, mm; k – length of umbo, mm; l – thickness of the bivalve, mm; m – ribs (figure 1). Measurement error in the use of these methods does not contribute significantly to the variation of the characters. We chose the characters previously used by the authors in the morphological diagnosis of mollusc shells [43, 44]. The descriptive statistics of morphometric characters and the degree of compliance with the laws of distribution were performed in the Excel program.

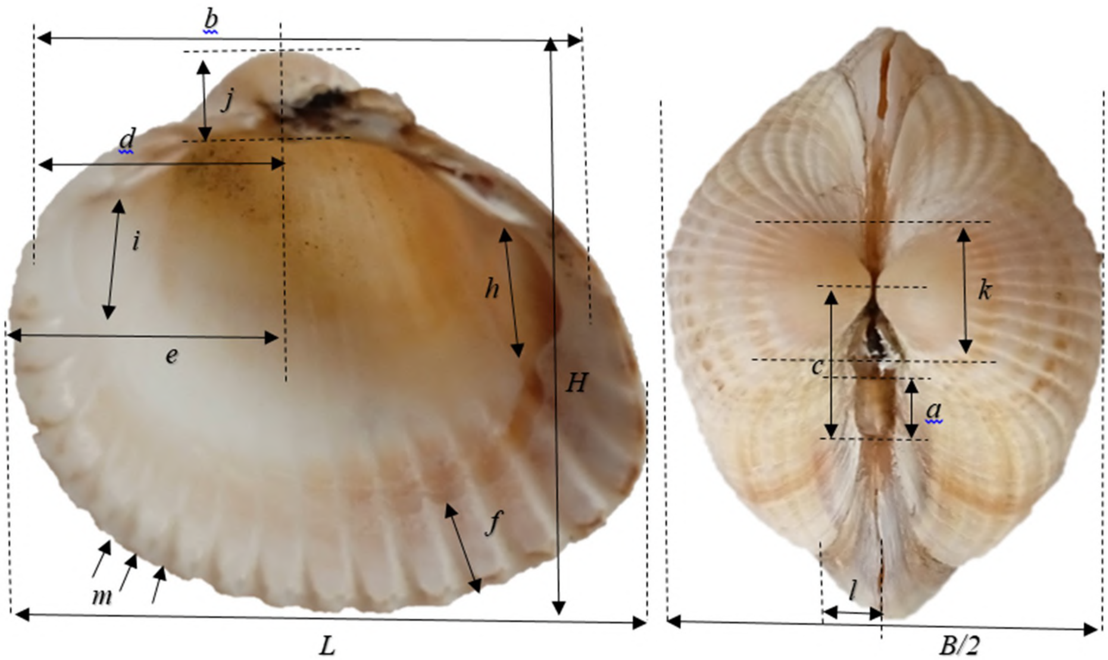

Figure 1. Shell traits measured for each individual clam in *Cerastoderma glaucum*: H – shell height, mm; B/2 – shell width, mm; L – shell length, mm; a – ligament length, mm; b – length of the upper edge of the shell, mm; c – length from anterior edge of the ligament to the apex, mm; d – length from anterior edge of the shell to the apex, mm; e – distance between the anterior end of the shell and the apex, mm; f – distance from the mantle edge to the shell edge, mm; h – width of the posterior adductor scar, mm; i – width of the anterior adductor scar, mm; j – height of umbo, mm; k – length of umbo, mm; l – thickness of the bivalve, mm; m – ribs.

4. Results

The investigated populations of *C. glaucum* had their own morphological features. The coefficient of variation of morphometric characteristics of the shell of *C. glaucum* in the Site 1 was in the range of 0.09 to 0.35%. The shell of the cockleshell of the Site 4 ranged from 0.07 to 0.43%. These small differences in values indicate similar conditions of the cockleshell populations. The smallest sizes were the cockleshells collected at Site 3 and Site 5. The coefficient of variation of Site 3 was in the range of 0.06 to 0.55%. The value (CV) for Site 5 was in the range of 0.09–0.32%. In the Site 2 population, the coefficient of variation ranged from 0.07 to 0.41%. The ratio of cockleshell sizes showed a trend of variation depending on the habitat. Analogous in appearance shells were found at sites 1, 3, and 5. The shells were rounded, the contour of the shells globularly swollen, the crowns wide, usually strongly protruding. The symmetry of the form of shells in a ratio of height to length was observed. The slightly elongated hind margin of shells of the *C. glaucum.* At the Site 2 and 4 the shells also possessed strongly swollen roundish form. Asymmetry in relation to height to length and with more or less smoothed angles at the transition of dorsal margin to anterior and posterior, if there is an angle of posterior shoulder, it is usually equal. The Site3 population differed from all other populations, showing the lowest values.

The morphological distinction of the cockle shells in the Azov Sea was the arrangement of the ribs. The cross-section was shaped, of different height and length. Usually the flaps in the front part of the shell were found with rounded ribs in cross section, in the middle trapezoidal, or in the second half of the middle part triangular with the triangular apex shifted to the lateral posterior facet. Most of the sample data on the number of ribs ranged between 17 and 27. The mean number of ribs was high for Site 1 populations, 21.19 $\pm$ 0.29 having a relationship with shell size. Only Site 4 showed a similarly high number of shell ribs (table 2). Once again confirming the similarity of habitat conditions.

The analysis of the histograms showed that the value of the index H (shell height) varies depending on the shell collection area. The highest index in the area of the Site 3, the lowest in the area of Site 5. In terms of the B/2 shell thickness, the values are off the charts at the Site 4. The value L is the length of the shell, corresponding to the height. A slight elongation of the posterior end of the shell indicates the depth of burrowing into the ground. The normal location of the clam in the ground is 3/1 of the entire length of the shell of individuals. The highest values are at the Site 1 and 4. The index a - ligament length varies insignificantly compared to the variability of this trait. The dependence of ligament length as well as ligament shape on shell contour is practically not traced. The ligament length predominates in the largest individuals of Site 1 and 4, respectively. At the Site 3, the shortest shell ligaments were found, which belong to mollusks with abnormalities in the structure. The characters b, c, d, e, f, h, i, j correspond to the proportions of shells of mollusks. The number of ribs index - m, varied depending on the size and age peculiarities of cockles in individual study areas. Trait - l, hypothetical suggests that shell thickness indicates water salinity. The highest index at Site 1 was 1.03 $\pm$ 0.05 (figure 2).

5. Discussion

Each morphological trait describes the environment in which the cockleshell exists. Indicating which environmental factors are the main in the formation and growth of *C. glaucum.* It is a known fact that the growth of the cockleshell is 5–250 mcm daily during the first years of life. The stoppage of growth is observed in winter, during breeding and in old age [45]. The formation of the mollusc shell occurs as a result of extracellular growth. The epithelium of the outer surface of the mantle extrudes shell-building products into the extrapallial fluid. The ratio of height to length of the ravine indicates normal growth. Deviations are not significant. The total maximum height of the Azov Sea shells was 29.3 mm, a figure rather insignificant compared to data from southern studies, where the maximum shell size was 53,2 mm [19], and in some areas 29 mm Tunisia Laguna Bugrara [26], 32 mm Egypt Lake Timsah [46], 37 mm at the Gabes coast [25].

Table 2. Descriptive statistics of shell morphometric traits: shell height, mm; B/2 valve width, mm; L – shell length, mm; a – ligament, H – length, mm; l – thickness of the bivalve shell; m – ribs.

Traits	H	B/2	L	a	l	m
			Site 1, N = 42			
Mean±st.error	18.26±0.78	7.50±0.30	19.41±0.80	4.05±0.25	1.03±0.05	21.19±0.29
Maximum	29.3	12.10	31.90	7.30	1.62	27
Minimum	11.2	4.40	12.30	1.20	0.51	19
CV, %	0.28	0.26	0.27	0.35	0.30	0.09
			Site 2, N = 42			
Mean±st.error	16.34±0.32	6.65 ±0.21	18.27±0.36	2.45 ±0.19	0.47 ±0.04	19.98±0.20
Maximum	23.40	12.70	24.80	6.20	1.06	23.00
Minimum	11.90	5.20	14.60	1.20	0.11	18.00
CV, %	0.13	0.20	0.13	0.41	0.23	0.07
			Site 3, N = 52			
Mean±st.error	13.65±0.37	6.24±0.28	15.26±0.41	1.04±0.15	0.62±0.23	20.90±0.17
Maximum	24.10	10.90	26.50	3.60	1.34	24.00
Minimum	8.50	3.20	8.70	1.20	3.65	19.00
CV, %	0.19	0.32	0.19	0.33	0.55	0.06
			Site 4, N = 127			
Mean±st.error	18.43±0.39	8.82±0.18	21.7±2.40	3.37±0.35	0.72±0.03	21.64±0.14
Maximum	28.90	19.70	34.5	7.6	1.29	26
Minimum	8.40	3.80	10.70	1.30	0.11	17
CV, %	0.24	0.43	0.26	0.37	0.41	0.07
			Site 5, N = 41			
Mean±st.error	14.56±0.35	7.30±0.34	16.56±0.39	3.19±0.30	0.59±0.04	21.37±0.32
Maximum	21.50	12.90	23.90	4.20	1.23	25.00
Minimum	10.00	3.60	11.90	1.90	0.38	17.00
CV, %	0.15	0.30	0.15	0.25	0.32	0.09

Inferring from the size of the shells from the Sea of Azov, it is possible to assume the age of the cockles. The literature indicates that the maximum life span of cockles of *C. glaucum* is 5 years. Depending on the environmental conditions with regard to mortality and poor growth, this figure can often be reduced to 2 – 3 years [38, 39]. It is worth assuming that life expectancy varies in the Sea of Azov from 1 to 3 years except for single individuals. Following the morphological differences in the shells of *C. glaucum* from different collection areas, it should be assumed that the change in their size depends on environmental factors in different geographical collection sites. Increased temperature, salinity and oxygen levels contribute to favorable growth and longevity of cockles at Site 1 and 4. Conditions at Site 5 show a difference in reduced growth, abundance, and shell size. From the other side, the environmental conditions of Sites 2 and 3 [47] showed that low average salinity and lower water temperature have a positive effect on the growth of the *C. glaucum* shell. Challenging assumptions about the factors affecting viability in the literature is a contradiction and indicated that elevated temperatures and high levels of phytoplankton in Gabes Bay [25] promote rapid growth.

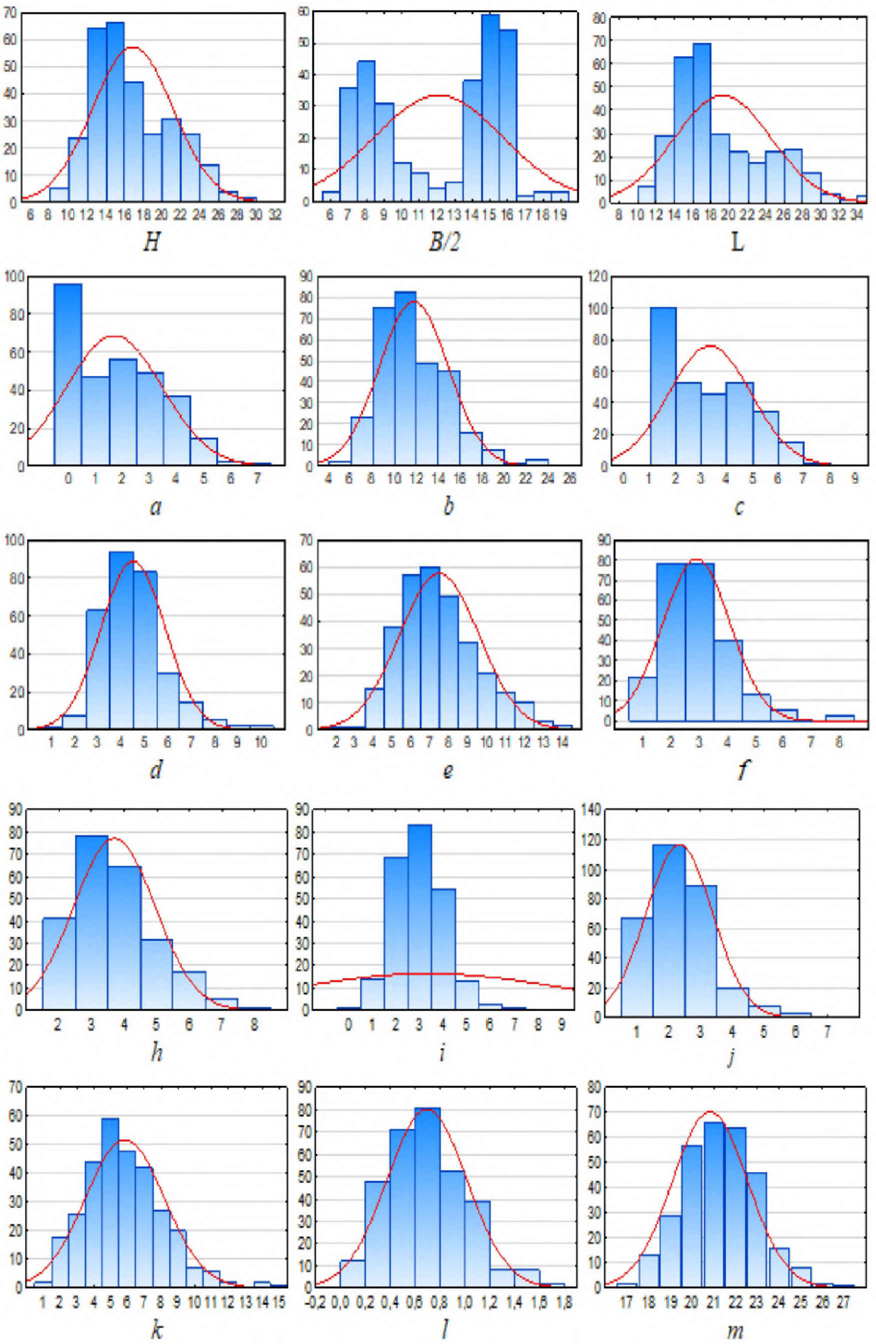

Figure 2. Histograms of morphometric traits of *Cerastoderma glaucum* shells.The red line indicates the histogram normal distributions: H – shell height, mm; $B/2$ – shell width, mm; L – shell length, mm; a – ligament length, mm; b – length of the upper edge of the shell, mm; c – length from anterior edge of the ligament to the apex, mm; d – length from anterior edge of the shell to the apex, mm; e – distance between the anterior end of the shell and the apex, mm; f – distance from the mantle edge to the shell edge, mm; h – width of the posterior adductor scar, mm; i – width of the anterior adductor scar, mm; j – height of umbo, mm; k – length of umbo, mm; l – thickness of the bivalve, mm; m – ribs.

On the other hand, [21] showed that low mean salinity negatively affects the growth of *C. glaucum* from the Baltic Sea. [32, 48] described respectively isometric and positive relative growth in *C. glaucum* from several Mediterranean, Atlantic and Baltic sites. This wide variation in the relative growth of the species is certainly due to genotype [49], but also various local specific environmental factors can strongly influence the variations in shell shape present in bivalves. It is worth noting that the allometric growth of *C. glaucum* are a functional response to different habitat typologies. Thus, allometry was evident in Site 2 and 4. Indeed, bivalves are known for their remarkable morphological diversity and phenotypic plasticity, which is perceived as the main algorithm that allows organisms to survive under changing environmental conditions [50, 51] especially for *C. glaucum*, which proved its ability to withstand extreme and unstable environmental conditions in different areas of the Azov Sea.

It is hypothesized that shell thickness indicates the level of salinity. Thickening of the shell is observed with growth and age. The thickening process occurs uniformly along the entire axis height, from the apex to the ventral edge. The variation in the thickness of Azov Sea cockleshells indicates variations in salinity. Following from the indices of thickness of cockle shells of Site 1 the indices of water salinity should prevail over the rest of the study area. Slightly lower is the thickness of the shells of Sites 4 and the thinnest shells of Site 2, 3, and 5. Referring to [30] the shell thickness of 0.76 mm indicates that the shells are two years old. The measurements obtained in this work indicate a suppression of growth on this trait at Sites 2,3 and 5. According to literature sources, a sharp increase in the salinity of the Sea of Azov was observed from 2007 – 2008, annually adding 0.25 ppm on average. In 2020, more than 15 ppm, that is, 15 grams of salt per liter of water. In the Black Sea, in the surface layer, where it adjoins the Sea of Azov, 17 ppm [52]. The salinity is explained by the low water exchange between the Black Sea and the Sea of Azov.

An important morphological trait is the number of ribs. Their number is directly related to salinity. The number of ribs in the Sea of Azov varies from 17 to 27. In the Black Sea from 18 to 28 [47]. In the Mediterranean near Tunisia, 19 to 21; La Skhira beach 23; Lac Ichkeu; 19 to 24 ribs; [26]; Near Greece, 17 to 28 [19]; In northwestern Europe, 18 to 20 [53]; On the Irish coast, 22 to 28 [54–56]. Another presumed factor influencing the morphological changes of *C. glaucum* shells is the process of sea eutrophication. Many factors of abiotic and biotic type influence on the starting mechanism of mass development of nutrients. The greatest harm is caused by irrational use of a water body. Human activity destroys natural habitat of marine organisms, affecting it by aggressive factors. All wastes of industrial, economic activities are discharged into drains and utilized in the sea with high content of organic and inorganic substances. From factories and iron and steel works: mercury, lead, phenols, oil products, phosphates, nitrates and various organic substances. Huge amounts of agricultural products: pesticides, detergents, ammonium salts and nitrates. Subsequent over-fertilization of the Azov Sea was followed by an increase in the number and biomass of phytoplankton. Massive growth of the diatom-cyanobacterial algal complex resulted in sea blooms, changes in color, transparency, and increased CO_2 levels [57]. As a result, affecting the number, diversity, and distribution of marine life.

6. Conclusion

During the morphological measurements of cockleshells of *Cerastoderma glaucum* in the five studied sites of the Sea of Azov revealed differences. According to the complex of morphological features, the most distinguishable were the size and allometric shape of the shell, its thickness, and the number of ribs. The result of the work showed that the most favorable conditions for the full development and life of cockles are the areas of Sites 1 and 4 based on their size, and therefore the age of the mollusc. Although small deviations from the norm were observed. As for the rest of the study areas, the area is subject to constant natural fluctuations in the environment. From what was observed uneven morphological and physiological development of individuals, early mortality. The supposed hypothesis that eutrophication of the Sea of Azov affects the morphological development of cockles is not confirmed. For more exact statement it is necessary in the further researches to carry out a number of researches connected with physiology of mollusc *Cerastoderma glaucum*.

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To cite this article: A I Sydorenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012060

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012060 doi:10.1088/1755-1315/1049/1/012060

Assessment of the impact of technogenic monitoring sites on seasonal migration ornithocomplexes

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Abstract. Today, the Azov-Black Sea coast of Ukraine is one of the most important migration routes in Europe, which is used by up to 15 million birds every season. The development of a scientific and information system for monitoring, assessing and predicting the state of biodiversity on the territories of wind power plants (WPP) in the Azov-Black Sea region is extremely important, and the study of seasonal ornithocomplexes is a key moment in the creation of wind farm sites. Assessment of the impact on them is paramount in the development of management plans and risk minimization. The studies were carried out in the Azov-Black Sea region of Ukraine at 12 monitoring sites in the period from 2010 to 2021 using modern international methods adopted in the European Community, used for these technogenic territories, as well as author's developments. The studies that were carried out using the WEBBIRDS WEB-application for monitoring seasonal ornithocomplexes and computer modeling of assessing the impact of the wind farm site based on the server accumulation of monitoring data (an author's development), software for calculating the risk assessment of bird collisions with wind turbines (CRM), assessing the potential biological removals (PBR) showed no significant adverse impact of wind farms on birds observed at all 12 sites. These monitoring studies make it possible to assert that the main impact on the stability of migratory bird complexes in the project area is exerted by various biotic and abiotic factors such as landscape-biotopic, forage, weather factors, and the impact of wind farms is minimal.

1. Introduction

The Azov-Black Sea coast of Ukraine is recognized as one of the most important migration routes in Europe. The most intense transcontinental migration corridor passes here, through which 8 – 15 million birds fly every season. At the same time, the Azov-Black Sea region of Ukraine has the largest wind potential in the country, which leads to the development of a large number of wind farms here.

The development of a scientific and information system for monitoring, assessing and forecasting the state of biodiversity in the territories of wind farms in the region is very important. This is due to the presence of natural areas on the Azov-Black Sea coast of Ukraine, which are not only reserves of unique biodiversity, but they also support numerous populations of migratory birds across Eurasia. This fact provides significant responsibilities for determining qualitative assessments of complex changes in controlled ecosystems, protection, monitoring and management of components of natural complexes both on natural and technogenic territories. The study of seasonal ornithocomplexes is a key moment in the creation of wind farm sites, and the assessment of the impact on them is paramount in the development of management plans and risk minimization.

To achieve this goal, old research methods are not enough. Therefore, there is a need for new technologies. At the initial stage, we used the recommendations of the Scottish Natural Heritage Foundation (SNH), which since 2016 have been generally accepted methods for carrying out research on the territories of wind parks and power transmission lines (PTL) in the European Union. On their basis, a team of authors developped the "WEBBIRDS" - "BirdsFly" - "EasyBirds" complex, designed to adapt the SNH recommendations to domestic realities. The material presented below is based on a number of methodological developments [1–8].

2. Material and methods

The studies were carried out in the Azov-Black Sea region of Ukraine at 14 monitoring sites with a total area of 462.42 km^2 in the period from 2010 to 2021 (figure 1). At the same time, the total number of projects for the justification of wind farms in the region for a given period of time, prepared by the team of authors, was 25 projects. 13 of them have been put into operation today.

Most of the expedition work was carried out using the methods of fixed vehicle and pedestrian census on transects, as well as using stationary vantage points (VP). For a more complete characterization of the species composition and abundance of ornithocomplexes, expedition trips to the study area were carried out during massive migration waves. In total, 14-17 expedition trips were made every year lasting 3-6 days each.

Surveys were made with Etherna binoculars (10x) and Nikon ACULON A211 10x50 and VIXEN Geoma telescope ($20 - 60x80$). To determine the species, sex and age of birds, as well as the characteristics of seasonal outfits, we used the European bird guide (Collins Bird guide / Second edition, 2009) [9]. Mapping of bird gathering places and spatial characteristics of routes were made using a GARMIN GPSMAP 78s navigator. Biotopes and birds were photographed with Canon EOS 450D and Nikon D700 cameras. The photographs were exported to the FastStone Image Viewer programme, which together with the camera software in the Exif metadata mode made it possible to control the geolocation data of the photographs taken, the date and conditions of shooting. Linear dimensions between objects and object heights were measured using a Nicon Forestry 550 laser altimeter. Statistical processing of the obtained data was carried out in Microsoft Excel 2010 and Statistica Release 8 (Basic Statistic module) programmes.

In addition to the methods of collecting and processing field data and the methods of analysis (statistical, mathematical, graphical) described above, methods for assessing the impact on ornithocomplexes were also used using the author's complex of "WEBBIRDS" – "BirdsFly" – "EasyBirds" web platforms.

The data, the possibility of entering which exists at all stages of functioning of the wind farm during planning, construction and operation, fall into a special Online Storage. The calculation of risk coefficients is based on the developped mathematical algorithms and international collision risk assessment models (CRM). The modular system uses both foreign modern models for analyzing the impact of wind farms and predicting the risk of collisions, as well as its own models based on Big-Data Algorithms, Regression analysis methods, Clustering, Artificial intelligence and Computer vision. Each of the Web Platform applications works according to its own data processing algorithm, but uses a common data storage for analysis:

- "WEBBIRDS" assesses the risk of bird collisions with wind turbines based on surveys of movement across the territory [10];
- "BirdsFly" analyzes migration processes, calculates risk ratios for migratory birds and identifies zones of dangerous bird concentration during migrations [11];

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012060 doi:10.1088/1755-1315/1049/1/012060

Figure 1. The territory of monitoring work at wind farms in the Azov-Black Sea region in 2010-2021.

- "EasyBirds" makes analysis based on CRM (Collision Risk Model is carried out according to the recommendations of the Scottish Natural Heritage Foundation) and PBR (Potential Biological Removal) calculations [12].

This development is an important point for the unification of methods for monitoring and assessing the impact on ornithocomplexes.

At the moment, there is the main international approach, the recommendations of the Scottish Natural Heritage Foundation (SNH) [7] based on observations at special sites (vantage points, VP), on the basis of which mathematical calculations are carried out:

(i) Intensity of airspace use.
(ii) Distribution of birds in three altitude intervals (below the rotor-swept area or outside the risk zone, at the height of the rotor-swept area or the risk zone, above the rotor-swept area or also outside the risk zone).
(iii) Probability of bird collisions with wind turbines, etc.

The most important aspect of performing work according to the methodology of the Scottish Natural Heritage Foundation is the assessment of the impact on mortality rates, the calculation of the probability of bird collisions with wind turbines (Collision Risk Model, CRM) and potential biological removal (Potential Biological Removal, PBR).

The authors of the project have developped a web application that includes 3 software products: the "WEBBIRDS" – "BirdsFly" – "EasyBirds" complex (hereinafter referred to as the WEBBIRDS complex), which models and makes a mathematical assessment of the impact on birds. The system of the computer programme includes the route census of birds and short-term surveys at the places of the highest concentration of birds. In addition, the WEBBIRDS complex also has a mathematical model for calculating PBR and CRM indicators.

The purpose of our research was the unification of these methods, ensuring the availability of their implementation and the unity of methodological approaches. In our opinion, the "WEBBIRDS" – "BirdsFly" – "EasyBirds" software complex has a number of advantages:

(i) Coverage area of the WPP territory and buffer zones by monitoring studies of seasonal ornithocomplexes. According to the Scottish Natural Heritage (SNH) methodology, the coverage area of the study territory due to control VPs is approximately no more than 30% (in general, from 8.8 to 24.3%), while the area of each VP is on average 100-300 ha, and these studies are clearly limited by the boundaries of the WPP site. The WEBBIRDS complex mainly includes a route survey of various biotope complexes and places of the highest concentration of birds (water (wetland) areas), as well as buffer zones (BZ) of 500 m, which is not less than 50% (mainly 65-80%) according to studies carried out at 10 wind farm sites in 2015-2021. This area is formed due to 100% reliability of census in the 200 m zone on both sides of the route (the distribution of bird census zones on the transect occurs in gradations of $0-25$ m, $26-100$ m and $101-200$ m);

(ii) The SNH method preferentially takes into account migratory birds, and less attention is paid to perched birds, since the observer is sitting at one point. The WEBBIRDS complex takes into account almost all the migrants seen and perched ones, as well as all the bird voices heard.

(iii) The time aspect of surveys: morning and evening surveys according to the SNH method in total amount to approximately 6 hours, and according to this method, they are not summed up, but will be 6 hours a day for both a WPP with three VPs and a WPP with 12 VPs. When using the WEBBIRDS complex, the number of hours for carrying out research depends on the area of the WPP and averages $5-7$ hours. But it should be noted that the number of observation days for seasonal ornithocomplexes both for the SNH method and when using the WEBBIRDS complex is approximately the same, and is maximum 12 days (with the established minimum number of observations at a VP 72 hours per year) for census at vantage points and minimum 12 days for census on fixed transects (route census);

(iv) Coverage by monitoring studies of nearby areas of high biodiversity (objects of the Nature Reserve Fund, the Emerald Network). According to the SNH method, in these areas the studies are carried out only in relation to certain species and groups of birds (gatherings of diurnal birds of prey, wintering and migratory waterfowl, especially geese and swans, coastal species, including breeding gulls, etc.). When using the WEBBIRDS complex, a detailed accounting of all biotope complexes with the corresponding seasonal species composition of birds is carried out. The latter makes it possible to determine the movement of birds from buffer zones to the WPP site during periods of seasonal and foraging migrations, covering a larger number of species. The composition of the seasonal ornithocomplex can be presented in dynamics, based on the databases in the WEBBIRDS programme at different stages of the existence of wind farm sites (design, construction, operation);

(v) The SNH method focuses on target species, while the WEBBIRDS complex includes a larger list of species (88 species and 4 taxonomic groups of birds) that are characterized as "vulnerable due to the operation of wind farms" and are included in the "EU Guidance on wind energy development in accordance with the EU nature legislation" [13];

(vi) The budget for monitoring time in the SNH method depends on the number of VPs. When using the WEBBIRDS complex, 1-2 vehicles with 3 researchers can be involved in a small WPP area. At the same time, when using the SNH method, additional time is incurred for placing observers at the VP: in the morning, the expeditionary vehicle transports the observers (one for each VP), takes them after 3-hour observations, and also transports and takes the observers in the afternoon after the similar 3-hour observations.

(vii) Mobility in the processing of census results. The use of the WEBBIRDS complex allows you in the field to enter the information about birds on tablets or electronic media, and online data is generated on GIS maps of the given territory. When using the SNH method, this process is in a more primitive state (in the field, the observer enters the results of observations on a paper form and the corresponding paper chart, then there is mandatory cameral processing of the material, followed by entering the information obtained into an electronic database);

(viii) PBR calculations both in the case of the SNH method and in the case of calculations of the WEBBIRDS complex are made using the same set of indicators (a – is the age of the first breeding year; s – is the probability of survival of an adult; f – is the protection coefficient; N_{min} – is the minimum estimated number of individuals in the subregional abundance), but the WEBBIRDS complex uses the N_{min} indicator directly for the WPP territory, while the SNH method takes into account the regional territory. CRM calculations take into account 25 criteria, as opposed to 5 criteria in similar calculations of the SNH method;

(ix) Special parameters and indicators taken into account only in WEBBIRDS calculations, for example, flight intensity (ind./h) and average flock size (ind.) separately in the morning and evening hours, etc.;

(x) Complementarity of WEBBIRDS databases with ArcGIS software tools. When using the SNH method for the formation of GIS maps, additional steps are taken to create databases. When using the "WEBBIRDS" complex, databases are automatically created and available for the formation of a variety of GIS formats.

Thus, the use of the WEBBIRDS complex makes it possible to reduce labour costs with a greater coverage of the territory and a functional assessment of seasonal ornithocomplexes, and allows characterizing the degree or level of wind farm impact on ornithocomplexes.

3. Results and their discussion

Ornithological research at wind farm sites is based on generally accepted methods, but at the same time includes important specific features. The implementation of the latest scientific and practical developments, that allow assessing the impact of the construction and operation of wind farms on natural components, occurs during monitoring work.

Due to the use of a mobile WEB-application based on the server accumulation of monitoring data collected during the periods of monitoring studies, maps are automatically created in linear and three-dimensional format based on Google Earth. This is a new approach in the cartographic presentation of bird census results. At different scales, it is possible to obtain data on bird gatherings in a general form for the wind farm site and buffer zones, as well as with significant detail information on individual sites, taking into account the name of the bird species, abundance, dates of research and their location. Of particular importance are voluminous cartographic formats for presenting monitoring information with significant detail information on individual sites, taking into account the names of birds, abundance, dates of research and their location.

But this is not the whole range of tasks that this programme can perform. Let us look at an example of a summary table generated using the functions of the WEBBIRDS web application and the tools of the Birds Fly programme, which, based on the analysis of a number of parameters, displays the risk coefficient for bird species. As an example, let us consider ornithological surveys during monitoring studies of migrations at the site of the Overianivka and Novotroitsk wind farms in March 2019 – February 2020. This summary table consists of 36 columns, the principle of which is described below.

The mechanism for creating a summary table. Column 1. Data on migratory birds were taken in the WEBBIRDS web application by: enter the Programme - menu "Reports" - select "Migrations" (viewing recorded migrations), in the "Site" column, using the arrow, and select from the drop-down list the site we need –the Overianivka and Novotroitsk wind farms. The filter selected the WPP data, including data from all studies in this area in the table. Using the filter in the "Date" column, select the "between" function, set the values: 03.01.2019 and 02.29.2020. The generated table provides data on bird migration at the Overianivka and Novotroitsk wind farms during the monitoring period. If you go to the drop-down list in the "Species" column,

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012060 doi:10.1088/1755-1315/1049/1/012060

you can see a list of bird species recorded during migration studies in March 2019 – February 2020, and listed in the Programme in the “Migrations” section (figure 2).

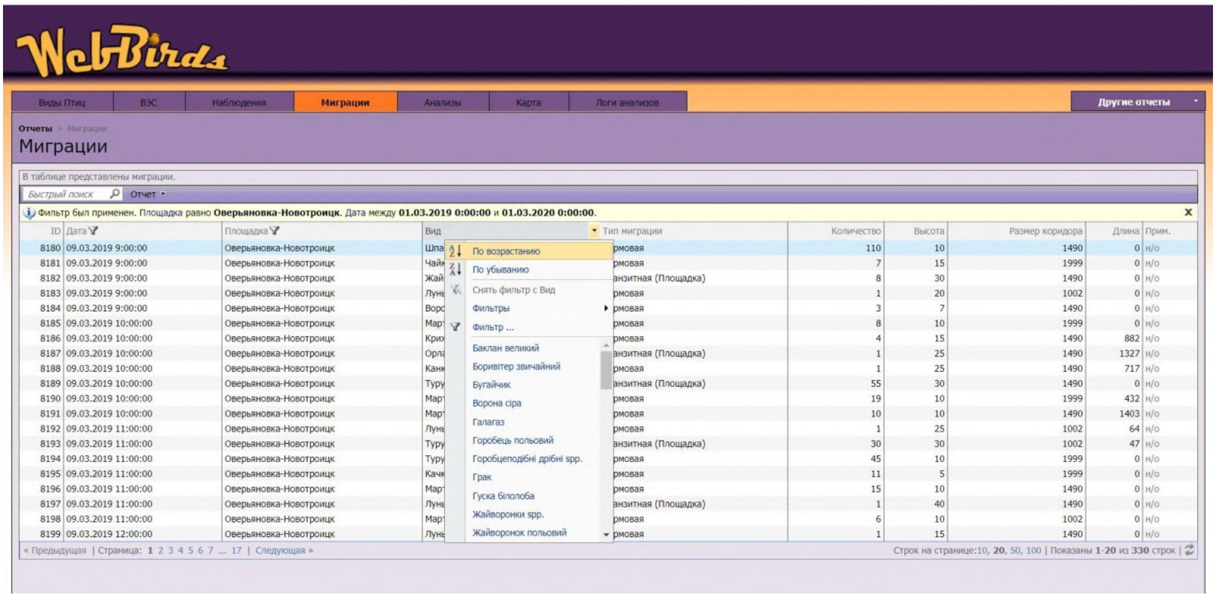

Figure 2. A fragment of the list of bird species recorded during migratory movements at the Overianivka and Novotroitsk wind farms in March 2019 – February 2020, which appears in the menu of the “Species” column when generating the Migration Report in the “WEBBIRDS” Programme.

The mechanism for creating a summary table. Column 2. Data for column 2 “Population abundance”, received in the “WEBBIRDS” Web application where it, in turn, was listed in the line “Population abundance” (Programme menu: “Settings”, “Bird Species” window at the figure 3) based on data provided by BirdLife International, 2015 (http://datazone.birdlife.org/species/search)

As a result, we have obtained a list of 45 species and 7 taxonomic groups that have not been identified as a species (*Passerinae spp., Alauda spp., Anatidae spp., Anas spp., Chlidonias spp., Larus spp., Calidris spp.*), which made migratory movements in March 2019 – February 2020 on the territory of the Overianivka and Novotroitsk wind farms, and were recorded during the research.

The mechanism for creating a summary table. Column 3. Data on the survey period (“Period” column) – a year, spring migratory, breeding, post-breeding, autumn migratory – is automatically generated by the Programme based on the time frames previously set by the User (for example, spring migratory: 01.03 – 30.04; breeding: 01.05 – 30.06, etc.).

The mechanism for creating a summary table. Columns 4-9. Data on the number of censuses (columns 4 and 7), the number of birds maximum and per day (columns 5 and 8), the average size of a flock (columns 6 and 9) are generated based on data previously entered into the programme by the User. These 2 blocks (“Census” and “Census on the territory”) contain data on recorded “immovable” birds of species, which also had migratory movements. Although these data are not included in risk coefficient calculations, as well as PBR and CRM calculations, they can be used by an expert in assessing the impact on a particular species at risk.

The mechanism for creating a summary table. Columns 10-21. Data on the number of migrations (columns 10 and 16), the number of birds (columns 11 and 17), the average and maximum number of birds per day (columns 12 and 18; 13 and 19), the average size of a flock

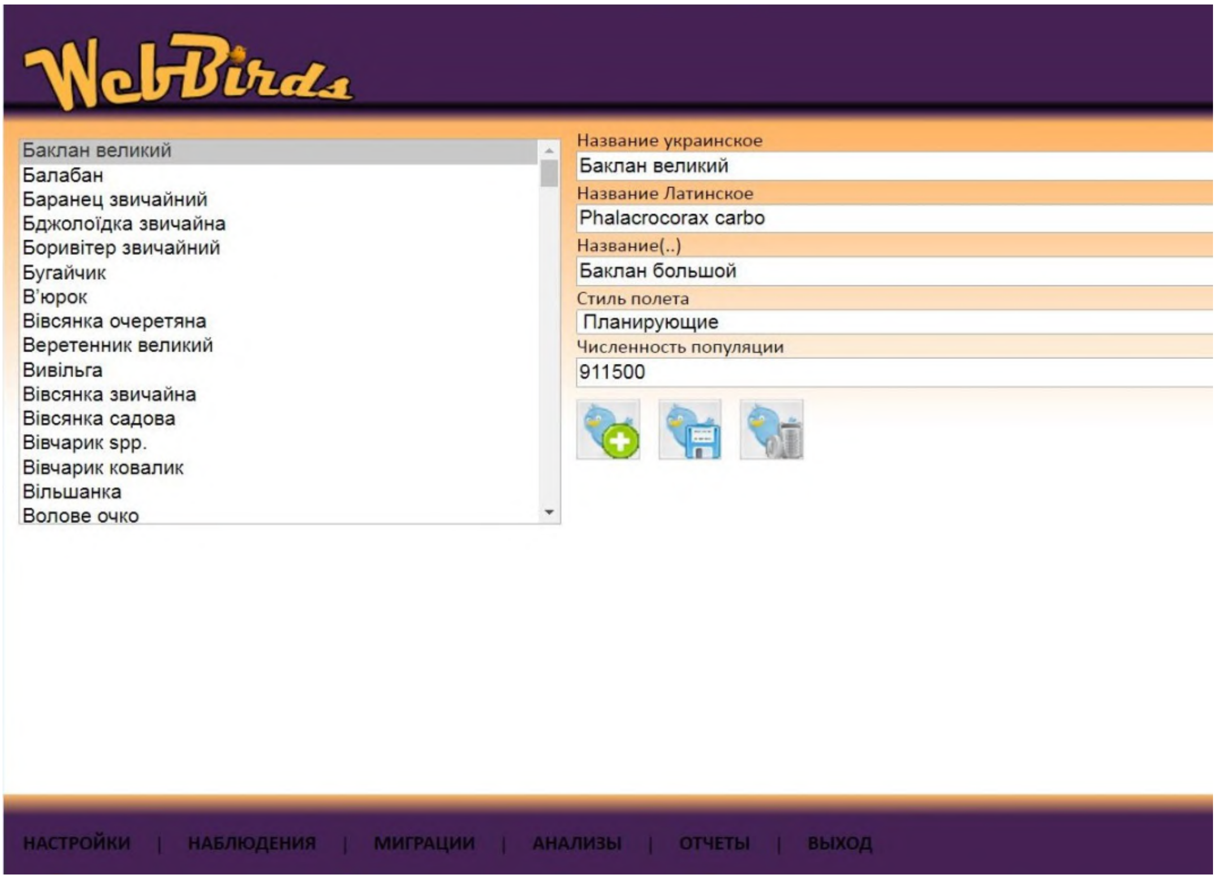

Figure 3. Page of the "WEBBIRDS" programme for entering data on bird species.

(columns 14 and 20), the average height of migration (columns 15 and 21) are generated by the Programme on the basis of the data entered by the User on the number and distribution of recorded migrants with the delimitation of birds that flew across the territory of the WPP and outside it.

The mechanism for creating a summary table. Columns 22-23. The average migration length of the species across the territory of the wind farm (column 22) and the area of the passage corridor (column 23) are calculated by the Programme based on the data entered into the WEBBIRDS or Birds Fly web application during surveys. You can track a specific species on the page of the analysis generated in the WEBBIRDS web application. For example: *Sturnus vulgaris* is the most massive migrant in March 2019 – February 2020, which accounted for 53.57% of all migrants per year: the length of the path over the wind farm site averaged from 818 to 1005 m per season (figure 4).

The mechanism for creating a summary table. Columns 24-33. These columns (included in the blocks "Migrations across the territory taking into account the height" and "Number of birds for a period") are created by the programme based on the available data on migratory birds. Information about birds recorded in potentially dangerous altitude intervals is displayed here. If representatives of the species were not recorded at dangerous heights, then the programme puts a dash for the given season in the columns mentioned above. There is no information in columns 24-33 in March 2019 – February 2020 (since not a single bird was recorded at dangerous heights directly on the territory of the wind farm).

The mechanism for creating a summary table. Column 34. The next column is Filtration

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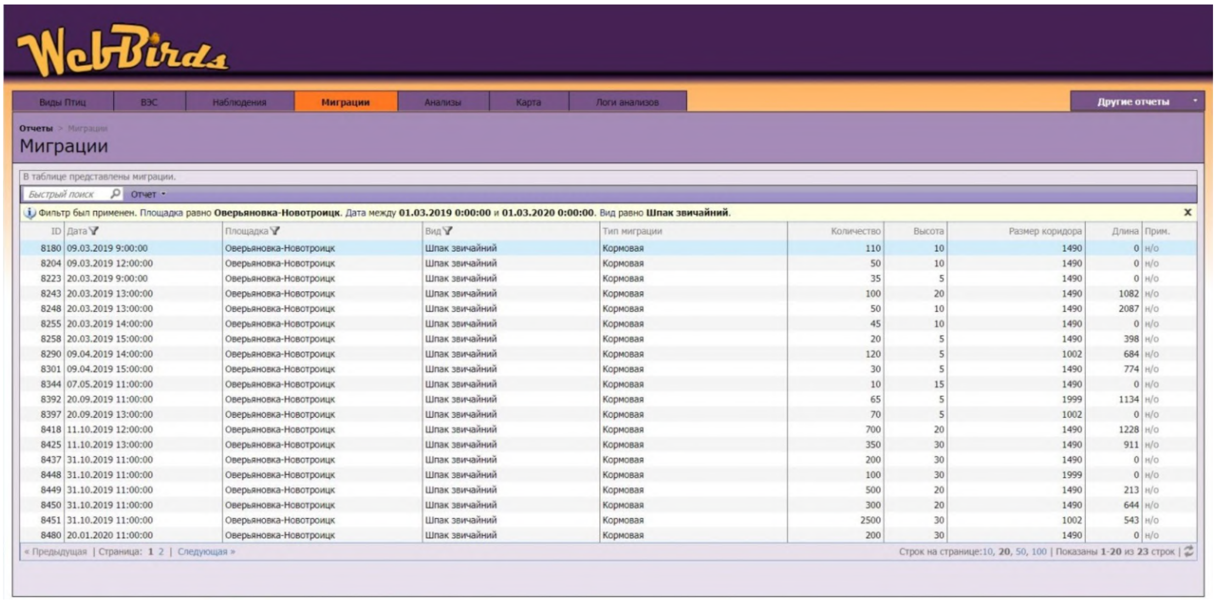

ID	Дата	Площадка	Вид	Тип миграции	Количество	Высота	Размер коридора	Длина	Прим.
8180	09.03.2019 9:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	110	10	1490	0	н/о
8204	09.03.2019 12:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	50	10	1490	0	н/о
8223	20.03.2019 9:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	35	5	1490	0	н/о
8243	20.03.2019 13:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	100	20	1490	1082	н/о
8248	20.03.2019 13:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	50	10	1490	2087	н/о
8255	20.03.2019 14:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	45	10	1490	0	н/о
8258	20.03.2019 15:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	20	5	1490	398	н/о
8290	09.04.2019 14:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	120	5	1002	684	н/о
8301	09.04.2019 15:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	30	5	1490	774	н/о
8344	07.05.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	10	15	1490	0	н/о
8392	20.09.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	65	5	1999	1134	н/о
8397	20.09.2019 13:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	70	5	1002	0	н/о
8418	11.10.2019 12:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	700	20	1490	1228	н/о
8425	11.10.2019 13:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	350	30	1490	911	н/о
8437	31.10.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	200	30	1490	0	н/о
8448	31.10.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	100	30	1999	0	н/о
8449	31.10.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	500	20	1490	213	н/о
8450	31.10.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	300	20	1490	644	н/о
8451	31.10.2019 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	2500	30	1002	543	н/о
8480	20.01.2020 11:00:00	Оверьяновка-Новотроицк	Шпак звичайний	Кормовая	200	30	1490	0	н/о

Figure 4. Analysis of the abundance, flight height and migration length of *Sturnus vulgaris* during surveys at the Overianivka and Novotroitsk wind farm site.

coefficient, which reflects the design parameters of the WPP territory and is calculated using the following formula:

$$K_{filtration} = |\overline{V}| * \rho_{WPP} * |\sin(\Delta\alpha)|$$

$|\overline{V}|$ - The length of the path vector across the WPP territory. It is set depending on the size of the WPP and the interaction scenario.

ρ_{WPP} is the location density of WTGs in the studied area of the WPP, which is calculated as $\rho_{WPP} = 2L_{WPP}/R_{WPP}$, where L_{WPP} is the size of the wind turbine blade (indicated in the “Settings” menu, through the “WPP” window), R_{WPP} is the distance between the WTGs, $|\sin(\Delta\alpha)|$ is the sine of the difference between the path vector angle $|\overline{V}|$ and the WTG direction angle.

The mechanism for creating a summary table. Column 35. After the formation of the previous columns, the abundance coefficient is calculated. The abundance coefficient (AC) is the main parameter that should reflect the assessment of the species abundance, calculated after the formation of the previous columns. The WPP area is formed by the User in the software environment, where the vector of movement and bird gathering is plotted.

The mechanism for creating a summary table. Column 36. On the generated page, you can also see an indicator from the average heights at which migratory birds were recorded. These indicators are needed to derive the height coefficient.

The height coefficient plays a very significant role in calculating the loss of migratory species. In the event that the range of bird flight heights does not coincide with the height interval determined by the dimensional characteristics of the blades, taking into account their length, the wind turbine is not a factor impacting the analyzed species.

The sigmoid function is used for the calculation of $\delta_{heights}$. The sigmoid is a smooth, monotonically increasing, non-linear S-shaped function that is often used to smooth out jump values in some quantity. That is, when the flight altitude of the species differs by more than a meter from the danger zone, the height coefficient is 0. As soon as this value approaches 0, or falls into the danger zone, then the coefficient is equal to one.

The most important for assessing the impact of wind farms is the model of the migration process. This is a multi-criteria model based on parameters of the scenario, the species composition of birds, technological parameters of the WPP and WTG territory. As a result, when using this model, it is possible to obtain a value that, when compared with an expert's assessment, gives the final results for the analysis of the migration process and can be the basis for managing the operation of individual wind turbines in certain seasons of the year.

For all wind farm sites, the results of studies that are included in the programme, tables similar to the summary table described above with the calculation of the Risk coefficient are generated by the "BirdsFly" tool as part of the summary general table with the calculation of PBR and CRM, and, if necessary, they are filtered.

In March 2019 – February 2020, 45 species of birds and 7 taxonomic groups were recorded at the Overianivka and Novotroitsk wind farm site (*Passerinae spp., Alauda spp., Anatidae spp., Anas spp. and Calidris spp.*), which made migratory movements. The calculation of the probable number of collisions was made for all 5 seasons – spring migration, breeding, autumn migration, wintering and total for the whole year.

From the data of 52 species and taxonomic groups of birds that moved through the project area, for 10 species and 1 taxonomic group (*Passer montanus, Passerinae spp., Corvus cornix, Galerida cristata, Riparia riparia, Hirundo rustica, Emberiza calandra, Pica pica, Motacilla alba, Motacilla flava and Upupa epops*) there is no threat of collision. The explanation for this fact lies in the peculiarities of the biology of the above-mentioned species, which move at safe ground heights up to 25 m (and more often up to 10 m), and the probability of finding them in a potentially dangerous altitudinal range is extremely low.

For the other 35 species and 6 taxonomic groups, there is a theoretical threat of collisions. Such species, according to common European practice, are designated as those that may be "threatened due to the operation of wind farms" (European Commission recommendations, 2010). But for all of them, collisions are not expected in all 5 seasons, either due to the absence of a threat of collision (i.e., ground flight heights), or due to the fact that the migration process on the territory of the wind farm is insignificant (a small total number of representatives of a species, or the main bird movements took place outside the wind farm site, and only a small percentage flew across the wind farm territory).

In general, the following can be stated. The territory of the Overianivka and Novotroitsk wind farm sites is not a place of significant concentrations and migratory movements of birds; the species that we observed within the wind farm are mainly characterized by the heights of flights under the rotor-swept area, the main part of which is the common starling. Species that may feel the impact of the wind farm make regular forage and transit flights mainly within the nearby wetlands (*Larus spp., anseriformes*), or they are not numerous (*falconiformes*). The most "intense" are the periods of seasonal migrations, when the number of birds and the intensity of their flights increase (149 records of 3720 individuals in spring and 108 records of 6056 individuals in autumn versus 41 records of 1283 individuals in winter and 32 records of 423 individuals in summer).

Among the migratory birds there were only 3 representatives of the Red Data Book of Ukraine (*Circus cyaneus, Grus grus and Larus ichthyaetus*), but they were recorded at safe heights and did not feel the impact of the WPP.

It should also be noted that according to the reference data [6], there is mortality of 1 bird individual per 10 MW of electricity produced at the wind farm. This empirically confirmed relationship was determined based on many years of research on 109 operating wind farms in Europe and North America. That is, with a total capacity of the Overianivka and Novotroitsk wind farm of approximately 140 MW, 14 bird individuals should die. According to our calculations, based on the available data on the number of birds at the height of the rotor-swept area and the directions of their movement, the probability of bird collision with the wind turbines was extremely low.

The same work carried out in 2018-2021 on the territory of the Botiieve wind farm showed similar results.

Thus, in 2018, 64 species and 2 groups of birds that were not identified to species were recorded at the Botiieve wind farm site. For 34 species and 1 group of birds (53.0%), collisions are not expected in all seasons either because there is no threat of collision or because the migration process on the territory of the wind farm is insignificant. For 6 species (9.1%), *Corvus cornix, Alauda arvensis, Chloris chloris, Hirundo rustica, Sturnus vulgaris and Carduelis carduelis*, the threat of collisions is insignificant in all seasons. For 16 species and 1 group of birds (25.8%), *Passer montanus, Passer spp., Columba palumbus, Turdus pilaris, Turdus merula, Fringilla coelebs, Falco vespertinus, Riparia riparia, Tadorna tadorna, Emberiza calandra, Parus major, Pica pica, Apus apus, Motacilla alba, Motacilla flava, Philomachus pugnax and Larus minutes*, the threat of collisions is not significant in 2 seasons. At the same time, for all of them, it is generally not significant throughout the year.

In 2018, 8 species fell into the potential risk group: *Falco tinnunculus, Columba livia, Corvus frugilegus, Buteo buteo, Circus aeruginosus, Larus cachinnans, Larus ridibundus* and *Larus melanocephalus.* For *Falco tinnunculus* and *Corvus frugilegus*, the threat is significant in one season, but it is insignificant throughout the year (the death rate is predicted to be no more than 2 individuals for *Falco tinnunculus* and 30 individuals for *Corvus frugilegus* - 50.0% and 33.0% of the "permitted" PBR calculations). For *Columba livia, Buteo buteo, Circus aeruginosus* and *Larus melanocephalus* the collision threat is defined by the programme as significant in one season, and significant throughout the year. The predicted mortality is 100% of the "permitted" PBR calculations for *Columba livia, Buteo buteo* and *Circus aeruginosus*, and 150% for *Larus melanocephalus.* And only for Larus cachinnans and Larus ridibundus the threat is significant throughout the year (the predicted assessment of mortality is 112.5% and 100% of the "permitted" PBR calculations respectively, or 9 and 4 individuals).

According to the results of research in 2019, we can state the following: the vast majority of migratory birds of the Botiieve wind farm ornithocomplex – 45 out of 46 species and one taxonomic group have a risk coefficient of 0. The reason for this is the absence of bird migrations recorded during the research at altitudes of the dangerous range (from 51 up to 150 m), so their height coefficient is 0 this year, and respectively, the value of the risk coefficient of the species indicated in the table is 0%. The exception is *Larus ridibundus*, which has a height coefficient of 0.9991% and a risk coefficient of 3.41%. The explanation for the conclusion of the programme, which determined the result "Threat: NOT SIGNIFICANT" by calculating the risk coefficient, is that 45 individuals of this species were recorded in spring at a height of 90 metres, their route ran along the coast of the Sea of Azov and was partly reflected within the study area, which gave the programme grounds to pay attention to these processes.

For 45 out of 46 recorded species and 1 group of birds, there is no threat of collisions in all periods of the year. And for *Larus ridibundus*, the annual number of which is 195 individuals, 45 of which were recorded in the danger zone, the programme predicts 8 collisions per year and therefore gives a conclusion about a significant threat (8 is bigger than 3, where 3 are PBR individuals) in the spring, when dangerous heights used by birds of this species were just recorded; the result obtained is 3, the conclusion gives (3 is smaller than or equal to 3) "the threat is not significant, monitoring is necessary."

In 2020, out of 30 species for which there was a theoretical threat of collisions with wind turbines (out of 47 species and 2 taxonomic groups registered in the project area during the year), 24 species of them are not expected to have collisions in all 5 seasons, either due to the absence of a threat of collision (i.e., ground flight heights), or because the migration process through the wind farm is insignificant (a small total number of representatives of the species, or the main movements of birds took place outside the site, and only a small percentage flew across the wind farm). For 3 species *Falco tinnunculus, Corvus frugilegus* and *Larus cachinnans*, which were recorded at dangerous heights directly on the territory of the WPP, the Programme found no impact (risk coefficient is 0%) due to small numbers and a small percentage of the time. Another 2 species *Corvus corax* and *Larus ridibundus* were identified as endangered, but the impact of the Botiieve wind farm on them was determined by the Programme as not significant. For *Corvus corax* as a whole, a loss of 1 individual is predicted for the year, for *Larus ridibundus* – 12 individuals. And only for *Buteo buteo* the programme concludes that there is a significant threat, since the loss of 2 individuals is predicted for the year, although this scenario is quite unlikely.

And, finally, in 2021, according to the results of research, almost all species of the Botiieve wind farm ornithocomplex, 45 out of 46 species and one taxonomic group (*Tringa spp.*), have a risk coefficient of 0. This result was facilitated by the absence of representatives of these species registered during bird migration studies at heights of the dangerous range (from 51 m to 150 m) above the territory of the wind farm, therefore, their height coefficient is 0 this year, hence the value of the risk coefficient will be 0. As an exception, one species *Pandion haliaetus* has the risk coefficient of 0.94%. The comment of the programme regarding the threat is as follows: "the threat is not significant". For the entire period of research, only one individual of this species was recorded on September 14, 2021 at 10:00 a.m. on a forage flight 50 meters high. This height is close to the range of dangerous heights. The average number of birds of this species, both for the season and for the year, respectively, was 1 individual, hence the average height of migration is 50 metres, therefore, the height coefficient is 1. Considering these values, calculations were made for the flow filtration coefficient and the population coefficient, which affected the value of the risk coefficient.

It should be noted that *Pandion haliaetus* is not the only species recorded during research at a height of 50 m, which is close to dangerous ones ($51 - 150$ m). *Merops apiaster*, 20 individuals, and *Circus aeruginosus*, 1 individual, were at such height. The average number of birds, both of the first and second species, and the average flock size are bigger than 1 and, accordingly, the average flight height for all records of these species will be already below the risky one. But an important criterion for concluding that there is no risk for these two species is the fact that flights at an altitude close to dangerous were made off the site.

4. Conclusions

Thus, the assessment of the impact of wind farms on the ornithological component of the territory is a complex functionally dependent model characterized by a number of factors.

Factors can be divided into the following features:

- factors relating to the scenario of behaviour (depending on the phase of the life cycle);
- factors of species composition of birds;
- WPP territory factors;
- factors of expert assessment.

To measure the quantitative changes in the species composition of birds, a population coefficient was proposed, calculated on the basis of the total abundance of the recorded species within the project area of the WPP site and the European abundance of the species.

The most important for assessing the impact of wind farms is the model of the migration process. This is a multi-criteria model based on parameters of the scenario, species composition and technological parameters of the WPP territory. As a result, when using this model, you can get a value that, when compared with the expert's assessment, gives the final results for the analysis of the migration process.

The implemented mathematical model and the WEBBIRDS programme, based on it, allows you to analyze the impact of wind farms on the ornithological component within the WPP site and for the region as a whole.

The developped “WEBBIRDS” web application is a multifunctional solution that supports the use of mobile devices, GPS systems to determine the current coordinates during surveys and the ability to generate reports.

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PAPER • **OPEN ACCESS**

Use of the Esri's ArcGis products to create indicators of the integrated characteristics of the WTG placement in the geoecological system on the territories of wind farms

To cite this article: K H Aleinykova and V D Siokhin 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012061

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012061 doi:10.1088/1755-1315/1049/1/012061

Use of the Esri's ArcGis products to create indicators of the integrated characteristics of the WTG placement in the geoecological system on the territories of wind farms

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Abstract. With the development of wind energy in the south of Ukraine, there was a question of the safety of its operation for the ecosystems of the region. The goal of many years of work was the development of methods for geoecological analysis of natural and technical geosystems in the territories of wind farms to assess the impact of wind turbine placement. An integrated approach in carrying out monitoring work and individual methods of analysis, as well as the characteristics of the natural and technical geosystem, using an integral approach, made it possible to synthesize various aspects into a single geoecological system, the analysis of which gives a more complete picture of the relationships and connections of the objects of the territory as a complex natural and technical geosystem. The resulting analysis of the criteria provides a better environmental assessment and selection of means to minimize the negative consequences of the impact on the natural environment.

1. Introduction

With the development of sources of energy-saving systems, wind power plants have become widespread. In the last 20 years, the number of such power generation projects and their importance as a source of renewable energy has been constantly growing. Much attention is paid to the protection and conservation of biological diversity within the borders and adjacent territories to wind farms, both on the part of the state at the level of implementation of legislative acts, and on the part of the public at the level of environmental initiatives.

The south-east of Ukraine (the Azov-Sivash region) since 2000 has been a region for the development of wind energy. A powerful natural and technical geosystem of the regional level has been formed on this territory, including natural landscapes and systems of technical objects, represented by 10 wind farms and a network of power transmission lines. During the construction and development of the wind farms, as well as service roads, the degree of negative technogenic impact on the natural environment reaches its maximum. In addition, enterprises of the food industry, agriculture, transport, and recreational development of the coast are functioning here. When the construction work is completed, the influence is reduced to the functioning of the WF.

When the elements of the technogenic block interact with the components of the natural block, peculiar, still insufficiently studied natural and technical geosystems are formed. In the case when the components of the environment, natural and modified by man, are studied, it is common to speak about "geosystems".

Back in the mid 1960s, I. P. Herasymov, L. F. Kunitsyn, V. S. Preobrazhenskyi, A. Yu. Reteyum, K. N. Dyakonov and others developed the concept of geotechnical systems. A geotechnical system is a set of natural objects and engineering structures interconnected and functioning as a single entity [1]. It is an open system that exchanges components with the environment. The geotechnical system also includes a control and management unit. Information about the state of natural objects is an obligatory component of geoecological monitoring. Natural processes in the transformed landscapes are changed by the functioning of geotechnical systems. In this regard, it is relevant to assess the impact of wind farms on natural complexes and their components. Let us evaluate the indicators of wind turbine placement using a complex geoecological analysis.

Geoecological analysis is the identification of signs that characterize the current and expected state of the environment [2, 3]. It is based on impact monitoring of the environment. The main purpose of such monitoring is to solve the problem of improving the environmental situation, optimizing the existing nature management. When analyzing a specific system, it is important to assess the level of impact of technological and technical processes within the boundaries of the geosystem and in adjacent territories. The process of changing the natural block of the technogeosystem as a result of economic activity proceeds through specific migration channels: air, land, water. At the same time, when the processes of the impact of technogenic processes are superimposed on natural processes and phenomena, the effect of its impact is enhanced [4]. One of the main tasks of geoecological analysis is to assess the state of the study area as a geosystem of the topological level - the main carrier of ecological and geographical information, on which ecological situations and problems arise [2,5,6]; to evaluate specific violations and ways to eliminate or mitigate them, preventing the development to a higher hierarchical level [7].

The objectives of the environmental assessment (EA) of projects are to determine quantitative criteria for making decisions on the admissibility or inadmissibility of project implementation, to ensure the choice of an option and type of planned economic activity with the lowest environmental and social costs, to obtain quantitative criteria for evaluating the effectiveness of environmental measures planned by the project, to choose an acceptable for society the rate of return in the implementation of the project [8]. Environmental Assessment (EA) accompanies all stages of the monitoring cycle. Natural-economic (geosystem) monitoring is a complex system of observations and assessment that allows you to track the state and changes in natural geosystems and the consequences of their transformation into natural-technical ones, assess the state of the territory where the differences of parameters from the baseline due to intense anthropogenic impacts are recorded, assess qualitative and quantitative content of the studied indicators of geosystems within any region [9].

2. Material and methods

Geoecological research methodology allows at a higher scientific level to approach the assessment of the impact of technogenic processes, namely the placement of wind turbine generators (WTG) and the formation of the wind power plant (WPP) site, on the state of the components of the environment – avifauna and chiropterofauna, which are considered as one of the important bioindicators of the ecosystem state.

The validity of ecological conclusions is significantly increased when using geoecological analysis, which is increasingly being introduced into theoretical and practical ecology. Its use is especially effective in the assessment of natural and technical geosystems. To date, there is no single methodology for the ecological and geographical analysis of geosystems, and an individual approach is used for each type of natural and technical geosystem.

Geoecological analysis within the limits of the natural and technical geosystem, a component of which is the ecological system, with the dependence between the initial and its constituent changes, makes it possible to model the ecological situation on the basis of computer technologies using modern software and hardware. As a result, a geographic information system (GIS) is being created. In a broader sense, it is a geo-environmental information and cartographic support for the studies carried out, as a set of environmental information and cartographic material about the processes, phenomena, events, objects inherent in the geosystem under study.

When processing information data and preparing for mapping, as the main product of the analysis, GIS technologies were used, namely Esri's ArcGis software products (satellite images for geographical analysis of the territory, a set of program functions for information processing).

Work on assessing the impact of wind farms on biological complexes and their components has been carried out for many years at the sites of wind farms in the Azov-Black Sea region. As a result, various approaches and methods of analysis were developed, new technologies and software were implemented, which were tested in practice and developed into a huge methodological material with an integrated approach. Thus, the Biodiversity Research and Training Centre developed and implemented the WebBirds Web application [10], designed analytical and information databases of bird census and migrations [11], developed research methods at wind farm sites [12], and also considered the features of using new technologies when carrying out monitoring studies at WPP sites [13, 14]. The accumulated methodological experience allows us to talk not only about the analysis of the territory of the wind farm, but also a complex regional assessment that is due to the growth of the wind farm network in the south of Ukraine, and the cumulative impact on each other.

The developed methods of geoecological analysis were carried out on the basis of the functionality of the ArcGis 10.4 – ESRI software complex for the WPP sites. Complex analysis is achieved by superimposing information layers, existing and developed by the team of the Biodiversity Research and Training Centre, and author's methods of analysis on the cartographic material.

According to the requirements of the project documentation, when carrying out research for each territory, complex monitoring work was carried out, during which lists of discovered species of animals and plants and their belonging to international conservation lists were compiled, their habitats were mapped, quantitative and qualitative parameters of populations were taken into account, and critical significant habitats were determined. As a result of the work carried out, detailed maps were obtained in the studied and adjacent territories, which made it possible to conduct a complex analysis during the operation of wind farms, and at the early stages of design to correct the installation sites of wind turbines to free up territories valuable for natural significance.

Let us consider the method of analysis using the example of the Overianivka and Novotroitsk wind farm, located in the Kherson Region near the Sivash, with monitoring data over 10 years of research.

3. Methodology

1. To analyze the territory, it is first necessary to determine the boundaries. That's why it is necessary to know the geolocation of the wind turbines that form the WPP site (figures 1–19).

In larger wind farms, the turbines are usually arranged in groups or in a line perpendicular to the prevailing wind direction, or are located along the contour of hills where the wind speed is higher.

2. The formation of the boundaries of the WPP site is based on 500 m buffer zones around the WPP, the zones of potential impact. According to international requirements, the boundaries of the site are at a distance of 500 m from the extreme wind turbines (figure 3).

3. When assessing the impact, ***the main zones of impact around the WPP*** are identified. These are buffer zones of 500 m, 250 m and 140 m (150 m).

Each of the buffer zones characterizes the impact of certain processes.

To neutralize the consequences of blade separation, the following set of measures is applied:

A safe distance is determined; wind farms are designed and placed in such a way that there were no buildings or settlements in the possible directions and within the possible spread zones of the blades. It is unlikely that such a safety distance will exceed 300 meters, although it may vary depending on the size, shape, weight and speed of the wind turbine, as well as the height of the wind turbine [15, 16].

The main factor determining the distance between the turbines in a wind farm is the speed and turbulence of the air flow. As a general rule of thumb, the distance between adjacent turbines located in the direction of the wind is equal to 5-7 rotor diameters. The size of the site required to place a wind farm depends on the planned number of turbines; however, the actual area of land disturbed by the location of the wind farm (for example, the area required for turbines and access roads) is significantly less than the total area of land occupied by the project. For example, a typical wind farm with 20 turbines may be located on a 1 square kilometer site, but most likely only 1 percent of that land will be actually used [17].

Wind turbines are placed at specific intervals to maximize the potential of wind power while using minimal space. The main factors in determining the distance between the turbines are the speed and turbulence of the air flow. As a rule, the distance between wind turbines is from 3 to 5 rotor diameters perpendicular to the prevailing wind direction, and along the prevailing wind direction – from 5 to 7 rotor diameters [17]. In some countries and territories, the minimum recommended distance between wind turbines is 200 meters, so as not to interfere with the passage of birds between the turbines [18]. If the distance between the turbines along the prevailing wind direction is less than 5 rotor diameters, significant energy losses due to the formation of a turbulent wake are very likely [19].

So, on the example of the Overianivka and Novotroitsk wind farm, where the rotor diameter is approximately equal to 125 m, the minimum distance equal to 3 rotor diameters is 375 m, the maximum distance is 7 rotor diameters, or 875 m, at least 5 diameters is the optimal distance in order to avoid energy loss and is equal to 625 m. After analyzing the technical characteristics of the wind turbine, in which the diameter of the rotor can vary from 90 to 150 m, the indicators were averaged and the optimal buffer zone around the wind turbine was selected that meets the technical requirements of the wind farm in order to avoid energy loss, and a comfortable zone, which should not be less than 500 m between the wind turbines and meets international requirements. For biological objects and the formation of comfortable movement corridors, as well as for choosing the route of census and the VPs, 500 m buffer zones are used, the overlay of which shows the zones of attention for biological objects (figure 4).

Formation of 140 m buffer zones around the WTG is a risk zone (125 m is the maximum diameter of the rotor plus about 7 m for vortex flows that can impact on insects, birds and bats) (figure 5).

To neutralize the consequences of ice breaking and other physical impacts, a zone of direct influence was chosen, for which the following set of measures is applied [20]:

- During the formation of ice, the operation of wind turbines stops;
- Warning signs are installed within a radius of at least 150 meters from the wind turbine; Outside these zones, one can observe free space for the formation of movement corridors and migration of animals.

4. Analysis of the ratio of risks and free zones of movement. The methods of mathematical analysis to assess the actual impact and its percentage are used. Knowing the technical characteristics of the wind turbines that are being built on the site and mathematical methods, it is possible to calculate the amount of space occupied by the wind turbine and, accordingly, the percentage ratio attributable to the risk zones on the entire wind farm site. This is a rather rough estimate, but it gives an opportunity to understand the spatial representation of the degree of interference. Using the main physical characteristics of wind turbines (figure 6), it is possible to calculate the share attributable to technical structures at the wind farm site, which is the actual impact on the environment.

5. Characteristics of the density of the WTG placement as an element of the formation of barrier risks. Considering the 500 m buffer zones around wind turbines as a component of the site for geosystem objects, it is possible to identify areas that are under the influence of more than one wind turbine. In such territories, there is an imposition of 500 m buffer zones of several wind turbines, on the other hand, this territory is free from the direct physical influence of wind turbines, along which ecosystem objects move. The overlay of buffer zones shows the density of the wind turbines and the nature of the free space between them (figure 7-8). It can be seen from the illustrations that the fewer overlaps, the more comfortable the site is, especially for birds and bats.

If we consider the area with a radius of 500 m between the wind turbines as comfortable, then the area attributable to this site is 78.5 hectares. Accordingly, the area attributable to one wind turbine should not be less than this value.

6. Construction of Thiessen polygons and their analysis to determine areas of barrier risks. Thiessen polygons are an important component of spatial analysis concepts such as assessment of the nearest neighbour and proximity. The Thiessen polygons, named after the American meteorologist Alfred H. Thiessen, are a more specific application of the Voronoi diagram in meteorology and geophysics [21].

An important characteristic of the site is the nature of the placement of wind turbines and the assessment of placement using Thiessen (Voronoi-Thiessen) polygons. This approach makes it possible to determine the zones of impact of each wind turbine. Critical characteristics of the site forms barrier zones and risk zones.

The Thiessen polygons have the unique property that each polygon contains only one input point, and any location within that polygon is closer to its associated point than to any other polygon point. The Thiessen polygons can be used to subdivide a point coverage into regions (zones of impact), known as the Thiessen polygons or Voronoi diagrams. Each zone (region) contains only one coverage input point. Each region has a unique property, the essence of which is that any location within the region is closer to the point of the region than to the point of any other region (figure 1). In other words, wherever an object is located inside the polygon, the nearest point of the region to it will be a point inside the polygon (the polygon is the zone of impact of the point of the region for any object), thus, the limits of impact are formed (figure 10).

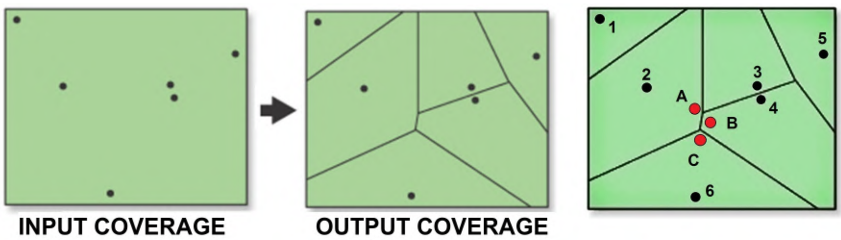


Figure 1. Thiessen polygons from point features (for object A, the nearest point of impact will be 2, for B it will be 4, for C it will be 6).

Let us consider the nature of the location of wind turbines (point objects), using the Thiessen polygon function, which allows you to divide the area where the wind farm is located into the zones of each wind turbine impact. The territory is divided into polygons, inside which there is only one wind turbine, and any object located inside the polygon, the nearest wind turbine for it will be a wind turbine from the same polygon (that is we can talk about the zone of impact of a wind turbine) and the formation of boundaries of this impact. Having the boundaries of impact zones, it is possible to estimate their area. Knowing the acceptable values of areal characteristics, which corresponds to a 500 m buffer zone around the wind turbine and is equal to 78.5 ha, it is possible to build a gradation of values. In this gradation, we can distinguish risk zones (the sites with an area of less than 78.5-80 ha), border territories (80-100 ha), satisfactory sites (100-130 ha) and comfortable ones (with an area of more than 130 ha) (figure 10).

Assessment of the wind farm impact on the components of wildlife

The greatest number of questions is caused by the impact of wind farms on the avifauna. Indeed, wind farms, as vertical structures with moving elements, pose a certain risk to birds. As the main factors of the impact of wind turbines on the avifauna, one can single out: physical impact in a collision with turbines, blades and towers; habitat disturbance; violation of the bird migration route. Possible indirect effects on birds include those caused by changes in the habitat and the presence of a disturbance factor in the territory of the wind farm, quantitative and qualitative changes in the species composition of animals that are prey for predatory birds, changes in the nature and number of places for bird breeding and resting due to natural changes in the habitat, as well as the use of wind turbines by birds as seats. Impacts on birds and bats depend on the scope of the project and other factors, including technological aspects (e.g. a tower size and a turbine design), wind turbine lighting and a wind farm layout. In addition, the impact may be affected by the characteristics of the wind farm area, including its relief and topographical and biotopic characteristics (for example, proximity to large concentrations of birds, bats or prey species), the number of birds and bats flying through the territory of the wind farm, the features of their behaviour that put them at particular risk (for example, bird soaring heights and migration routes of bats), as well as meteorological aspects.

The assessment of the wind farm impact depends on many factors starting from the location of the wind farm (relief, location of wind turbines on the site), meteorological factors, species diversity, etc. It should be noted that careful planning of the location of wind farms in cooperation with expert ornithologists, in order to minimize the impact on the avifauna, allows achieving a relatively low level of mortality of birds and bats.

When carrying out such research work, one inevitably encounters natural factors of dynamic variability, which should be separated from the impact of wind farms on natural components. For example, in the same time periods, monitoring data may differ depending on temperature indicators, the level of water and anthropogenic transformation of the territory, etc.

Having the technical characteristics of the site and the data of the territory as a geoecological system makes it possible to conduct an associated analysis of heterogeneous spatially coordinated data (vegetation, the presence of the NRF objects and eco-networks, agricultural use, monitoring data on flora and fauna objects and species diversity). Special attention was paid to the analysis of territories for the presence of objects of the natural reserve fund of Ukraine, territories promising for inclusion in the list in the NRF, objects proposed for inclusion in the ecological network, territories of the forest and wetland fund of Ukraine, as well as territories of natural significance.

To obtain data on the state of geoecological nature for the implementation of a complex analysis, the work was carried out due to the specifics of their implementation, namely, the need to accurately indicate the contours and locations of objects on the ground, which often, by their nature, do not have clear boundaries and move in space.

7. Allocation of natural areas. Using satellite imagery data, as well as analysis of the territory, monitoring of the main groups of animals and plants, complex information is collected and put on cartographic material. Then analysis and calculation of assessment criteria are carried out (figure 11a).

8. Emerald Ecological Network. Particular attention is paid to the territories of the NRF, which are within the boundaries of the WPP or are located in its buffer zones (figure 11b, figure 12).

9. Analysis of biotopic and species diversity in the assessment of the impact area, as an integrated approach to the study and analysis of the WPP territory (figure 13).

10. Particular attention is paid to ornithological census. The data of monitoring census of birds and other animals are considered within the site and 500 m zones of impact, so we have an integrated approach to the natural and technical geosystem. This gives us the opportunity to analyze in space the degree of risk for migratory and settled birds within 500 m of buffer zones (figure 14).

11. Using the characteristics of the barrier effect and monitoring data of migrations, ***zones of tension*** where the density indicators of wind turbines are critical and large flows of bird movement at dangerous heights are indentified. The use of such an analysis clearly shows areas requiring additional attention during mass migrations (figure 15).

12. Analysis of breeding complexes taking into account risk zones. Let us consider the location of the main breeding complexes and their quantitative characteristics taking into account 500 m zones and barrier risks (figure 16).

13. Analysis of bird density. Using the density of gatherings and migrations with superimposition of layers of natural sites to identify zones of maximum biodiversity and increased abundance, identify corridors, take into account barrier areas to implement measures to minimize the impact of WPP. The analysis of bird density shows the main places of bird concentrations and areas that require special attention (figure 17).

Similar mechanisms have been worked out for bats, with individual assessment parameters, which made it possible to analyze the situation and identify places that require additional attention (figure 18).

14. After analyzing the territory of the WPP and the objects under study, with a complex comparison of all the information received, ***risk zones were identified***. They were places with the highest concentration and species diversity of wildlife objects. Recommendations and mechanisms have been developed to minimize the impact of wind turbines on the biological components of the geosystem (figure 19).

4. Results

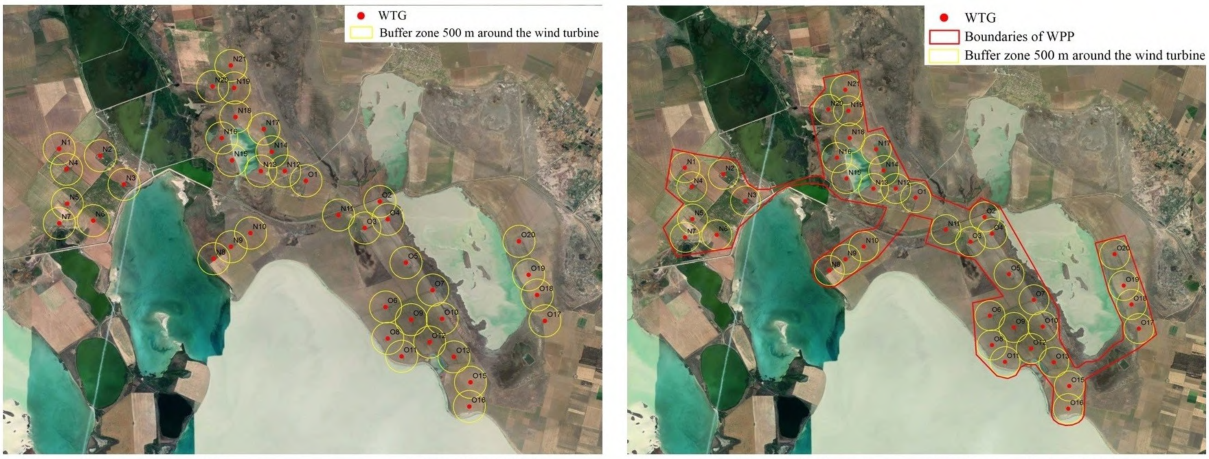
The application of this metod of geoecological analysis gave us the following results:

1. Placement of point data for the location of wind turbines (figure 2).
2. Formation of the boundaries of the WPP site based on 500 m buffer zones around the WTG or zones of potential impact (figure 3).
3. Formation of impact zones (figures 4 and 5).
4. Analysis of the ratio of risk volumes and free movement zones (figure 6).

The number of wind turbines at the WPP site is 40, the area of the WPP site is 4304 ha = $43*10^6$ m^2.

If we talk about the volume of the obstacle in the section of the WPP site, then we can discuss the volume of all towers and their share relative to the rest of the space (figure 7). The volume of one tower outside the rotation area $V1 = 1060$ m^3. As there are 40 towers, then $V2 = 42.4 * 10^3$ m^3 is the volume of all towers in the WPP site which is a static obstacle. The volume of space with a height of 54 m above the ground of the WPP site is $V3 = 23.2 * 10^8$ m^3 (figure 8). Scheme of volumes attributable to the wind turbine rotors. The volume of towers from the entire space is 0.002%, the percentage of a static obstacle at a height of up to 54 m from the ground (refers to insects and species of birds and bats that live or hunt at these heights).

Figure 2. Placement of wind turbine location points.



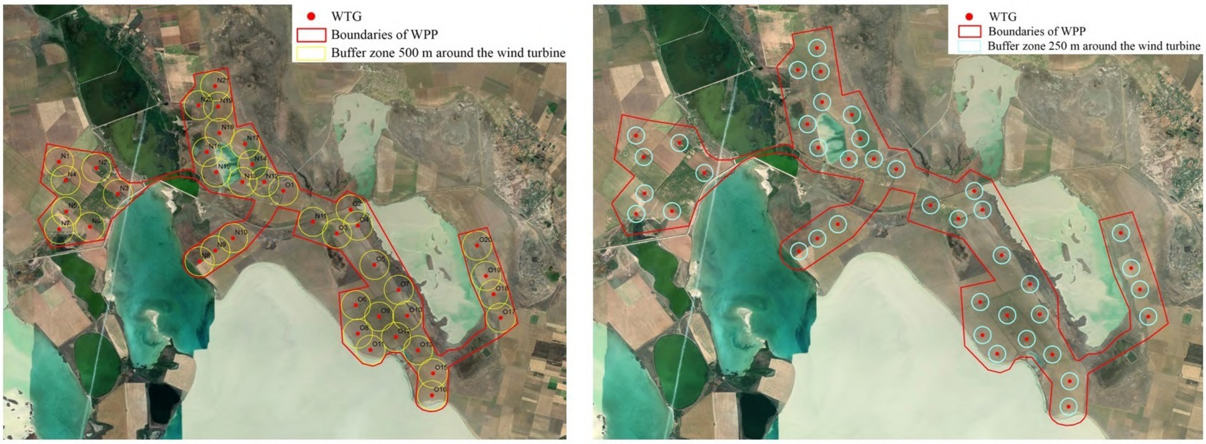
500 m buffer zones around the WTG   Formation of the boundaries of the WPP site

Figure 3. Formation of the boundaries of the WPP site.

As a result of the blade rotation, a plane of rotation is formed, which also rotates in space depending on the wind direction. As a result of rotation, there is a sphere – a ball (figure 8). The sphere volume V4=$1*10^6$ m^3 is an obstacle volume for one WTG which is a dynamic obstacle. Reasoning further, we can talk about the volume of the rotational element and its share in space. The volume of all elements in space is V5 = $40*10^6$ m^3 of the volume of space in which the rotational elements are located. V6=$5.4*10^9$ m^3 is the site volume. Accordingly, the percentage of spatial dynamic risk is 0.74% of the total space at the height of 54 m to 180 m.

5. Characteristics of the density of the WTG placement as an element of the formation of barrier risks (figure 9).

In the presented examples, we can see the density of the wind turbine placement according



500 m buffer zones

250 m buffer zones which are not intersect show that the distance between wind turbines is 500 meters or more

Figure 4. Buffer zones of 500 m and 250 m around wind turbines.

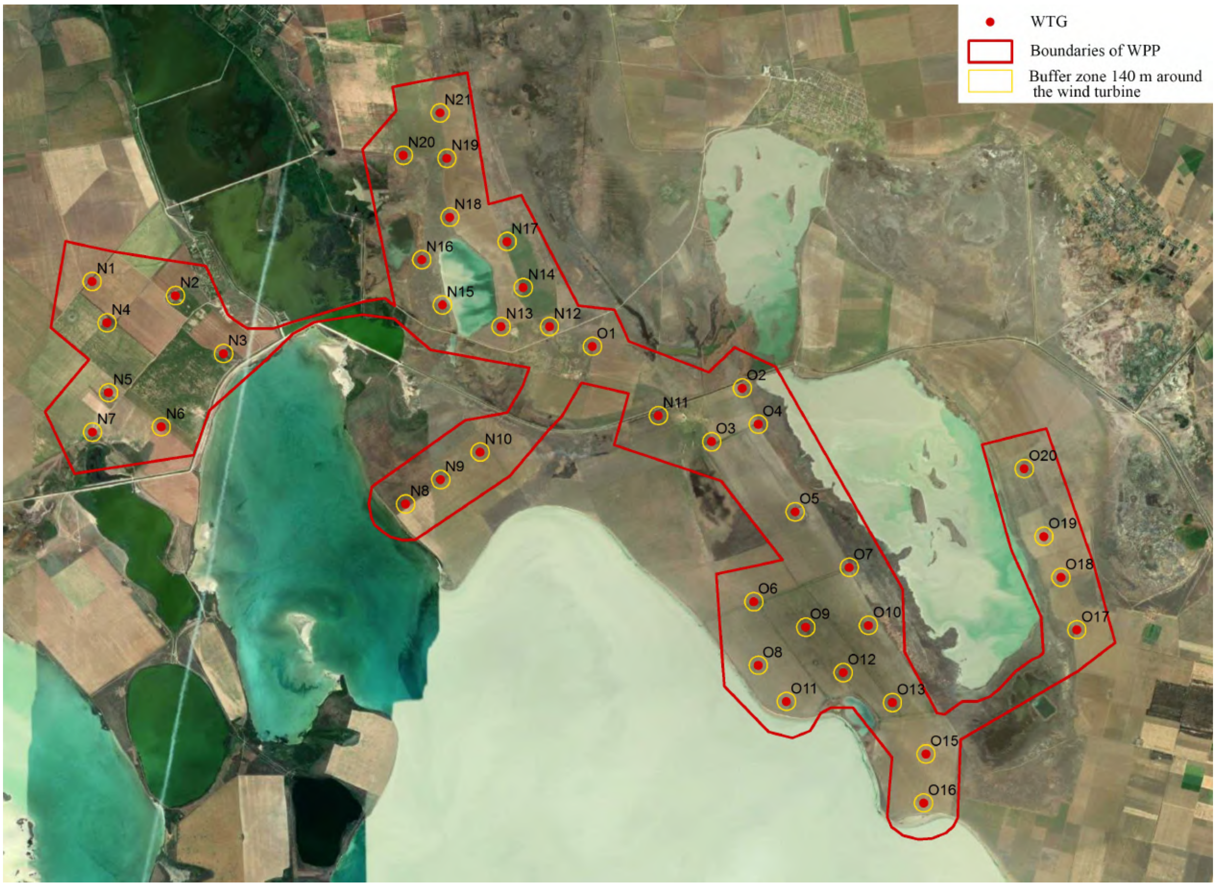


Figure 5. 140 m buffer zones around wind turbines.

to 500 m buffer zones around each wind turbine, which allows us to draw certain conclusions about the density of wind turbines at the wind farm site, the comfort of their placement and the

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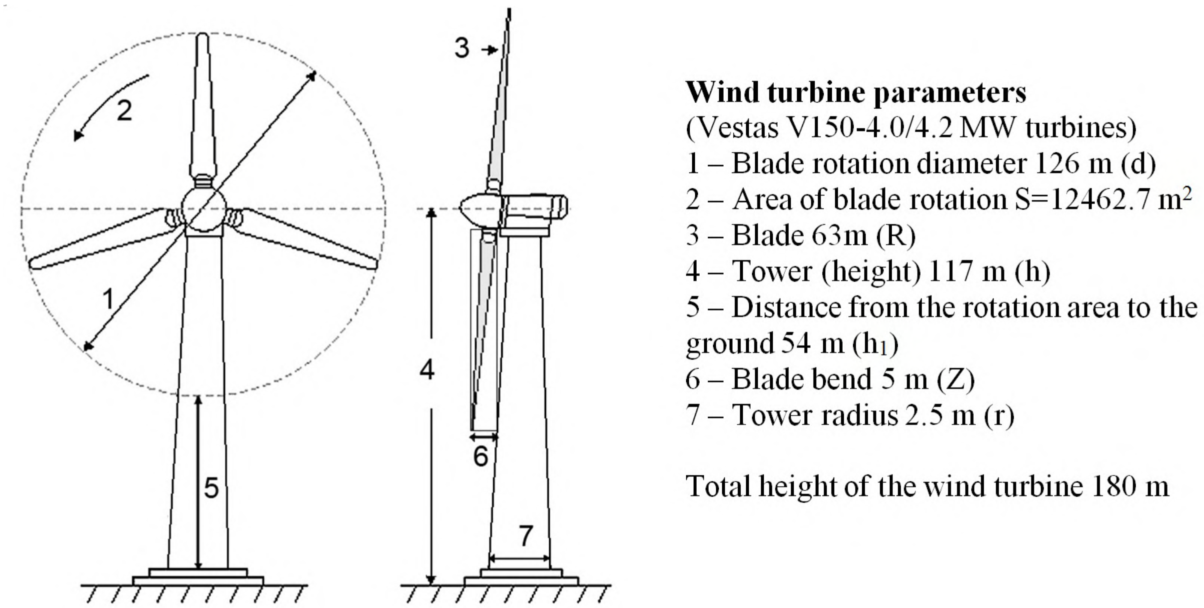


Figure 6. Scheme of towers in space.

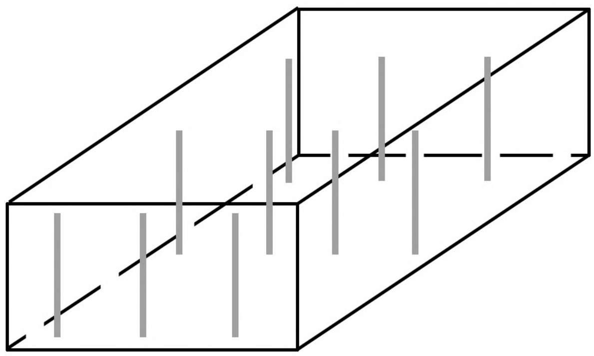


Figure 7. Scheme of towers in space.

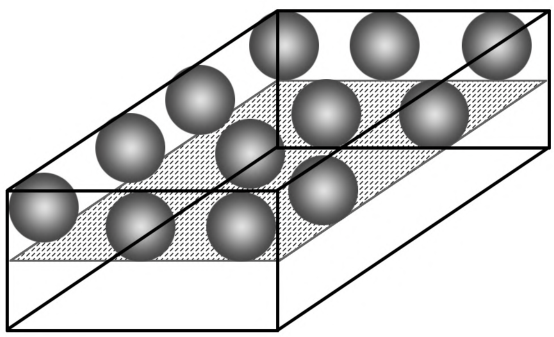
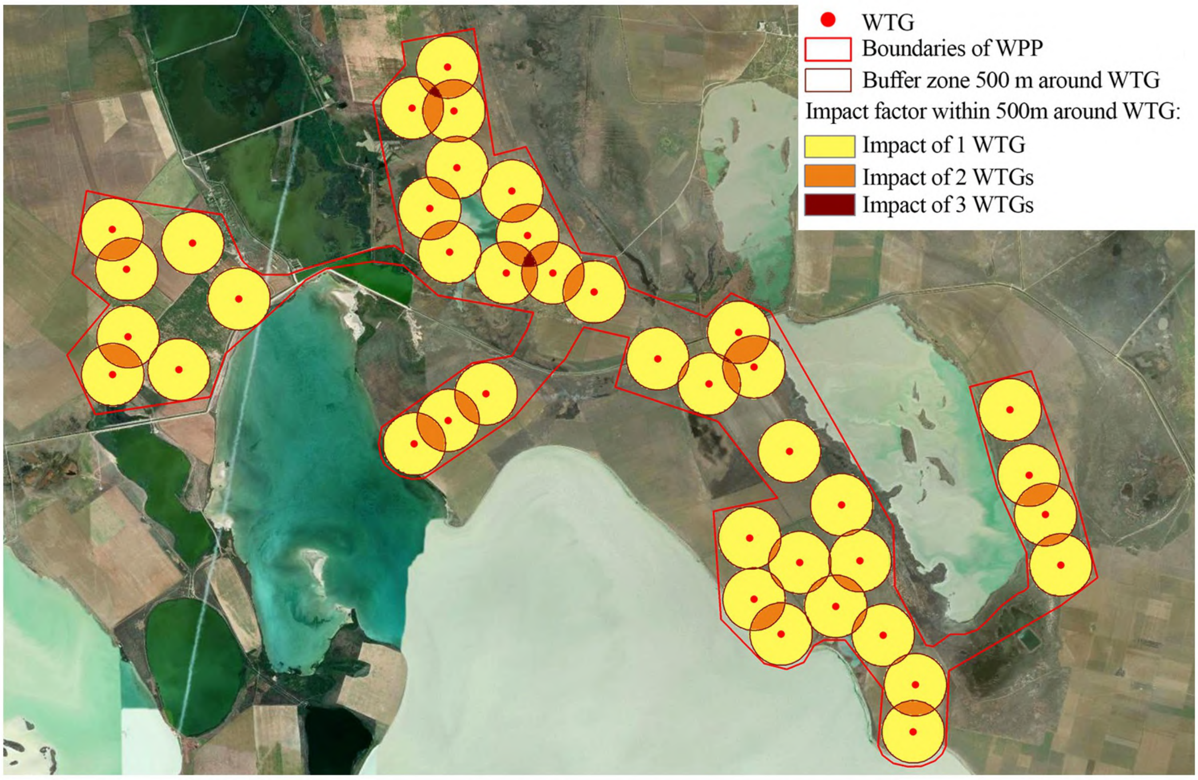
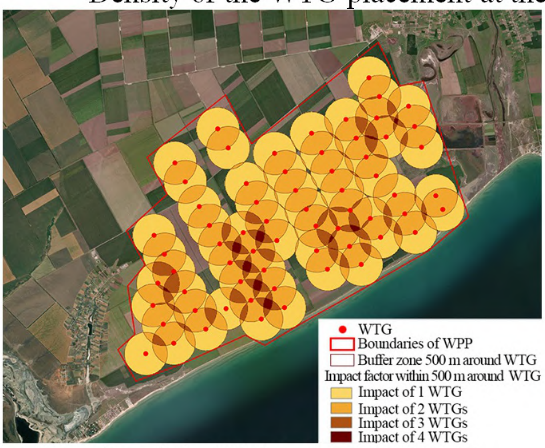


Figure 8. Scheme of volumes attributable to the wind turbine rotors.

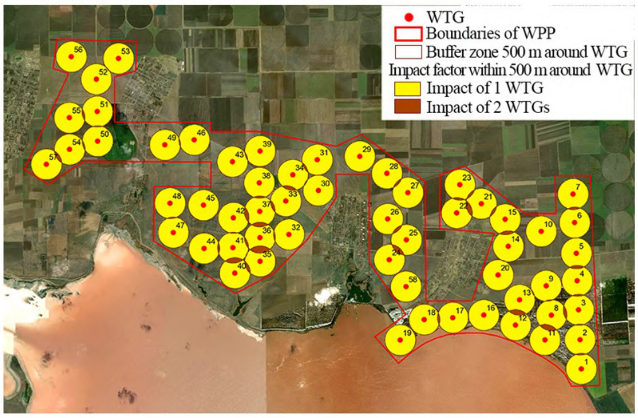
criterion for interference and disturbance for environmental components already at the initial stage.



Density of the WTG placement at the Overianivka and Novotroitsk WPP



Density of the WTG placement at the Botiieve WPP



Density of the WTG placement at the Chaplynka WPP

Figure 9. Density of WTG placement at different WPP sites.

6. Construction of the Thiessen polygons and their analysis to determine areas of barrier risks (figure 10).

As a result of the performed analysis, we can see a site divided into polygons, the colour gradation of which corresponds to the value of the area of the site. Risk zones are highlighted in dark (which are recommended to be avoided at the design stages), brown colour are border areas. Research, management and impact minimization work is recommended for these two types of territories. Beige and yellow colours are satisfactory and comfortable zones, respectively, they

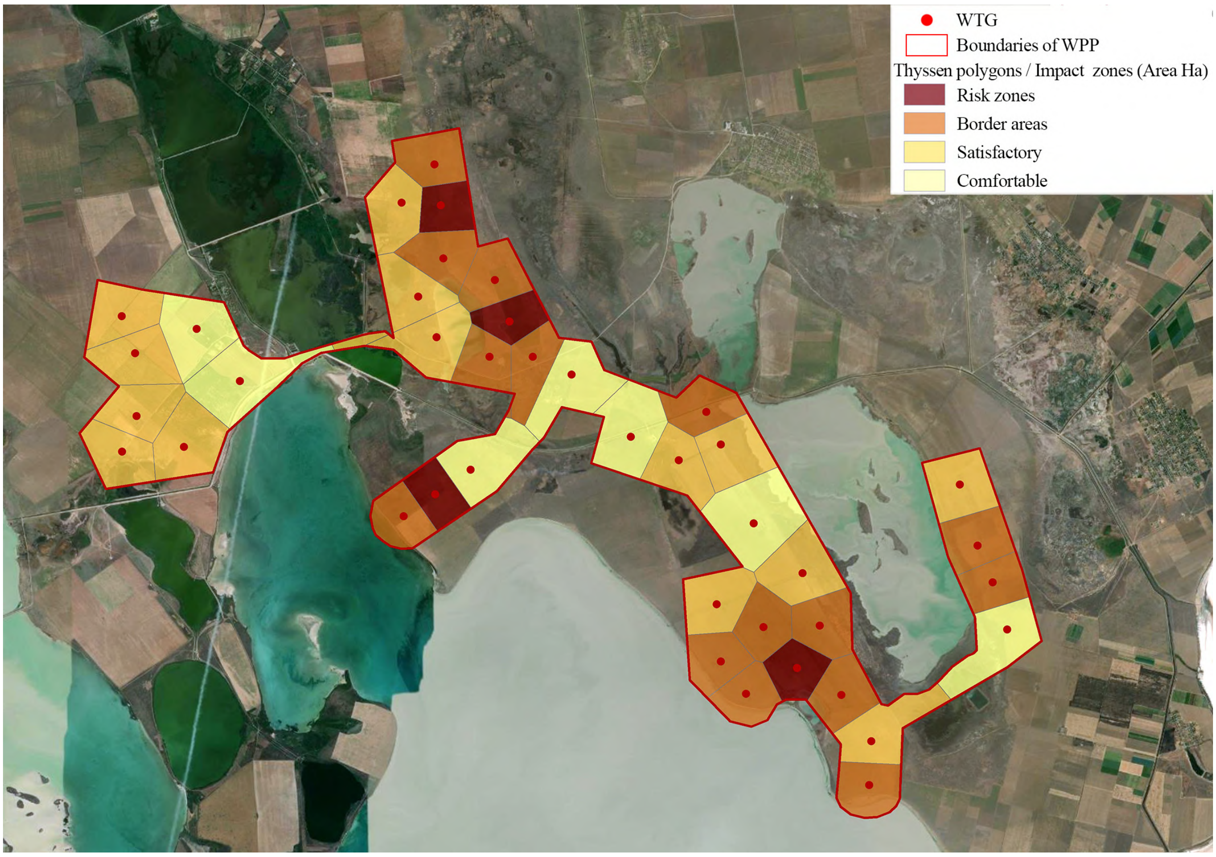


Figure 10. Using the proximity analysis method, the Thiessen polygons for the Overianivka and Novotroitsk WPP site.

require surveys and analysis of additional factors (where these sites are located: natural or anthropogenic biotopes, territories of the NRF, habitats of rare and red book species, etc.).

The use of information layers on technical characteristics in combination with layers of geoecological nature will provide more complete information about the interaction of technogenic and environmental components.

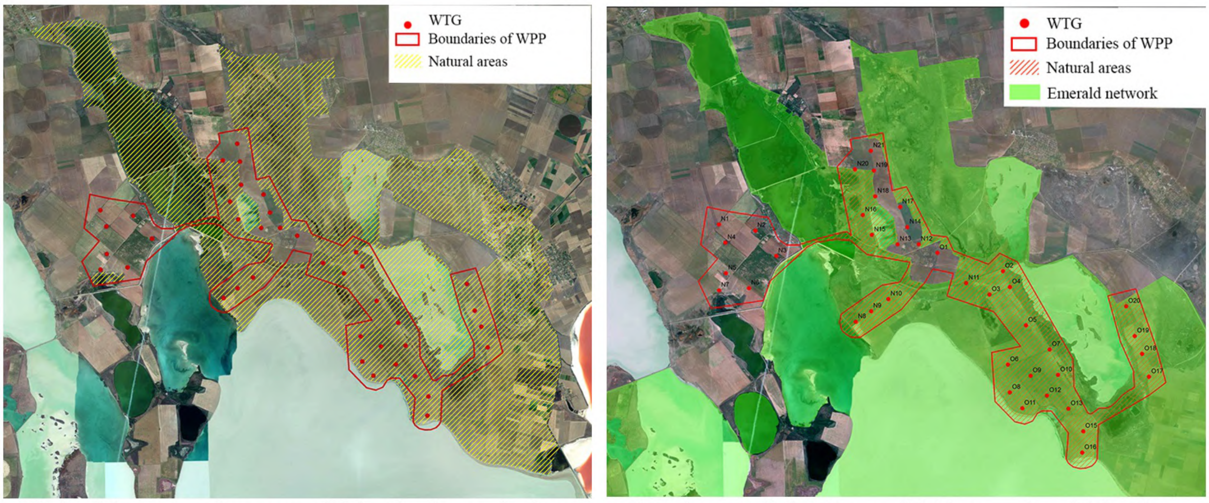
7. Identification of natural areas (figure 11a).
8. Emerald Ecological Network (figure 11b).

An integrated approach was used in assessing the territory of the emerald network within the boundaries of the WPP and 500 m buffer zones (figure 12). The territory of the emerald network was considered in detail: which parts of it are natural and which are anthropogenic. Particular attention was paid to natural areas and their location relative to the 500 m zones of impact.

Estimated characteristics based on the cartographic analysis are presented in table 1.

Using the information layers of the Emerald Network, natural areas, 500 m buffer zones around the wind turbine, there is made an analysis of the territory that fell into the impact zone of the wind turbine, its qualitative and quantitative characteristics, i.e. what territory it is, natural or anthropogenic, in what percentage in what zone is it located, etc., which makes it possible to analyze the impact of wind turbines in the NRF.

9. Analysis of biotopic and species diversity in the assessment of the impact area as an integrated approach to the study and analysis of the territory, using the example of vegetation and bird census (figure 13).



Valuable natural areas within the boundaries of the site and adjacent territories A

Territory of the Emerald Network within the boundaries of the site and buffer zones B

Figure 11. Placement of natural and reserve areas within the WPP site.

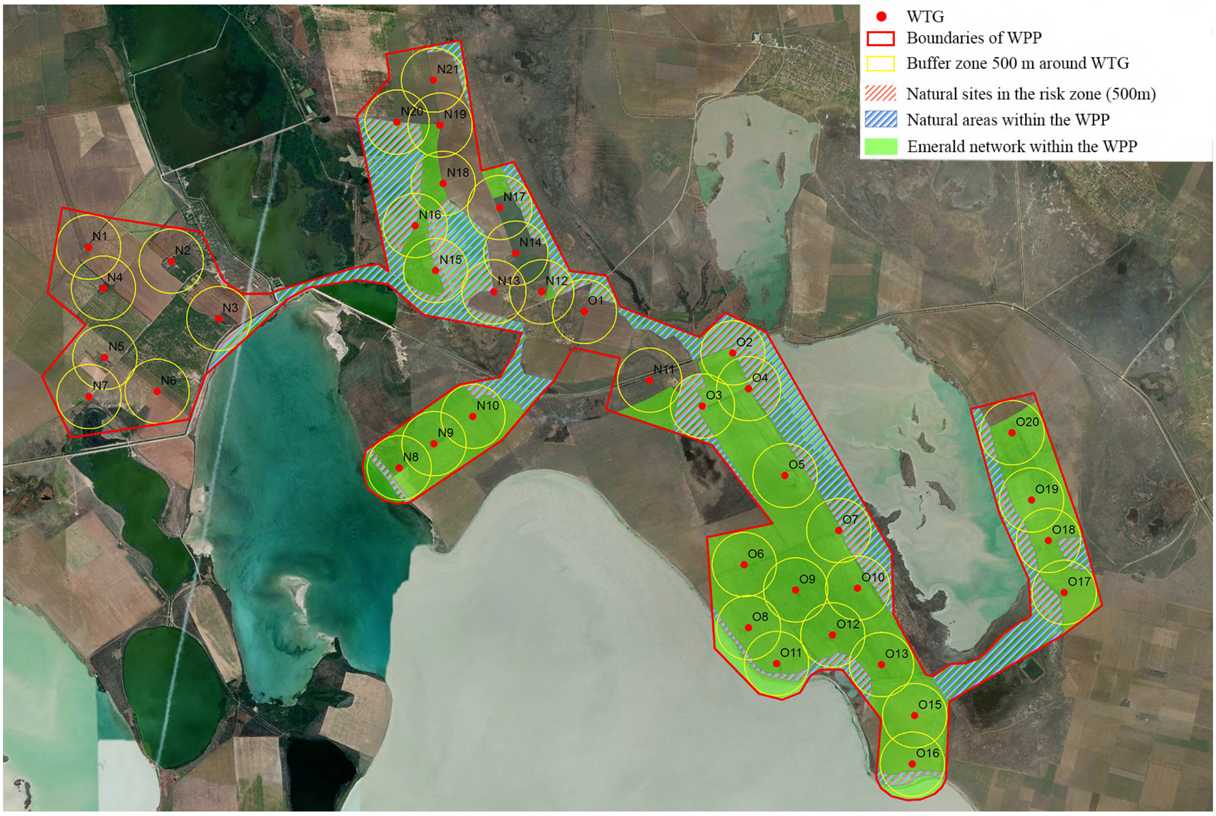


Figure 12. Analysis of the emerald network sites that fell into the 500 m buffer zone.

10. Spatial analysis taking into account 500 m buffer zones (figure 14).
11. Analysis of migrations at dangerous heights taking into account barrier risks (figure 15). In this case, the map shows areas (in dark colour) where the wind turbines are located more

Table 1. Assessment characteristics of natural areas within the boundaries of the WPP site.

Area within the boundaries of the WPP	Area (ha)	Percentage
The Overianivka and Novotroitsk WPP (the entire site)	4304	100
The Overianivka and Novotroitsk WPP (within the Emerald Network)	2921	67,9
Natural areas that are within the WPP	1155	26,8
Natural areas within the 500 m risk zone	539	12,5

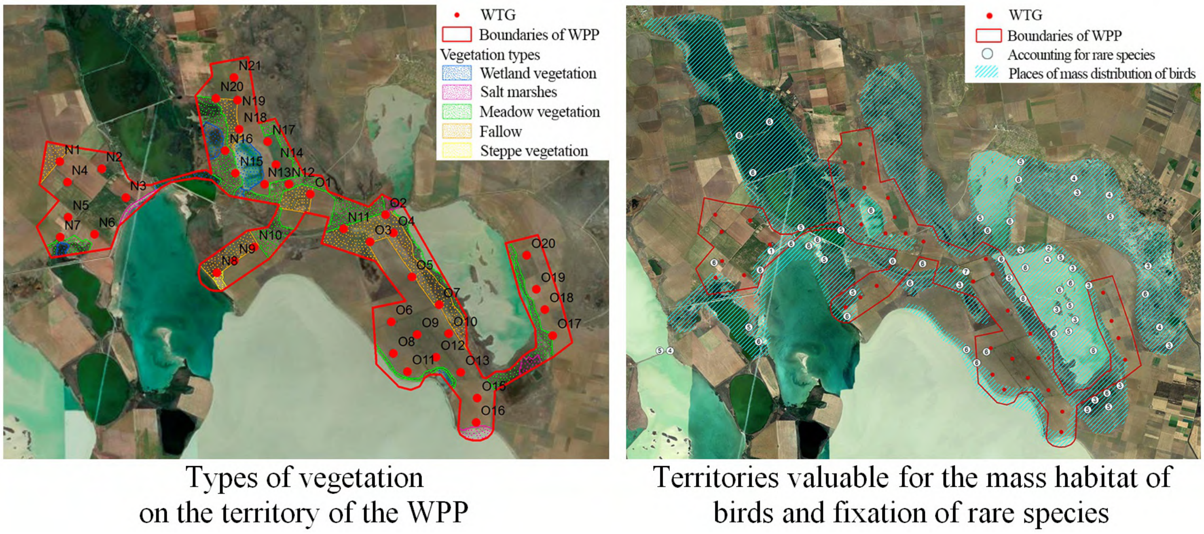


Figure 13. Types of analysis on the territory of the WPP.

densely and make a certain risk zone for mass migrations at dangerous heights.

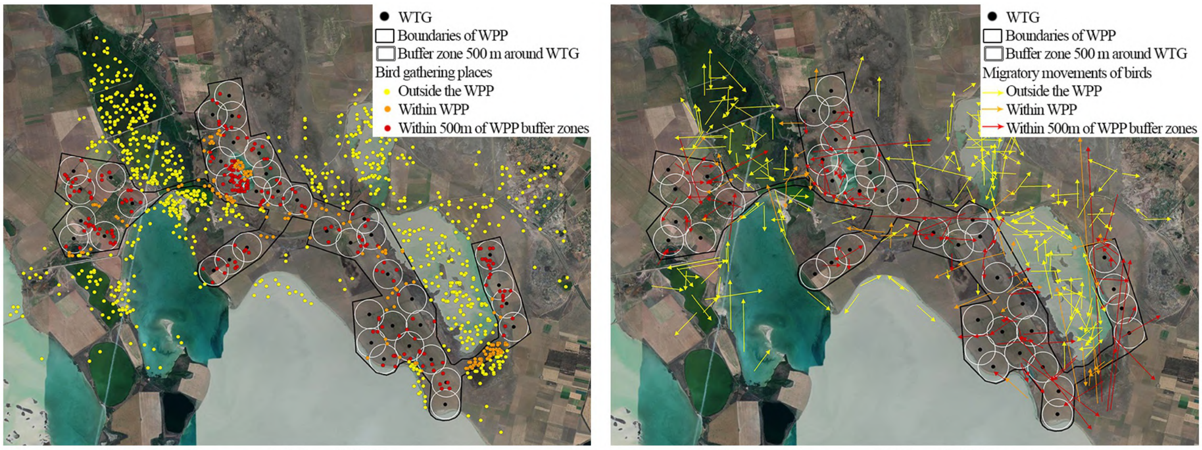
12. Analysis of breeding complexes in risk zones.

The results of census data for the breeding period of 2021 are presented in figure 16 and table 2, where areal indicators are considered.

Table 2. Characteristics of breeding complexes within the boundaries and buffer zones of the WPP site.

Locations of breeding gatherings	Area (ha)	%
Total area of breeding gatherings	3483	100
Within the WPP	643	18,46109676
Outside the WPP	2840	81,53890324
Water breeding gatherings	2352	67,52799311
Ground breeding gatherings	1131	32,47200689

After analyzing the locations of breeding gatherings and their numbers, it is possible to identify areas that require special attention and measures to minimize the impact of wind farms



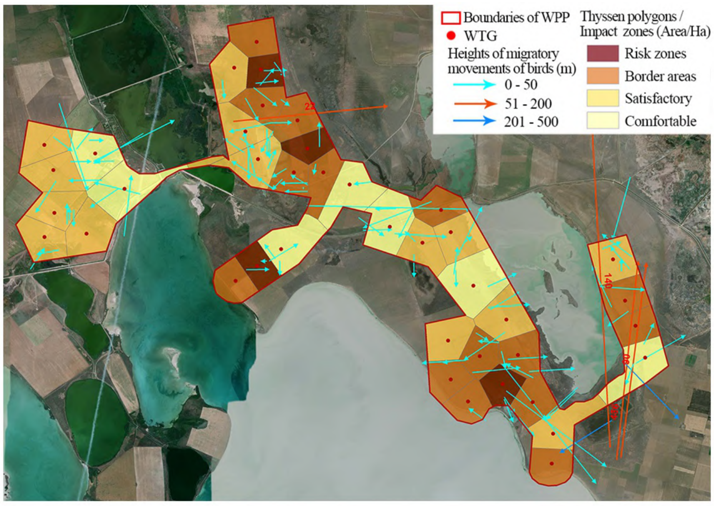
Migrations within 500 m zones

Migrations	Number	%
Total	24503	100
Outside the WPP	14120	57,63
The WPP	10383	42,37
500 m zone around the WTG	7560	30,8

Gatherings within 500 m zones

Gatherings	Number	%
Total	175754	100
Outside the WPP	144657	82,31
The WPP	31097	17,69
500 m zone around the WTG	15295	8,7

Figure 14. Spatial analysis of birds getting into the 500 m zone and their percentage.



Within 500 m at the height of 50-200 m	Number	Altitude
Anser albifrons	486	90
Branta ruficollis	90	90
Branta ruficollis	140	120
Grus grus	22	200
Total	738	
% of total migratory birds	3,01	

Figure 15. Analysis of bird movements at dangerous heights and their percentage (March 5, 2021. Spring migrations).

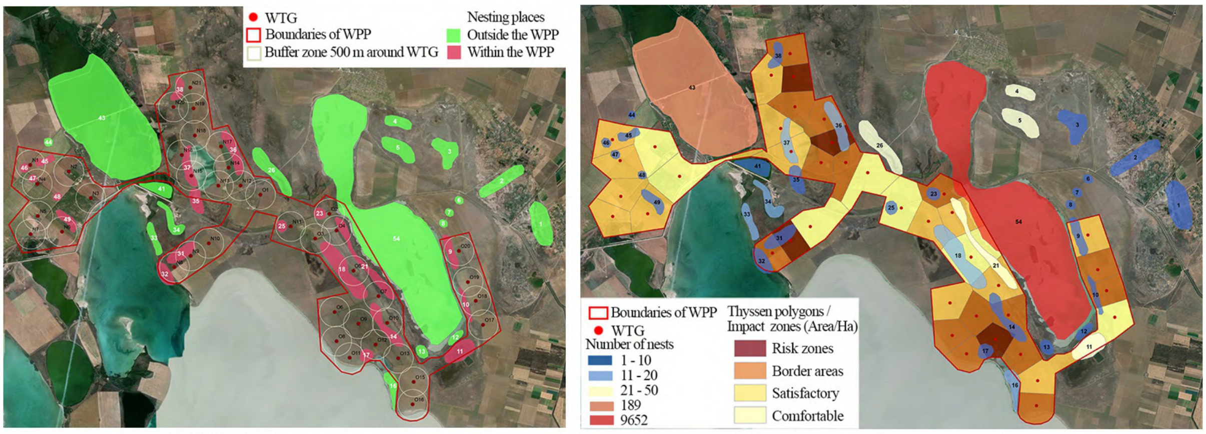
during the breeding period.

13. Analysis of the population density

Analysis of the placement density for the most vulnerable species of animals (birds and bats) (figures 17, 18).

Analysis of the abundance and location of their concentrations makes it possible to identify areas of large bird gatherings taking into account barrier risk zones, to analyze the ornithological situation at the wind farm site.

14. Allocation of zones for the implementation of mechanisms to minimize the impact of wind turbines on geoecological systems (figure 19).



With 500 m zones Including barrier risks

Figure 16. Placement of breeding gatherings.

5. Conclusions

Particular attention is paid to ecogeographic mapping and the scheme of its implementation based on GIS technologies, the purpose of which is to prevent, reduce and compensate for environmental damage.

Geoecological analysis made it possible to compare various spatial information with each other and present the results of the analysis in a convenient form for perception. Work made for geoecological analysis and assessment of the state of the study area and its mapping made it possible to move to a geoinformation system as the basis of geoecological information and cartographic support for research.

The results obtained when performing system monitoring and geoecological analysis showed that there were zones of local "stress" in the study area, which is typical to some extent for natural and technical geosystems. And it is necessary to carry out specific work and implement some means to minimize the environmental load. Numerous kinds of work have made it possible to develop a methodology of geoecological analysis for wind farm sites based on GIS technologies. This makes the geoinformation system an indispensable tool for analyzing information on the state of natural and technical geosystems.

Geoecological analysis contributed to a complex assessment of the ecological state of the WPP site and the development of recommendations for minimizing the impact of the WPP on the natural environment and its components. Based on the data obtained, recommendations and justifications were made on the possibility (or impossibility) of building a wind farm and its infrastructure, on limiting the impact on individual biocomplexes, on minimizing damage to flora and fauna during the construction and operation of a wind farm for the entire site as a whole and its individual parts. There were made expected impacts on ecosystems. The main advantages of this analysis are mobility, georeferencing accuracy, further use of data in the design and monitoring work, compatibility with subsequent geoinformation data for subsequent analysis, convenience in visualization, ease of perception and clarity of thematic maps.

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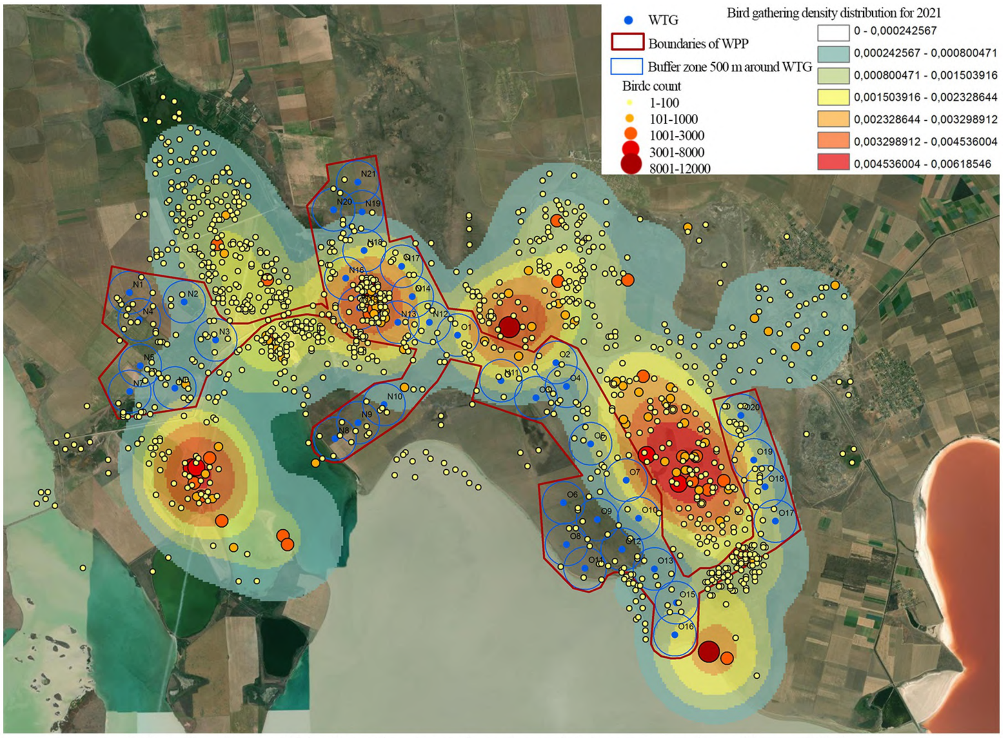
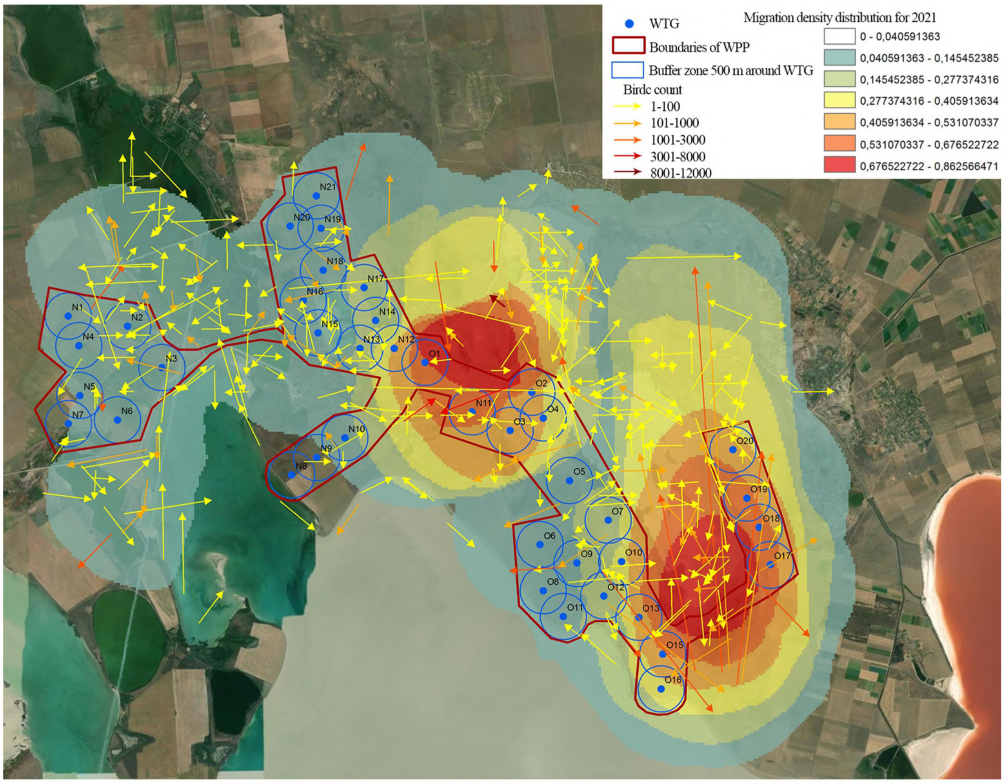


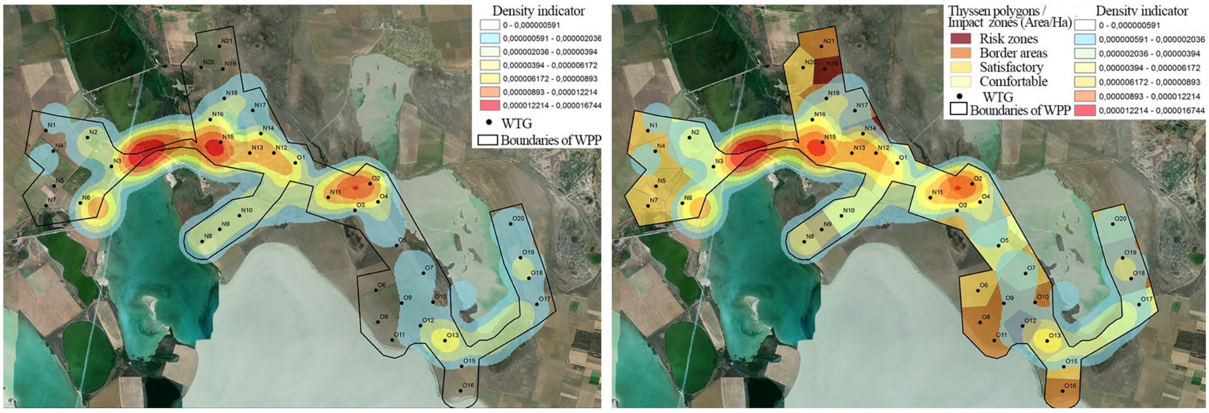
Distribution of bird gathering density within a search radius of 2 km



Distribution of bird migration density within a search radius of 2 km

Figure 17. Distribution of the density of bird gatherings and migrations for 2021.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012061 doi:10.1088/1755-1315/1049/1/012061



Placement density of bats at the WPP site within a search radius of 1 km

Analysis of placement density of bats and territories of barrier impact

Figure 18. Analysis of the density and places of bat concentrations for 2021.

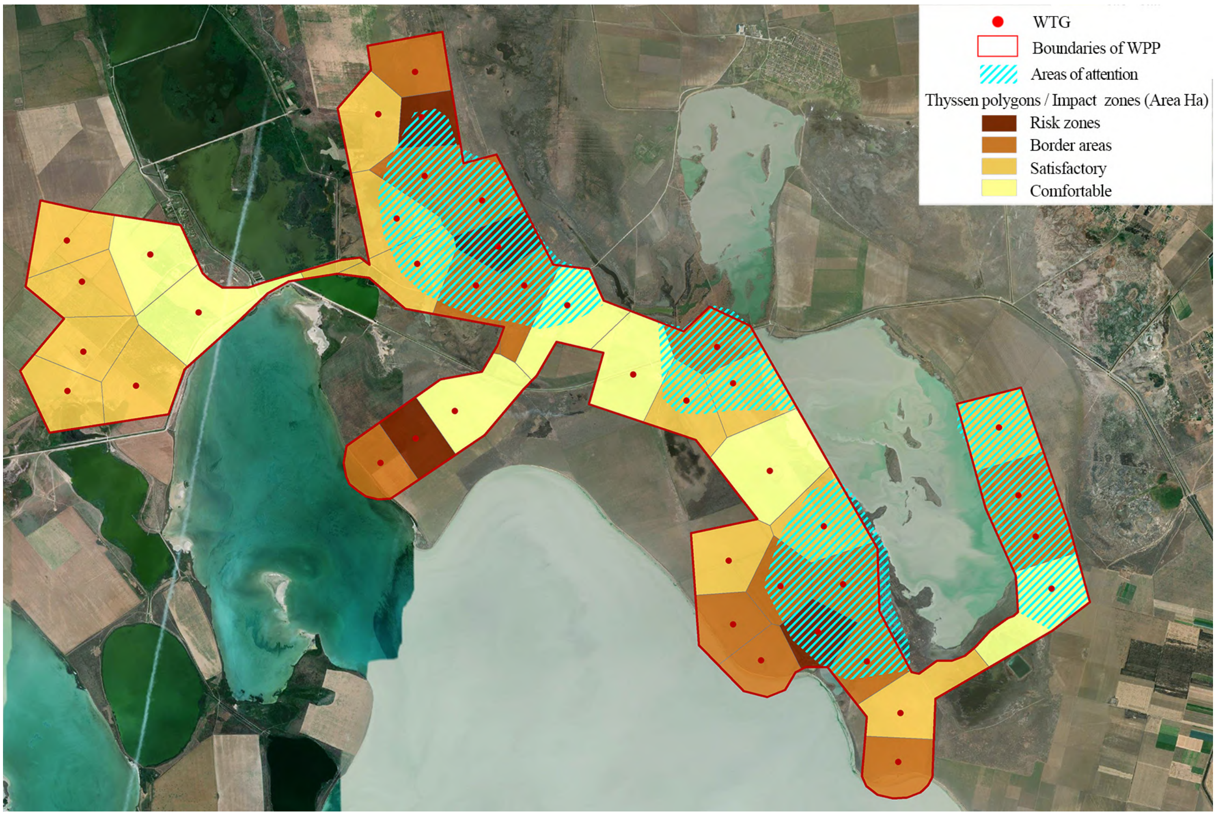


Figure 19. After analyzing the technical component of the site, as well as the location of the main biocomponents, with an analysis of their life and places of concentration, areas of special attention were identified. In these territories, there were recommended the means of minimizing the impact of wind turbines and controlling the environmental situation.

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Response of earthworms to changes in the aggregate structure of floodplain soils

To cite this article: G F Tutova *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012062

Response of earthworms to changes in the aggregate structure of floodplain soils

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Abstract. Earthworms are actively involved in the transformation of organic matter and in the formation of water-resistant soil aggregate structure. In the short time perspective earthworms are a factor that affects soil properties. However, other factors also influence soil properties and it is these factors that determine the total level of earthworm abundance and patterns of their spatial distribution. In urban park environments, the recreation load is an additional factor. The recreational load significantly affects the physical properties of the soil. An aggregate soil structure regulates the ratio of solid, liquid, and gaseous soil fractions and thus determines the living conditions of soil animals. Purpose/objective. The study tested the hypothesis about the influence of the aggregate structure of soil on the spatial distribution of earthworms under recreational load conditions. Methodology. Geostatistical methods and evaluation of animal response models to environmental factors. Results/findings. The aggregate structure of the soil is an important factor that affects the spatial patterns of earthworms under recreational load conditions. Earthworms prefer sites with a predominance of meso-aggregates. A recreational load leads to an increase in the proportion of macro- and micro-aggregates, which negatively affects the living conditions of earthworms. Conclusions. The processes of mutual influence of earthworms and soil aggregate structure have different temporal scales: earthworms influence soil structure in the time range of a few days or weeks, and aggregate structure influences in the time range of a few months or years.

1. Introduction

Soil is a specific environment for living organisms [1]. Soil is a polydisperse combination of three phases: liquid, solid and gaseous. The spatial and temporal organisation of these phases is the soil aggregate structure. The soil aggregate structure forms an ecological space in which a great diversity of forms of living organisms exist [2]. In turn, the living organisms influence the soil, which is reflected in the changes in its aggregate structure [3]. Earthworms play an important role in controlling soil structure dynamics [4]. The trophic and burrowing activities of earthworms greatly influence the physical environment in which they live and the dynamics of soil structure and the corresponding regulation of soil ecological functions and ecosystem services [5]. Soil aggregate structure controls water retention [6, 7], and infiltration [8]. The size distribution of the aggregate fractions significantly affects the gasses flux [9]. The importance of organic matter in the formation of soil aggregates is great [10,11] . An optimal aggregate structure is a condition for storage of organic matter in soil [12]. The aggregate structure regulates the dynamics of nutrients in the soil. The destruction of the aggregate structure leads to the opening of initially inaccessible areas within the aggregates for the action of soil microorganisms and stimulates the turnover of nutrients, which is reflected in a significant decrease in their available forms [13]. The microbial trophic structure depends on soil texture and suitable habitable pore space, which determines the energy flow in terrestrial ecosystems [14]. Plant roots affect soil structure, and soil structure affects roots through regulation of root water uptake. The roots can decrease the average size of a soil aggregate as it grows among large soil peds, but can also increase the size of the aggregate if the aggregates are initially small [15]. Aggregate structure determines the sustainability of soil to water and wind erosion [16].

Aggregate structure forms the pore space of the soil. There is a significant correlation between average aggregate size and average pore size in the soil [17]. The size categories of soil animals are distinguished by their relation to the most typical conditions in the soil, which depend on the size of the soil pores [18]. The available soil pore volume determines the biomass of bacteria and their consumers among animals [19]. Small soil animals, such as Protozoa, are actually hydrobionts, since they live in the films of water that almost always cover soil particles. Mesofauna inhabit the soil crack system and are smaller than the soil pores. Soil macrofauna are larger than most soil pores and therefore have to either actively create soil tunnels to move, or use tunnels created by other soil animals or cavities that remain after the decomposition of plant roots [20]. The covers of most soil animals do not protect them from water evaporation, so the environment in which they live must have 100% humidity. Soil animals also need oxygen for active life. If the importance that the aggregate structure has for the formation of pore space, water regime and gas exchange is taken into account, the significance of the size ratio of aggregate fractions in shaping the living conditions of soil animals becomes clear [21].

The area of influence or volume of soil affected by earthworms is called the drilosphere [22,23]. Bioturbators affect the soil structure by forming a system of burrows and moving soil aggregates without changing their internal organization [3]. Galleries are formed by earthworms moving in the soil and create large networks that occupy a significant volume of soil [4,24,25]. These large macropores are crucial for regulating water infiltration, solvent diffusion [26, 27], gas exchange and aeration through the soil [28, 29]. Earthworm burrows affect the spatial distribution of roots and plants [30]. The interaction between plant roots is two-way: plant roots tend to determine the distribution of earthworm burrows and some plant roots tend to follow the burrows [31]. Soil aggregate reorganisers are capable of altering soil structure both by building galleries and by consuming soil aggregates called biogenic aggregates [32]. Most earthworm species belong to this group [33]. This group is characterised by the ability to alter the internal organisation of soil aggregates. The amount of soil aggregates created by soil engineers is difficult to estimate [34]. The earthworm casts may constitute a large part of the soil aggregates on the soil surface or even an entire soil horizon [35]. Earthworm activity is important for the long-term stabilisation of organic matter in soils [36]. The reorganisation of soil aggregates by earthworms is very important and leads to completely different physical, chemical and biological properties of the soil [37]. This occurs when the pre-existing microstructure of the soil aggregate is completely destroyed in the foregut [38]. Then, during transit through the gut, clay minerals and organic materials are closely mixed and coated with mucus, creating a new core to form microaggregates [39, 40]. Within excreted casts, drying and ageing promotes the strengthening of bonds between organic materials, mucus and minerals to stabilize newly formed micro-aggregates [36]. Earthworms can also select and enrich soil aggregates in terms of organic matter and clay content, which contributes to the stability of soil aggregates [41].

2. Research aim and objectives

There is thus a consensus in the current scientific literature on the great importance of aggregate structure in soil function. The aggregate structure is seen as a factor that shapes the habitat of the soil biota [42, 43]. The dependence of the aggregate structure on the influence of living organisms, primarily ecosystem engineers, is also recognized [44]. However, information on how aggregate structure directly affects soil animal populations is extremely scarce. There is also no information on the role of soil animals in the spatial variation of aggregate structure.

The aim of our work was therefore to solve two tasks:

(i) to find out how soil aggregate structure affects earthworm abundance at the ecosystem level;

(ii) to reveal how earthworms affect soil aggregate structure at the ecosystem level.

3. Material and methods

3.1. Study area

The study was carried out in the elm oak forest in the floodplain of the Dnipro River (Dniprovsko-Orilsky Nature Reserve, Ukraine). Soil properties were measured at 105 points, which were located on a regular grid. The points are located in the center of 3×3 meter squares, within which the relevés was made [45]. The squares are contiguous with each other, constituting a polygon. On the opposite corners of the polygon were placed locations where vertical soil transects were made.

3.2. Description of soil morphology

The study of the soil profile morphology was performed in accordance with the guidelines of the field description of soils FAO [46]. Genetic type of soil profile was determined according to Rozanov [47]. The classification of soils was performed according to IUSS Working Group WRB [48]. The classification position according to WRB was Fluvic Gleysol (Arenic, Ochric).

3.3. Plant community description

The vegetation description was performed at polygon consisted of 105 sampling points (relevés). The points were located along 7 transects with 15 sampling points each. The distance between points in the transect as well as the distance between transects was 3 m. The adjacent sampling points were in close proximity to each other. Vascular plant species lists were recorded for each 3×3 m sampling point, along with a visual assessment of species coverage using a Braun-Blanquet scale [49]. The projective cover of plant species was measured at soil level, understory (up to 2 m in height), and canopy (above 2 m in height). Seedlings and seedlings of tree species were subsequently excluded from the analysis. Plant taxonomic names follow the Euro+Med Plantbase resource (http://ww2.bgbm.org/EuroPlusMed). A phytoindication of environmental factors was performed based on the Didukh [50].

3.4. Soil properties measurement

The soil penetration resistance was measured in the field using the Eijkelkamp manual penetrometer, to a depth of 100 cm at 5 cm intervals [51, 52]. The average error of the measurement results of the device is ± 8%. Measurements were made with a cone with a cross section of 1 cm2. At each measurement point, the soil penetration resistance was performed in only one replication. The aggregate fraction size distribution was carried out by dry sieving in a system of sieves [53].

3.5. Statistical analysis

The phytoindication estimates of environmental factors obtained on the basis of species composition and grass projective cover were used as predictors of the environment, as well as data on the crown cover of trees. The data on crown density and projective cover of herbaceous plants were transformed: $asin((c_i)^{0.5})$, where c_i is the projective cover of the i-th species. Species that occurred in the relevés at least 10 times were selected for the ordination procedure. There were 18 such species. The ordination of the plant community was performed using the method of nonmetric scaling [54] using the Bray-Curtis distance [55, 56]. According to the criterion of decreasing stress, the ordinal solution with four dimensions was found to be optimal [57]. The environmental factors were fitted to the ordinal dimensions using the envfit function from the vegan package [58]. The soil penetration resistance data for each soil layer were standardised, after which their average value was set to zero, and the value itself was presented in units of root mean square deviation. A matrix consisting of standardised soil penetration resistance values was subjected to a Redundancy Analysis (RDA) [59, 60]. Based on the local coordinates of the sampling points, a distance matrix between points was generated. The distance-based Moran's eigenvector maps [61, 62] were computed from the distance matrix using the function dbmem from the package adespatial [63]. The 48 dbMEM eigenfunctions were extracted. Each of the dbMEM eigenfunctions models a spatial pattern with a frequency that increases in proportion to the order number of the function. The dbMEM eigenfunctions were used as predictors in the Redundancy Analysis procedure of standardised soil penetration resistance data. The explanatory power of the predictors in the Redundancy Analysis was estimated using the function RsquareAdj2.rda [64]. A scalogram was constructed by estimating R^2 for each spatial predictor separately. The vegetation ordination dimensions were also considered as conditional predictors.

4. Results

Three species of earthworms were found in the ecosystem studied: *Dendrobaena octaedra* (Savigny, 1826), *Aporrectodea trapezoides* (Dugés, 1828), and *Aporrectodea rosea* (Savigny, 1826). The abundance of the epigeic earthworm *D. octaedra* was 0.26±0.043 ind./m^2. The abundance of the endogeic earthworm *A. trapezoides* was 3.84±0.25 ind./m^2. The endogeic earthworm *A. rosea* occurred sporadically.

The aggregates with sizes 2–3 and 3–5 mm were the most abundant in the aggregate structure (23.77±0.198 and 21.57±0.061%, respectively) (figure 1).

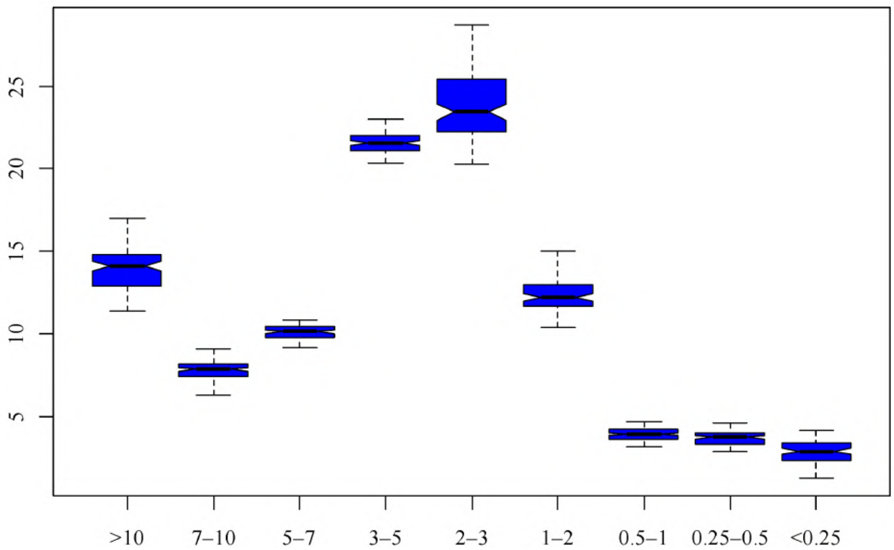

Figure 1. Proportions of aggregate fractions of soil. Abscissa axis is fraction size (in mm), ordinate axis is fraction proportion by weight (in %).

The aggregates of size <0.25, 0.25–0.5, and 0.5–1 mm had the lowest proportion (2.81±0.067, 3.71±0.041, and 3.92±0.040%, respectively). Other fractions had intermediate proportions in the aggregate structure. The electrical conductivity of the soil was 0.22±0.009 dSm/m. The height of litter was 2.42±0.04 cm, soil moisture content was 17.34±0.13%, bulk density was 1.12±0.0037 g/cm^3. The soil penetration resistance increased with depth (figure 2). In the upper soil layer, the penetration resistance was 1.28±0.023 MPa. Up to the depth, the penetration resistance changed insignificantly. From a depth of 25–30 cm to a depth of 65–70 cm a rapid increase in the penetration resistance with depth was found. With further increase in depth, the soil penetration resistance changed slightly. At the depth of 95–100 cm the soil penetration resistance was the highest and was 9.96±0.0078 MPa. There were 52 plant species identified in the vegetation cover of the studied polygon. The phytoindication assessment indicated that the moisture regime was suitable for mesophytes, and the estimate of the range of available moisture was 127 mm (figure 3).

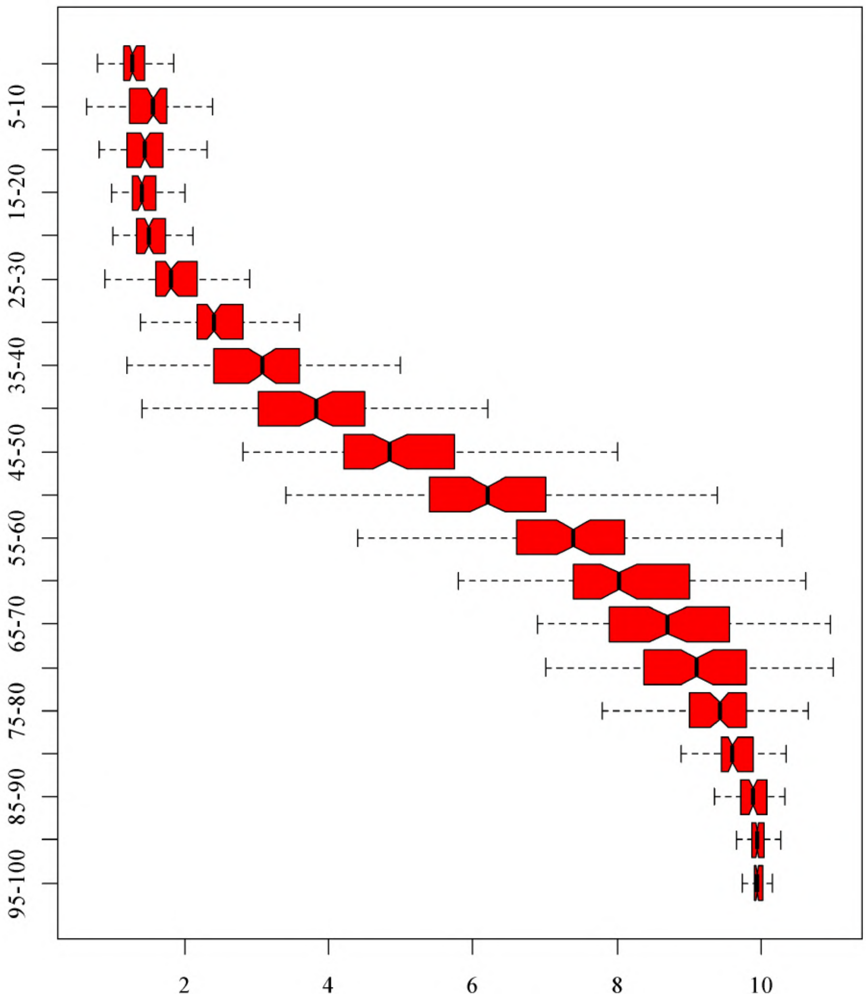

Figure 2. Variation of soil penetration resistance. Abscissa axis is penetration resistance, MPa, ordinate axis is soil layers: 0–5, ..., 95–100 cm.

The regime of the contrasting conditions of soil moisture favored plants adapted to forest-meadow habitats with moderately irregular moistening of the soil layer, fully saturated by precipitation or groundwater. The phytoindication assessment indicated soil acidity, which was pH = 6.6. Trophic conditions were favorable for mesotrophs, which inhabit soils not very rich in salts (95–150 mg/l). The plants avoid carbonate substrates (CaO, MgO = 0.5%). The phytoindication of the cryoregime indicates the average temperature of the coldest month was

$-0.64°C$.

The coarse aggregates (greater than 10 mm and up to 5 mm in size) and fine aggregates (less than 1 mm in size) were positively correlated with each other and were negatively correlated with aggregate fractions of 1 to 5 mm in size (Figure 4). The aggregate structure was correlated with other soil properties. A decrease in soil electrical conductivity and moisture content and an increase in soil density were related to an increase in the proportion of aggregates larger than 5 mm or smaller than 1 mm (table 1).

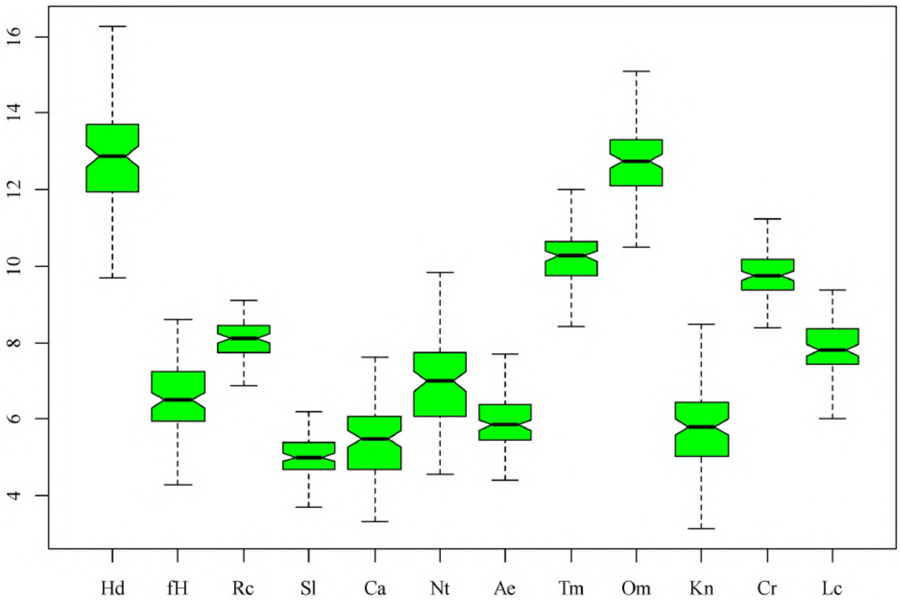

Figure 3. Phytoindication assessment of environmental factors: Hd is the soil water regime, fH is the variability of damping, Rc is the soil acidity, Sl is the total salt regime, Ca is the carbonate content in soil, Nt is the nitrogen content in soil, Ae is the soil aeration, Tm is the thermal climate, Om is the ombroregime, Kn is the continentality, Cr is the cryo-climate, Lc is the light regime.

The spatial component described 34.32% of the variation in soil aggregate structure ($F = 2.13$, $p < 0.001$). The profile variation in soil penetration resistance explained 26.05% of the variation in soil aggregate structure ($F = 2.83$, $p < 0.001$). The phytoindication estimates of ecological properties explained 21.83% of the variation in soil aggregate structure ($F = 3.42$, $p < 0.001$). Three sets of predictors together explain 47.05% of the variation in soil aggregate structure ($F = 2.15$, $p < 0.001$). 3.9% of the variation in soil penetration resistance is spatially structured, as is 9.3% of the variation in phytoindication estimates (figure 5).

Aggregate fractions formed gradients of environmental conditions in which the abundance of earthworms varied in a pattern (figure 6, 7). The earthworms *A. trapezoids* and *D. octaedra* responded with a decrease in abundance when the proportions of aggregate fractions larger than 5 mm increased. With increasing aggregate fractions of 2–3 mm the abundance of earthworms increased. For the other aggregate fractions, the response of the earthworm *A. trapezoids* was bell-shaped symmetrical or asymmetrical.

An increase in aggregates smaller than 0.25 mm had a negative effect on the abundance of the earthworm *D. octaedra*. The response of the earthworm *D. octaedra* to an aggregate proportion of 0.25–0.5 mm was bell-shaped symmetrical, while the response to an aggregate proportion of 0.5–5 mm was monotonic with the presence of a plateau. The earthworms responded negatively to a high proportion of aggregates of 0.5–1 mm or a low proportion of

1–2 and 3–5 mm in size. The residuals of the CCA model with spatial variables, soil penetration rates and phytoindication scales as constrained variables correlated with earthworm abundance (table 2). As the abundance of *A. trapezoides* increased, the proportions of fractions larger than 5 mm decreased and those of 2–5 mm increased compared to the prediction of the CCA model. The abundance of this earthworm species had no effect on the predicted proportions of the other fractions. The abundance of *D. octaedra* negatively correlated with model residuals for the 7–10 mm fraction.

Table 1. Correlation matrix of aggregate fraction content and the physical properties of soil in the 0–10 cm layer (correlation coefficients are shown significant for $p < 0.05$).

Fraction size, mm	Electrical conductivity	Litter depth	Wetness	Bulk density
> 10	0.36	–0.26	–0.49	0.56
7–10	–0.34	–	–0.55	0.52
5–7	–0.47	–0.25	–0.44	0.49
3–5	–	0.36	–	–0.24
2–3	0.46	0.23	0.35	–0.53
1–2	0.46	0.20	–	–
0.5–1	–0.54	–0.26	–	0.31
0.25–0.5	–0.63	–0.34	–	0.30
<0.25	–0.74	–0.33	–	0.30

5. Discussion

A soil texture is inherited from the parent material [65]. The soil texture is the ratio of primary soil particles of different sizes [66]. However, these primary particles are not separate, but are combined into aggregates [67]. The primary soil particles are bounded into the aggregates and are retained in this state by adhesives of organic and inorganic origin [68]. The adhesives of organic origin provide the aggregates with water resistance, i.e. the ability to persist in both dry and wet conditions [69]. Non-water-resistant aggregates, which exist in the dry state due to inorganic adhesives, disintegrate when wet. the arrangement of soil aggregates is called soil structure which is an important soil physical property [70]. Soil aggregation is a key ecosystem process leading to the formation and stabilization of soil structure, consisting of soil aggregates and the resulting matrix of pore spaces.

The aggregate structure is the proportion of aggregates of different sizes. The size and shape of aggregates is the result of the influence of two opposing complexes of processes: the formation and destruction of aggregates. These processes are biotic and abiotic in origin [71]. The ability to form soil aggregates depends on the size of the soil particles [72]. Large particles (sand) are less tend to form aggregates than fine particles (silt and clay) [73]. Thus, the spatial variability of soil texture determines the level of soil aggregate formation. In floodplain soils, the soil texture strongly depends on the processes of redeposition of turbid substances during flooding, which strongly influences the mosaic texture of floodplain soils and causes spatial patterns in the aggregate structure [74,75]. Distance from the river and channel networks are the most important environmental variables for predicting the soil textural fractions in floodplain soils [76]. Freezing and thawing of soils leads to the formation or destruction of soil aggregates [77]. The role of the temperature regime is superimposed on the moisture regime, since dry soils are less affected by freezing/thawing processes than wet soils [78, 79]. The constant variability of the water regime as a result of floods, which is superimposed on the variability of the temperature regime in winter, is important for the area we studied. The average temperature of the coldest month has a value slightly less than zero, which confirms the presence of constant weather variability and the alternation of freezing and thawing of the soil. The spatial variability of soil moisture can strongly influence aggregation under the influence of temperature differences near the zero level.

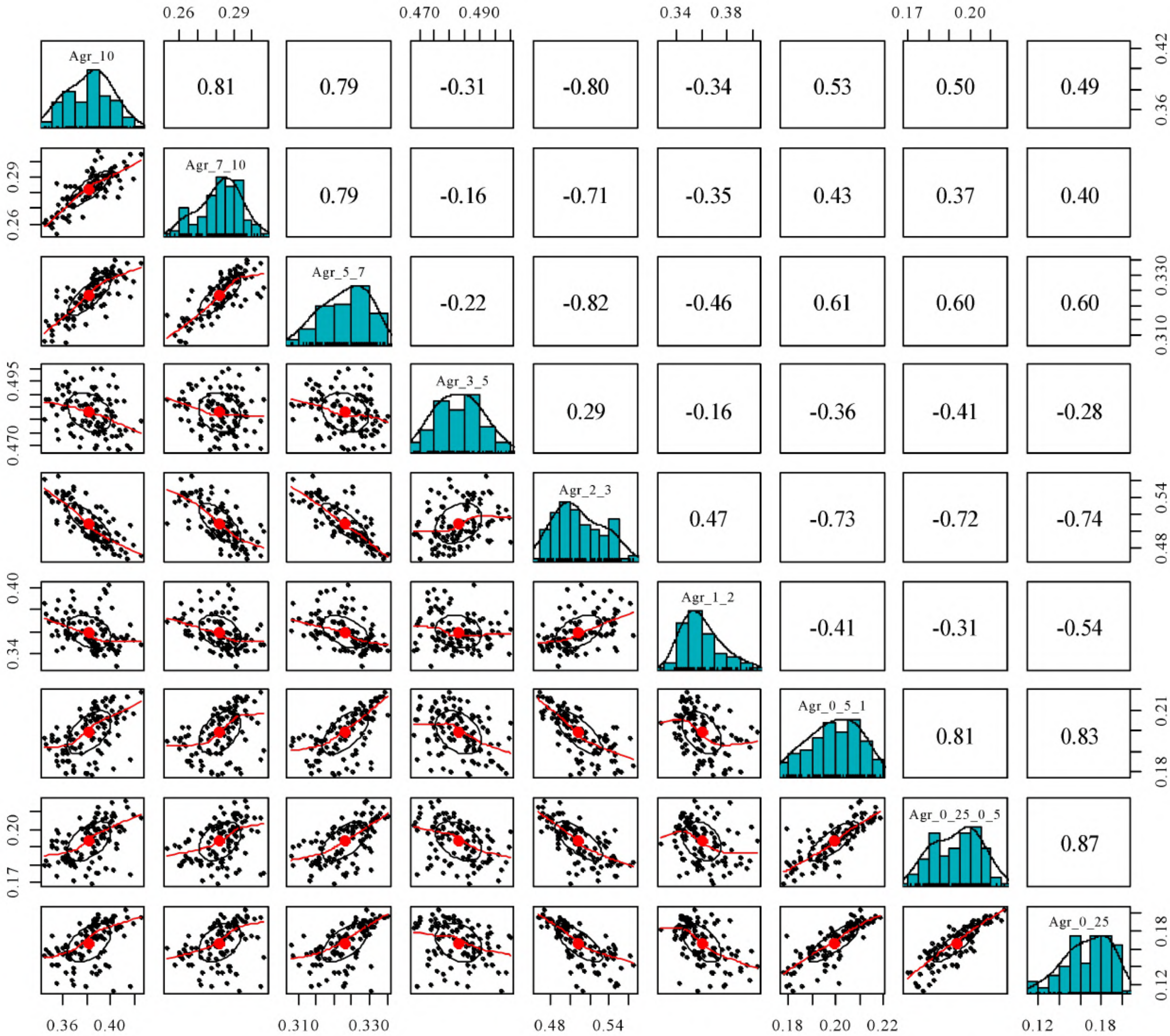

Figure 4. Correlation matrix of aggregate fractions (after arcsine transformation).

Swelling and shrinkage also affect the formation of aggregates [80]. An increase in silt and clay contribute to the intensification of these processes [81]. Also the phenomena of soil salinisation, which are typical for the floodplains of steppe rivers [82, 83], affect the soil aggregate formation and the resistance to destruction. The average size of aggregates decreases as the sodium content of the soil increases. The decrease in aggregate stability under the influence of sodium is caused by a weakening of the binding capacity of the cementitious substances that connect the domains that form the aggregates [17]. Thus, the presence of spatial patterns in the variability of soil aggregate structure can be explained by the spatial organization of the soil formation process in the floodplain. This assumption is confirmed by the fact that the variability of soil penetration resistance in the soil profile allows us to explain the variability of the aggregate structure in the upper soil layer. Also, the profile distribution of soil properties is spatially structured. Obviously, the structuring factors are soil-forming processes in the soil.

Plants are important in the formation of soil aggregates [84]. The root system of plants contributes to the formation of soil aggregates, mainly mesoaggregates [85]. Plants also enrich the soil with organic matter, which contributes to the formation of water-resistant aggregates [86]. Obviously, the spatial organization of the plant community determines the spatial patterns of aggregate structure [87]. The results obtained indicate that the influence of the plant community on the aggregate structure is fully spatially structured. The generation and redistribution of organic matter should be noted to affect soil animals as well [42]. The plant organic matter is the basis of the trophic chains of pedobionts [88]. Also organic matter in the form of forest litter forms microclimatic conditions, which affect the spatial distribution of soil animals [45, 81].

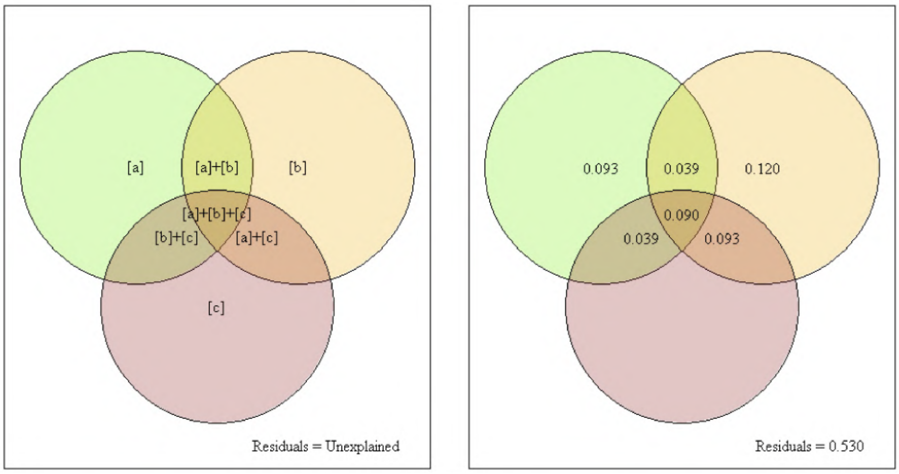

Figure 5. Variance partitioning between spatial and soil explanatory variables: [a] – variation explained solely by the values of penetration resistance within the soil profile; [b] – variation captured by the spatial (dbMEM) variables corresponds to pure space (residual spatial component); [c] – variation explained solely by the phytoindication assessments of environmental factors; [a]+[b] – variation explained both by the spatial and soil penetration resistance variables; [a]+[c] – variation explained both by the soil penetration resistance variables and phytoindication values; [b]+[c] – variation explained both by the spatial (dbMEM) variables and phytoindication values; [a]+[b]+[c] – variation explained by spatial, soil penetration resistance variables and phytoindication values. All the variance fractions shown are significant ($p < 0.001$).

The combination of factors and processes that influence the formation of soil structure creates the ecological environment for the existence of soil animals. The soil aggregates structurise the internal space of the soil, dividing it into intra-aggregate and inter-aggregate pore space [89]. The inter-aggregate space provides the soil biota with air [90–92], while the intra-aggregate space is a reserve of soil moisture [93]. Thus, due to the aggregate structure, the soil combines anaerobic and aerobic conditions [94]. The final outcome of aerobic processes is mineralization of organic matter, which makes nutrients available to plants [95]. The final outcome of anaerobic processes is humification, which provides stability of the soil environment both through immobilization of nutrients in the organic matter of the soil and through the formation of a water-resistant soil structure [96].

A high proportion of mesoaggregates provides the optimal ecological regimes in the soil. Coarse or fine aggregates create unfavorable living conditions for the majority of pedobionts. Our results indicate that the abundance of earthworms decreases under conditions of predominance of large aggregates (size greater than 5 mm).

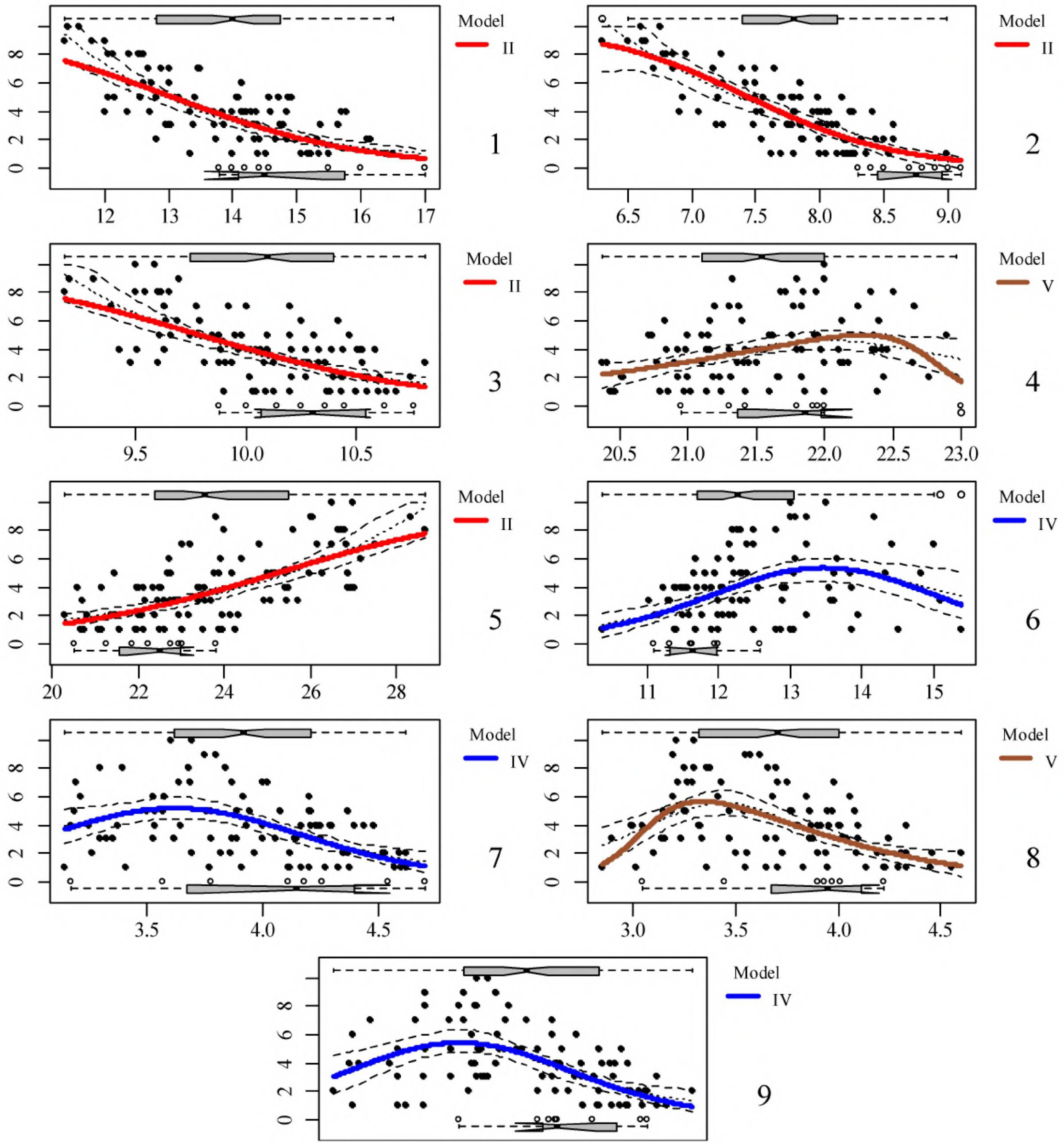

Figure 6. Response of *A. trapezoides* abundance in a gradient of aggregate fraction proportions. The ordinate axis is the number of worm individuals in a 25×25 cm soil sample; the abscissa axis is the proportion of aggregate fractions; 1 – fractions > 10 mm; 2 – fractions 7-10 mm; 3 – fractions 5-7 mm; 4 – fractions 3-5 mm; 5 – fractions 2-3 mm; 6 – fractions 1-2 mm; 7 – fractions 0.5-1 mm; 8 – fraction of size 0.25-0.5 mm; 9 – fraction of size <0.25 mm; model II – monotonic response; IV – symmetrical bell-shaped response; V – asymmetrical bell-shaped response (response models from the HOF list of functions [97, 98]).

This result is true for both endogeic *A. trapezoides* and epigeic *D. octaedra*. The large aggregates provide conditions for hyperaeration of the soil and its rapid desiccation. Obviously, this very reason explains the negative response of earthworms to the high proportion of large aggregates. This assumption is confirmed by the fact that an increase in the proportion of large aggregates is accompanied by changes in other soil properties, including a decrease in soil moisture [83].

The role of aggregate structure is more important for the endogeic earthworm *A. trapezoides*. For the epigeic earthworm *D. octaedra*, aggregate structure is also important, but it is most probable that the influence of aggregate structure is mediated by the coordinated variability with other soil properties. Thus, an increase in the proportion of large aggregates is associated with a decrease in the depth of the forest litter, which is the habitat of *D. octaedra*. The response of *D. octaedra* to some aggregate fractions also has a plateau, indicating the presence of some zone of indifference of the epigeic earthworm to the aggregate structure.

Table 2. Correlation of earthworm abundance with CCA model residuals with spatial variables, soil penetration indices and phytoindication scales as constrained variables (correlation coefficients are shown significant for $p < 0.05$).

Fraction, mm	*A. trapezoides*	*D. octaedra*
> 10	–0.44	–
7–10	–0.34	–0.32
5–7	–0.28	–
3–5	0.24	–
2–3	0.26	–
1–2	–	–
0.5–1	–	–
0.25–0.5	–	–
<0.25	–	–

Thus, the aggregate structure of soil, the variability of which is coordinated with the variability of other soil properties and processes, affects earthworms. However, earthworms are also active aggregate formers, and they also affect the aggregate structure. To distinguish in this case the cause from the effect is extremely difficult, because suitable for earthworms are conditions with the predominance of meso-aggregates. The earthworms form zoogenic aggregates (coprolites), which are also mesoaggregates in size [99]. We hypothesized that earthworms, in the case of their influence, should explain that part of the variability of soil aggregate structure that factors of other origin do not explain. The soil penetration resistance is a reliable marker of variability of a whole complex of properties. A measurement of this index in the soil profile indirectly indicates variation in other soil properties. The phytoindication estimates show not only the variability of the vegetation structure, but also on the environmental factors that caused this variability. The spatial variables reflect the fact of the spatial structure of both soil properties and vegetation properties. They are also proxies for other environmental factors that have not been explicitly measured, but are spatially structured. The model residuals with these factors as constrained variables were found to be correlated with earthworm abundance. In this case, the hypothesis that earthworms are the cause of such deviations rather than the consequence should be considered the most probable. However, one cannot exclude the mechanism of an inverse positive relationship, when the production of mesoaggregates by earthworms contributes to the optimization of living conditions for earthworms and thus

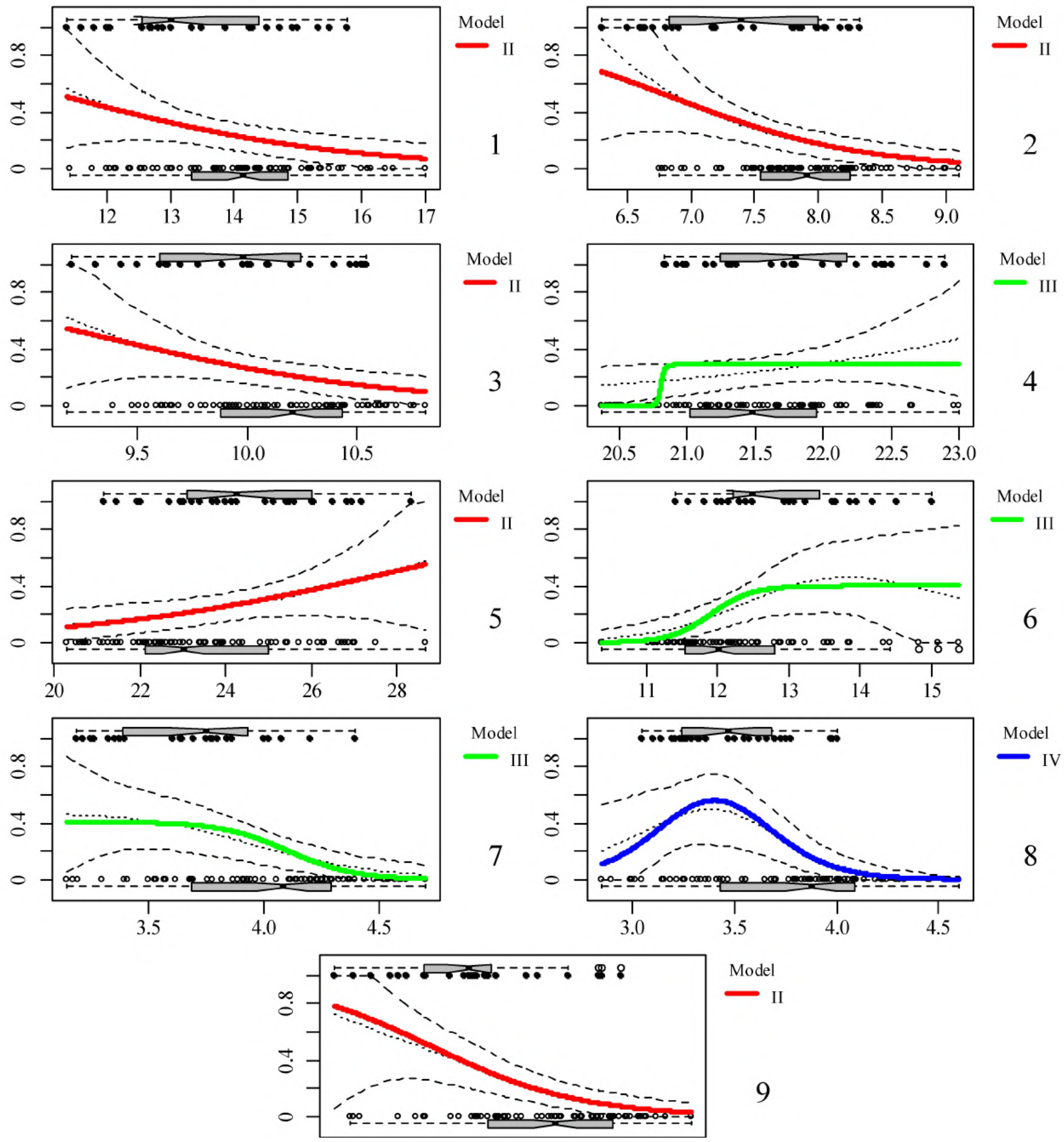

Figure 7. Response of *D. octaedra* abundance in a gradient of aggregate fraction proportions. The ordinate axis is the number of worm individuals in a 25×25 cm soil sample; the abscissa axis is the proportion of aggregate fractions; 1 – fractions > 10 mm; 2 – fractions 7-10 mm; 3 – fractions 5-7 mm; 4 – fractions 3-5 mm; 5 – fractions 2-3 mm; 6 – fractions 1-2 mm; 7 – fractions 0.5-1 mm; 8 – fraction of size 0.25-0.5 mm; 9 – fraction of size <0.25 mm; model II – monotonic response; II – monotonic response with plateauing; IV – symmetrical bell-shaped response; I V – asymmetrical bell-shaped response (response models from the HOF list of functions [97, 98]).

stimulates the development of their populations. The water stability of coprolite aggregates of Aporrectodea caliginosa is 2–2.5 times higher than that of soil aggregates of the same size [99]. The coprolite aggregates contain more clay particles and organic matter and less sand than the surrounding soil, because earthworms selectively absorb smaller particles and organic residues. The average size of mineral particles found in the digestive tract of earthworms is 100–500 m [100]. The shape and increased stability of coprolites positively affect aeration, water infiltration, water-holding capacity of soils, and increase their specific surface area. The coprolites and coprogenic aggregates have high water stability. The coprolites can persist for several months or even years, depending on soil moisture and temperature [101,102]. The water stability of coprolites depends on their enrichment with polymeric compounds and calcium (excreted by earthworms), poorly decomposed organic matter, clay and silt particles, humates, and microbial polysaccharides [103]. An important role in increasing the water stability of coprolite aggregates belongs to fungi, which form a branched mycelial network on the surface and inside coprolites [100]. There is notable that the abundance of earthworms explains the variability of the model residuals, which by definition are without the spatial component of variability within the chosen sampling strategy. The influence of earthworms can be assumed to be spatially structured at the spatial level, to account for which studies with a more detailed spatial resolution are necessary.

6. Conclusion

The aggregate structure of the soil is influenced by the pedogenic, phytogenic and zoogenic factors. The action of these factors is spatially structured. The endogeneous earthworm *A. trapezoides* is more sensitive to the effects of soil aggregate structure than the epigeneous *D. octaedra*. An increase in the proportion of large aggregates (greater than 5 mm in size) negatively affects earthworm abundance. The response of earthworms to the proportion of meso-aggregates is predominantly bell-shaped. Earthworms at the ecosystem level stimulate an increase in the proportion of meso-aggregates.

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Spatial distribution of micromollusks under the impact of recreation

To cite this article: O Kunakh *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012063

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012063 doi:10.1088/1755-1315/1049/1/012063

Spatial distribution of micromollusks under the impact of recreation

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Abstract. Anthropogenic impacts lead to a decrease in the abundance and diversity of communities of living organisms. The rate of recovery of populations is inversely proportional to size: the smaller the size, the greater the potential for population recovery after negative impact. Therefore, under conditions of extremely high levels of anthropogenic impact, small-sized animals are a reliable source of ecosystem state. The aim of the work is to: 1) to evaluate rates of the micromollusc *Vallonia pulchella* (Müller, 1774) abundance in ecosystems that are subject to extremely high levels of recreational pressure; 2) to identify factors that influence the spatial patterns of soil micromollusks; and 3) to investigate the possibility of using micromollusks for the purposes of bioindication of recreational pressure. The soil sampling was performed on a regular grid with recording of local coordinates. The micromollusks were extracted from the soil samples by hand sorting. Physical properties of soil sensitive to recreational load were also measured. Micromolluscs were found to exhibit a non-linear response to recreational impact. The maximum abundance of animals is observed at a certain distance from recreational trails. This distance is specific for different species of micromollusks. Micromollusks have high population abundance even under conditions of high recreational load. The regular spatial patterns of these animals are caused by changes in the soil habitat, which are induced by recreational load. This circumstance allows to consider micromollusks as a reliable indicator of the level of recreational load.

1. Introduction

Sustainable environmental solutions require discussion on a wide range of urban ecology issues [1]. Cities are home to the majority of the world's population and concentrate enormous flows of matter and energy. The biota that exist in urban environments are under the significant anthropogenic pressure, yet continue to perform important ecological functions. Management, including environmental management, must be based on the quantitative indicators of the state of the managed object. In this regard, the bioindication is a source of ecologically relevant information that is the basis for the development of environmental protection strategies. The methods and principles of biological indication of ecological regimes in natural conditions have been developed over a long period of time and have shown their effectiveness. Under conditions of anthropogenic impact, many ecological relationships undergo significant transformation, so methodological approaches that are relevant for natural conditions cannot be extended to anthropogenic conditions without additional adaptation. Anthropogenic factors occur within a background of the natural gradients, forming a complex mosaic of ecological regimes in the urban environment. Soil moisture, precipitation, wind speed, atmospheric temperature, atmospheric humidity and atmospheric pressure have been shown to be informatively important predictors of the ecological niche of terrestrial invertebrates of anthropogenically transformed ecosystems [2, 3]. The moisture content of technosols is the most important factor determining the temporal dynamics of the terrestrial invertebrate community under semi-arid climate and reclamation-formed ecosystem conditions [4, 5]. The response of species to soil water content is influenced not only by soil water content, but also by a complex of other environmental, temporal and spatial factors [6].

Urbanization takes many forms and recreational load is an important aspect of anthropogenic influence in the urban environment [7]. An important aspect of anthropogenic transformation in the urban environment is recreation. Urbanization affects environmental factors that are essential for terrestrial molluscs. Terrestrial gastropods, especially snails, can be used as the potential bioindicator organisms for assessing the environmental quality and thus for predicting the potential hazards to human health [8]. Hemeroby is a degree of deviation of ecological conditions from the natural state [9]. This deviation can result from the various anthropogenic influences, including recreation [10]. Recreational load leads to soil compaction, which causes negative trends for the urban environment. Topography and tree stand densities influence the spatial variation of soil penetration resistance [11] and soil electrical conductivity [11] in an urban park. The recreational impacts in the form of spontaneous pathways significantly alter the soil properties in the artificial park spaces. The zone of influence of this transformation was shown to be significantly larger than the visible edges of the pathways [12]. The main tendencies of transformation are the increase of penetration resistance and soil density, deterioration of the air and water regime, and negative changes in the aggregate structure of the soil [13]. This transformation affects the living conditions of soil micromolluscs [14]. Their abundance and diversity is significantly higher in undisturbed conditions. Living conditions deteriorate when approaching pathways, leading to a sharp decrease in micromollusc abundance. The micromollusc *Vallonia pulchella* (Müller, 1774) was sensitive to recreational pressure [15].

Hemeroby is a comprehensive indicator for measuring human impacts on ecological systems. Hemeroby have a complex nature and a variety of mechanisms for impact on ecosystems. Under natural forest conditions, tree placement leads to multiscale spatial structuring and is important in shaping the spatial patterns of soil macrofauna [16, 17]. The vegetation ecological factors are more important for the broad-scale component, edaphic factors for the medium-scale component, and both vegetation and edaphic factors for the fine-scale component [18]. For litter-dwelling animals the most typical spatial patterns occur at the broad-scale and medium-scale levels. For endogeic and anecic animals, the most significant variability is observed at the fine-scale level [19, 20]. The role of the hemeroby gradient was shown to structure the soil macrofauna community. Species of soil macrofauna differed in their optimum and specialization to the hemeroby factor. A regular change in the abundance and diversity of the soil macrofauna community in the gradient of hemeroby was recorded [21]. Soil macrofauna is a bioindicator of urban soil contamination with heavy metals [22].

Anthropogenic disturbances have a central importance in forming the species diversity and community structure of terrestrial snails [23]. The mechanical resistance of the soil, the size distribution of aggregates, the electrical conductivity of the soil, the physiological characteristics of the vegetation and the Didukh phytoindication scale were used as ecogeographic predictors of the ecological niche properties of *Brephulopsis cylindric* molluscs. The ecological niche of the mollusc is determined by both edaphic factors and ecological features of the vegetation [24]. The ecological niche of the micromollusk *Vallonia pulchella* in reclaimed soils was found to be determined by both edaphic factors and ecological features of the vegetation. The optima of the ecological niche were represented by integral variables such as the axes of marginality and specialization, which exhibit regular patterns of geographical space [25]. Morphometric data from molluscs are widely used to estimate intraspecific and inter-population variability as well as for bioindication and environmental assessment. The vegetation type and humidity was shown to influence the variation in shell shape of *Chondrula tridens* [26]. Shell shape also changes according to the level of anthropogenic pressure [27].

2. Research aim and objectives

Snails are organisms with a low dispersal capacity, so they have no ability to escape negative impacts and are very susceptible to anthropogenic activities. Micromolluscs (¡5 mm in diameter) are very sensitive to disturbance due to their very restricted mobility and dispersal ability, and their high dependence on microenvironmental conditions [28]. This suggests to consider the micromolluscs as potentially useful indicators for assessing the impact of recreation [29].

The aim of our work was therefore to solve two tasks:

(i) to evaluate rates of the micromollusc *Vallonia pulchella* (Müller, 1774) abundance in ecosystems that are subject to extremely high levels of recreational pressure;

(ii) to identify factors that influence the spatial patterns of soil micromollusks;

(iii) to investigate the possibility of using micromollusks for the purposes of bioindication of recreational pressure.

3. Material and methods

3.1. Study area

The research was conducted within two polygons, which were located in Novooleksandrivskiy Park (Melitopol, Ukraine) [15]. Each polygon consisted of 7 transects with 15 sampling points each. The spacing between the points in the transect, like the spacing between the transects, was 3 metres. The total area of the polygons was 1134 m^2. The tree stand in the park plantation was represented by *Quercus robur*, *Sophora japonica*, and *Acer campestre*. Shrubs were represented by *Ulmus laevis*, *Tilia cordata*, *Celtis occidentalis* and *Morus nigra*.

3.2. Mollusc collection

The sampling was conducted in October 2020 (in one polygon only) and in May 2021 (in two polygons). At each sampling point, a cylindrical shaped soil sample (9 cm diameter, 8 cm height, volume $\approx$ 500 cm^3) was collected from the soil surface to a depth of 8 cm. From this sample 10 sub-samples of 10 grams of soil were taken. Each sub-sample was examined with the help of a dissecting needle to extract micromolluscs [25].

3.3. Soil properties measurement

The soil penetration resistance was measured in the field using the Eijkelkamp manual penetrometer, to a depth of 50 cm at 5 cm intervals. The average error of the measurement results of the device is $\pm$ 8%. The measurements were made with a cone with a cross section of 1 cm^2. At each measurement point, the soil penetration resistance was performed in only one replication. The soil aggregate fractions size distribution was determined in accordance with the Soil Sampling and Methods of Analysis recommendations [30]. To measure the electrical conductivity of soil in situ the HI 76305 sensor (Hanna Instruments, Woodsocket, R. I.), working in conjunction with the portable instrument HI 993310 were used. The tester estimates the total electrical conductivity of the soil, i.e. combined conductivity of soil air, water and particles [25]. Soil moisture was measured under field conditions using a dielectric digital moisture meter MG-44 (vlagomer.com.ua). The core method was used for measurement of the soil bulk density [31].

3.4. Statistical analysis

The descriptive statistics were calculated using the program Statistica (Statsoft). Huisman-Olff-Fresco (HOF) [32] models were used to explain the responses of species to environmental gradients. Huisman-Olff-Fresco (HOF) models allow to achieve a statistical correctness, flexibility and possibility of ecological interpretation for modeling the responses of species to environmental gradients [33]. They were first developed by Huisman et al. [32] as a set of the five hierarchical models with an increasing complexity. The following types of models were identified: no response (I), increasing or decreasing response without (II) or with (III) a plateau, and asymmetric (IV) and symmetric (IV) unimodal responses. This list of models was extended to include seven ecological models [34]. In addition to the five model types mentioned above, bimodal asymmetric (VI) and symmetric (VII) response forms were included to deal with species that are constrained to the extreme gradient values due to competition. The parameters of the ecological niche of species can be calculated from the models and be used for further analysis [33]. To improve simulation results, model selection stability was tested using bootstrapping (100 samples, default package setting) to ensure model robustness, and using Akaike's information criterion corrected for small data sets (AIC_c, default setting) [35]. Where the two procedures differed in choosing the best type of model, the bootstrapping model was preferred [33]. The Huisman-Olff-Fresco models were computed using the statistical program R (v. 3.6.3; R Developmental Core Team) [36], with the package "eHOF" (version 1.9) [34].

4. Results

The abundance of *Vallonia pulchella* (Müller, 1774) was higher in autumn than in spring (Planned comparison t = –5.19, $p < 0.001$) (table 1). Polygons I and II had no statistically significant difference in mollusc abundance (Planned comparison $t = 0.13$, $p = 0.90$).

Table 1. Abundance of micromollusc *V. pulchella* (ind./m^2 in the 0–5 cm soil layer).

Polygon	Mean±st.error	Median	Q1	Q3
I (Spring 2021)	2818±262	1096	1644	3836
II (Spring 2021)	2732±278	1041	1562	2603
I (Autumn 2020)	5215±367	1129	4516	8468

The aggregate structure of the soils in the different polygons and at different times exhibited a certain level of similarity. The structure was dominated by the size fractions > 10 mm, 1–2 mm, and < 0.25 mm (figure 1). In autumn the proportion of fractions < 0.25, 0.25–0.5, and 0.5–1.0 mm increased significantly while the larger fractions decreased. In autumn, the soil water content was significantly lower than in spring (Planned comparison $t = 32.2$, $p < 0.001$), which explains the decreased pore volume of soil occupied by air in spring (Planned comparison t = –15.3, $p < 0.001$) and the greater electrical conductivity of soil (Planned comparison t = 16.6, $p < 0.001$) (figure 2). The soil bulk density was slightly higher in autumn than in spring (Planned comparison t = –6.2, $p < 0.001$). The differences between polygons in spring were statistically significant only for the moisture content (Planned comparison t = –6.6, $p < 0.001$) and the soil bulk density (Planned comparison $t = 4.6$, $p < 0.001$). The spring differences in soil volume occupied by air and soil electrical conductivity were not statistically significant (Planned comparison t = –0.4, $p = 0.67$ and t = –1.7, $p = 0.09$ respectively). The profile distribution of soil penetration resistance in autumn was characterised by a sharper increase in layers 5–10, ..., 30–40 cm than that observed in spring (figure 3).

The soil predictors and distance from the walkways and trees were able to explain 23–83 % of the variation in the proportions of aggregate fractions (table 2).

Table 2. General linear model of dependence of proportions of aggregate fractions on soil properties and distance from trees and walkways (beta regression coefficients±st.error).

Predictors	Fraction size, mm ($R_{adj}{}^2$) > 10 (0.56)	7–10 (0.23)	5–7 (0.62)	3–5 (0.63)	2–3 (0.63)	1–2 (0.51)	0.5–1 (0.51)	0.25–0.5 (0.46)	<0.25 (0.83)
Soil penetration resistance in the soil layer, cm									
0-5	–	–	−0.4±0.12	−0.4±0.11	–	–	–	–	–
5-10	–	–	–	–	−0.5±0.17	–	–	0.6±0.19	0.3±0.10
10-15	–	–	–	−0.5±0.18	–	–	–	–	–
15-20	–	–	–	–	−0.5±0.16	–	–	–	0.2±0.09
20-25	–	–	–	–	–	–	–	–	0.3±0.11
25-30	–	–	–	0.4±0.20	–	–	–	–	−0.2±0.12
30-35	–	–	–	–	–	–	–	–	−0.4±0.15
35-40	–	–	–	0.6±0.27	0.6±0.28	–	–	–	0.5±0.16
40-45	–	–	–	–	−0.9±0.25	–	–	–	0.4±0.14
45-50	–	1.6±0.35	–	0.5±0.26	–	–	−0.8±0.28	–	−1.0±0.15
50-55	−1.3±0.40	−1.4±0.45	–	–	–	–	–	–	0.7±0.19
55-60	1.2±0.39	–	–	−0.7±0.33	−0.8±0.34	–	–	–	–
60-65	–	1.5±0.50	0.9±0.39	1.4±0.3	1.2±0.38	–	−1.3±0.40	–	−1.31±0.21
65-70	–	−1.6±0.52	–	–	−1.4±0.40	–	–	−1.5±0.4	1.0±0.22
70-75	−0.8±0.40	0.9±0.45	–	–	–	–	–	–	−0.9±0.19
75-80	–	–	–	–	0.8±0.38	–	0.8±0.40	0.9±0.42	–
80-85	–	–	–	−0.7±0.32	–	–	–	–	0.8±0.18
85-90	–	–	–	–	–	–	–	–	–
90-95	–	–	–	–	–	–	–	–	–
95-100	−2.2±1.1	–	–	–	–	–	–	–	–
Soil properties									
Wetness	–	–	–	–	–	–	–	–	−0.2±0.05
Density	0.3±0.07	–	−0.2±0.06	−0.2±0.06	−0.2±0.06	−0.3±0.06	–	0.2±0.06	0.1±0.03
Distance									
Trail	–	–	–	−0.4±0.16	−0.5±0.16	−0.5±0.18	–	0.6±0.18	0.2±0.09
lTrail^2	–	–	–	–	0.4±0.15	–	–	−0.4±0.17	−0.2±0.09
Tree	–	−0.2±0.07	–	–	–	−0.2±0.06	0.2±0.06	−0.2±0.06	0.1±0.03
Polygon*									
1	0.9±0.14	0.4±0.15	–	–	−0.3±0.12	–	−0.8±0.12	–	−0.6±0.07
2	0.4±0.15	0.3±0.16	–	–	–	–	−0.9±0.13	–	−0.3±0.07

* Polygon I (Autumn 2020) is the reference polygon against which the influence of other polygons is evaluated: a positive coefficient indicates that the compared polygon exceeds the reference polygon by this parameter; a negative coefficient indicates the opposite.

An increase in moisture content led to a decrease in the proportion of aggregate fractions of <0.25 mm. A change in soil bulk density affected the proportion of all fractions. The increase in soil bulk density was associated with an increase in aggregate fractions sized > 10 mm and less than 0.5 mm and a decrease in fractions sized 1 to 7 mm. The effect of distance from walkways was nonlinear for fractions < 0.25, 0.25–0.5, and 2–3 mm. At distances of 1–4 m from the walkway, a local maximum of < 0.25 and 0.25–0.5 mm fractions was observed.

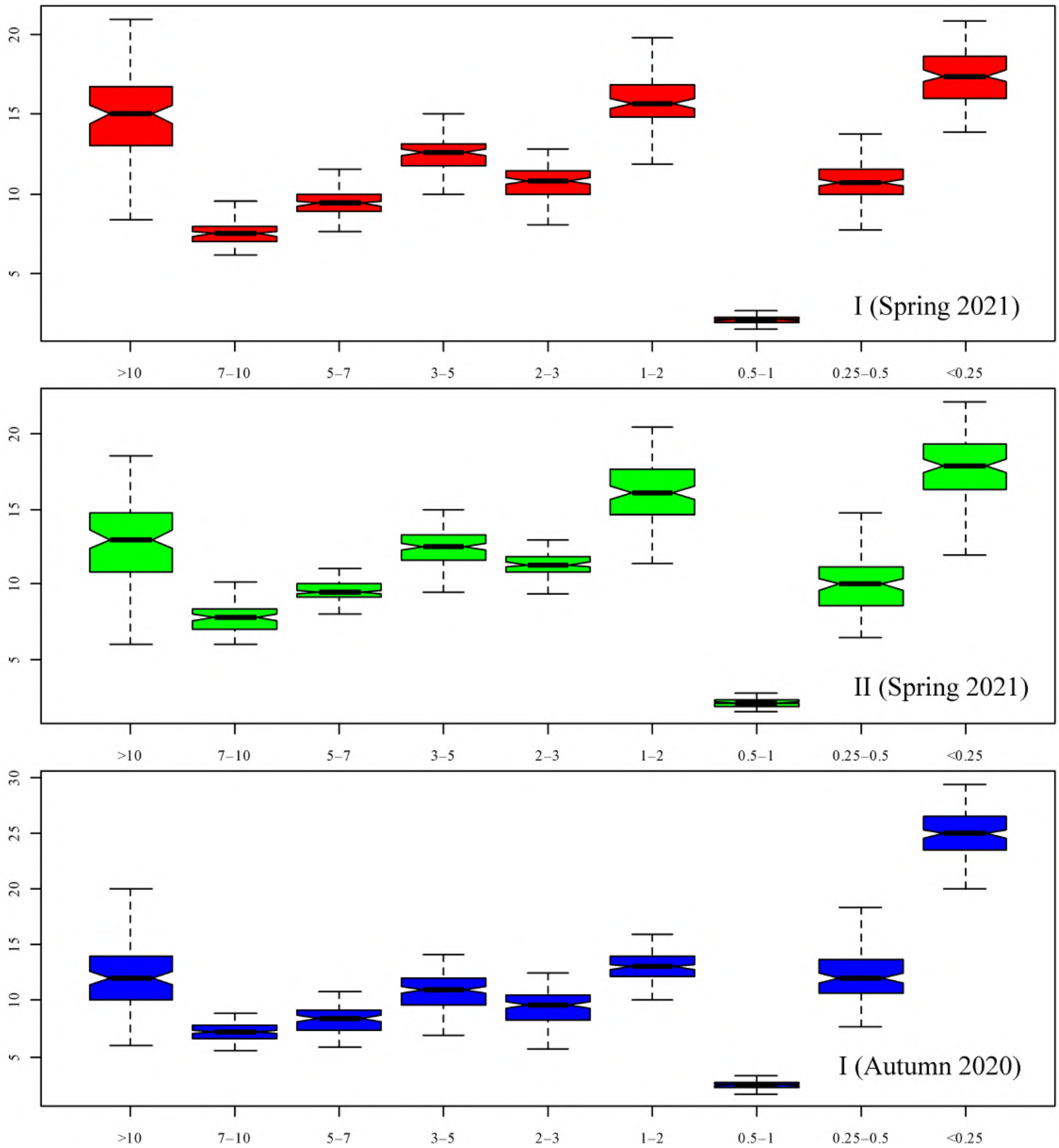

Figure 1. Aggregate structure of soils: Abscissa axis is the aggregate fractions (in mm); ordinate axis is the proportions of fractions (in %).

At a distance of 2–8 m, a local minimum of 2–3 mm fractions was observed. The proportion of 1–2 and 3–5 mm fractions decreased monotonically with the distance from the walkway. As the distance from the trees increased, the proportion of fractions sized 0.25–0.5, 1–2, and 7–10 mm decreased and the proportion of < 0.25 and 0.5–1 mm fractions increased. The aggregate structure in the 0–5 cm soil layer correlated with the variation in soil properties in the soil column.

The soil penetration resistance negatively affected the abundance of *V. pulchella* (figure 4). The limiting effect of soil compactness manifested itself from maximum values up to a level of 3–3.5 MPa. Other factors influenced the abundance of micromolluscs at lower levels of soil penetration resistance. The effect of soil moisture on *V. pulchella* abundance was obviously non-linear. Low soil moisture was an extremely negative factor.

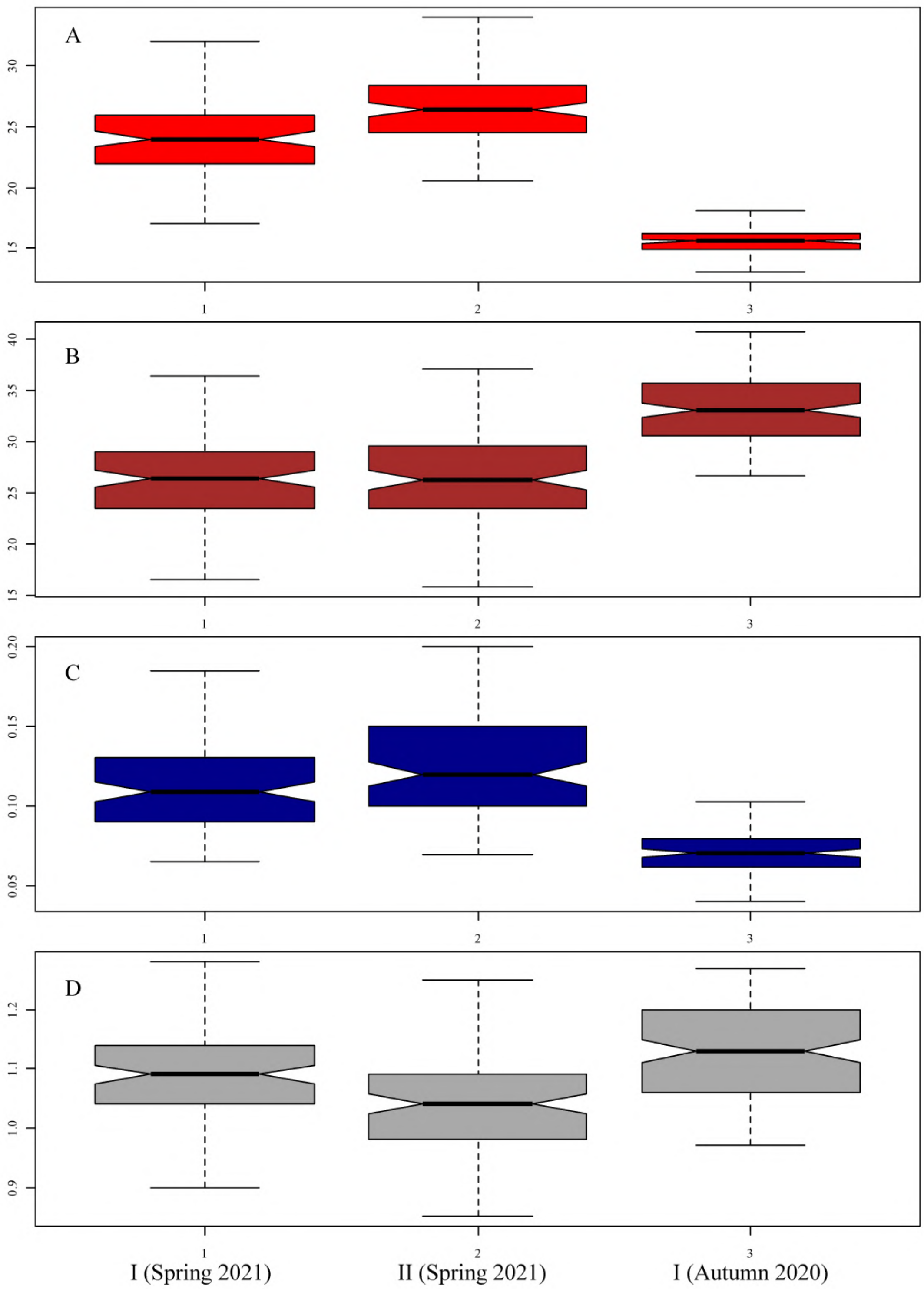

Figure 2. Variation of soil physical properties: A – soil water content, %; B – soil air content, %; C – soil electrical conductivity, dSm/m; D – soil bulk density, g/m^3.

At 15–18% moisture content the abundance of molluscs reached maximum values. With further increase in humidity the abundance of mollusks decreased monotonically.

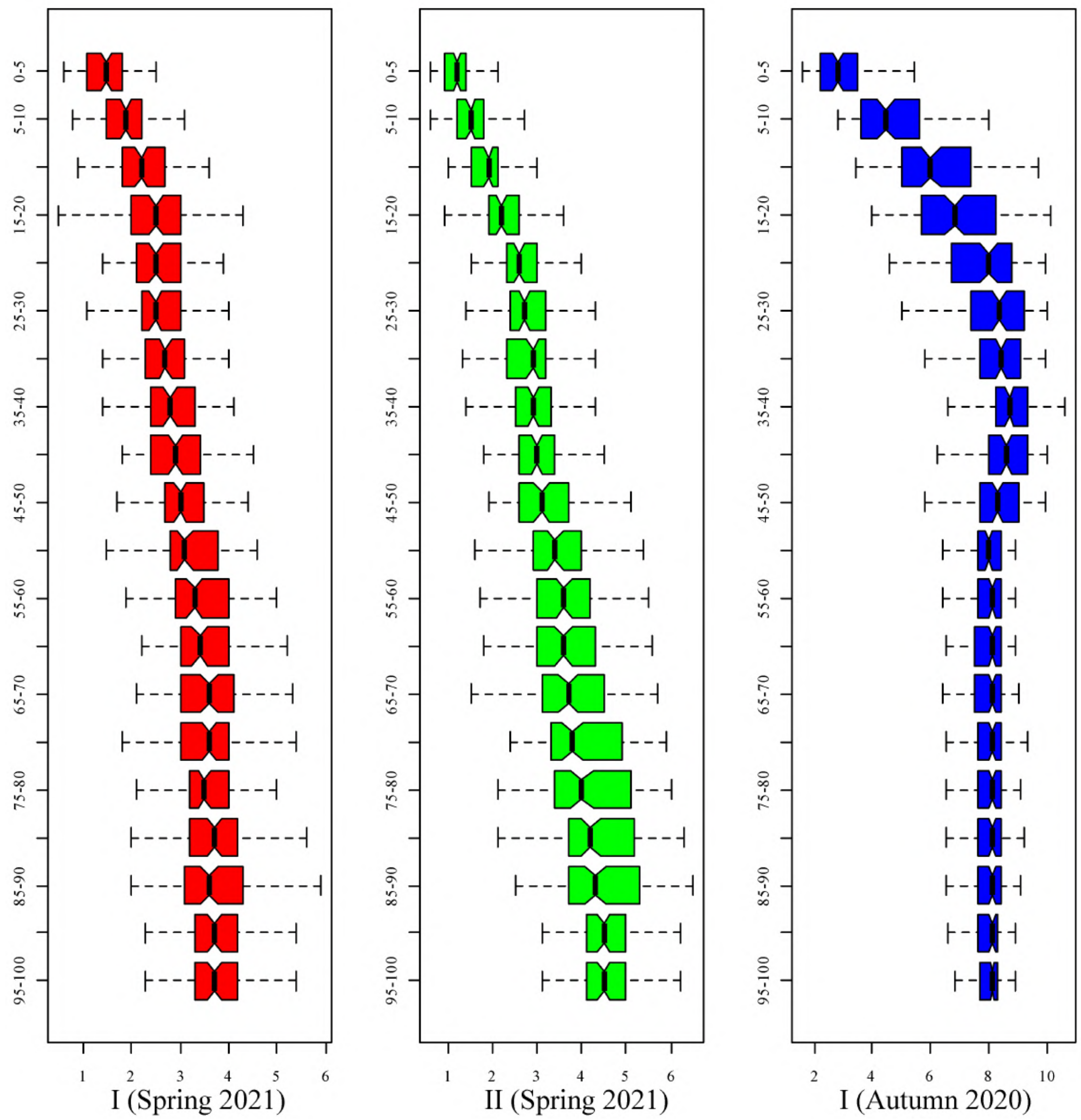

Figure 3. Profile distribution of soil penetration resistance. The abscissa axis is the soil penetration resistance, MPa; the ordinate axis is the depth of soil layers, cm.

The soil air supply had a strong influence on the abundance of micromolluscs. The abundance of micromolluscs was very low when the soil volume filled with air was less than 25%. With increasing soil air volume, there was an increase in the abundance of micromolluscs. In the immediate proximity of walkways the abundance of micromolluscs decreased sharply. However, already at a distance of 3–4 m a local maximum of animal abundance was observed. As the distance from the trees increased, the abundance of mollusks increased.

At soil electrical conductivity of 0.8–0.9 dS/m, a local maximum of micromollusc abundance was observed. Increasing or decreasing soil electrical conductivity from this range led to a decrease in micromollusc abundance. The abundance of molluscs decreased monotonically with increasing soil bulk density.

The proportion of aggregate fractions > 10 and 7-10 mm had a negative effect on the abundance of *V. pulchella* micromolluscs (figure 5).

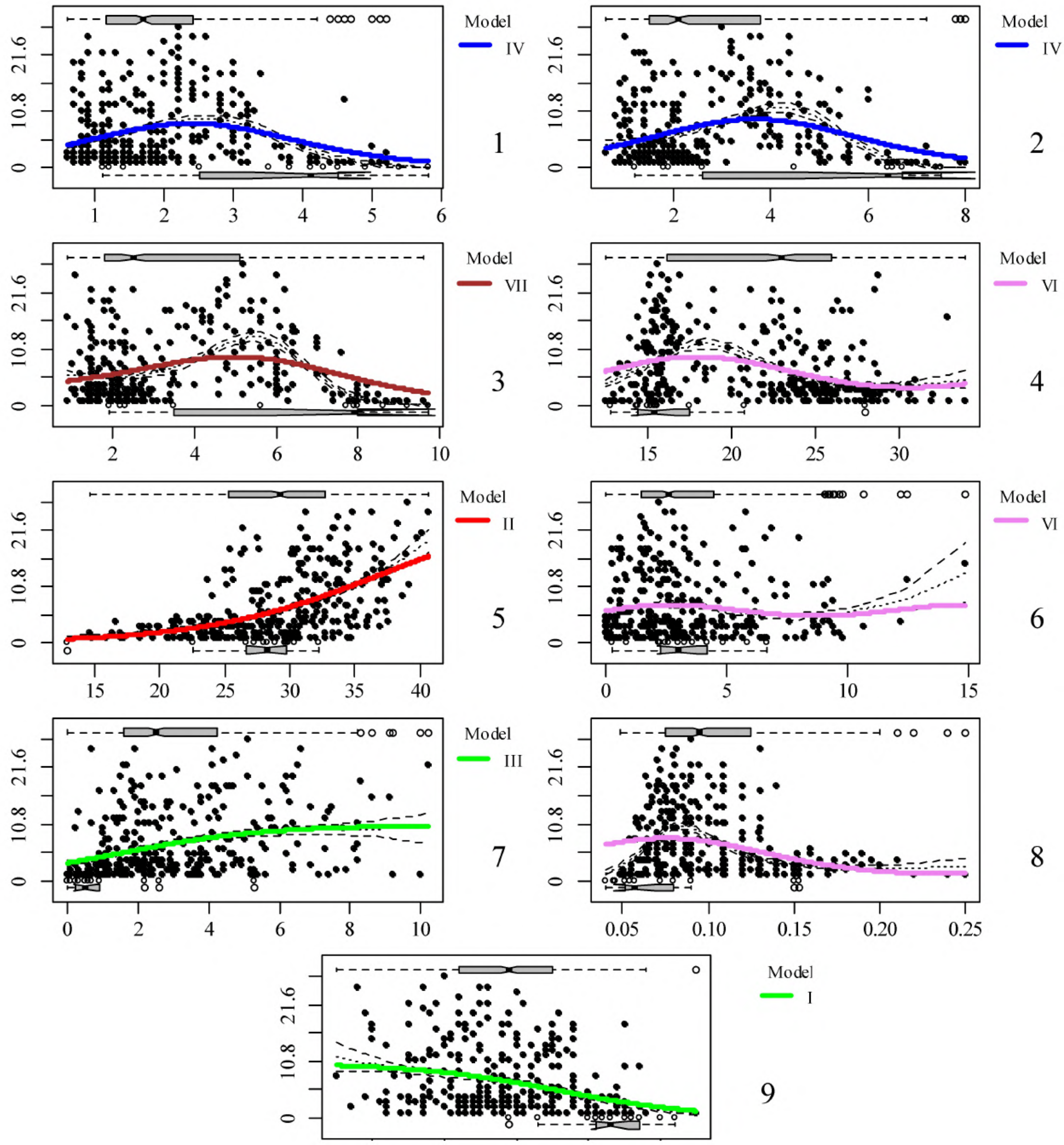

Figure 4. Response of *V. pulchella* abundance in a gradient of aggregate fraction proportions. The ordinate axis is the number of micromollusc individuals in a 100 g soil sample; the abscissa axis is the soil properties: 1 – soil penetration resistance in the soil layer 0–5 cm, MPa; 2 – soil penetration resistance in the soil layer 5–10 cm, MPa; 3 – soil penetration resistance in the soil layer 10–15 cm, MPa; 4 – soil water content, %; 5 – soil air content, %; 6 – trail distance, m; 7 – tree distance, m; 8 – soil electrical conductivity, dSm/m; 9 – soil bulk density, g/m^3.

The increase in the proportions of aggregate fractions of 0.5–1 and 2–3 mm had a positive effect on the micromolluscs. The response of micromollusk to the proportions of fractions 0.25–0.5, 3–5, 5–7, and <0.25 mm was bell-shaped with the presence of an optimum zone.

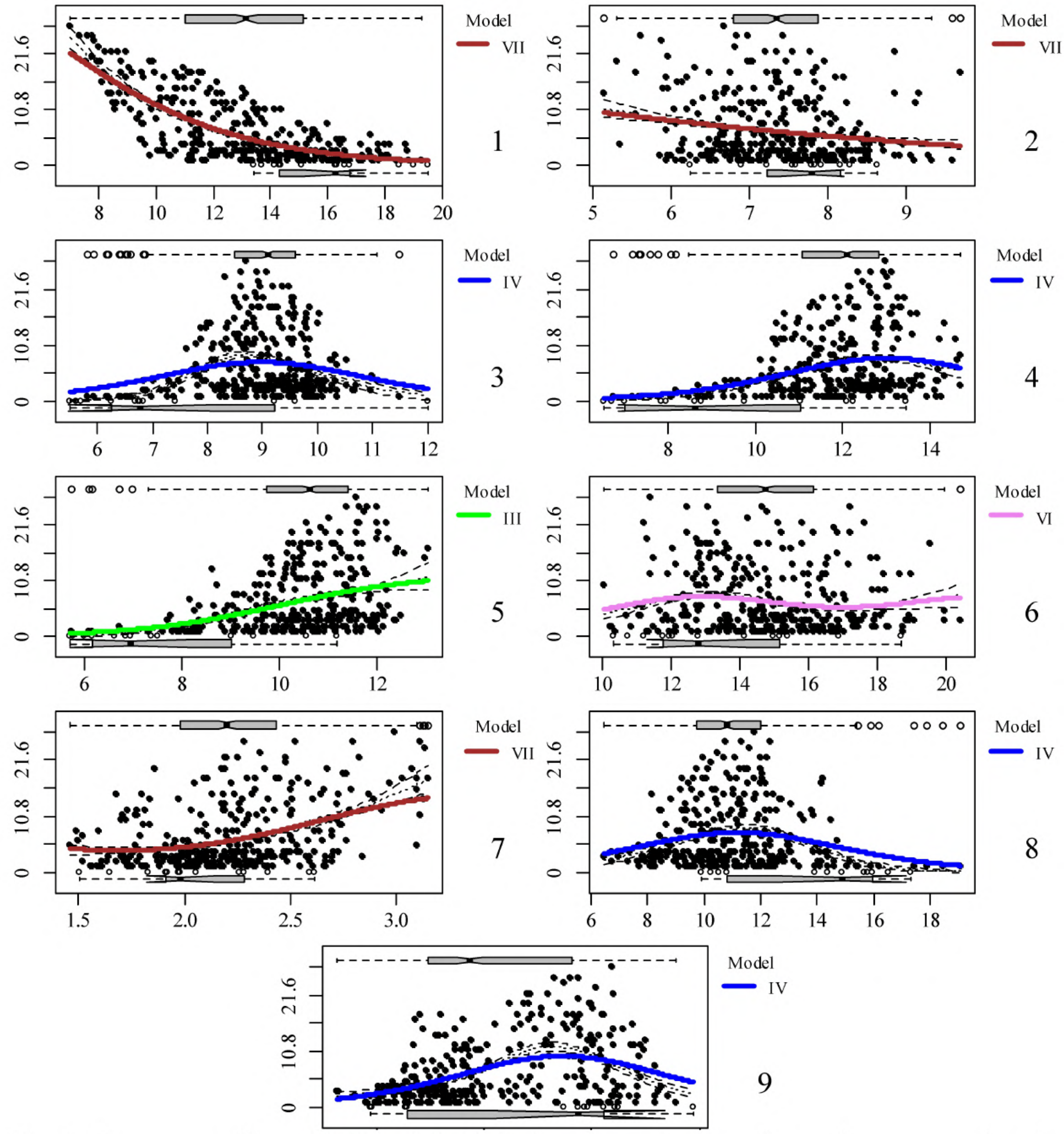

Figure 5. Response of *V. pulchella* abundance in a gradient of aggregate fraction proportions. The ordinate axis is the number of micromollusc individuals in a 100 g soil sample; the abscissa axis is the proportion of aggregate fractions; 1 – fractions > 10 mm; 2 – fractions 7-10 mm; 3 – fractions 5-7 mm; 4 – fractions 3-5 mm; 5 – fractions 2–3 mm; 6 – fractions 1–2 mm; 7 – fractions 0.5–1 mm; 8 – fraction of size 0.25–0.5 mm; 9 – fraction of size <0.25 mm; model II – monotonic response; IV – symmetrical bell-shaped response; V – asymmetrical bell-shaped response (response models from the HOF list of functions [15, 34]).

5. Discussion

A lot of investigation was carried out on habitat preference by terrestrial snails on a broad scale level [37–44]. Humidity and available calcium content were found to be the most significant ecological drivers controlling the species richness and composition of terrestrial mollusk communities [45]. The species richness and abundance of terrestrial mollusk communities respond positively to the calcium available and negatively to soil acidity [46, 47]. The effect of calcium on snail distribution is mediated by vegetation [40]. A study of the microspatial distribution of mollusk species within a patch is of great importance and practical significance [48–58]. The selection of suitable micro-habitats within the biotope avoids extreme environmental conditions [59–61]. The humidity and productivity of the ecosystem are the most important environmental conditions structuring mollusc communities [62]. The spatial distribution of molluscs was studied in relation to forest litter moisture, shading, air humidity, and groundwater level [54, 55, 63]. Particular mollusc species prefer the leaves of different tree species, so the diversity of mollusc communities depends on the diversity of the litter [54, 64]. Calcium content in soils is a strong regulator of species composition, total community abundance and the abundance of species on a fine scale [52]. Land snail species tend to cluster in the most favourable habitats, rather than replacing one species with another [65–68].

Our research revealed that the abundance of the micromollusc *Vallonia pulchella* (Müller, 1774) population reaches very high levels under recreational conditions. The population abundance is 2.7–2.8*10^3 ind./m^2 in spring and 5.2*10^3 ind./m^2 in autumn. Within the same ecosystem, the abundance of micromolluscs can vary by a factor of two. The high abundance and variability in population density suggest that this species has a high potential as an indicator of environmental properties and is also highly important in soil ecosystem functioning. The abundance of *V. pulchella* is significantly lower in spring than in autumn. Of all the predictors considered, the volume of soil that is occupied by air can be recognized as the most probable cause of the variation in population abundance. In spring, a considerable volume of soil pore space is occupied by water, so the level of supply of soil biota with air is very low. In autumn, the soil moisture level decreases and the pore space that is released is filled with air. Thus, at least 20-25 % of the soil pore space must be filled with air for normal life of the *V. pulchella* population. In addition to moisture content, soil density is an important factor that controls the volume of the pore space. The soil compaction that occurs as a result of recreational use leads to an increase in soil density and soil penetration resistance.

A linear and bell-shaped relationship was found between the soil moisture and the number of land snail species [49]. The plant cover determines the environmental conditions of the molluscs [69]. Soil electrical conductivity is a sensitive indicator of recreational load [11]. Soil electrical conductivity is a good predictor of *V. pulchella* population density. The electrical conductivity of soil depends on the distribution of soil phases: solid, liquid and gaseous. Gaseous phase practically does not conduct electric current while liquid phase conducts current in the best way. The ratio of the gaseous and liquid phase of the soil determines the living conditions of micromolluscs in the soil. This explains the correlation between the electrical conductivity of the soil and the abundance of *V. pulchella*. Thus, the pattern of micromollusk response to soil electrical conductivity integrates the animal response to both the soil density and soil moisture. The labor intensity of instrumental determination of soil moisture and soil electrical conductivity, should be noted to be commensurate, whereas the labor intensity of the soil density determination is very high and requires soil sampling and processing in the laboratory. In this regard, the soil electrical conductivity can be regarded as a convenient and reliable predictor of soil conditions for soil animals.

The important drivers of soil heterogeneity in urban parkland conditions are trees and recreational pathways. The most important environmental factor affecting the qualitative and quantitative features of mollusc populations at the landscape level is the soil calcium content [38, 44]. The thickness of forest litter, the organic matter content of the topsoil and the average annual temperature are important environmental conditions affecting molluscs [44]. Moisture levels in forest litter are particularly important for micromolluscs [51,54,55,67]. Within recreational pathways and in their proximity the abundance of micromollusc populations is at a very low level. Obviously, the high soil compactness due to recreational load leads to a reduction in pore space volume, which has a negative effect on the living conditions of the soil animals. The abundance of micromolluscs increases sharply at a distance of up to 5 metres from the recreational pathway and reaches its maximum. The reason is undoubtedly the greater supply of air to the soil in this area. An increase in micro-relief in the form of a scarp is formed near the walkway. The scarp is subjected to more drainage, so its moisture content is lower, and therefore the supply of air to the soil is greater. Thus, the impact of walkways on the surrounding soil far exceeds their visible limits. This impact is multidirectional. There is a decrease in the abundance of the micromollusc population close to the walkways, while at greater distances there is a sharp increase in the abundance of the population. Walkways are an important factor in the spatial heterogeneity of the *V. pulchella* population under recreational load conditions. An increase in soil mechanical impedance has a negative impact on the abundance of *V. pulchella* population [25].

The pure influence of structured tree space on the soil animal community was represented by large-scale and mesoscale components. The soil animal community exhibited patterns of change in the structured tree space. The spatial heterogeneity induced by trees was found to affect the vertical stratification of the soil animal community. The complex nature of soil animal community variability as a function of distance from trees depended on tree species interactions in their impact on soil animals. The importance of spatial patterns interacting with soil, plant and tree factors in the formation of soil macrofauna communities has been shown [17]. Trees also influence the spatial variability of soil properties, which is reflected in the abundance of *V. pulchella*. Near the tree trunks the abundance of micromolluscs decreases and increases monotonically with distance from the trees. In autumn, the aeration regime is the most important driver of such changes. As one moves away from the tree trunk, the volume of soil air increases due to a decrease in the soil density. Thus, the superposition of the effects of heterogeneity induced by the recreational load and the positioning of trees in the park plantation forms heterogeneous conditions to the variability of which the *V. pulchella* population responds with its abundance.

The response of micromolluscs to the gradient of the soil properties considered is of a common pattern. A range of factor can be identified at which the abundance of micromolluscs is very low and there is a critical point after which this factor has almost no effect on the micromollusc. Obviously, in addition to the overall distribution between the solid, liquid and gaseous phases of the soil, the structure of the pore space is important. This structure is characterised by the distribution of the size fractions of the soil aggregates. The aggregates larger than 10 mm are negatively influenced by soil micromolluscs. Their high proportion is formed in very compact soils, where the soil space limits the living possibilities of micromolluscs. The small pores in large aggregates are predominantly filled with water, which displaces the air required for respiration. In addition, the pores themselves are smaller than the molluscs, so the opportunities for animal movement in such soils are extremely limited. The large cracks between the macroaggregates drain quickly and hyperaeration and rapid desiccation of the soil areas in contact with them occurs. Such an ecological regime is extremely unfavourable for the soil micromolluscs. Apparently, there is an optimum distribution of inter- and intra-aggregate pore space at which micromolluscs achieve their greatest abundance. Such a soil condition is achieved when the proportion of mesoaggregates in the soil is sufficient. It is important to note that the optimality criteria are close for both micromolluscs and plant roots. Such conditions are the provision of moisture to the roots for nutrition and air for respiration. Our results are in line with the evidence which indicates that an increased content of 1–3 mm aggregates in the soil coincides with a higher abundance of *B. cylindrical* individuals. The *B. cylindrical* individuals avoid areas with increased alkalinity and soil salinity, identified by both the phytoindication approach and soil conductivity data [24]. The *V. pulchella* was shown to prefer the microsites with higher soil electrical conductivity, larger aggregate fractions with low mechanical resistance and low temperature at 0–10 cm depth, with a more developed layer of dead plants, low light and low values of the hygro- and heliomorphic vegetation index [56]. Under habitat conditions in reclaimed soils, *V. pulchella* prefers microstations dominated by soil aggregates 2–10 mm in size and avoids conditions where aggregates smaller than 2 mm predominate in the soil structure [25]. For micromolluscs, adequate humidity (100% moisture content in the soil air) is necessary as a protection factor against drying out, as the thin shell coverings of the mollusk with a relatively high body surface due to its small size are not a sufficient protection against drying out. Molluscs need air in the same way as plants do, to breathe. In general, mollusc abundance increases with increasing mesoaggregates and decreases with increasing macroaggregates.

6. Conclusion

The high abundance of the soil micromollusc *V. pulchella* in the anthropogenic soils and its sensitive response to the change of soil properties makes it a reliable indicator of the recreational load. The high abundance of the population (over 2.5-3*10^3 ind/m^2 in spring and over 8.4*10^3 ind/m^2 in autumn indicates optimal soil conditions both for the life of the micromolluscs and for the life of the soil biota as a whole. The decrease in abundance of micromolluscs under the influence of recreational load occurs mainly as a consequence of a decrease in soil air volume. This effect results from the compactness of the soil and changes in the aggregate structure of the soil. Under significantly transformed conditions, the proportion of the microaggregates increases and the proportion of the mesoaggregates decreases.

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IOP Conference Series: Earth and Environmental Science

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To cite this article: Y O Zhukova and I S Mytiai 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012064

Spatial organization of the soil macrofauna community in a floodplain forest

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Abstract. Soil fauna is an important functional component of terrestrial ecosystems. Several hierarchical levels of spatial organization of pedobionts communities can be distinguished: point level, ecosystem level and landscape level. Of particular importance is the ecosystem level of spatial organization where the results of interaction between soil animals and soil and plant environmental factors, as well as the results of the influence of factors of neutral nature are expressed to the greatest extent. The aim of the work is to test the hypothesis that the spatial patterns of soil macrofauna at the ecosystem level can be explained by ecomorphs. Soil animals were sampled in floodplain ecosystems in the Dnieper River valley. Animals were sampled according to a regular grid with recording of local coordinates of sampling points. At the same points, soil properties were measured and geobotanical descriptions of vegetation were made. Phytoindication assessment of environmental factors was carried out on the basis of vegetation descriptions. The soil animal community is represented by high taxonomic and ecological diversity. The spatial distribution of soil macrofauna is not random and is a consequence of environmental factors and causes of a neutral nature. The ratio of these factors varies depending on the scale level. The fine-scale level is represented by factors of neutral nature. Medium- and broad-scale components are determined by soil and vegetation factors. The main spatial patterns of variation in the soil animal community correlate with the ecomorphic features of the animals. The ecomorphic approach allows interpreting the information on the spatial organization of pedobionts communities.

1. Introduction

The species composition of communities according to niche theory can be explained by environmental variables [1, 2]. Abiotic environmental factors act as ecological filters selecting those species appropriate to specific habitat conditions [3]. Abiotic and biotic drivers can generate spatial patterns of the community [4]. According to neutral theory, dispersal limitation and ecological drift are important factors in shaping soil communities [5–9]. The structuring of communities is influenced by non-environmental factors such as dispersal and other population processes [10]. The probability of colonizing some space depends on the dispersal potential [11]. Ecological drift is the result of random fluctuations in the abundance of species [5]. The dispersal limitation and ecological drift are able to produce spatial patterns in the community structure, which can be revealed by spatial filters [12]. The ratio of the importance of environmental and neutral factors in community structuring can vary considerably. The importance of environmental factors compared to those of neutral nature increases as the spatial scale increases, which is explained by the coverage of greater environmental heterogeneity [13–17]. The leading role of dispersal limitation as an assembly process leads to the fact that community composition and species distribution can be spatially structured independently of the variability of environmental properties [18, 19]. A fraction of community variation that is spatially structured but not explained by environmental factors is called a pure spatial component. The pure spatial component represents the role of a dispersion limitation only when all significant environmental variables were accounted for [20].

Environmental factors, such as soil property gradients and vegetation composition, have a major influence on the distribution of soil organisms [21–24]. The ecological selection shapes the structure of the soil community [25, 26]. Biotic forces, such as competition and predation, as well as abiotic ones, shape the soil biota [27]. The control of soil macrofauna communities can be from the bottom due to resource shortages or from the top by predators [28, 29]. Soil and vegetation factors are important in structuring the communities of soil macrofauna at the level of beta diversity. The distribution of soil pore sizes, soil microclimate, structure of roots and above-ground vegetation determine the fine-scale distribution of soil fauna [30, 31]. The vegetation structure and quality of above-ground litter affect soil macrofauna communities [32]. The quality and quantity of food of soil macrofauna depends on the plants [33]. The production of aboveground litter depends on the nature of the vegetation [32]. The diversity of plants stimulates the diversity of soil fauna due to the fact that soil animals additionally use forest litter of different origin and different chemical composition [34]. The spatial distribution of plant root systems also causes the formation of spatial patterns of soil macrofauna [35, 36]. The vegetation density and litter height have a positive effect on the abundance of soil animals [37]. Herbaceous vegetation promotes the abundance and species richness of soil-dwelling animals, such as earthworms. Plant biomass and primary production have a positive effect on the abundance of soil fauna, which may not depend on plant diversity. [38]. The effect of above-ground vegetation on soil animals is due to the fact that plants change the microclimate near them, cooling the soil in the shade of their leaves [33]. The vegetation structure determines the diversity of microhabitats and the living conditions of macroinvertebrates [32]. The earthworms respond with increased abundance to shading effects, lower soil temperatures, and higher soil moisture in the vicinity of trees [39]. Species diversity of stands stimulates the diversity of the soil macrofauna community by creating a variety of small-scale microhabitats [40]. The most important factors in the organization of the spatial structure of the soil macrofauna of forest ecosystems are the density and diversity of tree stands [41].

A significant portion of the variation explained by soil properties in an Eastern European poplar-willow forest in the floodplain of the River Dnipro was spatially structured. The large-scale component of community variation was shown to be induced by stands that modified herbaceous vegetation structure at soil properties. Calcium-rich herbaceous plants strongly influenced the spatial placement of soil animals [42]. Soil and plant factors play an important role in structuring soil macrofauna communities of the Dnipro river arena terrace. The sensitivity of communities to environmental factors changes in space and is spatially structured. Specific spatial patterns of community sensitivity are distinguished for different ecological factors [43]. The spatial variation of soil macrofauna was fractionated into three components: broad-scale, medium-scale, and fine-scale. The broad-scale component depended on vegetation cover, the medium-scale component depended on soil properties, and the fine-scale component depended on vegetation and soil properties. For litter-dwelling animals, the most characteristic spatial patterns were at the broad-scale and medium-scale levels. For endogeic and anecic animals, the most significant spatial patterns were observed at the fine-scale level [44].

2. Research aim and objectives

The aim of our study was to reveal the role of plant and soil factors in the spatial organization of the soil macrofauna community of the floodplain ecosystem.

We tested the following hypotheses:

(i) plant, soil, and neutral factors act at different spatial levels;

(ii) topsoil properties and soil properties in the profile affect different spatial patterns of soil macrofauna;

(iii) soil animals modify the soil as a result of soil-forming activities, which causes new spatial patterns in the variability of vegetation, soil, and soil macrofauna properties.

3. Material and methods

3.1. Study area

The study was carried out in the elm oak forest in the floodplain of the Dnipro River (Dniprovsko-Orilsky Nature Reserve, Ukraine) (48.50 °N 34.77 °E). The soil properties measurement, description of plants, and collection of soil macrofauna were performed in 105 locations, which were located on a regular grid. The locations were 3×3 meter squares. The squares were adjacent to each other, forming a polygon. The description of plants was performed within each square, and the measurement of soil properties and sampling of soil animals were performed in the center of each square.

3.2. Description of soil morphology

The study of the soil profile morphology was performed in accordance with the guidelines of the field description of soils FAO [45]. Genetic type of soil profile was determined according to Rozanov [46]. The classification of soils was performed according to IUSS Working Group WRB [47]. The soils classification position according to WRB was Fluvic Gleysol (Arenic, Ochric) and Fluvic Mollic Gleysol (Loamic, Humic).

3.3. Sampling methods

The polygon consisted of 7 transects. Each transect was made up of 15 sampling points. The distance between rows within the polygon was 3 m. Soil macrofauna was defined as an invertebrate group found within terrestrial soil samples which has more than 90% of its specimens in such samples visible to the naked eye (macroscopic organisms) [48]. Samples consisted of single blocks of soil, 25×25×30 cm^3 deep, dug out quickly. A quadrat was fixed on the soil surface prior to taking the soil samples. The litter macrofauna was manually collected from the soil samples. The soil macrofauna were sorted and the animals were stored in 4% formaldehyde.

3.4. Plant community description

The vegetation description was performed at polygon consisted of 105 sampling points (relevés). The points were located along 7 transects with 15 sampling points each. The distance between points in the transect as well as the distance between transects was 3 m. The adjacent sampling points were in close proximity to each other. Vascular plant species lists were recorded for each 3×3 m sampling point, along with a visual assessment of species coverage using a Braun-Blanquet scale [49]. The projective cover of plant species was measured at soil level, understory (up to 2 m in height), and canopy (above 2 m in height). Seedlings and seedlings of tree species were subsequently excluded from the analysis. A phytoindication of environmental factors was performed based on the Didukh [50].

3.5. Soil properties measurement

The soil penetration resistance was measured in the field using the Eijkelkamp manual penetrometer, to a depth of 100 cm at 5 cm intervals. The average error of the measurement results of the device is ± 8%. Measurements were made with a cone with a cross section of 1 cm^2. At each measurement point, the soil penetration resistance was performed in only one replication. The aggregate structure was evaluated by Savinov's dry sieving method. The percentage content of such fractions was established: <0.25, 0.25–0.5, 0.5–1, 1–2, 2–3, 3–5, 5–7, 7–10, >10 mm, and plant roots. The bulk density of the soil was estimated by the Kachinskiy method, soil moisture by the weight method.

3.6. Statistical analysis

Canonical correspondence analysis (CCA) was used for analysis of the variance soil macrofauna species composition. Soil mechanical impedance, soil electrical conductivity, litter layer thickness, moisture and soil bulk density were log transformed. The significance of CCA global model was first tested. The geographic coordinates of sampling locations were used to generate a set of orthogonal eigenvector-based spatial variables (dbMEMs), each of them representing a pattern of particular scale within the extent of the sampling area [11]. All statistical analyses were conducted in R (v. 3.5.0., R Foundation for Statistical Computing, Vienna, AT), using the following packages: vegan (v. 2.5-2, https://CRAN.R-project.org/package=vegan) for the multivariate analysis and for the computation of global and partial Moran's I. [51], adespatial (v. 0.3-2. https://CRAN.R-project.org/package=adespatial) for the forward selection and for the generation of spatial filters [52].

4. Results

The soil macrofauna community included 46 species with a total abundance of 293.9±38.84 ind./m^2 (table 1). The earthworms were the most abundant group of soil animals and were represented by the 3 species. The abundance of earthworm cocoons was 16.91±2.44 ind./m^2. Endogeic species (*Melolontha melolontha*, *Isomira murina*, *Serica brunnea*) were also highly abundant. The group of epigeic animals was diverse and abundant.

Table 1: Taxonomic diversity and abundance (ind./m^2) of the soil animals.

Taxon	**Mean±st.error**
Annelidae	
Oligohaeta	
Haplotaxida	
Lumbricidae	
Aporrectodea caliginosa trapezoids (Duges, 1828)	71.92±4.13
Aporrectodea rosea (Savigny, 1826)	0.30±0.21
Dendrobaena octaedra (Savigny, 1826)	4.42±0.70
Lumbricidae sp. sp.	16.91±2.44
Arthropoda	
Arachnida	
Araneae	
Lycosidae	
Xerolycosa miniata (L.C. Koch, 1834)	9.60±1.29
Chilopoda	
Geophilomorpha	
Geophilidae	

Table 1 – continued from previous page

Taxon	Mean±st.error
Geophilus proximus C.L.Koch 1847	9.60±1.10
Pachymerium ferrugineum (C.L.Koch 1835)	8.08±1.72
Lithobiomorpha	
Lithobiidae	
Lithobius (Monotarsobius) aeruginosus L. Koch 1862	0.30±0.21
Lithobius (Monotarsobius) curtipes C.L. Koch 1847	2.44±0.56
Diplopoda	
Julida	
Julidae	
Megaphyllum rossicum (Timotheew, 1897)	6.86±1.10
Insecta	
Coleoptera	
Carabidae	
Amara familiaris (Duftschmid, 1812)	27.58±2.49
Amara similata (Gyllenhal, 1810)	1.98±0.64
Calathus (Calathus) fuscipes (Goeze, 1777)	2.90±0.99
Calosoma (Calosoma) inquisitor (Linne 1758)	0.46±0.26
Harpalus (Pseudoophonus) griseus Panzer, 1796	0.15±0.15
Chrysomelidae	
Chrysolina (Fastuolina) fastuosa (Scopoli 1763)	1.07±0.39
Curculionidae	
Otiorhynchus (Cryphiphorus) ligustici (Linnaeus 1758)	4.88±1.04
Elateridae	
Agriotes (Agriotes) lineatus (Linnaeus 1767)	1.98±0.52
Agrypnus murinus (Linnaeus 1758)	0.76±0.33
Athous (Athous) haemorrhoidalis (Fabricius 1801)	9.14±1.28
Cardiophorus rufipes (Goeze, 1777)	8.99±1.26
Prosternon tessellatum (Linnaeus 1758)	1.52±0.46
Silphidae	
Dendroxena quadrimaculata (Scopoli 1772)	0.15±0.15
Staphylinidae	
Drusilla canaliculata (Fabricius, 1787)	0.46±0.26
Othius punctulatus (Goeze 1777)	0.30±0.21
Platydracus (Platydracus) fulvipes (Scopoli 1763)	0.76±0.33
Tenebrionidae	
Cylindronotus (Nalassus) brevicollis Kuster, 1850	0.15±0.15
Helops coeruleus (Linnaeus 1758)	0.30±0.21
Isomira murina (Linnaeus 1758)	16.76±1.57
Opatrum sabulosum (Linnaeus 1761)	0.15±0.15
Melolonthidae	
Amphimallon solstitiale (Linnaeus 1758)	6.25±0.93
Melolontha melolontha (Linnaeus 1758)	33.68±3.10
Polyphylla (Polyphylla) fullo (Linnaeus 1758)	3.35±0.88
Serica brunnea (Linnaeus 1758)	11.43±1.40
Dermaptera	
Forficulidae	
Forficula auricularia Linnaeus 1758	2.13±0.65
Diptera	

Table 1 – continued from previous page

Taxon	Mean±st.error
Therevidae	
Thereva nobilitata (Fabricius 1775)	0.61±0.30
Asilidae	
Asilidae sp.1	0.30±0.21
Rhagionidae	
Rhagio scolopaceus (Linnaeus 1758)	0.76±0.33
Tabanidae	
Tabanus bromius Linnaeus 1758	1.07±0.39
Tipulidae	
Tipula (Lunatipula) lunata Linnaeus 1758	0.30±0.30
Empididae	
Empis (Kritempis) livida Linnaeus 1758	0.15±0.15
Lepidoptera	
Noctuidae	
Agrotis segetum (Denis & Schiffermüller, 1775)	7.16±1.40
Malacostraca	
Isopoda	
Trachelipodidae	
Trachelipus rathkii (Brandt 1833)	11.28±1.18
Mollusca	
Gastropoda	
Pulmonata	
Cochlicopidae	
Cochlicopa lubrica (O.F. Muller 1774)	0.15±0.15
Helicidae	
Cepaea (Austrotachea) vindobonensis (C. Pfeiffer 1828)	4.27±0.95
Valloniidae	
Vallonia pulchella (O.F. Muller 1774)	0.15±0.15

The detrended correspondence analysis found that the largest axis had a length of 2.3, which exceeds the conditional limit of 2, so a canonical correspondence analysis was chosen as the ordination procedure. The spatial variables were able to explain 39.6% of the variation in the soil macrofauna community ($F = 2.8$, $p < 0.001$). Topsoil characteristics were able to explain 8.8% of community variation ($F = 1.8$, $p < 0.001$). The soil penetration resistance characteristics in the soil profile were able to explain 10.6% of the variation in the soil macrofauna community ($F = 1.7$, $p < 0.001$). Vegetation features were able to explain 10.9% of the variation in the soil macrofauna community ($F = 1.9$, $p < 0.001$). Different sources of community variation had a pure effect on soil macrofauna and also interacted with each other (figure 1).

The analysis of the scalogram allowed to extract the three scale components of the spatial community variation: broad-scale, medium-scale, and detailed-scale (figure 2). The broad-scale component was explained by the dbMEM 1–8 and was able to explain 8.3% of the community variation ($F = 2.7$, $p < 0.001$). The medium-scale component was explained by the dbMEM 13, 15–17, 19 and was able to explain 5.0% of community variation ($F = 1.6$, $p = 0.014$). The fine-scale component was explained by the dbMEM 29, 34, 35, 38, 38, 39, 41, 42, 44, 48 and was able to explain 7.5% of the community variation ($F = 1.8$, $p = 0.002$).

The topsoil properties as a conditional variable reduced the variability of the soil macrofauna community that could be explained using the spatial variables to 34.3% ($F = 2.1$, $p < 0.001$).

The broad-scale component explained 7.8% of community variation ($F = 2.4$, $p < 0.001$), the medium-scale component explained 4.9% of community variation ($F = 1.6$, $p = 0.007$), and the fine-scale component explained 6.6% of community variation ($F = 1.5$, $p = 0.004$). Thus, the topsoil properties mainly influenced the spatial patterns of the soil macrofauna community at the fine-scale level and had less influence on the broad- and medium-scale patterns. The *Otiorhynchus ligustici*, *Cepaea vindobonensis*, *Melolontha melolontha*, *Polyphylla fullo*, and *Dendrobaena octaedra* were most sensitive to the influence of soil properties (figure 3).

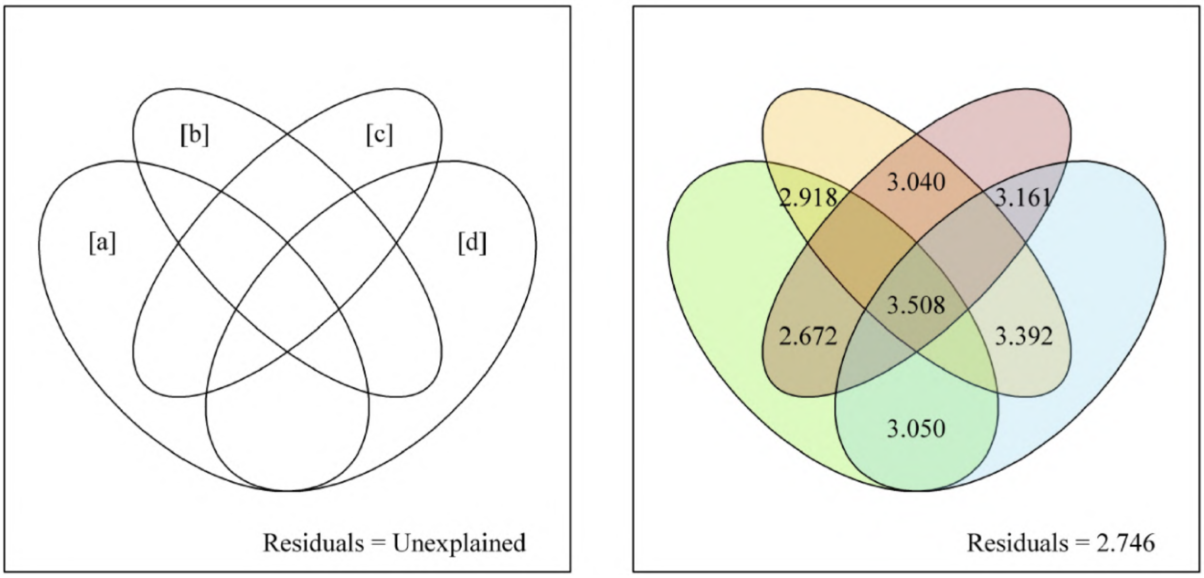

Figure 1. Variance partitioning between spatial, topsoil, profile soil, and plant explanatory variables. [a] – variation captured by spatial (dbMEM) variables corresponds to pure spatial component; [b] – variation explained solely by topsoil variables (soil electric conductivity, forest litter depth, soil water content, soil bulk density, aggregate fractions composition in the soil layer 5 cm deep from the surface); [c] – variation explained solely by soil penetration resistance variables measured to a depth of 1 meter at intervals of every 5 cm; [d] – explained solely by plant variables. The intersection of the ellipses corresponds to the variations explained by the respective sources together. All the variance fractions shown are significant ($p < 0.001$).

The profile values of soil penetration resistance as a conditional variable reduced the community variability that could be explained by spatial variables to 34.9% ($F = 1.9$, $p < 0.001$). The broad-scale component explained 6.7% of community variation ($F = 2.1$, $p < 0.001$), the medium-scale component explained 4.4% of community variation ($F = 1.6$, $p = 0.007$), and the fine-scale component explained 7.2% of community variation ($F = 1.9$, $p < 0.001$). Thus, the soil penetration resistance mainly influenced broad- and medium-scale patterns and had no effect on fine-scale patterns. The *Otiorhynchus ligustici*, *Lithobius curtipes*, *Cepaea vindobonensis*, *Megaphyllum sjaelandicum*, and *Polyphylla fullo* were most sensitive to the influence of soil properties (figure 3).

The phytoindicative estimates of environmental factors as a conditional variable reduced community variability that could be explained by the spatial variables to 39.5% ($F = 1.9$, $p < 0.001$). The broad-scale component explained 6.7% of the community variability ($F = 1.9$, $p = 0.002$), the medium-scale component explained 2.7% of the community variability ($F = 0.9$, $p = 0.47$), and the fine-scale component explained 6.9% of the community variability ($F = 1.5$, $p = 0.006$). Thus, the vegetation mainly influenced broad- and medium-scale patterns and had no effect on fine-scale patterns. The *Prosternon tessellatum*, *Pachymerium ferrugineum*, *Cepaea vindobonensis*, *Megaphyllum sjaelandicum*, *Geophilus proximus* were most sensitive to the influence of vegetation (figure 4).

The pure spatial component was able to explain 21.9% ($F = 2.0$, $p < 0.001$) of soil macrofauna community variation. The broad-scale component explained 6.1% of community variation ($F = 1.7$, $p < 0.001$), the medium-scale component explained 3.0% of community variation ($F = 1.5$, $p = 0.007$), and the fine-scale component explained 4.7% of community variation ($F = 1.4$, $p = 0.002$). The spatial component of community variability formed a pattern, the deviation from which can be interpreted as the result of the influence of individual soil and plant factors (figure 4).

5. Discussion

Soil and plant environmental factors influence variation in the soil macrofauna community [42, 53]. These factors interact with each other and are spatially structured [51]. The study was conducted within a relatively small area, but within which there is a significant variability in gradients due to which the response of most animal species is not monotonic, but is more bell-shaped. For this reason, we chose canonical correspondence analysis for the ecological ordination procedure. A considerable heterogeneity of ecological conditions is typical of floodplain ecosystems [2, 54]. The dynamics and variability of floods leads to the different intensity of redeposition of alluvium, as a consequence of which there is a significant variability in the granulometric composition of the soil-forming sediments of floodplain soils [55]. The granulometric composition is a factor that determines other physical properties of soil, as well as water, air regime and salt accumulation regime [52, 56].

The influence of soil properties in the upper soil layer on soil macrofauna is completely spatially structured and correlated with the variability of soil properties in the soil profile as a whole, as well as correlated with the variability of vegetation cover. The microorganisms in the litter layer are limited mainly to nitrogen, while the soil microorganisms are limited mainly to phosphorus. The earthworms are limited by carbon availability. Earthworms and microorganisms compete for carbon resources, with microorganisms being more competitive when carbon and nutrients are available [32]. An important aspect of the influence on the soil macrofauna is the spatially structured relationship between all three sources of influence considered: the top soil layer, the soil profile, and the vegetation cover [43, 57]. The upper soil layer has a certain spatial independence in comparison with the soil profile as a whole [44, 58]. The reason for this phenomenon may be twofold. First of all, the independence of variation of the upper soil layer may be due to the fact that alluvial processes primarily affect the upper soil layer. The redeposition of suspended matter and organic matter occurs primarily on the soil surface. The deeper soil layers of floodplain soils are involved in the processes of redeposition of matter during periods of significant floods, which occur relatively rarely [59]. Another reason for the isolated variability of topsoil properties may be the backward influence of soil animals [60]. The soil animals are important factors of soil formation and influence soil properties [61]. This influence is proportional to their abundance, so in microsites, which are favorable for the development of populations of soil animals, especially ecosystem engineers, there is a significant transformation of soil properties [41]. The basis of the structure of the studied soil macrofauna community is composed of earthworms, which can significantly change the aggregate structure of soil, create a system of soil galleries, and promote the movement of dead plant residues from the soil surface deep into the soil [62]. The community of earthworms is represented by the epigeic *D. octaedra* and the top-layer endogeic *A. c. trapezoids*. The soil-forming activity of these animals is focused on the litter or upper soil layer. The mid-layer endogeic earthworm *A. rosea* was observed sporadically. The endogeic species of soil animals are represented mainly by phytophages, whose spatial distribution depends on the spatial organization of the vegetation

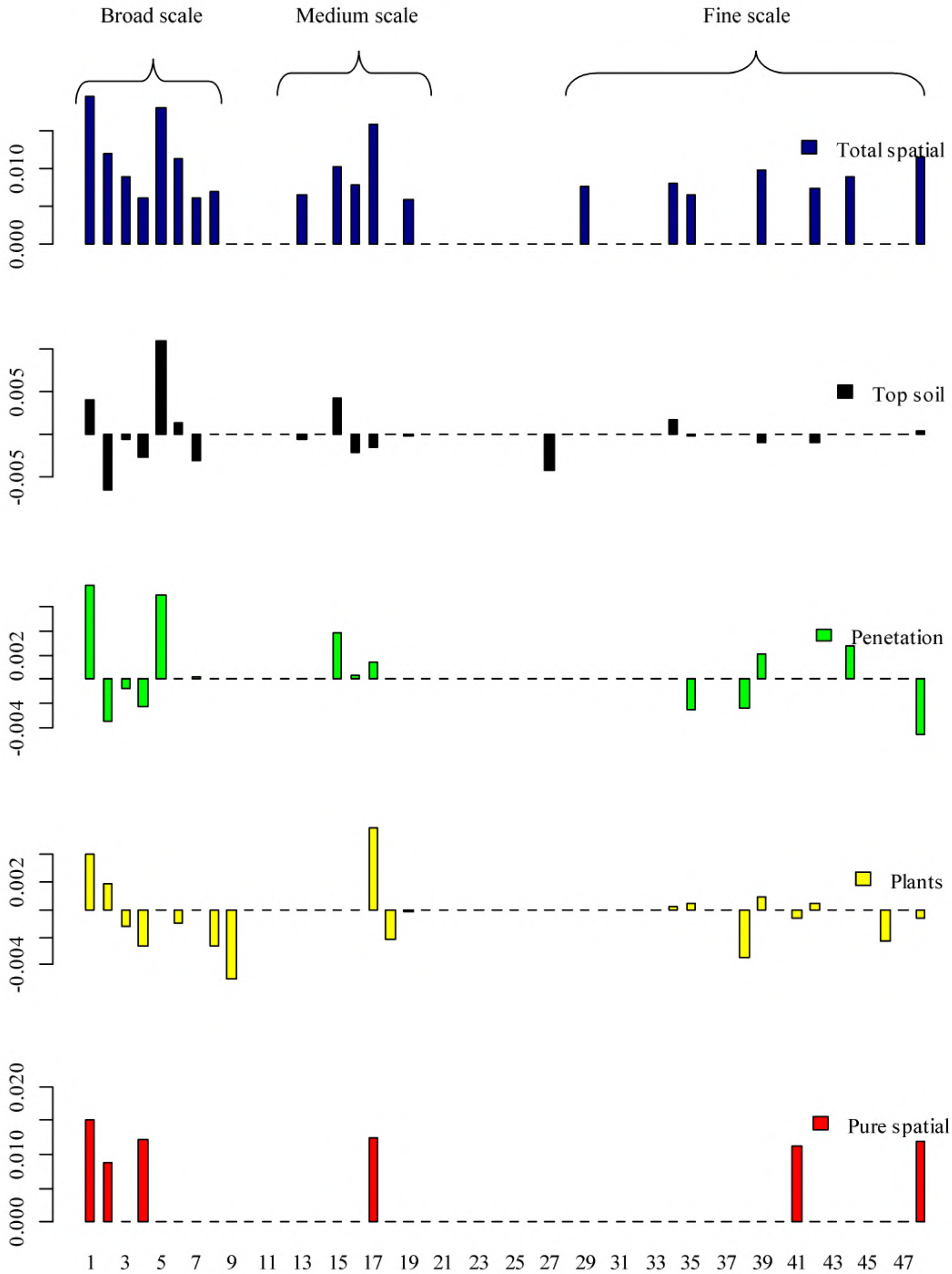

Figure 2. Scalograms illustrating the scaling of spatial structured variation in soil macrofauna community data (No variables as covariates, blue bars) and residuals of the spatial models (red bars), topsoil models (black bars), soil penetration models (green bars) and plant models (yellow bars). The value of R^2_{adj} is the variation explained by individual dbMEM variables for spatial structured variation and pure spatial models, and the differences between variations explained by the spatial models and explained variations for topsoil, profile soil and plant models. The dbMEMs are ordered decreasingly according to the scale of spatial patterns they represent x-axis is the number of dbMEM.

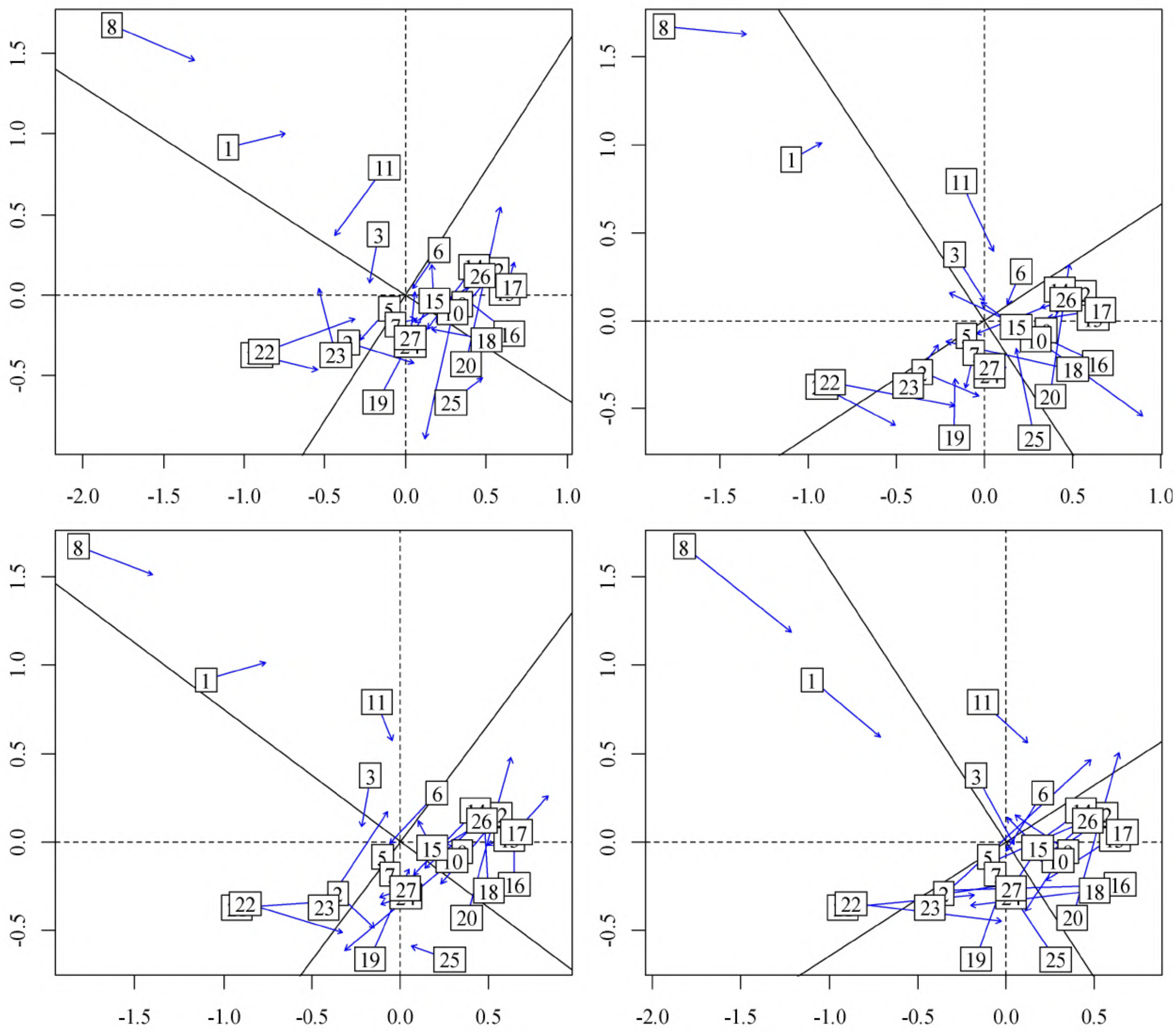

Figure 3. Procrustean analysis of the effect of soil properties in the topsoil as a conditional variable on ordinal solutions with spatial variables as predictors: 1 – *Agriotes lineatus*, 2 – *Agrotis segetum*, 3 – *Amara familiaris*, 4 – *Amara similata*, 5 – *Amphimallon solstitiale*, 6 – *Aporrectodea trapezoides*, 7 – *Athous haemorrhoidalis*, 8 – *Calathus fuscipes*, 9 – *Cardiophorus rufipes*, 10 – *Cepaea vindobonensis*, 11 – *Chrysolina fastuosa*, 12 – *Dendrobaena octaedra*, 13 – *Forficula auricularia*, 14 – *Geophilus proximus*, 15 – *Isomira murina*, 16 – *Lithobius curtipes*, 17 – *Lumbricidae sp* , 18 – *Megaphyllum sjaelandicum*, 19 – *Melolontha melolontha*, 20 – *Otiorhynchus ligustici*, 21 – *Pachymerium ferrugineum*, 22 – *Polyphylla fullo*, 23 – *Prosternon tessellatum*, 24 – *Serica brunnea*, 25 – *Tabanus sp 1*, 26 – *Trachelipus rathkii*, 27 – *Xerolycosa miniata*.

cover [63]. Therefore, the specificity of the spatial variability of soil properties indicated by the zoogenic factor covers the upper soil layer to the greatest extent.

The spatial component of the variability of topsoil soil properties is most represented by the broad- and medium-scale components, which also confirms our assumptions about the sources of influence that generate the corresponding patterns. The broad-scale component may be generated by microrelief features, which are formed as a result of flooding [64]. The micro-relief features are places of concentration of forest litter and moisture [65, 66]. These conditions are

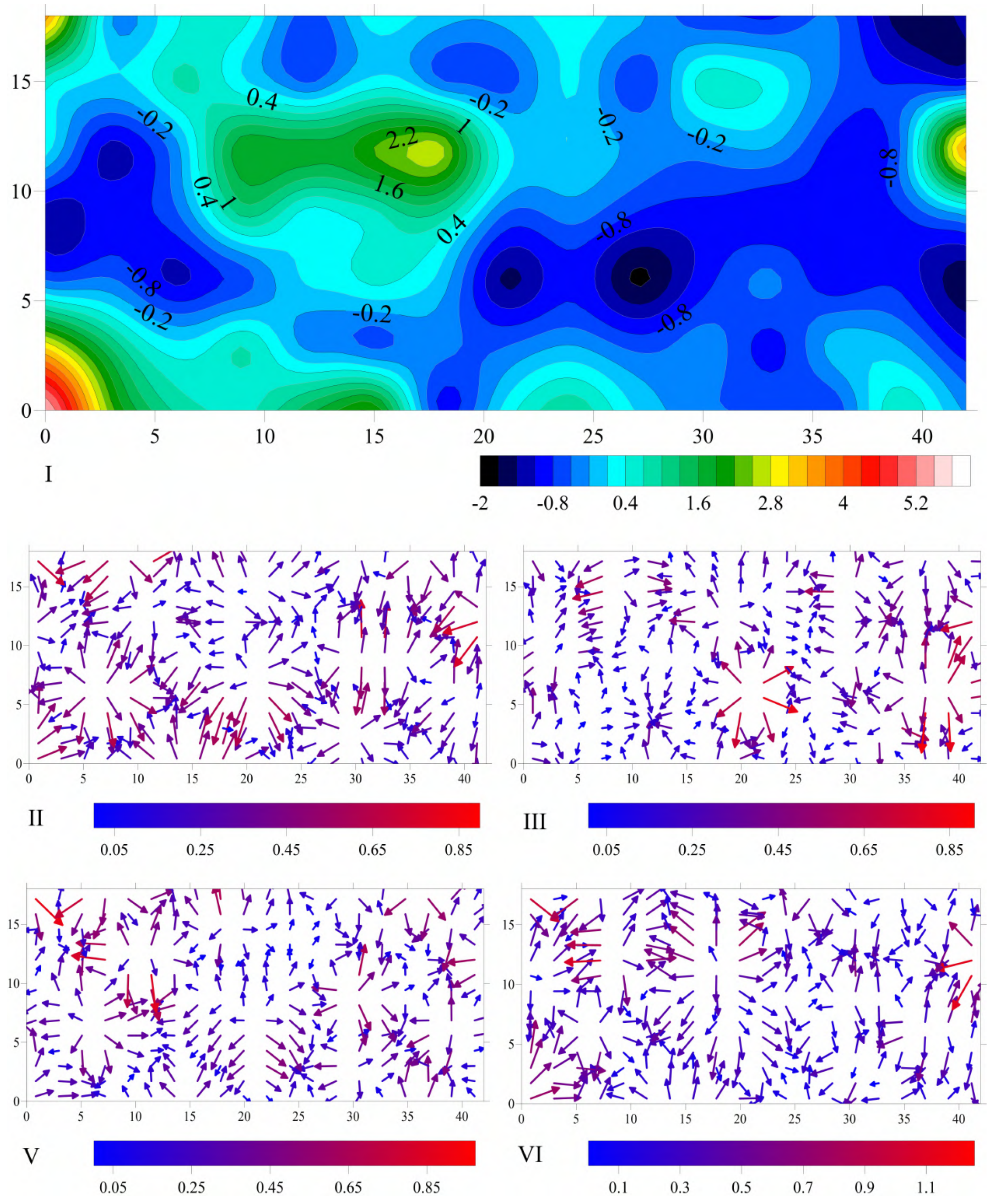

Figure 4. The spatial component of soil macrofauna community variation (I) and the direction and intensity of deviation from it as influenced by topsoil properties (II), soil profile properties (III), vegetation, and the difference between total spatial variation and net spatial component (IV) measured in procrustean residuals.

favorable for epigean soil animals and become foci of their development. As a consequence, a broad-scale spatial pattern is formed. The effect of variation of soil properties in the top horizon is closely correlated with the vegetation cover, which suggests the presence of a phytogenic component as a factor in the variability of soil properties. The phytogenic factor can explain the presence of a medium-scale component in the spatial pattern [67]. The vegetation cover modifies the microclimatic regime of the ecosystem, is a source of dead plant residues that fall to the surface or directly into the soil profile [68]. The soil animals respond to these processes, resulting in the formation of individual patterns of organization of the soil macrofauna community.

The variation of soil properties in the soil profile causes a separate spatial pattern of soil macrofauna, as well as a pattern that is induced by the joint influence of soil properties and vegetation. The peculiarities of the spatial pattern of soil-forming parent materials can be the cause of variation in soil properties throughout the profile [69]. The endodynamic soil-forming processes that encompass the soil profile as a whole also shape the living conditions of soil animals, which causes the structuring of their community. The plants are also important in the variability of soil properties [70]. The hierarchical organization of variation of soil properties in the profile is represented by broad-, medium-, and fine-scale components. The broad-scale component can be explained by the topography and mosaic nature of the soil-forming material. The medium-scale component can be explained by the vegetation factor. The fine-scale component can be induced by endogenetic processes of soil formation.

The medium-scale component is the most important for explaining the influence of vegetation on soil macrofauna. The presence of a "negative" explained variance of vegetation should also be noted. An additional explained variance of the soil macrofauna community, which is the cause of the "negative explained variation," occurs when the influence of vegetation is extracted. The estimation without vegetation extraction provides misinformation, or false information about the absence of plant influence at some spatial levels, as a consequence of which the explained variance is smaller than after extraction of vegetation influence. We can assume that a competing source of information is superimposed on the overall spatial pattern, which is significantly inferior in power to the dominant pattern, but can be established after filtering. The mechanism of the competing influence is the endogenetic dynamics of the vegetation cover, which superimposes its own pattern on the processes caused by soil heterogeneity. Remarkable is that the "negative" dispersion is also observed in the detailed-scale processes in the soil profile, which we also interpreted as endogenetic.

The pure spatial component of macrofauna community variation can be a consequence of the influence of unmeasured environmental factors, or be of a neutral nature [13]. The hypothesis that the purely spatial component is a neutral factor is valid only when all important environmental variables are taken into account. Otherwise, the unknown fraction of the purely spatial component may be represented by unmeasured environmental variables [18, 71]. The pure spatial pattern has three scale components. The broad-scale component may be a consequence of topographic heterogeneity of the studied polygon, which was not directly measured. In the floodplain, the topography has a wave-like character with frequency characteristics that are quite consistent with the large-scale component of the pure spatial pattern [72]. The medium-scale component can be induced by unmeasured vegetation indices. The phytoindicative assessments of environmental factors reflect changes in vegetation structure, but do not fully characterize them [31, 73]. The fraction of vegetation variability that also affects soil animals may be independent of environmental gradients or environmental scales may not always be sensitive to such gradients. The medium-scale component of pure spatial variability may be due to the vegetation variability that cannot be fully characterized by phytoindicator scales [73]. The fine-scale component represents the variability of the soil macrofauna community, which is related to factors of a neutral nature. An important component of the soil macrofauna community is represented by insect larvae. At the place of egg laying, larvae aggregation can be observed, which is caused by factors of a neutral nature rather than particularly favorable habitat conditions. The soil larvae, especially C-shaped larvae, have low migratory capacity, so such aggregations may persist in the soil for a long period of time. The small dispersal radii of larvae in soil are the reason why the corresponding spatial patterns are fine-scale.

6. Conclusion

The community of soil macrofauna of floodplain forest is spatially structured. The factors of spatial organization are soil properties, influence of vegetation cover and pure spatial component of variability. The influence of factors of different nature manifests itself at different scale levels. The soil factors form large-scale patterns, the vegetation factors form medium-scale patterns, the factors of neutral nature form fine-scale patterns. The soil animals are important factors in the formation of the spatial structure of the soil cover and, by a positive feedback mechanism, can form conditions that contribute to the growth of populations and the functional activity of macrofauna.

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To cite this article: J I Chernichko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012065

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012065 doi:10.1088/1755-1315/1049/1/012065

Possible impact of different scenarios of climate change on the formation of some ecosystem services in the Azov-Black Sea region

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Abstract. To estimate possible changes for some economical branches in South Ukraine which use the nature resources, three scenarios of climate changes were reviewed: increase of temperature and increase of precipitation; increase of temperature and decrease of precipitation; decrease of temperature and increase of precipitation. Impact on the Azov Sea ecosystems under these three scenarios was considered in respect of changes in salinity and temperature of water that consequently effects on ichthyofauna and fish industry. Trends of fish suffocation are also described. Agricultural risks induced by pests (on an example of the locust) under extreme high temperatures in a spring-summer season were discussed, with identification of possible distribution sites of the pest. The research carried out in the framework of the project "Building Capacity for a Black Sea Catchment Observation and Assessment System supporting Sustainable Development" (2009-2013) of the 7^{th} Framework Programme

1. Introduction

As a rule, the researchers now understand ecosystem services as the quite wide range of the forms of the use of the functions of ecosystem, based on the need of the society to use the natural resources in the sparing mode which will not lead the natural processes and the individual ecosystems to depletion [1–4]. Biodiversity has been and remains as one of the most difficult service which is amenable to research and forecasting. At the same time, the climatic changes influence on significantly both biodiversity as a whole, its individual components, and the welfare (well-being) of the person, which he receives on the basis of biodiversity [5, 6]. And if the influence of the climatic changes directly on the individual aspects of diversity is in the focus of the scientific research today [7–9], so the assessment of the influence of such changes on ecosystem services in the Ukraine has been studied weakly yet.

On this background, realizing the need to move forward on the path to the solution of the actual problems of management of natural, semi-natural and artificial ecosystems, there have been arisen the views which the authors have tried to express in the article. Dialectically, these views are not new, and they suggest gradually moving from the particular to the general, including the individual ecosystems or their composite biota in the research cycle, on the example of which it can be traced the possible qualitative and quantitative changes reliably that reflect on the socio-economic consequences of the exploitation of bio-resources of these ecosystems inevitably.

We have been made the attempt to present such consequences on the example of ecosystems and the individual elements of biota, which are significantly separated from each other at first sight, which have been the most studied, and the consequences of the exploitation of these resources can change the accents of ecosystem services. To such ecosystems, the use of resources by human "lies on the surface" and forms the significant services for the economy, we have attributed the ecosystem of the Sea of Azov with its historically established fish resources, the ecosystem of the Delta of the Danube, where renewable storage of building reed has become the important branch of the economy, the zonal steppe ecosystems and their surrogate derivatives such as agroecosystems that will change inevitably under the influence of the different scenarios of the impact of climate. The presented results of the research will help people who make decision in the questions of the use of nature during the formation of the strategy of the sustainable development of the region.

It should be noticed, the importance of finding solutions for the management of individual ecosystems requires an understanding of trends in the climate change and the transformation in the biocenoses structure.

Previous studies [10–12], which were focused on finding management solutions did not always take into account these aspects and could not become effective tools for ecosystem restoration. Also, in many similar solutions the impact of climate was considered quite generally and used stereotypical statements about the negative effects of climate change.

In this paper, we aimed to demonstrate various aspects of climate impact in a fairly wide region at the individual components level of ecosystems.

2. Material and methods

This work uses series of monitoring observations for the period 2009 – 2012. In addition, we studied available retrospective data on the Azov Sea ecosystem and changes in this sea ichthyocoenoses, as well as the data on the Danube Delta intrazonal ecosystem and production of its key species – the reed *Phragmites australis* which forms the delta landscapes. Geobotanical survey was performed in 42010 – 2011 on monitoring plots in zonal (steppe) and intrazonal (meadow) vegetation communities of the Azov Sea Region; preliminary predictions for these communities were made. For some ecotone ecosystems of the Azov Sea Region there was developed a prognostic scenario on dynamics of an agricultural pest, the locust (*Locusta migratoria L., Acrididae, Orthoptera*).

Analysis of changes in the Azov Sea ecosystems is based on main trends of hydrometeorological conditions, taken from specialized sources [13], and information of the National Climatic Data Center (NCDC) [14].

Authors are grateful for the long-term data on the amount and localization of fish suffocation phenomena kindly provided by the Ichthyologic Service of the Azov Basin Department for the Protection, Use and Reproduction of Water Bioresources and Fishery Management ('Azovrybokhrana').

Dynamics of reed communities in the Danube Delta was studied from 1998 to 2011 by common methods of geobotanic survey, along census routes, in permanent and half-permanent plots [15–17]. A method of test and control was used to reveal impact of the winter reed harvest on the vegetation condition. Transects for the survey were made from outer edge of the island to the inner part, each 500 m along the perimeter, with GIS coordinates affixment, and control mowing of vegetation in 1 m^2 in areas with different ecological conditions of growth (constant underflooding, prolonged or periodical underflooding or no underflooding).

Morphometrical parameters of the reed were studied in testing and control areas, and in areas of commercial harvest. For the all observation period over 700 descriptions of vegetation were made, 475 survey mowing on 1 m^2 were cut, over 2500 plants and more than 8500 morphometrical parameters were measured, among them the total vegetation mass from 1 m^2 (including the reed mass, number of reed stalks, their height and diameter, number of flowering and pest-damaged plants, etc.)

Steppe and meadow communities were monitored in $2010 - 2011$, from the third decade of June to the third decade of October in control plots of the North Azov Region. Phytomass of communities were measured in 213 sample plots (each 30 to 100 m^2) in zonal steppe communities, and in 45 sample plots in intrazonal meadow communities. Description of areas was given according to standard geobotanic methods [17, 18]. Exposition and steepness of slopes, general microrelief, types of soil and their characteristics were fixed. Qualitative ratio of species in plots was determined by 5-point Braun-Blanquet cover-abundance scale. Phytomass of meadow biotopes was evaluated by mowings of vegetation within $1m^2$ plots. The mown phytomass was weighted by electronic scale with 1 g accuracy.

The abundance of the locust *Locusta migratoria L.* (*Acrididae, Orthoptera*) was estimated by census routes method (44 censuses in $2010 - 2012$), in 3 permanent plots located in the North Azov Region. The calculations used a relative abundance per 1 km of the route. Larvae and swarms were estimated as number of individuals per 1 m^2.

In literature, there are no unequivocal views about scenarios of climatic changes. In various geographic areas these changes manifest themselves differently. In addition, they are amplified by human interference and nature management. The analysis of hydrometeorological data in the Azov Sea Basin gives a possibility to determine several, the most probable for the region, scenarios of climate changes:

(i) increase of temperature and increase of precipitation;
(ii) increase of temperature and decrease of precipitation;
(iii) decrease of temperature and increase of precipitation.

3. Results and discussion

Azov Sea ecosystems. Main trends of climate changes for the Azov Sea ecosystem are the following:

(i) Increase of average annual air temperature at the sea coastal meteostations for the last 30 years by $0.42 - 0.55$°C per each 10 years;
(ii) Increase of average annual water temperature by 1 °C for the last 50 years;
(iii) Decrease of salinity for the southern coast by $2.28g/l$, and for the northern coast – $2.67g/l$ for the last 30 years.
(iv) Sea level rise with the average rate of 2.11 $cm/year$

These changes of basic parameters have provoked a succession dynamics of main hydrobiological indices of the ecosystem.

Increase of precipitation and, correspondingly, the volume of river drainage is a major determinant of salinity. It influences on fish productivity, forming the food base in the former decades, increase of salinity in the Sea of Azov brought about the appearance of the comb jellyfish *Mnemiopsis leidyi* which greatly undermined zooplankton biomass and affected productivity of most short-cycle fish species European anchovy (*Engraulis encrasicolus*) and Azov Sea sprat (*Clupeonella cultriventris*).

For the Sea of Azov, we can forecast the changes of fish communities and general indices of fish productivity according to three above-mentioned scenarios. These scenarios can have a noticeable impact on socio-demographical situation in the region.

1^{st} scenario will lead to decrease of salinity due to increased drainage of the rivers. This scenario is the closest to present conditions. Increase of air temperature will bring about increase of water temperature. As it was mentioned above, this trend will lead to further desalinization of the Azov Sea. Currently, the sea salinity is 10.2 g/l which is typical for a natural (before the construction of Tsymlyansky Hydrocomplex) condition of the sea.

Further decrease of salinity up to $9.5 - 10$ g/l will not lead to any considerable changes in ichthyofauna structure. The European anchovy and Azov Sea sprat will remain to be dominating commercial species and current trend of their number growth will continue. The increase of stocks of these fish species will assist to improvement of socio-demographic situation in the industry. The increase of their catch will promote the growth of work places in extractive and processing fish industries. An important element of the development of fish extraction enterprises will be a possibility to catch fish using a fixed net in coastal waters without special vessels and trawls. It can assist to the development of small business in the coastal villages.

Decrease of salinity lower than 9 g/l will be critical for the Azov Sea ecosystem because under these conditions a majority of Ponto-Caspian species cannot live. In this case it is possible essential changes in the structure of communities negative for fish productivity and fish industry on the whole.

Increase of temperature to some degree will compensate the considerable freshening of the sea at the expense of evaporation from water surface. Especially strong evaporation may be observed in mouth zones of Molochny Liman and Sivash. Intensively evaporating, these water bodies will bring a great part of salts into salt balance of the sea.

An important consequence of increase of temperature will be increase of the frequency and area of suffocation phenomena. The combination of high summer temperatures and the calm lead to stratification of water and rapid decrease of the oxygen dissolved in lower water layers. The oxygen reduction lower than 3 mg/l results in mass mortality of bottom fish species – mostly gobies in present conditions (round goby *Neogobius melanostomus*, bullhead *Neogobius fluviatilis*, goad goby *Neogobius fluviatilis*, Syrman goby *Neogobius syrman*, etc.) (figure 2).

Analyzing the long-term hydrometeorological data [13], increasing frequency of high temperatures with windless conditions combination leads to water stratification and a critical decrease in dissolved oxygen. Linear trends of average monthly wind speed values calculated for the period $1945 - 2006$ made it possible to identify significant trends in wind speed decrease in all seasons of the year for most points on the coast of the Sea of Azov. On the northern coast of the Sea of Azov, there are statistically significant negative linear trends (with values from -0.16 to -0.33 m/s over 10 years).

Also noteworthy is the warming of the surface water layer in the summer season, mainly in August. The highest significant coefficients of linear trends ($0.051 - 0.087$ $^{\circ}C/year$) have been identified over the past 30 years on the entire sea coast [13]. In recent years ($1986, 1992, 2001, 2007, 2008$), the water temperature in August is significantly higher than long-term climatic values, and the entire sea area is occupied by strongly heated waters with a temperature of $27 - 28.5^{\circ}C$.

As for the socio-economical situation in the region, acceleration of such phenomena will lead to the following negative consequences: decline in fish stocks of bottom fish species; decrease of profitability of fish industry because of worsening of the production, e.g. even alive gobies captured in pre-suffocation period are lower in price; worsening of aesthetical and recreational potential because of mass discard of dead fish at beaches of the region.

Official data of the Azov Special Fish Protection Service show a trend of increase for the duration of suffocation phenomena and the volume of dead fish (figure 2).

Figure 1. Gobies on the Berdyansk beaches (photo http://www.brd24.com).

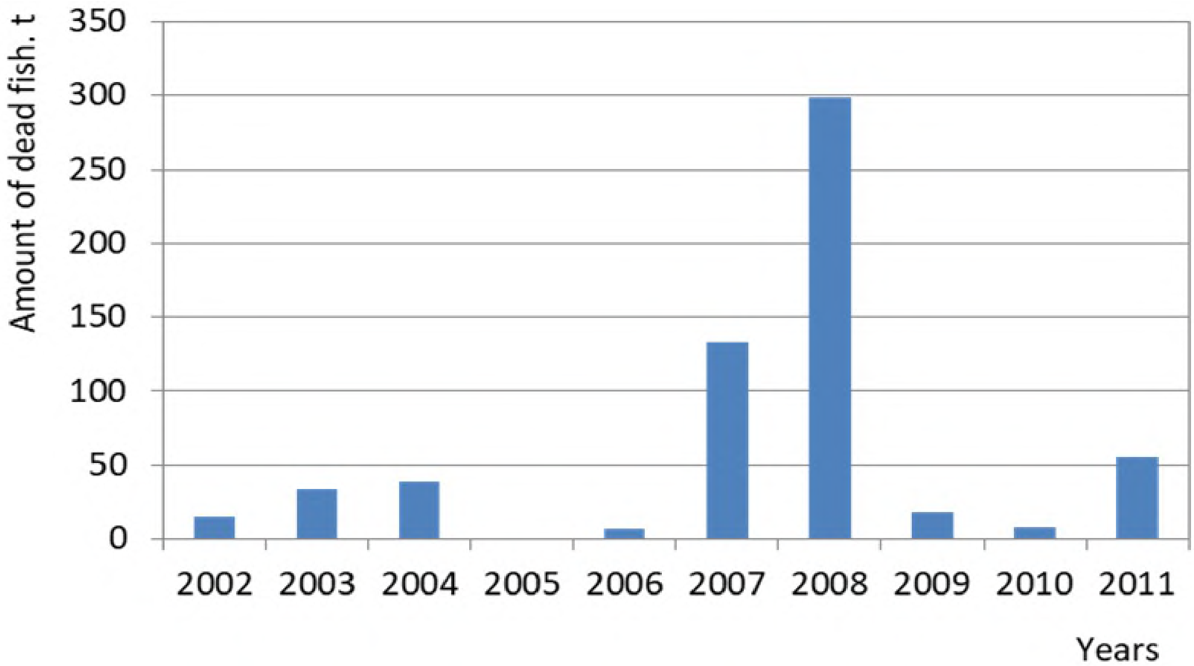

Figure 2. Summarized annual length of fish suffocation strip in the Sea of Azov during 2002-2011.

2^{nd} scenario (increase of temperature and decrease of precipitation) will lead to increase of salinity due to increase of evaporation from water surface. This condition of the sea already was in the period of $1960-1980s$. The only difference of that period was that the reduction of river drainage had anthropogenic reasons. In that period the sea salinity reached 14 g/l which is again possible in case of decrease of precipitation and increase of temperature in the region. In this situation a negative role of the jelly-like organisms in formation of food zooplankton will grow which will further result in reduction of stocks of the anchovy and Azov Sea sprat. In these conditions number of jobs in fish-extracting and fish-processing industries will considerably reduce because of decrease in fish catches. An alternative commercial species may be the so-iuy mullet (*Liza haematocheilus*) (it is an euryhaline species and in case of increasing salinity its number may grow). However, it should be noted that the number of work places connected with the so-iuy mullet catching is fewer than in case of catching and processing of the anchovy and Azov Sea sprat. That is why this scenario will apparently bring about the tension in fish industry of the region.

3^d scenario will lead to decrease of salinity and air temperature. It will be similar to the first scenario, with salinity as a main factor.

In the last decade main commercial groups of fish species have been already changed. Thus, to-date valuable sturgeon species (*Acipenseridae*) are lost, the pike-perch (*Sander lucioperca*), the turbot (*Psetta torosa*) and many freshwater species. At the same time, decrease of salinity and reduction of jelly-like organisms lead to increasing stocks of the European anchovy and Azov Sea sprat and positive trend of the round goby [19].

Intrazonal ecosystems of the Danube Delta. The reed harvest in the Ukrainian Danube Delta is one of the important economical branches of the region since it is harvested in winter when a part of the local people is unemployed, and this type of activity acquires a crucial importance.

Observation of the reed condition in $2011-2012$ allows to make a careful prognosis for the development of this type of activity. In 2011 and 2012 the flood in the Danube Delta was so low that water could not reach inner parts of islands and *plavni* ecosystems stayed almost all time without water. Only Stensovko-Zhebriyansky Plavni were inundated during all the vegetation period. This fact influenced the reed development and its general productivity. This factor was also added by other climate features of the year 2012. A prolonged winter 2011/2012 with quite low temperatures resulted in mortality of the wintering reed buds and delay of vegetation phase. The long cold winter and short spring were followed by the hot summer with occasional rains. The vegetation phase delayed $2-3$ weeks compared to average annual terms, and the phase of reed's flowers formation started in mid August. Over the whole territory of the Danube Delta the reed came into a flowering phase being much lower in height that that of all the preceding years. Changes touched also such indices as the reed diameter and density per 1 $sq.m.$

All of it affected the reed productivity in the whole territory of the Danube Delta. In August-September 2011 fires destroyed thousands of ha of *plavni* vegetation on a considerable part of delta islands. On these territories the reed development started already in $2-3$ weeks after the fire. By the early December 2011 the reed had grown only to $0.3-0.5$ m. There was no formation of young wintering buds in these territories so the reed parameters in the sites of summer fires of 2011 were even worse that in those where there had been no fires or they had been in winter.

Over the all territory, vegetation of the reed in 2012 came out from deeper buds of roots that reflected in the number of stalks, their height and diameter.

Climate changes will have an essential impact on the success of reed harvest. The observed rise of Black Sea level and increased frequency of wind-driven water level fluctuations may result in increase of water level in the secondary delta of Kilia Branch of the Danube Delta, reduction of the reedbeds surface area and increase of cattail-reed associations.

Trend of decrease of flood water level in the Danube will lead to expansion of saline meadow and marshy-meadow communities on high ridges, with low percentage of the reed.

In case of hot summer also the increase of fires frequency is expected. It will lead to changes in vegetation and formation of a marshy-meadow communities This process of meadow formation in plavni is already observed on considerable areas of the Kilia Delta. The fires will change the cell membrane structure of the reed due to accumulation of ash constituents in soil which make parenchyma thinner, and the stalk more fragile. The latter will substantially reduce its commercial value.

Increase of summer temperature even by $1.5 - 2.0°C$ will bring about the shifts in timing of the reed development, especially transition into a winter phase. During $2009 - 2012$, especially in winter 2011, the phase of leaf fall was practically absent and this substantially disrupted the terms of starting the reed harvest. It started only in early December, and the work was more expensive because of additional costs connected with cleansing the stalks from leaves when sorting and packing the reed for export.

As for positive trends in reed communities in terms of the reed harvest it is only the increase of the ecosystem mineralization due to the rise of the Black Sea level. The reed, growing in brackish areas, ripens more quickly and its stalks are stronger and adherent which increase its commercial value.

Taking all the above-mentioned into account we can make the following conclusions according to influence of climate changes on socio-economical conditions of residents of the region in connection with the reed harvest. Not stable qualitative characteristics of the reed require for a manual labour when sorting out the stalks. Therefore, the use of woman's work and especially elderly people will grow. Increase in the demand for manual labour will result in prolongation of the working period for almost the whole year.

Shortening of the harvest period directly in plavni as a result of delaying leaf fall and considerable fluctuation of water level will lead to survival of only powerful harvesting companies which will be equipped with "Seiga" combines. Increase of a portion of the cattail-reed communities will result in a new activity of local people - winter cattail harvest of the which is already appearing at the labour-market.

4. Changes in some zonal and intrazonal ecosystems of the azov sea region

Accoding to the results of the monitoring in the North Azov Region in $2010 - 2011$, we have noticed a meadowfication trend of steppe communities due to increase of phytocoenotic role of *Elytrigia repens, Cynodon dactylon* (on dark- and light-chestnut low fertile soils). In addition, retrospective data for the period $1952 - 2011$ show a clear phytomass increasing trend for steppe communities with the dominance of *Stipa capillata*. Phytomass growth is a direct consequence of increasing amount of precipitation and air temperature. If this trend of increasing precipitation and air temperature continues it may lead to meadowfication of southern steppes.

Meadow vegetation communities take an insignificant portion within the studied section of the coast, and changes in their structure cannot cause any serious economic effects. Though, at the local level, changes of the meadow communities productivity can have a substantially effect on productivity of pastures and hayfields. Thus, for two years of observation $(2010 - 2011)$ phytomass of meadow communities with the dominance *Elytrigia repens* in monitoring areas had a positive trend: from 4.2 to 22.0%.

In case of the 1^{st} scenario (increase of air temperature and decrease of precipitation) the productivity of *Puccinellia gigantea* meadows can reduce $2 - 3$ times. Respectively, number of grazing cattle or volume of haymaking will be also $2-3$ times reduced. With average productivity of these communities as $40 - 50$ kg/ha of green mass and market price of hay in the region as $1\ UAH$, loss because of lack of forage (for a single mowing) would be equal from 500 to 520 thou. a year (e.g. monitoring plot at the right coast of Molochnyi Liman). In meadow communities of

Elytrigia repens the productivity can drop $6-7$ times, and the loss will be about $80,000 UAH$.

In case of the 2^{nd} scenario (increase of air temperature and increase of precipitation) the productivity of meadow coenoses can rise by $20-30\%$. In this case the overall commercial volume of hay can increase to from 600 to $750-800$ thou. UAH/year (total for monitoring plots of Molochnyi Liman and Syvashik Bay).

At the present time, a major profitable type of activity in steppe areas is the cattle raising.

In case of the above-mentioned 1^{st} scenario (increase of air temperature and decrease of precipitation) and dominating processes of desertification, the productivity of steppe areas can reduce $4-7$ times in feather grass-fescue and fescue-feather grass communities. Respectively, heads of grazing cattle or volume of haymaking will be also $4-7$ times reduced. With average productivity of feather grass-fescue and fescue-feather grass communities as $200-300$ kg/ha of green mass and market price of hay in the region as 1 UAH, loss because of lack of forage (for a single mowing) would be equal from 450 to 550 *thou.* a year (control plot "Novopetrovsky") and $850-950$ thou./year for the Sivash monitoring area.

These consequences will be especially dramatic in Sivash Region where the hay-making is a major kind of use of vegetation resources. According to our observations the mowing takes place two times a vegetation season (May-June and the second half of August). In this case, we cannot exclude a possibility of steppe areas to be ploughed up as an alternative for haymaking or transition to sheep grazing which can successfully feed on low productive pastures. The sheep grazing will be even more destructive than ploughing and will greatly accelerate desertification.

Reducing productivity of steppe areas will probably be compensated by up-to-date techniques of the crop-growing including green forage crops (lucerne, esparcet, etc.). For Novopetrovsky area one of the solutions can be allocation of low productive steppe areas for building country cottages and recreation facilities.

In case of the 2^{nd} scenario (increase of air temperature and increase of precipitation) and dominating processes of meadowfication, the productivity of feather grass-fescue and fescue-feather grass communities can rise nearly 2 times due to their transformation in couch grass beds and reach to $5600-5800$ kg/ha. Respectively, heads of grazing cattle or volume of haymaking will become also 2 times greater. In this case the overall commercial volume of hay can rise to 1300 *thou.* UAH/year (control plot "Novopetrovsky") and to 2000 *thou.* UAH/year for the Sivash monitoring area.

5. Insects of ecotone systems

The situation in the Azov-Black Sea Region, observed in $2010-2012$, are connected with extreme high temperatures in the spring-summer period, and except for direct increase of air temperature and drought of soil, it leads to the considerable reduction of the watering area of near-water habitats and creates very favourable conditions for transformation of the locust (*Locusta migratoria L.*) in the gregarious (invasion) form. This situation is worsened with embankment and regulation of most rivers flowing into the limans of the Azov and Black Seas.

River banks, lake shores and sea coasts with reed and sedge thickets (particularly *Phragmites australis*) are the main habitat for this species. Such sites are often surrounded by the steppes and agrocoenoses which potentially are in the most dangerous situation. Long-term observations show that potentially the most dangerous localities of the locust in Ukraine are the Danube River Delta and lower reaches of the rivers entering into the eastern part of the Azov Sea (figure 3).

The solitary form of the migratory locust prefers wild crops (e.g. the reed and *Elytrigia*). Gregarious forms during the first few days after hatching start to form concentrations ("clouds") which density can reach to $80,000\ larvae/m^2$ for the 1^{st} age and $7,000\ larvae/m^2$ for the 5^d age. These clouds can move for a relatively large distances (marching "clouds"). In case of rare vegetation cover, the clouds of 5^{th} age larvae can cover up to 3 km a day. The gregarious imagoes form swarms circa in 10 days after getting winged. In spite of the single form, the

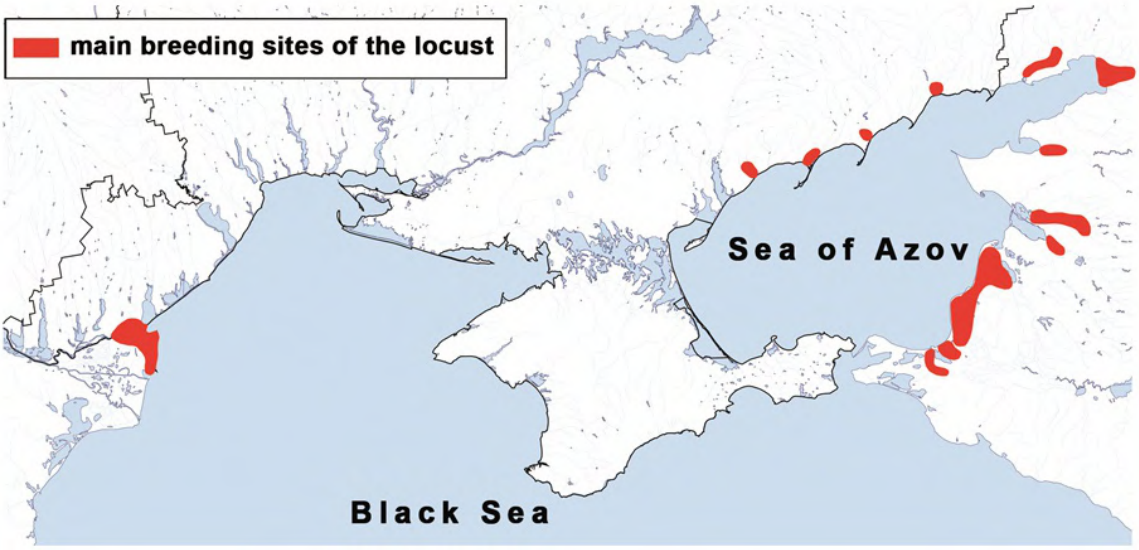

Figure 3. Localities of possible mass reproduction of the locust at the Azov-Black Sea coast.

individuals of the gregarious form can eat plants of many families when they are far from their breeding area or when the preferred forage is lacking i.e. can considerably change their food preferences in almost unlimited range. Every individual of the locust eats 300 to 500 g of green forage during its life including in the diet almost all agricultural crops, fruit trees, hayfields and pastures.

In 2012 the locust invasion has seriously damaged agricultural lands in south regions of the Russian Federation. But appearance of the locust outbursts at the Ukrainian Black Sea coast is only a question of the time. The situation with its harm to agriculture is worsened by imperfection of means of struggle against the locust, above all different pesticides. Implementation of new and high-effective chemical (hormonal) and biological means of struggle which will also entail the rise of financial costs for the harvest protection.

During monitoring of the locust indicator species, the changes in phenology of other species of insects were also recorded. In this respect, the year 2012 was characterized by an unusually early start of a very warm season, and terms of imago emergence for a majority of night Macrolepidoptera were ahead of normal time at least 14 – 16 days. Some representatives of this group demonstrated even more substantial time advance – up to 1.5 months in the light crimson underwing *Catocala promissa* (Noctuidae; Lepidoptera). The early start of a 2012 warm season was added by a prolonged period of the warm and dry weather.

These examples give an additional confirmation that phenological responses include not only a shift of insect development at the start of the season to earlier terms but further changes in phenology. Thus, phenophases, connected with the end of seasonal development, on the contrary, usually shift to later dates. It leads to prolongation of a period of active development, including that for pests, which can provide extremely negative socio-economic effects.

6. Conclusions

(i) The global changes of climate cause the fluctuations of the natural conditions which determine the vital processes and the state of the individual species, grouping, ecosystems. At the same time, all existing scenarios have negative changes and they differ only in the large-scale negative transformations and the terms of the occurrence of the number of threats. Generaly, climate change affects the quality and availability of ecosystem services in the Azov-Black Sea region.

(ii) For the Azov-Black Sea region, the climatic changes lead to changes not only at the level of the transformation of grouping, but also exert influence on the socio-economic conditions of the region. It has been investigated that changes of the salinity of the Sea of Azov, the increase of the water temperatures leads to suffocation phenomenon of resource species of fish and the decrease of the general fish productivity. It should be noted, according the official data during the period $2002-2012$ in the summer there is a tendency to increase both the length of hypoxia phenomena and the volume of dead fish. These changes significantly affect the productivity of commercial fish stocks and threaten to reduce jobs in the region.

(iii) In Delta of the Danube, where as the result of the increase of the summer temperature by $1.5 - 2.0°C$ there is the dislocation of the terms of the development of reed and its transition to the winter phase, which leads to no leaves loss until harvest. Unstable quality characteristics of reeds require manual labor when sorting stems. It leads to the additional costs for the processing of the important building materials, and, accordingly, it affects the profitability of laying-in of reed.

(iv) The amount of precipitation determines the state of meadow grouping in the basins of the small rivers of Pryazovia and can affect significantly the productivity of pastures and hayfields. So, for two years of the observations ($2010 - 2011$) the phytomass of meadow grouping with dominance of Elytrigia repens in the zones of monitoring has had the positive dynamics: from 4.2 to 22.0%. It determines the profitability of stockbreeding in the region and affects significantly the socio-economic development of rural areas.

(v) Extremely high temperatures in spring and summer period, except the direct increase of the temperature of air and soil drought lead to the significant decrease of humidity, which creates the favorable conditions for the transformation of locusts (*Locusta migratoria L.*) in herd (invasive) form. The mass development of this species can affect significantly agriculture of the southern regions of the Ukraine. In general, it should be noted that the different scenarios of the climatic changes affect the quality and availability of ecosystem services in the Azov-Black Sea region.

Acknowledgments

The research carried out in the framework of the project "Building Capacity for a Black Sea Catchment Observation and Assessment System supporting Sustainable Development" of the 7^{th} Framework Programme.

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IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Effect of recreation on the spatial variation of soil physical properties

To cite this article: P M Telyuk *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012066

Effect of recreation on the spatial variation of soil physical properties

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Abstract. Recreation affects various components of ecosystems. A significant transformation occurs in the soil cover in urban parks. The physical properties of soil are sensitive indicators of the level of anthropogenic transformation, and also allow to assess the state of soil as a habitat for plants and soil animals. The question of quantitative patterns of soil properties variability under the influence of recreation is not solved. There is also little information on the spatial aspect of the variability of soil physical properties in urban ecosystems. The aim of our study is to test the hypothesis that the recreational loads cause the formation of spatial patterns of soil properties, which by their extent greatly exceed the zone of direct influence. The spontaneous walkways within an urban park were investigated as an example of recreational loading. The physical soil properties were measured on a regular grid. The distance to the walkway was treated as a proxy variable that indicates recreational load. The application of multivariate statistical methods allowed to reveal the components of the variation of soil properties of different nature. The effect of recreational load is superimposed on the natural variability of properties. The peculiarity of the influence of recreation consists in sharp increase of soil penetration resistance in the upper soil layers and decrease of this index in the lower layers. The recreational load affects the physical properties of the soil. The soil compaction is the main direction of transformation. This effect gradually attenuates with distance from the source of exposure while occupying a significant portion of the space. The variation of soil properties affects the redistribution of soil moisture and soil air, which significantly affects the living conditions of soil biota.

1. Introduction

Park plantations are an important component of the urban environment that perform a wide range of critical ecological functions [1–3]. A significant number of these functions are related to the condition of the soil cover of parks. The recreational load strongly affects the soil [4–6]. The compactness of anthropogenic soils is a consequence of technological procedures [7, 8]. The recreation leads to the development of a network of spontaneous trails. Understanding the effects of human-induced disturbance on ecosystem processes is important for recreational area management [9]. The soil penetration resistance is an informative indicator for monitoring soil compaction [10]. The physical properties of the soil within these paths are significantly altered [8]. Above all, the urban soil is compacted. Human trampling of the soil causes most of the impacts that recreation has on soil and vegetation [11]. All soil components (mineral matter, air, water, dead organic matter and living organisms) are disturbed by trampling [12, 13]. Both short-term and long-term trampling reduced vegetation cover, plant height and species density, although the long-term impact was more pronounced than the short-term impact. Leaf litter biomass decreases and soil density increases with trampling intensity. Other soil characteristics such as soil moisture, total soil organic matter content and total organic nitrogen content were marginally sensitive to short-term or long-term trampling [14]. Most of the dead organic material in soil is concentrated in the upper layers, especially in the surface layer, which usually consists mainly of organic matter [15]. This layer, called the organic horizon, is crucial to soil health as it plays an important role in the biological activity of the soil [16, 17]. The organic horizon also contributes to a good water regime by increasing the absorption capacity of the soil, reducing runoff and increasing moisture retention [18]. Organic horizon is a source of nutrients needed for plant growth and can effectively buffer the underlying mineral soil horizons, which are more vulnerable to compaction [19] and erosion by rainfall [20]. Organic horizons are generally less susceptible to erosion than mineral soil, but if organic matter is crushed by trampling, it can also be eroded, exposing the mineral soil beneath it [21–23]. When trampling compacts the mineral soil, which does not have the physical elasticity of organic matter, the particles are pressed tightly together, dramatically reducing the number of pores between the particles [24–26].

The soil penetration resistance along with other morphological and physical properties is used to diagnose urban soils [4, 27] and is a reliable indicator of recreational load [4, 25]. The soil compaction modifies the soil moisture regime and can inhibit root growth if certain boundary levels are exceeded, resulting in the plant not being able to obtain water or nutrients at depth [28, 29]. The larger pores promote better soil drainage and are usually filled with air can be practically eliminated by trampling [30]. Their elimination can reduce aeration and water availability and make it difficult for plant roots to penetrate the soil. These changes can reduce both the success of germination and the viability of rooted plants and can be detrimental to soil-dwelling organisms [31, 32]. The soil penetration resistance was shown to be an important attribute of the ecological niche of mollusks under land reclamation [29, 33]. Poor root development makes mature trees more susceptible to windthrow [34]. The soil compaction increases the resistance of the soil to plant root growth [35, 36] and impedes the movement of soil animals [37, 38], reduces porosity, which slows water transfer and air diffusion, and decreases the rate of mineralization of nutrients [39]. The loss of soil-dwelling biota can lead to further impacts on soil and vegetation, as these organisms are important contributors to soil structure and play an important role in the nutrient cycle. Compacted soils lose much of their infiltration capacity, resulting in increased surface runoff after rainfall or other precipitation [40]. This runoff often leads to increased soil erosion where the soil has been compacted, on trails, in picnic areas, on lookouts and along riverbanks. However, soil compaction is reversed by biotic and frost processes in the soil [41].

2. Research aim and objectives

The main qualitative aspects of the impact of recreational pressure on soil are known, but the quantitative patterns of spatial variability of soil patterns under the influence of trampling are in need to be studied. The aim of our study is to test the hypothesis that the recreational loads cause the formation of spatial patterns of soil properties, which by their extent greatly exceed the zone of direct influence.

3. Material and methods

The study of the influence of recreational load on the physical properties of soil was carried out in Novooleksandrivskiy Park (Melitopol, Ukraine). Two polygons were set up. The soil penetration resistance and soil moisture measurements were carried out in polygon No. 1 in October 2020 and in April 2021. The measurements in polygon No. 2 were taken in April 2020. Each polygon consisted of a network of 105 sampling points located along 7 transects with 15 sampling points each. Along the transects the sampling points were spaced 3 metres apart. The distance between transects was also 3 meters. The soil moisture in the 0–5 cm layer was measured at each point using a field moisture meter. A hand-held penetrometer was used to measure the soil penetration resistance to a depth of 100 cm at 5 cm intervals (a total of 20 measurements at each point). The soil penetration resistance was measured in the field using the *Eijkelkamp* manual penetrometer, to a depth of 100 cm at 5 cm intervals [8, 42]. The average error of the measurement results of the device is ± 8%. Measurements were made with a cone with a cross section of 1 cm^2. At each measurement point, the soil penetration resistance was performed in only one replication. The location of trees within the polygon and in the 3 meters vicinity was also mapped. The location of spontaneous pathways was mapped. Based on the results, a geographical information database was created in the software ArcGIS (ESRI). Descriptive statistics have been calculated in the software STATISTICA (Statsoft).

4. Results

The polygons 1 and 2 differed in the level of recreational load, which was characterised by the distances from the spontaneous walkways. The distance from the pathways within the polygon 1 was 3.1±0.24 m (maximum distance was 9.4 m). The distance from the pathways within the polygon 2 was 4.1±0.32 m (maximum distance was 14.9 m). The differences were statistically significant (t-value was –3.08, p=0.002). The distance to trees within the polygon 1 was 3.2±0.19 m (maximum distance was 10.0 m). The distance to trees within the polygon 2 was 2.5±0.15 m (maximum distance was 7.6 m). The differences were statistically significant (t-value was 2.28, p = 0.022). There was a statistically significant correlation (r = –0.36, p < 0.001) between distance to pathways and trees.

The soil moisture within the polygon No. 1 in October 2020 was 15.53±0.1% and was in the range of 12.8–18.50% in 95% of the cases (table 1). The distribution of this parameter was symmetrical and without kurtosis. The soil penetration resistance was the lowest at the depth of 0–5 cm, where it was 3.01±0.08 MPa. With increasing soil depth this index increased sharply up to the depth of 35–40 cm, where the soil penetration resistance reached its maximum of 8.66±0.08 MPa. With further increase in depth the soil penetration resistance decreased slightly and reached a plateau. The asymmetry of distribution was positive in soil layers 0–20 cm, while in deeper layers the asymmetry was negative. This indicates that the distribution of the soil penetration resistance in the upper soil layers was shifted to the left, so that the median was less than the mean value of the index. In deeper soil layers the distribution was shifted to the right, so the median was greater than the mean. The kurtosis was statistically significantly different from the random alternative in layers 5–25 cm. The kurtosis indicated that values close to the modal were more frequent than the random distribution would suggest.

The soil moisture within the polygon No. 1 in April 2021 was 24.19±0.32% and was in the range of 18.0–32.0% in 95% of cases (table 2). The distribution of this index was symmetrical and without kurtosis. The soil penetration resistance was the lowest at the depth of 0–5 cm, where it was 1.44±0.04 MPa. With increasing depth, this index increased sharply up to a depth of 95–100 cm, where the soil penetration resistance reached its maximum of 3.75±0.06 MPa. The local maxima of the soil penetration resistance were at depths of 15–25 and 75–80 cm. The asymmetry maximum was found at a depth of 25–30 cm, which indicated a shift of asymmetry to the left. This feature explains why the median of the soil penetration resistance in this soil layer was smaller than the mean value. The distribution of the soil penetration resistance in the profile either had no kurtosis or the kurtosis was negative, indicating that the observed values tended towards the modal level. The distribution was bimodal at a depth of 25–30 cm.

The soil moisture within the polygon No. 2 in April 2021 was 26.44±0.26% and was in the range of 22.0–32.1% in 95% of cases (table 3). The distribution of this index was symmetrical and without kurtosis. The moisture content in the polygon No. 1 was lower than in polygon

Table 1. Descriptive statistics of soil moisture and penetration resistance variability at different depths within polygon 1 (2020, October) ($N = 105$).

Soil layer, cm	Mean±st.error	Median	Percentile		Skewness±st.error	Kurtosis±st.error
			2.5%	97.5%		
Soil moisture, %						
0–5	15.53±0.11	15.60	12.80	18.50	–0.02±0.22	0.69±0.43
Soil penetration resistance, MPa						
0–5	3.01±0.08	2.80	1.80	5.20	0.89±0.22	0.02±0.43
5–10	4.73±0.12	4.47	2.80	7.50	0.66±0.22	–0.49±0.43
10–15	6.09±0.14	6 .00	3.60	9.15	0.39±0.22	–0.67±0.43
15–20	6.95±0.13	6.80	4.60	9.70	0.18±0.22	–0.92±0.43
20–25	7.63±0.12	8.00	5.00	9.80	–0.37±0.22	–0.76±0.43
25–30	8.19±0.11	8.36	6.00	9.80	–0.60±0.22	–0.34±0.43
30–35	8.35±0.08	8.42	6.00	9.78	–0.62±0.22	0.03±0.43
35–40	8.66±0.08	8.73	6.55	10.27	–0.62±0.22	0.34±0.43
40–45	8.48±0.09	8.62	6.20	9.83	–0.76±0.22	0.01±0.43
45–50	8.17±0.09	8.29	6.00	9.40	–0.76±0.22	0.05±0.43
50–55	7.95±0.05	8.05	6.66	8.75	–0.70±0.22	–0.17±0.43
55–60	7.96±0.05	8.06	6.66	8.80	–0.56±0.22	–0.45±0.43
60–65	7.96±0.05	8.08	6.86	8.77	–0.55±0.22	–0.49±0.43
65–70	7.96±0.05	8.06	6.78	8.81	–0.60±0.22	–0.35±0.43
70–75	7.96±0.05	8.07	6.76	8.71	–0.61±0.22	–0.22±0.43
75–80	7.96±0.05	8.10	6.72	8.71	–0.69±0.22	–0.18±0.43
80–85	7.96±0.05	8.09	6.67	8.71	–0.66±0.22	–0.11±0.43
85–90	7.97±0.05	8.10	6.62	8.70	–0.68±0.22	–0.12±0.43
90–95	7.95±0.05	8.07	6.73	8.67	–0.74±0.22	0.12±0.43
95–100	7.95±0.05	8.07	6.75	8.68	–0.73±0.22	0.12±0.43

No. 2 ($t = 6.61$, $p < 0.001$). The soil penetration resistance was lowest at a depth of 0–5 cm, where it had a value of 1.18±0.03 MPa. With increasing depth, this index increased sharply up to a depth of 95–100 cm, where the soil penetration resistance reached its maximum of 4.54±0.07 MPa. The local maximums of the soil penetration resistance were at depths of 15–25 and 75–80 cm. A general decreasing trend along the profile was detected for the asymmetry index. The highest level of asymmetry was found for the upper soil layers 0–25 cm, indicating a leftward shift in distribution. The two local minima of soil penetration resistance were found: at a depth of 30–35 and 80–90 cm. At these depths the asymmetry was not statistically significantly different from zero, indicating a symmetrical distribution. The kurtosis also had a decreasing trend with depth. The local minimum of kurtosis was at a depth of 55–90 cm, indicating the bimodal nature of the distribution.

The soil penetration resistance was greater the lower the soil moisture content (figure 1). After log-transformation the dependence had a linear character.

A General Linear Model with moisture and distance from walkways and trees as predictors was able to explain 74–94% of the variation in the soil penetration resistance (Table 1). The regression coefficients indicated that the soil penetration resistance decreased with increasing moisture content. The dependence of the soil penetration resistance on the distance to the walkways and trees was non-linear and statistically significantly described by a second-degree

Table 2. Descriptive statistics of soil moisture and penetration resistance variability at different depths within polygon 1 (2021, April) (N = 105).

Soil layer, cm	Mean±st.error	Median	Percentile 2.5%	Percentile 97.5%	Skewness±st.error	Kurtosis±st.error
Soil moisture, %						
0–5	24.19±0.32	24.00	18.00	32.00	0.21±0.24	0.06±0.47
Soil penetration resistance, MPa						
0–5	1.44±0.04	1.50	0.75	2.45	0.21±0.24	–0.76±0.47
5–10	1.87±0.05	1.90	0.90	2.90	0.00±0.24	–0.50±0.47
10–15	2.23±0.06	2.20	1.00	3.50	0.28±0.24	–0.65±0.47
15–20	2.54±0.08	2.50	1.20	4.10	0.14±0.24	0.07±0.47
20–25	2.56±0.05	2.50	1.70	3.67	0.27±0.24	–0.61±0.47
25–30	2.59±0.06	2.50	1.65	4.30	0.74±0.24	0.85±0.47
30–35	2.70±0.06	2.70	1.60	4.00	0.18±0.24	–0.36±0.47
35–40	2.80±0.06	2.77	1.70	4.00	0.06±0.24	–0.61±0.47
40–45	2.91±0.06	2.90	1.90	4.10	0.26±0.24	–0.62±0.47
45–50	3.05±0.06	3.00	2.00	4.40	0.33±0.24	–0.40±0.47
50–55	3.28±0.07	3.10	2.25	4.53	0.16±0.24	–0.78±0.47
55–60	3.39±0.07	3.30	2.20	4.50	0.18±0.24	–0.85±0.47
60–65	3.50±0.07	3.40	2.30	4.80	0.24±0.24	–0.61±0.47
65–70	3.54±0.07	3.60	2.30	5.00	0.22±0.24	–0.49±0.47
70–75	3.54±0.07	3.60	2.30	4.80	0.15±0.24	–0.17±0.47
75–80	3.62±0.07	3.50	2.30	5.00	0.33±0.24	0.18±0.47
80–85	3.70±0.07	3.70	2.00	5.15	0.10±0.24	0.09±0.47
85–90	3.69±0.08	3.60	2.30	5.30	0.25±0.24	–0.52±0.47
90–95	3.75±0.06	3.70	2.60	5.00	0.19±0.24	–0.20±0.47
95–100	3.75±0.06	3.70	2.60	5.00	0.16±0.24	–0.27±0.47

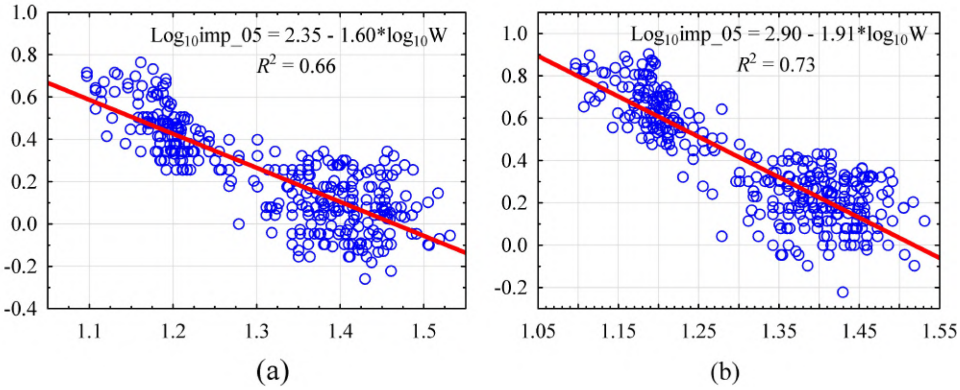

Figure 1. Dependence of soil penetration resistance in 0–5 cm layer (a) and 5–10 cm layer (b) (ordinate axis, MPa, log-transformed data) on soil moisture (abscissa axis, %, log-transformed data).

polynomial. The calculation made it possible to find the distances at which the soil penetration resistance reached a local minimum.

Table 3. Descriptive statistics of soil moisture and penetration resistance variability at different depths within polygon 2 (2021, April) ($N = 105$).

Soil layer, cm	Mean±st.error	Median	Percentile 2.5%	Percentile 97.5%	Skewness±st.error	Kurtosis±st.error
Soil moisture, %						
0–5	26.44±0.26	26.40	22.00	32.10	0.21±0.24	–0.19±0.47
Soil penetration resistance, MPa						
0–5	1.18±0.03	1.15	0.70	2.00	0.79±0.24	0.38±0.47
5–10	1.50±0.04	1.50	0.90	2.50	0.46±0.24	0.04±0.47
10–15	1.88±0.05	1.90	1.10	2.80	0.38±0.24	–0.60±0.47
15–20	2.31±0.06	2.20	1.40	4.00	0.71±0.24	0.70±0.47
20–25	2.68±0.05	2.64	1.70	3.90	0.29±0.24	–0.03±0.47
25–30	2.80±0.06	2.70	1.62	4.00	0.17±0.24	–0.22±0.47
30–35	2.80±0.06	2.90	1.50	3.93	–0.11±0.24	–0.25±0.47
35–40	2.86±0.06	2.90	1.70	4.10	0.01±0.24	–0.41±0.47
40–45	3.03±0.06	3.00	1.90	4.50	0.51±0.24	0.43±0.47
45–50	3.18±0.07	3.10	2.10	5.10	0.55±0.24	–0.29±0.47
50–55	3.46±0.08	3.40	2.00	5.20	0.43±0.24	–0.28±0.47
55–60	3.68±0.09	3.60	2.00	5.31	0.21±0.24	–0.77±0.47
60–65	3.73±0.09	3.57	2.10	5.41	0.38±0.24	–0.78±0.47
65–70	3.88±0.09	3.70	2.40	5.63	0.27±0.24	–0.77±0.47
70–75	4.03±0.09	3.80	2.50	5.63	0.33±0.24	–1.03±0.47
75–80	4.19±0.09	4.00	2.50	5.86	0.12±0.24	–1.02±0.47
80–85	4.37±0.09	4.20	2.50	5.98	–0.02±0.24	–0.73±0.47
85–90	4.44±0.10	4.30	2.60	6.09	–0.03±0.24	–0.95±0.47
90–95	4.54±0.07	4.49	3.20	6.09	0.31±0.24	–0.30±0.47
95–100	4.54±0.07	4.49	3.20	6.09	0.34±0.24	–0.31±0.47

The local minimum was observed at a distance of 3.0–3.9 meters from the recreational paths. At depths of 0–5 and 50–55 cm, a significant increase in this index was observed to 4.7 and 5.3 meters respectively.

Thus, an increase in the soil penetration resistance indices was observed both near the recreational paths and at a considerable distance from them. A minimum value of the soil penetration resistance was observed at a distance of 3–5 meters from the recreational paths. A similar pattern was observed with regard to the effect of distance from trees on the soil penetration resistance. The soil penetration resistance was greatest near the trees and at a considerable distance from the trees. A local minimum of the soil penetration resistance was observed at 1.1–7.7 meters. At a depth of 30 to 60 cm a local minimum of the soil penetration resistance was observed at a distance of 6.3–7.8 meters from the trees. At a depth of 60–95 cm a local minimum of the soil penetration resistance was observed at a distance of 1.1–2.2 meters from the trees.

5. Discussion

Soil penetration resistance measured with a cone penetrometer is an important parameter in many soil management studies [43,44]. The level of soil penetration resistance depends on many factors. The penetration resistance is a physical property of soil that depends on soil texture

Table 4. The regression coefficients obtained from GLM analysis of the dependence of the soil penetration resistance on the soil moisture and the distance from the recreational paths and trees. The extreme distances indicate the distance at which there is a minimum value of the soil penetration resistance at the distance from the paths or trees, calculated on the basis of a quadratic model (statistically significant beta regression coefficients for $p < 0.05$ are shown).

Layer	R^2_{adj}	Wetness	$log_2 Trail$	$log_2 Trail^2$	$Log_2 Tree$	$Log_2 Tree^2$	Extremum distance, m	
							Trail	Tree
0–5	0.74	–0.25±0.06	–0.51±0.10	0.38±0.10	–0.97±0.11	0.73±0.11	4.7	4.7
5–10	0.82	–0.15±0.05	–0.51±0.09	0.47±0.09	–0.71±0.09	0.49±0.10	3.5	5.3
10–15	0.85	–0.17±0.05	–0.42±0.08	0.38±0.08	–0.66±0.09	0.47±0.09	3.5	5.1
15–20	0.85	–0.16±0.05	–0.32±0.08	0.28±0.08	–0.43±0.09	0.26±0.09	3.8	6.9
20–25	0.90	–0.15±0.04	–0.29±0.07	0.27±0.07	–0.19±0.07	0.05±0.07	3.4	7.8
25–30	0.92	–0.12±0.04	–0.19±0.06	0.19±0.06	–0.19±0.06	0.08±0.06	3.3	7.5
30–35	0.94	–0.11±0.03	–0.16±0.05	0.15±0.05	–0.17±0.05	0.10±0.05	3.4	7.3
35–40	0.94	–0.08±0.03	–0.12±0.05	0.12±0.05	–0.15±0.05	0.09±0.05	3.0	7.1
40–45	0.93	–0.08±0.03	–0.12±0.06	0.11±0.06	–0.12±0.06	0.08±0.06	3.4	6.3
45–50	0.90	–0.06±0.04	–0.07±0.06	0.06±0.06	–0.10±0.07	0.09±0.07	3.6	3.9
50–55	0.91	–0.06±0.04	–0.04±0.06	0.03±0.06	–0.03±0.07	–0.01±0.07	5.3	2.0
55–60	0.90	–0.12±0.04	–0.08±0.06	0.06±0.06	0.01±0.07	–0.05±0.07	3.9	1.3
60–65	0.90	–0.09±0.04	–0.21±0.06	0.19±0.06	0.03±0.07	–0.08±0.07	3.5	1.5
65–70	0.89	–0.08±0.04	–0.10±0.07	0.10±0.07	0.01±0.07	–0.05±0.07	3.3	1.1
70–75	0.89	–0.08±0.04	–0.11±0.07	0.11±0.07	0.02±0.07	–0.04±0.07	3.4	1.7
75–80	0.88	–0.06±0.04	–0.13±0.07	0.12±0.07	–0.01±0.08	–0.03±0.08	3.5	2.2
80–85	0.87	–0.05±0.04	–0.10±0.07	0.09±0.07	–0.04±0.08	–0.01±0.08	3.5	3.11
85–90	0.86	–0.07±0.05	–0.16±0.08	0.15±0.08	–0.08±0.08	0.04±0.08	3.4	4.1
90–95	0.91	–0.07±0.04	–0.18±0.06	0.17±0.06	–0.15±0.07	0.10±0.07	3.3	5.2
95–100	0.91	–0.08±0.04	–0.17±0.06	0.16±0.06	–0.15±0.07	0.11±0.07	3.4	5.1

and bulk density [45, 46], moisture content [47, 48], porosity and permeability [49], particle size distribution [50], structure, mineral and organic matter content of soil [51, 52], pH, cation-exchange capacity, clay particle thickness, presence of iron oxides and free aluminum hydroxide, which determine the nature of the resulting cohesive forces between soil constituent [53]. Soil penetration resistance is highly dependent on soil type and soil properties such as volumetric water content, soil matrix potential, bulk density, porosity and organic matter content [54]. The temporal and spatial dynamics of the soil moisture content are a significant cause that affects this indicator. To reduce the influence of water content on measured values, the measurement of soil penetration resistance data at soil water content close to field capacity was proposed [55], or to correct data obtained at different water content to a reference soil penetration resistance at field capacity [56–58]. The differences in observed soil penetration resistance values with varying water content and bulk density of different soils were attributed mainly to the influence of soil texture, organic matter and soil water retention curve [44, 50, 59–62]. In spring after snowmelt and relatively low intensity of evaporation of moisture from the soil surface, the soil moisture content is significantly higher than in autumn [33, 63]. The low precipitation in late summer and early spring, which is superimposed on the considerable intensity of moisture evaporation from the soil surface during the warm season, leads to a drastic reduction of its reserves in the soil [13, 64]. These processes explain the differences in soil penetration resistance between spring and autumn, as there is an inverse relationship between the soil moisture content and its penetration resistance. The differences in soil moisture can also be induced by the recreational load. An increase in recreational load leads to an increase in the soil compactness, the consequence of which may be a reduction in the volume of the soil pore space and thus a reduction in the volume available for the storage of water. Also, an increase in compactness leads to an increase in the proportion of small pores, which increases the intensity of capillary uplift of the water and thus contributes to an increase in the rate of evaporation of water from the soil surface.

The recreation can have not only a direct effect on soil moisture variation, but also an indirect one [65, 66]. Recreational impacts can lead to changes in the microrelief of an area, which affects the redistribution of moisture. Pathways lead to a higher density of soil, resulting in a localised lowering of the topography [67]. Therefore a berm is formed along the paths and water can run off along it. Also in pathways the aggregate structure is lost and consequently cracks form in them into which moisture can escape in case of precipitation.

There is a significant increase in the soil penetration resistance in the vicinity of the trails and on the trails themselves [5]. The mechanism for this phenomenon is quite obvious. The systematic movement of large numbers of people leads to an increase in the soil compaction, which is reflected in the soil penetration resistance. Evidence was obtained which indicated that human trampling had the greatest effect on overall porosity and soil penetration resistance [11]. The soil penetration resistance in the topsoil increased significantly after 200 and 500 passes compared to the control plots. The soil penetration resistance, which was 3.78 MPa in the topsoil of the control plots, reached 6.06 MPa after 500 passes. The total topsoil porosity after 500 passes was significantly different from the control plots. While the total porosity was 52.38% in the topsoil of the control plots, it decreased to 41.41% after 500 passes. Other soil properties were generally unchanged in the short term. The relative vegetation cover and relative vegetation height also decreased significantly after trampling. Relative vegetation cover, which decreased to 84% after 25 passes, decreased to 67% after 500 passes. Relative vegetation height was 69% after 25 passes and decreased to 27% after 500 passes. A significant reduction in total vegetation cover was observed after 200 and 500 passes. Compared to the control strip, vegetation height was significantly different after 25, 75, 200 and 500 passes [11]. Our results suggest that the compaction effect is observed over a much larger spatial range than the visible boundaries of trails. A soil compaction effect is observed at a distance of 3-5.3 metres from the trails. This effect is largely reflected in the compaction of the surface soil layer, but the soil penetration resistance of the soil is also sensitive to this compaction over the entire measured depth range. In addition, the compaction at a depth of 55–60 cm extends to a distance of up to 5 meters. Thus, the area of recreational influence exceeds the area of the visible network of spontaneous trails by a factor of 5–10.

The trees in the park plantation also have a non-linear effect on the soil penetration resistance. Plants affect the compactness of the soil [7, 69]. Tree stands in a riparian mixed forest are a significant factor structuring both the herbaceous community and the spatial variation of soil physical properties [70–72]. The roots transmit the weight of the trees into the soil, compacting it [73, 74]. As roots expand, they penetrate through the soil and modify the physical, chemical, and biological properties in the surrounding area, the rhizosphere [75, 76]. These changes can persist after root degradation, forming a branched system of associated biopores [77]. Natural disturbances such as geological events, glacial activity, or soil sliding can change the degree of the soil compaction on a large scale [19, 78]. Alternating wetting and drying can compact the soil as a result of swelling and shrinkage processes [79]. The soil near the tree trunks has greater penetration resistance. The oscillatory movements of the crown under the action of wind energy are transmitted through the trunk to the soil. The vibrational energy is transmitted to the soil and is spent on its compaction, which makes the soil near the trunks more compact. The trees also actively evaporate moisture, so the soil penetration resistance can be higher in the vicinity of the tree trunks. The effect of trees on the soil compactness extends over a distance of up to 8 meters. The greatest attenuation distance for the effect of trees is observed at a depth of 20–60 cm, which corresponds to the depth of the most dense root system of tree plants. The attenuation of oscillatory movements that are transmitted to the root system may be the cause of this local maximum. The second local impact peak is associated with the greatest measured depth and it cannot be ruled out that it is wiped out to a greater depth. Along with the attenuation of oscillatory movements, it can be assumed that a reduction in water content due to its intensive consumption by the roots of the tree plants may be the cause of the observed impact on the soil penetration resistance.

6. Conclusion

The arrangement of trees forms patterns that are similar to the mechanisms of variability in soil penetration resistance in natural conditions. The influence of spontaneous pathways on the spatial heterogeneity of soil properties is commensurate with the natural variability in magnitude. The superposition of these two sources of variation in the soil properties creates a mosaic of parkland soil cover. The effect of recreational pathways has considerable spatial extent, both horizontally and vertically. The boundaries of this effect extend considerably beyond the visible boundaries of the pathways. The findings point to the need for recreational space management to minimise the negative effect of spontaneous paths, the role of which has apparently been previously underestimated.

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To cite this article: N Turovtseva *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012067

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012067 doi:10.1088/1755-1315/1049/1/012067

Active garden therapy for the elderly and people with disabilities

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Abstract. Garden therapy has been used in the world medical practice for many decades. There are many examples where human interaction with plants has a positive impact or facilitates the lives of various segments and groups of society: children, youth, elderly people, with mental health problems, people with disabilities, crime victims, patients with cancer and Alzheimer's disease, mental health problems, drug addicts and alcoholics, combatants, victims of military or terrorist acts, etc. Garden therapy is the process of using plants and the garden to improve well-being through the effects on the mind, body and soul. Garden therapy combines gardening and rehabilitation and is a synthesis of landscape design, medicine and psychology. It can help work with different target groups: in hospitals, nursing homes, rehabilitation and cancer centers, hospices, as well as other medical and residential complexes. Despite this, garden therapy is still not widespread in Ukraine and requires wider development. This is due to the general set of social and health problems, as well as regional problems of modern times, including the post-Chernobyl factor, the mass factor of post-traumatic stress disorders among the affected population of the temporarily occupied territories and the contingent of ATO participants. Undoubtedly, the urgent task today is to develop garden therapy programs for recovery from illness and combating the stressful effects of prolonged self-isolation during quarantine activities related to the COVID-19 pandemic. The article considers an example of creating a location for active garden therapy for visitors to the Center for medical and social rehabilitation services in Melitopol, Zaporozhia region.

1. Introduction

Horticultural therapy is a relatively new discipline combining horticulture and rehabilitation disciplines. It uses plants and gardening activities in therapeutic and rehabilitative activities to improve human well being. Historically, the use of horticulture to calm the senses dates as far back as 2000 BC in Mesopotamia. Around 500 BC, the Persians began creating gardens to please all of the senses by combining beauty, fragrance, music (flowing water) and cooling temperatures [1, 2]. Around the world, there is growing interest in research results showing the impact of the physical environment on the health and well-being of people [3,4]. The importance of gardening in human well-being, social development and the study of the role of gardening as an active recreation reveal the work of M. B. Detweiler et al. [1], J. A. Spring [5], G. C. Butură [6], T. Korah et al. [7], O. F. Alkaisiet al. [8] etc. Of particular interest in this matter is garden therapy. The horticultural therapy is a time-tested practice. The therapeutic benefits of a garden environment have been documented since ancient times [9].

According to the American Association of Horticultural Therapy (AHTA), the horticultural therapy can be used for different categories of the population: by age, origin and abilities. Due to recent pandemic events, the participants in this therapy have expanded significantly. Social distancing and home sickness during the first COVID-19 outbreak were instrumental in helping to flatten the infection curve, but raised concerns about potential negative impacts such as prolonged isolation or sedentary lifestyles [10, 11]. In this scenario, gardening was identified as a reliable tool for protecting mental health and exposure to potential presence. Engaging in gardening is thought to promote psychological health by reducing COVID-related stress [12,13]. Thus, the development of garden therapy programs for recovery after illness and combating the stressful consequences of prolonged self-isolation during quarantine measures related to the COVID-19 pandemic is becoming an urgent task today [14, 15].

2. Research aim and objectives
Horticultural therapy has four major types of benefits: emotional, intellectual, social, and physical. The Hort Park Therapeutic Horticulture Program uses plants and related activities to improve people's well-being through active or passive participation [16].

The purpose of this article is to develop the principles of designing locations for active garden therapy.

3. Material and methods
All the necessary research has been performed to develop a project to create a location for active garden therapy. Inventory of existing plantations was carried out in accordance with the Instruction on inventory of green plantations in settlements of Ukraine [17–19]. Recommendations for the establishment of therapeutic gardens in Singapore were chosen as the basis for the future project [20]. Taxonomic identification of plant species composition is given according to the List of Plants [21, 22]. The Therapeutic Horticulture Programme at HortPark uses plants and plant-related activities to improve the well-being of individuals through active or passive involvement.

The programme aims to [20]:

- provide an enriching experience with nature
- promote social interaction and physical activity
- stimulate the senses through interaction with nature
- enhance physical and mental well-being
- promote interest in plants and gardening.

Horticultural therapy is a time-proven practice. The therapeutic benefits of garden environments have been documented since ancient times. All over the world there is an increasing interest inresearch results showing the impact of the physicalenvironment on people's health and well-being [4].

4. Results and discussion
In pursuance of the Law of Ukraine "On Rehabilitation of Disabled People in Ukraine" in 2003, the Center for Social Rehabilitation for Disabled Children of the Melitopol City Council of Zaporizhia region was established. The main task of the center is to provide rehabilitation services to people with disabilities through a range of social, psychological, pedagogical and physical rehabilitation measures.

In November 2011, Melitopol City Council decided to establish a Mixed type of Rehabilitation Center for the disabled people and children with disabilities in the city, which allowed not only children with disabilities aged 2 to 18, but people with disabilities aged 18 to receive services social, psychological and pedagogical, physical rehabilitation and vocational guidance in order to adapt and integrate them into society. The structure of the Center has two departments: rehabilitation of children with disabilities aged 2 to 18 years and rehabilitation of people with disabilities aged 18 years.

In 2017 the institution was transformed into the Center for Comprehensive Rehabilitation for People with Disabilities, due to changes in the legal framework of the Ministry of Social Policy of Ukraine. Center for Comprehensive Rehabilitation for People with Disabilities from July 1, 2020 – municipal non-profit enterprise "Center for Social Services and Medical Rehabilitation" Melitopol City Council of Zaporozhye region (KNE "CFSS&MR" MCC ZR). The territory of KNE "CFSS&MR" MCC ZR has a total area of 1,003 hectares. For many years, the Center has been cooperating with the city's higher educational institutions, in particular the Bogdan Khmelnitsky Melitopol State Pedagogical University.

As a result of the inventory, it was established that there are three buildings on the territory of the center, an inclusive sports ground on which are located: a football and basketball field, a playground with sports equipment, an spectator zone, and part of the territory with green plantings. Green plantations are represented by such species as the *Pinus nigra subsp. Pallasiana* (Lamb.) Holmboe, *Platycladus occidentalis* (L.) Franco, *Juniperus sabina* L., *Morus alba "Pendula"*, as well as ornamental herbaceous plants.

The area where we propose to place a rectangular garden therapy area (6.5×14 m) and is located in the southwestern part of the territory near the inclusive sports ground (figure 1). Its total area is 93 m^2. On the western and southern sides it is separated from the private sector by a fence. The relief of the territory is flat. The garden therapy area will be covered with paving slabs, as well as a path leading to this area. The width of the track should be at least 1.2 m, which will ensure the convenience of people in wheelchairs.

Figure 1. Territory for creating a location for active garden therapy.

We offer to place tables for growing plants in the amount of 3 pieces in this area (figure 2). It will be developed according to the recommendations of the Chicago and Singapore Botanic Gardens, which will ensure the convenience of working for people of different ages with disabilities, including in wheelchairs. The parameters of the tables (width 120 cm, length 2 m, height 70 and 15-25 cm tray for planting) provide the opportunity to carry out the work process without obstacles. Such tables can be modular, on wheels for convenience of their movement or stationary. The frame can be made of metal or wood. In our case stationary tables made of a wooden bar will be more convenient and economic. We offer to grow different cultivated plants on different tables: on the first – vegetable crops, on the second – spicy-aromatic and medicinal and on the third – ornamental and flowering plants.

Figure 2. Visualization of the location of garden therapy on the territory KNE "CFSS&MR" MCC ZR.

The garden therapy area will be covered with paving slabs, as well as a path leading to this area. The width of the track should be at least 1.2 m, which will ensure the convenience of people in wheelchairs.

We have chosen paving slabs of the Ukrainian manufacturer of the "Kvadrat" brand (400 $\times$ 400 $\times$ 60 mm) of gray color, in the tone of the existing covering on the territory the center. When we arrange the following locations, there are certain standards for paving pavements: level with good traction to prevent slipping when it is getting wet, without glare with a stable, light color.

We plan to install 2 benches along the fence for the convenience of recreation during the work for visitors to the center. Their form is designed with the specific characteristics of the institution, that is, it will be convenient for people with disabilities. In addition, it will have armrests with a width of at least 10 cm, which will provide comfort when a person gets up. The location of the backrest in relation to the seat will be at right angles.

According the specifics of our climate (very high temperatures in summer) benches can be equipped with frame canopies with twisted plants.

The territory of the center is very well maintained and landscaped. It is fenced with monolithic and metal sections. But part of the fence, namely on the western side of the development zone, is made of handy materials and has an unattractive appearance. Therefore, for its decoration and fence of metal sections, we propose to use vertical landscaping. For this we suggest to use *Lonicera caprifolium* L. with a planting scheme of 1.5 m. Many plants can be used for garden therapy, but the most important is that it must be safe.

It is desirable to use plants that emit phytoncides or have a pleasant aroma. People with visual impairments has a special interest of fragrant plants or those that are unusual and pleasant to the touch texture. Of course, when you choose plants you need to choose those that do not require heavy care. If you want to have a competent selection of plants for garden therapy, you need a consultation with a landscape design specialist.

Do not use plants with the following characteristics:

- poisonous;
- prickly;
- plants-allergens;
- with caustic juice;
- contain narcotic or hallucinogenic substances.

It is desirable to use plants that emit phytoncides or have a pleasant aroma. People with visual impairments has a special interest of fragrant plants or those that are unusual and pleasant to the touch texture. Of course, when you choose plants you need to choose those that do not require heavy care. If you want to have a competent selection of plants for garden therapy, you need a consultation with a landscape design specialist.

Medicinal and aromatic plants are very significant today. It occupies an important place in the aesthetic and functional aspects of the study of plant design with leaf shapes of different color textures and flowers of different shapes and colors. Unlike other landscaping works, plants used in therapeutic gardens should provide sensory perception, memory and stimulate creativity. In this context, choosing the right types of plants for use and placing them in the direction of the desired effect are the main factors influencing the success of plant design.

Aromatic and medicinal plants are usually easy to grow on garden therapy tables. Many plants are annuals and are grown by sowing seeds in the soil (fennel, salad mustard) or through seedlings (parsley, basil, savory, mint). Such perennial spices as thyme, lemon balm, oregano are well overwinter in the ridge, but it is desirable to mulch them for the winter with peat or humus. Rosemary is grown as a houseplant and taken to the garden in the summer. Most spicy-aromatic plants prefer the sun and nutritious soil.

Many herbaceous plants grown on the table can be brought into the room in the fall and continue to harvest in the winter. Many herbs can be dried and used in winter for cooking and fragrant teas.

Annual flowers. No garden can do without them. They are usually easy to grow, grow quickly, feel good in containers and on tables, add bright colors from mid-May (when planting flowering seedlings) and until the frosts. The huge variety of species and varieties makes it possible to choose the range of annuals for any conditions and for every taste. Many of them have a pleasant smell, many are used for bouquets.

Perennial flowers. You can choose the appropriate species for sunny or shady areas, from a wide range of perennial flowering plants. You can choose different plants in height, shape, color of leaves and flowers, flowering time of the plant.

Vegetable crops. They are easy to grow in containers, on raised beds and tables Choosing compact varieties, you can grow almost the full range of vegetables (radishes, onions, tomatoes, peppers, eggplant, cucumbers, zucchini, peas, beans, lettuce, parsley, etc.).

Salad vegetables are annual plants which leaves are eaten. Leafy vegetables are especially decorative in urban conditions. They quickly converge and develop rapidly. If you want, crops can be resumed several times a season. Salad vegetable plants include lettuce, spinach, watercress, chard.

An assortment of plants that meet these requirements was selected for this project: medicinal (*Thymus citriodorus* (Pers.) Schreb.; *Thymus serpyllum* L; *Origanum vulgare* L.; *Melissa officinalis* L.; *Mentha piperita* L.), vegetables (*Tagetes patula* L.; *Calendula officinalis* L.; *Callistephus chinensis* (L.) Nees; *Pelargonium* L'Hér), annual and perennial decorative plants (*Capsicum annuum* L.; *Capsicum chinense* Jacq.; *Capsicum frutescens* L.; *Capsicum baccatum*

L.; *Capsicum pubescens* Ruiz & Pav.; *Lactuca sativa* L.; *Brassica juncea* (L.) Czern.; *Spinacia oleracea* L.; *Beta vulgaris* L.; *Lepidium sativum* L.).

5. Conclusion

Recently, many garden therapy programs have appeared in the world for rehabilitation after the COVID-19 viral disease. Unfortunately, today the use of garden therapy technologies in Ukraine is limited due to the lack of methodological developments and specialists, specialized locations and the low level of popularization of garden therapy among the population. In view of the above, it can be argued that the development of this area in Ukraine is very important and the solution of these problems today is the main task of scientists. This project can be an example of creating a therapeutic environment to ensure the physical and psychological rehabilitation of their visitors.

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Assessment of the saline biotope state of the North-Western Pryazovia as breeding sites of *Glareola pratincola* with the help of remote sensing data

To cite this article: S V Vynokurova 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012068

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012068 doi:10.1088/1755-1315/1049/1/012068

Assessment of the saline biotope state of the North-Western Pryazovia as breeding sites of *Glareola pratincola* with the help of remote sensing data

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Abstract. Given the biology features of the pratincole (*Glareola pratincola*), the possibilities of using remote sensing data were studied for the assessment of the species breeding habitats. Sentinel-2 images allowed analyzing a number of vegetation indexes reflecting such specific habitat characteristics as humidity and vegetation cover. The surface temperature is also was investigated. Moreover, the GIS analysis revealed spatial distribution of the collared pratincole breeding colonies, primarily in relation to water sources, settlements and roads. *Glareola pratincola* chooses saline areas as breeding habitats, which are characterized by a wide range of values of vegetation indices: NDVI is from 0.143246 to 0.365503, MSI is from 0.987138 to 1.3531. All saline areas suitable for breeding were located in close proximity to the water body (not more than $300m$). The possible impact of the proximity of settlements and roads on the location of breeding colonies was not found. The salt marshes used by pratincoles for breeding were situated at an average distance of $1405 \pm 386m$ from settlements and $1714 \pm 274m$ from roads. The main disturbance factor is potentially cattle grazing. Accoding to results the North-Western Pryazovia is a significant breeding place for *Glareola pratincola* on the Azov-Black Sea coast of Ukraine. The obtained data can be used to determine an ecological niche of the collared pratincole and to develop its conservation strategy in North-Western Pryazovia.

1. Introduction

Glareola pratincola is a rare species listed in the Red Data Book of Ukraine, protected by a number of international conventions (the Birds Directive, the Bern Convention, the Bonn Convention, AEWA). It chooses mainly saline biotopes (salt marshes, solonetzes, salt meadows) for breeding. But these biotopes are very vulnerable to abiotic, biotic, and especially anthropogenic factors [1, 2]. In addition, even in the south of Ukraine, the distribution of salt marshes is very limited and segmented.

The availability of remote sensing data (RS) opens up new opportunities for assessing the state and monitoring of biotopes, including the saline ones. In particular, they are used to map saline biotopes [3, 4], vegetation status [5, 6], analysis of their spatiotemporal changes [7, 8].

The state assessment of the biotopes allows to identify some factors that affect the distribution of birds that inhabit them. Understanding the requirements of the species to the biotope, determining the quantitative characteristics of such requirements is the basis for management decisions on the protection of the species, and therefore, for the sustainable existence of the ecosystem.

The purpose of this paper is to assess the quantitative indicators of abiotic and individual biotic factors that affect the distribution of *Glareola pratincola*; to determine the possibilities of using remote sensing data to assess the state of saline biotopes as breeding sites of *Glareola pratincola*. Given the latter, of the full range of characteristics that can be determined by remote sensing, we consider only those that may be important for the formation of the ecological niche of the species.

2. Methods

The location and state of saline biotopes were determined on the basis of remote sensing data, namely satellite images of the European Space Agency Sentinel-2 Level-1C processing for the period from April 1 to June 30, 2020 (cloud cover is not more than 10%). In addition to the cases specified separately, the median image for each month was taken for analysis. Access to satellite data and related calculations were performed using the Google Earth Engine Cloud Computing Platform.

The location of saline biotopes in the North-Western Pryazovia was determined using a supervised classification, the Random Forest method. The data were verified during field expeditions to the research area.

In the spring and summer of 2020, field surveys were carried out at 44 control sites to assess the state of biotopes and determine the breeding sites of *Glareola pratincola*. In total $2325ha$ of saline biotopes were surveyed. Within each salt marsh, surveys were carried out along the transect routes with 20-fold binoculars. Gatherings of birds and finds of nests were recorded by GPS.

In order to assess the state of saline areas, vegetation indices were calculated on the basis of reflectence values in different spectral channels of remote sensing data. To assess the suitability of individual indicators for the purpose of the study, 14 indices were calculated, the calculation formulas of which are shown in table 1.

Soil samples were taken at 10 sites where *Glareola pratincola* nesting was determined to assess its field moisture. The hydrostatic weighing method was used for the analysis. Field soil moisture W (in %) is calculated by the formula: $W = 100 * a/b$, where a is the mass of evaporated water, g; b is the mass of dry soil, g [23].

DJI Mavic Pro shooting was performed at 9 control sites. The obtained images were digitized and divided into 2 classes: vegetation is present / vegetation is absent. The vegetation cover based on these images was calculated as the ratio of the area occupied by vegetation to the total area.

The results of the obtained indicators of moisture and vegetation cover were compared with the data of satellite images for the same time ($\pm$3 days).

The distance to roads and settlements, which was considered a sign of a possible factor in disturbance of birds, was also assessed as an “indirect” factor. In addition, during the field research there were recorded places of grazing sheep, as well as the number of heads, places of amateur fishing and beach recreation using GPS. Distance analysed were performed using the ArcGis 10.5 software package. Statistical analysis was carried out in the R programming environment.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012068 doi:10.1088/1755-1315/1049/1/012068

Table 1. Indices that were used to assess the state of saline biotopes.

№	Index	Formula	Link
		Water content indices	
1	Normalized Difference Water Index	$NDWI = \frac{Green - NIR}{Green + Nir}$	[9]
2	Modified Normalized Difference Water Index	$mNDWI = \frac{Green - SWIR1}{Green + SWIR1}$	[10]
3	Land Surface Water Index	$LSWI = \frac{NIR - SWIR2}{NIR + SWIR2}$	[11]
4	Normalized Multi-band Drought Index	$NMDI = \frac{NIR - (SWIR1 - SWIR2)}{NIR + (SWIR1 - SWIR2)}$	[12]
5	Normalized Difference Moisture Index	$NDMI = \frac{NIR - SWIR1}{NIR + SWIR1}$	[13]
6	Moisture Stress Index	$MSI = \frac{SWIR1}{NIR}$	[14]
7	Surface Water Capacity Index	$SWCI = \frac{SWIR1 - SWIR2}{SWIR1 + SWIR2}$	[15]
8	Shortwave Infrared Soil Moisture Index	$SIMI = \sqrt{\frac{SWIR1^2 + SWIR2^2}{2}}$	[16]
9	Visible and Shortwave infrared Drought Index	$VSDI = 1 - \frac{SWIR1 - Blue}{Red - Blue}$	[17]
		The broadband greenness indices	
10	Normalized Difference Vegatation Index	$NDVI = \frac{NIR - Red}{NIR + Red}$	[18]
11	Soil Adjusted Vegetation Index	$SAVI = \frac{NIR - Red}{NIR + Red + L} * (1 + L)$	[19]
12	Green normalized difference vegetation index	$GNDVI = \frac{NIR - Green}{NIR + Green}$	[20]
13	Infrared Percentage Vegetation Index	$IPVI = \frac{NIR}{NIR + Red}$	[21]
14	Enhanced vegetation index	$EVI = 2.5 * \frac{NIR - Red}{NIR + 6 * Red - 7.5 * Blue + 1}$	[22]

Notes: $Blue$ – reflectence value in blue band, $Green$ – reflectence value in green band, Red – reflectence value in red band, NIR – reflectence value in near infra-red band, $SWIR1$ – reflectence value in the first short wave infra-red band, $SWIR2$ – reflectence value in the second short wave infra-red, L is the correction coefficient for reducing soil noise (taking into account the vegetation sparsity, it was taken as 0.8).

3. Study area

In North-Western Pryazovia salt marshes are distributed along the banks of all estuaries located here: the Bolhradskyi Syvashyk, Utliutskyi, Molochnyi and Tubalskyi, in the lower reaches of some rivers, on some plains along the Sea of Azov, as well as on the Obytichna and Berdianska Spits. As mentioned in Methods section 44 sites of saline biotopes were selected for study (figure 1).

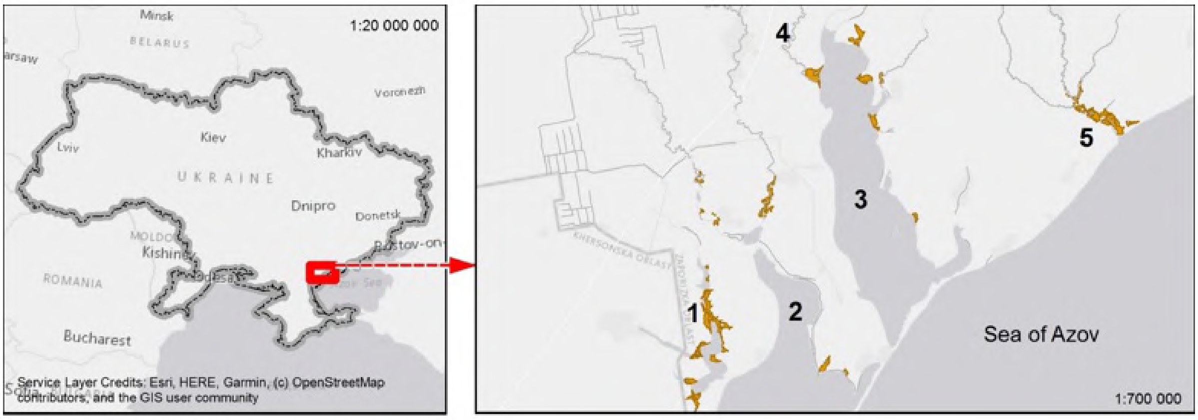

Figure 1. The study area. Legend: 1 – Estuary Bolhradskyi Syvashyk, 2 – Utliutskyi Estuary, 3 – Molochnyi estuary, 4 – Tashchenak River, 5 – Tubalskyi Estuary, brown colour – identified saline biotopes.

According to [24] there are: damp and wet, periodically flooded salt marshes dominated by *Salicornia perennans* (B: 4.111), salt marshes with an annual plant *Salicornion prostratae* and short-term flooding (B: 4.112), salt marshes with prolonged or periodic flooding dominated by *Halocnemum strobilaceum* (B: 4.121), loose salt marshes with short-term flooding dominated by *Halimione verrucifera* (B: 4.122).

4. Species characteristics

Glareola pratincola, like the vast majority of sandpiper species, is ground-breeding, but it nests in colonies. The species is characterized by its attachment to breeding sites under stable conditions there. The colonies can be located in almost the same places with minor differences for several years [25].

Glareola pratincola occupies nesting areas in April, and starts breeding in the third decade of May - early June. Repeated breeding is possible until mid-July because of the death of egg clutches.

According to the literature data [26, 27], breeding sites generally meet the following requirements:

(i) lowlands with solid ground, free from various kinds of barriers (ravines, trees, shrubs, high grass stand);
(ii) vegetation height is $6 - 20cm$, projective cover area is $9 - 35\%$;
(iii) certain proximity of water sources;
(iv) optimal climatic and microclimatic conditions (average temperature and low humidity);

At the same time, *Glareola pratincola* is a labile species and quickly respond to the disturbance factor, changes in the state of biotopes, and other factors [25, 26].

5. Results

There were identified 93 sites of saline biotopes due to additional classification of satellite images. The sites differed significantly in area (from 0.4 to 310ha). Their total area was 2864ha. The largest sites were situated on the banks of the Bolhradskyi Syvashyk, Tubalskyi and Molochnyi Estuaries. Colonies of *Glareola pratincola* were recorded only on 12 sites (figure 2). Single birds of this species were recorded on 6 more sites. In most cases colonies were located on salt marsh sites with an area of 10 to 50ha (median is 34.4ha). However, some colonies were recorded both on sites of less than 10ha and more than 100ha.

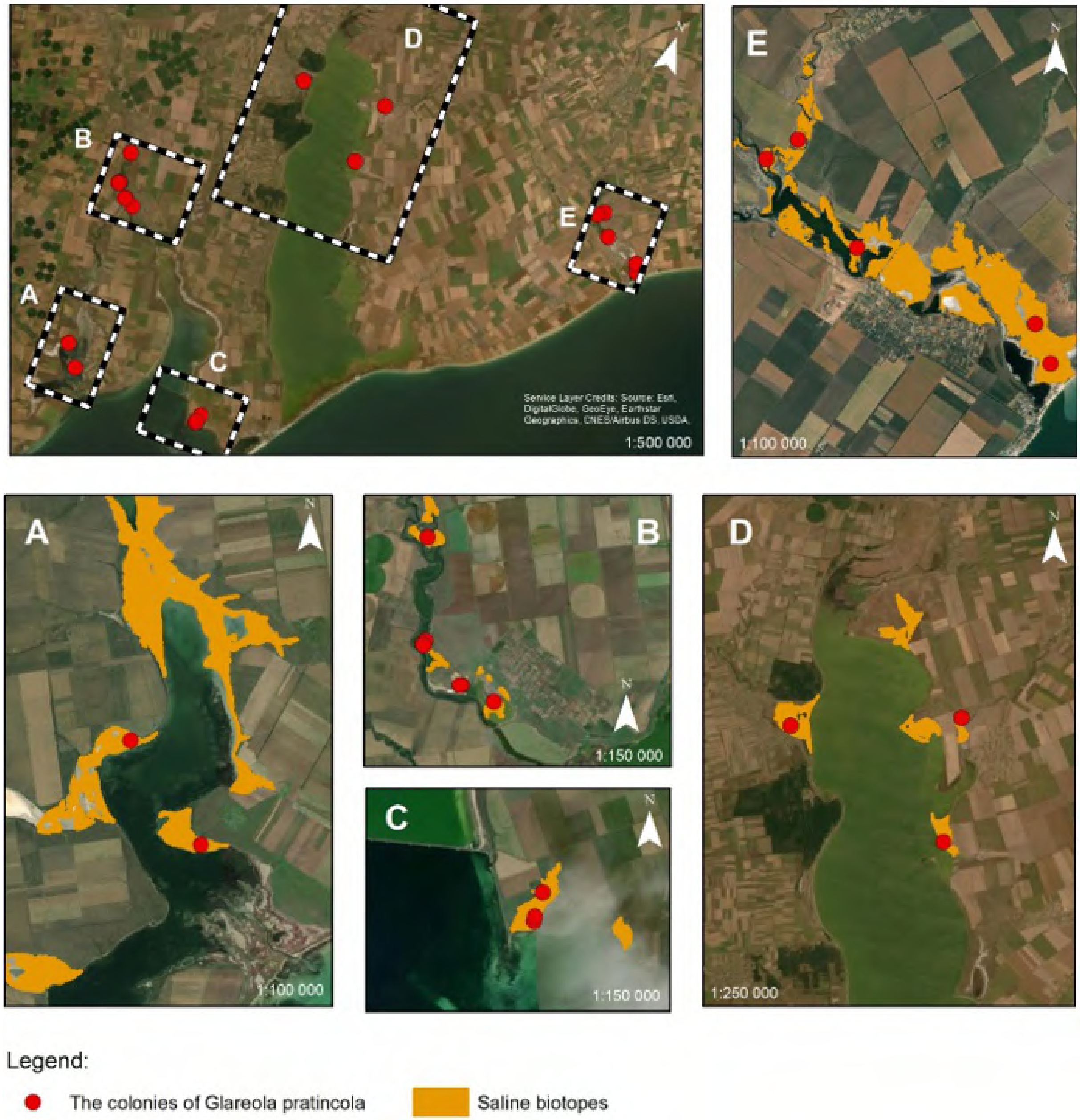

Figure 2. Distribution of the Glareola pratincola colonies in the study area.

6. Moisture dynamics of saline biotopes

To assess the moisture content of saline biotopes, 10 soil samples were taken, for which the percentage of moisture content was determined. For sampling sites, based on remote sensing data for the same dates (3 days), water content coefficients (NDWI, mNDWI, NDMI, NDDI, NMDI, MSI, LSWI, SWCI, SIMI, VSDI) were calculated. The most effective were indices based on the values of near (NIR) and middle (SWIR1) infrared spectral bands (MSI, NDMI). The MSI is characterized by a positive correlation (Pearson's correlation is 0.8148574, $p = 0.04824$), while the NDMI is characterized by a negative one (Pearson's correlation is -0.8287782, $p = 0.04147$).

Based on the median images for each month of the breeding period (April-June), the water content index MSI was calculated for all salt marsh sites, as well as mNDWI, as more frequently used in studies, which in the future may allow to compare our data with other regions. The obtained data are shown in table 2. For the sites that were used by *Glareola pratincola* as breeding ones, the MSI value in April was in the range from 0.8411 to 1.2132 (average 1.067 ± 0.036), in June from 0.9943 to 1.3289 (average 1.1701 ± 0.0264). The value of the index mNDWI fluctuated in April from -0.4576 to -0.1493 (average -0.3057 ± 0.03); in June from -0.4423 to -0.2424 (average -0.3694 ± 0.02).

According to the results of the analysis of soil samples, the moisture content of salt marshes during the breeding period of *Glareola pratincola* fluctuated in the range from 13.3 to 33.1%.

Thus, *Glareola pratincola* used salt marshes with a fairly wide range of moisture for breeding.

7. State of vegetation

In addition to estimating the vegetation cover (see "Methods") in the breeding sites of *Glareola pratincola* using a drone, the following vegetation indices for the same sites were estimated based on satellite data for the same dates (±3 days): NDVI, SAVI, GreenNDVI, IPVI, EVI. All calculated indices showed a statistically accurate correlation with the value of the actual projective cover. The lowest correlation coefficient was found for EVI (Pearson's correlation is -0.6867503, $p = 0.04101$), the highest one for SAVI, an index that takes into account the influence of soil in its value (Pearson's correlation is 0.8575388, $p = 0.003117$). But given that the most common index is NDVI, which in our studies also found a high correlation (Pearson's correlation is 0.8575214, $p = 0.003118$), we used it for further analysis. The value of NDVI in June, the period of maximum vegetation, for breeding sites of *Glareola pratincola* averaged 0.2544 ± 0.0160. According to our data, the vegetation cover of breeding saline biotopes, in some cases, was $24 - 66\%$, which is significantly higher than it is given in the literature [27].

The obtained values of all indices for breeding biotopes of *Glareola pratincola* are presented in table 2.

Table 2. Indices that were used to assess the state of saline biotopes.

	MSI	mNDWI	NDVI	SAVI
April	$1,067 \pm 0,036$	$-0,310 \pm 0,032$	$0,231 \pm 0,0195$	$0,416 \pm 0,035$
May	$1,144 \pm 0,022$	$-0,359 \pm 0,023$	$0,247 \pm 0,015$	$0,445 \pm 0,027$
June	$1,17 \pm 0,026$	$-0,373 \pm 0,019$	$0,254 \pm 0,016$	$0,458 \pm 0,029$

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012068 doi:10.1088/1755-1315/1049/1/012068

8. Soil surface temperature

Among the microclimatic parameters, the soil surface temperature during the egg-laying period is considered, which may be important for ground-breeding species. Since all the nests were found in June, the median value of the ground surface temperature was analyzed exactly for June using data from a satellite survey of the Landsat Missions, the sensors of which have a thermal band. For the sites used by *Glareola pratincola*, the soil surface temperature averaged 34.7 ± 0.2 °C. For comparison, the average soil surface temperature for land areas within the basins of the Azov estuaries was 32.68 ± 0.32 °C. Presumably, *Glareola pratincola* chooses warmer parts of the soil as a breeding habitat.

9. Distance to water

All considered saline areas suitable for nesting were located in close proximity to the water area. The average distance from the found colonial settlements of *Glareola pratincola* to the water body was $130.1 \pm 19.7m$ (minimum $19.9m$ in the Syvashyk Estuary, maximum $274m$ in the Molochnyi Estuary, the mouth of the Tashchenak River).

In relation to freshwater sources (a river, a canal or a well), the colonial settlements of *Glareola pratincola* were mostly located right next to the source, at the same time 3 colonies were at a distance of $720 - 1100m$, and 2 colonies in the Syvashyk Estuary were at a distance of about $10km$.

10. Disturbance factor

As mentioned above, the disturbance factor was assessed both through indirect data - the distance to potential sources of such a factor, and through the fixation of the direct facts of grazing, recreational activities, etc.

10.1. Indirect disturbance factors

On average, colonies of *Glareola pratincola* were located at a distance of $1919 \pm 342m$ from the settlements. One of the colonies was located at a distance of $400m$ from the edge of the village (the mouth of the Tashchenak River, and another 5 colonies at a distance of less than $1km$). It should be noted that the place of the colony, which turned out to be the closest to the settlement, in the past was a stable breeding place for *Glareola pratincola.* Its colonies have been recorded here from 2000 to 2013 mostly annually [28]. The colony of *Glareola pratincola* on the salt marshes of the Tubal Estuary, which according to research is also quite stable, was located less than $1km$ from the resort (the village of Prymorskyi Posad) and $444m$ from the sea shore, where there are places of unorganized beach recreation.

The average distance from the colonial settlements to the roads was $1714 \pm 274m$ (minimum $429m$ in the area of the Tubal Estuary).

10.2. Direct disturbance factors

In total, during the period of expeditionary research, there were recorded 9 facts that were assessed as a possible impact on the *Glareola pratincola* colonies. In 7 cases these were the facts of sheep grazing (meeting flocks of sheep or fresh traces of manure near the colony), in two other cases it was recreation (beach recreation on the shores of the Molochnyi Estuary and a place of amateur fishing on the shores of the Utliutskyi Estuary). We did not record such factors near the salt marshes of the Bolhrad Syvashyk Estuary or the Tubal Estuary. In the only colony, which was located less than $1km$ from the place of grazing sheep ($708m$), no birds or nests were found when re-visiting (but we did not establish the exact reasons for the disappearance of the colony). But it should be noted that a successful colony of *Glareola pratincola* was recorded $84m$ from the place of amateur fishing.

11. Discussion of results

Thus, the ranges of all indices and parameters of interest to us were estimated: water content (soil moisture), projective vegetation cover, soil temperature, distance to water, settlements, roads and other anthropogenic disturbance factors for birds. In most cases, a wide range has been identified within which *Glareola pratincola* chooses breeding habitats. For all analyzed salt marshes, no significant differences in the analyzed parameters for the sites used for breeding and not used were found.

Based on the 95% confidence interval of each of the analyzed parameters, 67% of the saline biotopes in the region meet the eligibility criteria.

It can be assumed that unoccupied areas include both sites that meet the needs of the species, but not occupied due to the small number of breeding pairs, and sites not suitable for breeding. But this assumption needs further verification.

It should be noted that not only estimation of projective cover is important, but also the structure of vegetation, plant height, which contributes to the protection of chicks, that also requires additional research. Further research is also needed to clarify the impact of disturbance factors, including non-anthropogenic factors.

12. Conclusions

Remote sensing data objectively reflect the current state of the saline biotopes, namely the state of soil moisture, vegetation and surface temperature. The obtained results can be a starting point for further monitoring of breeding sites of a very vulnerable rare species of *Glareola pratincola*, as well as for further assessment of its ecological niche.

Glareola pratincola chooses saline areas as breeding habitats, which are characterized by a wide range of values of vegetation indices: NDVI is from 0.143246 to 0.365503, MSI is from 0.987138 to 1.3531. All saline areas suitable for breeding were located in close proximity to the water body (not more than $300m$). The possible impact of the proximity of settlements and roads on the location of breeding colonies was not found. The main disturbance factor is potentially cattle grazing, which is confirmed by other researchers [29].

Based on the total area of salt marshes suitable for breeding, the North-Western Pryazovia is a significant breeding place for *Glareola pratincola* on the Azov-Black Sea coast of Ukraine.

Acknowledgment

The author is sincerely grateful to Iosif Ivanovych Chernichko for participation in field research and valuable comments on the manuscript.

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PAPER • **OPEN ACCESS**

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To cite this article: P I Gorlov *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012069

View the article online for updates and enhancements.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012069 doi:10.1088/1755-1315/1049/1/012069

Factor analysis of the Zaporizhzhia wind park impact on bats based on the index of their activity and dynamics of species diversity

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Abstract. Based on the studies in the period of 2010-2021, there was obtained some information on the behavior of bats and their species composition at the Zaporizhia wind park in the Zaporizhia Region, Ukraine. In the study area, there was established the presence of 10 species of bats belonging to 7 genera. The most complete results were obtained in 2019, when 4 field research methods were used, 28 expedition trips were carried out and 4177 bat signals were recorded. In total, the information on 43938 bat signals was collected in 2010-2021. The total operating time of the ultrasonic detectors was 4565 hours. There were calculated indices of the voice activity of bats for three research methods by seasons, different functional zones and phases of the annual cycle of animals. Surveys on transects with the geo-position of each recorded signal made it possible to characterize the distribution of bats over the territory of the wind farm, and the use of the Kernel Density tool allowed to differentiate the wind farm site of the Zaporizhia wind park into the zones that are conditionally safe for bats and high-risk zones. There have been determined the periods of the year and time periods of night activity, in which it is advisable to use measures to minimize the negative impact. Using international and own experience, there have been proposed methods for repelling bats away from the wind turbines.

1. Introduction

The complexity of the instrumental study of bats against the background of the legal requirement to assess the impact of WPP on bats makes the organization and implementation of monitoring of their existence conditions in technogenic areas unconditionally urgent.

National legislation clearly declares the need for such work, but unfortunately, there is no methodological standard for collecting and analyzing information [1]. That is why researchers of bats on the territories of wind parks are forced to rely on international practices [2–6]. This paper proposes some methods for carrying out bat research on the territory of the Zaporizhia wind park and the results of their application.

2. Survey techniques and standards

The study of bats was carried out on the territory of the Zaporizhia wind park (the Melitopol District, the Zaporizhzhia Region, Ukraine) in 2010-2021 (figure 1).

The main goal of research on the territory of the Zaporizhia wind park was to study the vocal activity of bats in order to find out changes in the ecological state of animal populations, potentially occurring because of the construction and operation of the wind park. The methodology was developped according to the recommendations of "Surveillance and Monitoring Methods for European Bats Guidelines produced by the Agreement on the Conservation of Populations of European Bats (EUROBATS)" [3]. The experience of carrying out similar studies in Germany was also used [4, 6].

Three types of ultrasonic detectors were used to record bat signals: Pettersson D240x (2 units), Pettersson D500x (1 unit) and LunaBat DFR-1 Pro (1 unit). Scanning of the territory was carried out using four methods.

3. Vantage Point Surveys (VP)

In total, 9 vantage points (VP) are located within the wind park (figure 1). A Pettersson D240x detector was used at each vantage point. The operating time of the detector was 10 min. The most complete work was carried out in 2019, when 28 expedition trips to the territory of the wind park were carried out from March 20, 2019 to November 13, 2019. The total time of work at a VP for one trip was 90 minutes, in total for a season - 2430 minutes. In total, 454 echolocation calls were recorded by the detectors.

4. Collection of information on transects

In total, 18 transects have been allocated in the Zaporizhia wind park, which are located along the lines of installation of wind turbines. Figure 1 shows a GPS track that covers all transects. The passage of the transects was carried out at a vehicle speed of 20-25 km/h. This speed allows to reduce the number of extraneous sounds and successfully record the bat echolocation calls. To work on transects, the LunaBat DFR-1 PRO ultrasonic detector with an external microphone (ME-4x in IP65/67 plug; cable length 1.5 m; figure 2) was used. The microphone was installed on a special plate fixed to the roof of the expedition vehicle. In total, 28 expedition trips were carried out in 2019. The total number of bat echolocation calls was 694. The length of individual transects was in the range of 1.6-10.6 km, and their total length was 91.1 km. Operating time for one night was about 6 hours (about 170 hours in 2019).

4.1. Static detector surveys at ground level

At the stationary vantage point, there was used the Pettersson D500x detector, which automatically and in a wide range recorded the echolocation calls of bats in the interval 18:00-06:00 (figure 3). The detector worked 28 nights in 2019. The total operating time was 336 hours. A total of 2882 bat signals were recorded.

4.2. Static detector surveys at height

Usually, the researcher is at the ground level during surveys, and an assessment must be made for the dangerous heights of the movable wind turbine. Accordingly, studies are needed at heights of more than 30-40 m above the ground where the wind turbine is installed. In 2017, for the first time in Ukraine, a broadband automatic detector Pettersson D500x was installed on the meteorological mast of the Zaporizhia wind park at a height of 42 m (figure 4). The detector setup was the same as during the surveys on the ground. In total, 5 nights of space scanning were carried out during the period of active autumn migration on September 19-25, 2017. There was obtained information about 22 echolocation calls of bats.

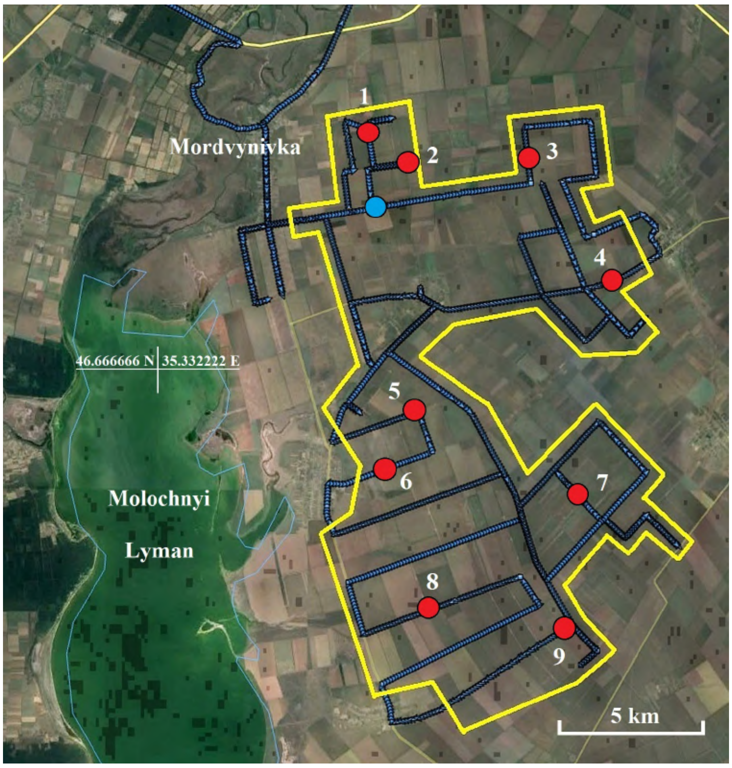

Figure 1. Research area within the Zaporizhia wind park (a yellow line is the boundaries of the wind park; red circle – vantage points; blue circle – the installation site of the Pettersson D500x detector; blue line – GPS track of the researchers' passage along the transect).

Figure 2. Using the LunaBat DFR-1 Pro detector with an external microphone on the Zaporizhia wind park transects in 2019.

Figure 3. A stationary vantage point (Pettersson D500x).

Figure 4. Using the Pettersson D500x detector at the height of 42 m.

In addition to the studies of 2019, we used data obtained in 2010-2021. During this period, ultrasonic detectors of three types recorded a total of 43,938 signals belonged to bats. The total operating time of the detectors was 4565 hours.

5. Research area zoning in terms of bat sound density

To obtain more specific information on the territorial distribution of bats in the project area, we used the Kernel Density method for point objects [7, 8].

The result of applying this technique is the construction of zones of increased activity of bats, both in certain periods and for all observation seasons, on a cartographic basis. Such zoning allows to identify places of potential risk for bats and to provide appropriate recommendations on environmental management and minimization of impacts.

5.1. Methodical substantiation of the Kernel Density technique application

The technique calculates the number of point or polylinear objects per unit area (density) using the function of the kernel to fit the surface which gradually narrows to each point or polyline (figure 5).

Conceptually, a smoothed curved surface is selected (built) for each point. The value of the surface is the maximum at the location of the point and decreases with increasing distance from

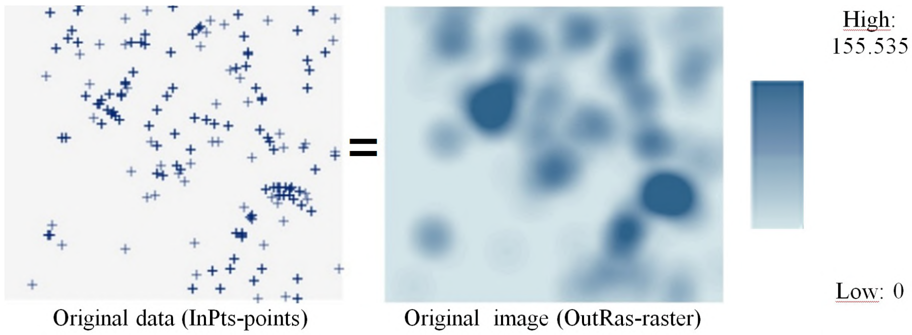

Figure 5. Principles of raster image construction for points that have different values [7].

the point, reaching zero at a distance equal to the specified search radius from the point. Only a circle environment can be used. The volume below the surface is equal to the value of the Population field for a point, or a unit, if set to "NONE". The density value in each cell of the original raster is calculated by adding the values of all kernels at those points where they are superimposed on the center of the raster cell. The core function is based on the quartet core function described in B W Silverman [8].

If the value of the Population field differs from the NONE value, the value of each element determines the number of point counts. For example, a value of three causes the point to be counted three times. Values can be integers or numbers with a floating point. To characterize the density of bats in different areas of the wind farm and at different times of the year, we gave 2-kilometer parameters of the radius of impact to each point (signal).

The species identification of bats was carried out based on the recommendations of M Barataud [9].

6. Determination of bat activity indicators

It is a common international practice to carry out such studies to determine activity indicators in order to assess the possible impact of a project wind farm on bats objectively.

Based on the results, the activity index for all bats is determined using the following formula:

$$I_x = N_x * 60/T$$

Where: I_x – activity indicator for the species or group of echolocation "x"; N_x – number of bat flights of the species or group of echolocation "x" observed during registration at the *point counting / transect* (or during all registrations taken into account);

T – is the total duration of the analyzed registration at the *point counting / transect* (or all registrations taken into account), indicated in minutes.

Such calculations make it possible to characterize the periods of minimum and maximum activity of bats for further action and measures for the management of natural environmental complexes.

7. Results

Sufficiently extensive field research data are needed for a qualitative assessment of the wind farm impact on bat populations. The most complete studies were in 2019, so we will give a brief description of them.

Table 1 shows the results of three methods that were applied on the territory of the wind park along the passage of the Power Transmission Lines (PTL), partly in settlements and during the expedition vehicle crossings between transects and vantage points.

Table 1. Field research results in 2019.

No	Date, 2019	Trans., min	Trans., sig.	VP*, min	VP*, sig.	SDet*, min	SDet*, sig	PTL*, min	PTL*, sig	ST*	MV*	Total, min	Total, sig
1	20-21.03	264	3	90	0	720	8	120	1	0	0	1194	12
2	27-28.03	256	1	90	0	720	0	–	–	0	0	1066	1
3	08-09.04	344	0	90	7	720	49	–	–	0	0	1154	56
4	11-12.04	350	8	90	9	720	42	–	–	1	1	1162	61
5	24-25.04	344	18	90	11	720	92	–	–	1	0	1155	122
6	29-30.04	350	18	90	15	720	96	57	0	1	0	1218	130
7	16-17.05	353	70	90	39	720	61	–	–	0	1	1164	171
8	28-29.05	295	33	90	24	720	191	–	–	5	6	1116	259
9	30-31.05	310	16	90	31	720	147	–	–	0	0	1120	194
10	04-05.06	318	25	90	15	720	273	73	2	1	6	1208	322
11	11-12.06	295	32	90	12	720	368	–	–	4	1	1110	417
12	10-11.07	302	21	90	6	720	67	–	–	4	6	1122	104
13	25-26.07	318	36	90	20	720	53	73	5	1	1	1203	116
14	29-30.07	302	22	90	16	720	66	–	–	4	2	1118	110
15	04-05.08	295	31	90	17	720	74	–	–	2	0	1107	124
16	12-13.08	391	24	90	35	720	197	73	13	1	1	1276	271
17	24-25.08	295	69	90	15	720	191	–	–	6	9	1120	290
18	29-30.08	353	52	90	28	720	254	–	–	13	8	1184	355
19	03-04.09	350	39	90	18	720	173	–	–	2	4	1166	236
20	09-10.09	344	40	90	21	720	136	–	–	0	1	1155	198
21	19-20.09	350	34	90	19	720	120	57	19	1	1	1219	194
22	24-25.09	350	21	90	33	720	54	–	–	0	1	1161	109
23	05-06.10	348	31	90	18	720	65	–	–	0	0	1158	114
24	15-16.10	355	16	90	11	720	34	–	–	1	0	1166	62
25	20-21.10	264	13	90	27	720	6	120	9	0	0	1194	55
26	27-28.10	256	9	90	5	720	31	–	–	0	0	1066	45
27	11-12.11	302	4	90	0	720	11	–	–	0	0	1112	15
28	12-13.11	350	8	90	2	720	23	100	1	0	0	1260	34
	Total	9004	694	2520	454	20160	2882	673	50	48	49	32454	4177

Notes*: Trans – transects; VP – vantage points; SDet – Static detector surveys at ground level; PTL – Power Transmission Lines; ST – registration of signals in settlements; MV – registration of signals when moving between transects and points.

As you can see, a total of 4177 signals were recorded. It is obvious that their maximum number was received at a stationary vantage point (2882 signals), since the detector worked all night. The study of voice activity on the transects gave us 694, and at the vantage points 454 signals.

To characterize the behaviour of bats, absolute indicators are insufficient, so there was used the activity index calculated for all three methods and shown in table 2 and figure 6. The maximum indicator in the first half of the year was in the middle of June (June 11 – 31 passes/h), which falls on the time of departure of young bats after the breeding season. In the second half of the year, the highest activity of bats was recorded at the end of August (August 29 – 19.8 passes/h) and indicates the beginning of autumn migration.

Long-term studies (2010-2021) show that in the second half of the year in August-September, the activity of bats was relatively higher than in the first half of the year. The differences with the data in 2019 are probably due to the fact that the detectors worked exclusively within the Zaporizhia wind park, which was represented by agricultural land. In previous years, the results of the analysis of bat activity also included data collected in settlements, on the coasts of the Molochnyi Estuary and the Sea of Azov. It is in these three biotopes that the foraging and migratory behaviour of bats has always been more active than in agrocenoses [6, 10–12].

Table 2. Field research results in 2019.

No	Date, 2019	Trans., N	Trans., T	Trans., I_x	VP*, N	VP*, T	VP*, I_x	SDet*, N	SDet*, T	SDet*, I_x	Total, N	Total, T	Total, I_x
1	20-21.03	3	264	0,68	0	90	0,00	8	647	0,74	11	1001	0,66
2	27-28.03	1	256	0,23	0	90	0,00	0	623	0,00	1	969	0,06
3	08-09.04	0	344	0,00	7	90	4,67	49	582	5,05	56	1016	3,31
4	11-12.04	8	350	1,37	9	90	6,00	42	572	4,41	59	1012	3,50
5	24-25.04	18	344	3,14	11	90	7,33	92	528	10,45	121	962	7,55
6	29-30.04	18	350	3,09	15	90	10,00	96	511	11,27	129	951	8,14
7	16-17.05	70	353	11,90	39	90	26,00	61	461	7,94	170	904	11,28
8	28-29.05	33	295	6,71	24	90	16,00	191	432	26,53	248	817	18,21
9	30-31.05	16	310	3,10	31	90	20,67	147	428	20,61	194	828	14,06
10	04-05.06	25	318	4,72	15	90	10,00	273	420	39,00	313	828	22,68
11	11-12.06	32	295	6,51	12	90	8,00	368	412	53,59	412	797	31,02
12	10-11.07	21	302	4,17	6	90	4,00	67	425	9,46	94	817	6,90
13	25-26.07	36	318	6,79	20	90	13,33	53	458	6,94	109	866	7,55
14	29-30.07	22	302	4,37	16	90	10,67	66	469	8,44	104	861	7,25
15	04-05.08	31	295	6,31	17	90	11,33	74	486	9,14	122	871	8,40
16	12-13.08	24	391	3,68	35	90	23,33	197	511	23,13	256	992	15,48
17	24-25.08	69	295	14,03	15	90	10,00	191	551	20,80	275	936	17,63

18	29-30.08	52	353	8,84	28	90	18,67	254	567	26,88	334	1010	19,84
19	03-04.09	39	350	6,69	18	90	12,00	173	584	17,77	230	1024	13,48
20	09-10.09	40	344	6,98	21	90	14,00	136	605	13,49	197	1039	11,38
21	19-20.09	34	350	5,83	19	90	12,67	120	639	11,27	173	1079	9,62
22	24-25.09	21	350	3,60	33	90	22,00	54	655	4,95	108	1095	5,92
23	05-06.10	31	348	5,34	18	90	12,00	65	692	5,64	114	1130	6,05
24	15-16.10	16	355	2,70	11	90	7,33	34	724	2,82	61	1169	3,13
25	20-21.10	13	264	2,95	27	90	18,00	6	740	0,49	46	1094	2,52
26	27-28.10	9	256	2,11	5	90	3,33	31	761	2,44	45	1107	2,44
27	11-12.11	4	302	0,79	0	90	0,00	11	802	0,82	15	1194	0,75
28	12-13.11	8	350	1,37	2	90	1,33	23	805	1,71	33	1245	1,59
	Total	694	9004		454	2520		2882	16090		4030	27614	
	General mean			4.62			10.81			10.75			8.76

Notes*: Trans – transects; VP – vantage points; SDet – Static detector surveys at ground level.

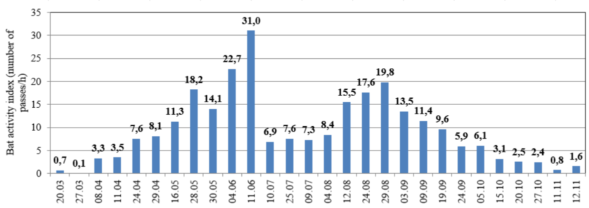

Figure 6. Dynamics of bat voice activity calculated as an activity index in 2019 on the territory of the Zaporizhia wind park (average for three methods).

An analysis of the bat behaviour in different periods of the life cycle is shown in table 3. As you can see, the maximum activity of animals was recorded in the period of disintegration of colonies, the beginning of autumn migrations and grouping in flocks (the second half of August), which confirms our long-term surveys. Such results will enable us to assess the wind park impact on bat populations and develop measures to minimize the negative impact.

8. Static detector surveys at height

Research carried out in 2017 showed the following:

- bats also hunt (migrate) at a height of 42 m and above;
- in total, 22 signals were recorded by detectors;
- the proportion of bats using these altitude intervals in different periods of the year ranged from 1.7 to 3.4% of the total number of recorded signals.

The technical complexity of installing and maintaining the detector on the meteorological mast did not allow us to collect more extensive data, but such work is very relevant and it is mandatory for wind parks.

Table 3. Bat activity index during different periods of the life cycle.

Life cycle	Life cycle	N	T	I_x
Leaving winter roosts by animals	15.03-30.03	12	1970	0,37
Spring migration and the formation of breeding colonies	01.04-20.04	115	2028	3,40
Reproduction and the peak activity of local bat populations	21.04-31.05	862	4462	11,59
Summer flight	01.06-10.08	1154	5040	13,74
Disintegration of colonies, the beginning of autumn migrations and grouping in flocks	11.08-30.08	865	2938	17,67
Autumn migrations and grouping in flocks	01.09-20.10	929	7630	7,31
Last flights between roosts and the beginning of hibernation	21.10-30.11	93	3546	1,57
Total	15.03-30.11	4030	27614	
General mean				8,76

Notes*: N – number of passes (signals), T – total duration of the analyzed registration in minutes, I_x – number of passes/h.

9. Species diversity of bats

6928 signals were analyzed for 5 seasons in 2010-2019, 6636 signals of them were identified to the species (genus). As we can see from the detailed characteristics of the species diversity in table 4, representatives of the Pipistrellus genus dominated in the territory of the Zaporizhia wind park. In total, 4 species of Pipistrellus were recorded, which in total amounted to 3852 signals (55.6%). Such a picture is typical for the entire Azov and Sivash areas, which is confirmed by our preliminary studies in the Azov-Black Sea region. The subdominants were Nyctalus noctula (1108 signals, 15.99%) and Vespertilio murinus (1064 signals, 15.36%). According to our data, these 2 species retain their positions throughout the region. However, they can change places depending on the season of the year and the place of research.

10. Discussion

Given the rather large area of the Zaporizhia wind park, it is expected that bats will use it unevenly. Thus, there is a need for zoning the entire territory and identifying places of animal concentration. To do this, we used the "Kernel Density" method. Thanks to the technical capabilities of the LunaBat DFR-1 Pro detector, each recorded signal of a bat had its own geographical coordinate. A total of 694 signals were documented. In more detail, by seasons, we gave such a characteristic in a previous article [10]. Figure 7 shows the results of such zoning for 2019.

Taking into account the numerical values and the 2-kilometer radius of influence of individual points, we divided the obtained indicators into 6 gradations, which were respectively characterized by low, medium and high signal density (two gradations each).

The northern sites of the wind park fell into the high-density zone, where according to the plan, the wind turbines No. 155, 157, 158, 163, 164, 165, 166 were installed. The Plantage forest

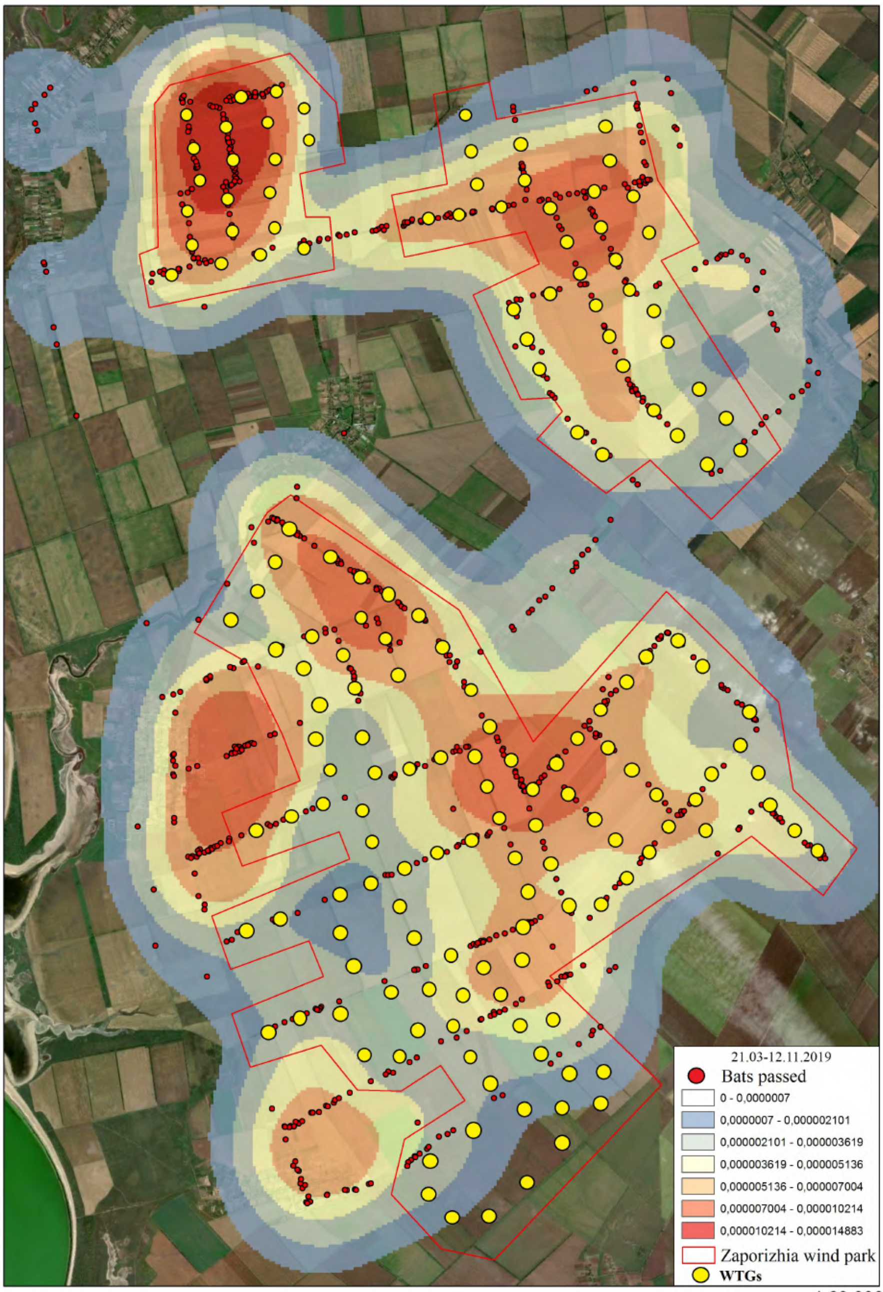

Figure 7. Kernel Density of count points of bats within the Zaporizhia wind park in 2019 (28 expedition trips, 694 signals).

Table 4. Species diversity of bats within the project area of the Zaporizhia wind park.

No	Species	2010, abs.	2010, %	2014, abs.	2014, %	2016, abs.	2016, %	2017, abs.	2017, %	2019, abs.	2019, %	2010-2019, abs.	2010-2019, %
1	*Plecotus sp.*	1	0,28			5	0,5			11	0,26	17	0,25
2	*Nyctalus noctula*	8	2,23	146	24,25	149	15,8	104	12,24	701	16,78	1108	15,99
3	*Pipistrellus kuhlii*	291	81,28	299	49,67	415	44,1	465	54,71	2061	49,34	3531	50,97
4	*Pipistrellus nathusii*	291	81,28	299	49,67	130	13,8	465	54,71	2061	49,34	130	1,88
5	*Pipistrellus pipistrellus*	4	1,12	17	2,82	27	2,9	12	1,41	32	0,77	92	1,33
6	*Pipistrellus pygmaeus*					42	4,5			9	0,22	51	0,74
	Pipistrellus sp.			15	2,49	11	1,2	22	2,59			48	0,69
7	*Vespertilio murinus*			42	6,98	62	6,6	73	8,59	887	21,24	1064	15,36
8	*Eptesicus serotinus*	51	14,25	33	5,48	49	5,2	39	4,59	255	6,1	427	6,19
9	*Hypsugo savii*							4	0,47			4	0,06
10	*Myotis mystacinus*	3	0,84					38	4,47	58	1,39	99	1,43
	Myotis sp.			4	0,66	9	0,9	47	5,53	5	0.12	65	0,94
	Not identified			46	7,65	42	4,5	46	5,41	158	3,78	292	4,21
	Total	358	100,0	602	100,0	941	100,0	850	100,0	4177	100,0	6928	100,0

area and the best-preserved forest belts of high bonitet are located here. For such locations, there is a high probability of bat collisions with towers and blades of WTGs, PTL, as well as receiving barotrauma [13].

Medium signal density levels were found in the following four zones.

(i) Installation locations of the wind turbines No. 126, 127, 130, 131, 132, 133, 134, 135, 140, 144.

(ii) Location area of the wind turbines 5, 6, 7, 11, 12.

(iii) Southeast part of the wind park. The wind turbines No. 20, 21, 41, 42, 73A, 99, 105, 106, 107 got into this zone.

(iv) Eastern outskirts of the village of Hirsovka and nearby areas where it is not planned to install wind turbines. The wind turbines No. 26, 27 are the closest to this zone with average values of density indicators. However, calculations show that they are installed in a low hazard zone.

The other areas of the Zaporizhia wind park are unattractive for bats, since the level of signal density is characterized by the lowest indicators. Thus, by applying the Kernel Density method, we were able to identify zones and compile a list of the wind turbines for which seasonal environmental management efforts are needed to minimize the possible negative impact on bat populations.

11. Dynamics of the bat species diversity

Indirect evidence of the stability of local bat populations is the dynamics of their species composition. Table 4 shows the ratio of bat species for 5 seasons in the period 2010-2019. In all years, representatives of the *Pipistrellus* genus occupied a dominant position. Their total part has always been more than 50% of the number of all other species. Understanding the complexity of identification to a species in the *Pipistrellus kuhlii + Pipistrellus nathusii* complex, we still tend to believe that *Pipistrellus* kuhlii is the most numerous. In the period 2014-2017, the subdominant was *Nyctalus noctula*, the share of which was 12.2-24.3%. In 2010, the second most important species was *Eptesicus serotinus* (14.3%), and in 2019, *Vespertilio murinus* (21.2%). Thus, over the entire period of research, the species diversity of the Zaporizhia wind park chiropterocomplex is represented by at least 10 species. According to the Eurobat commission, [14] *Pipistrellus* kuhlii is in the group with a low risk of collisions with wind turbine generators, while *Nyctalus noctula* (16% of the whole bat complex), has a high risk of falling under a moving rotor. A fairly effective method to reduce fatality is to change the rotation speed of wind turbines [15, 16].

Most species of bats marked by the detector within the wind farm and adjacent areas are widespread and with a stable population status (table 4).

In the project area of the wind farm there are no natural formations that could be used by bats for daytime, breeding and wintering. The main places of concentration of bats are the settlements, the population of which depends on the presence of hollow trees, convenient structures for habitation, in particular, high-rise buildings, and fresh water bodies [6, 10, 11].

The species composition of bats in the study area is poorer than in other natural areas. Analysis of literature data and recording of signals with the help of an ultrasound detector suggests that the fauna of bats here is close to that in the North Priazovia, where *Pipistrellus* dominate, in particular, *Pipistrellus kuhlii*) [12, 17].

The species spectrum of bats is represented by widespread species that have a fairly wide area of existence. No endemic species have been registered. There are no territories unique for bats too.

12. Environmental management of the Zaporizhia wind park

In accordance with the calculations of the activity index of bats, we state that the most dangerous period for them is August and the first half of September (tables 2 and 3). It is during this period that measures are needed to minimize the negative impact of wind turbines on bats, as also pointed out by L Rodrigues et al. [18].

As an environmental management of the Zaporizhia wind park area, we suggest using the experience of colleagues when the start-up rotor speed (define a threshold wind speed, at which the rotors start to operate) was increased from 3.5 to 5-6 m/s [19, 20]. This recommendation is based on the foraging behaviour of bats, which typically prey in wind speeds up to 3.5 m/s. At these speeds, bats are very sensitive to collisions and barotrauma (figure 8; [21]). The financial losses of wind farms when the start-up speed increases to 5 m/s are minimal and are in balance with the task of conserving bats [22].

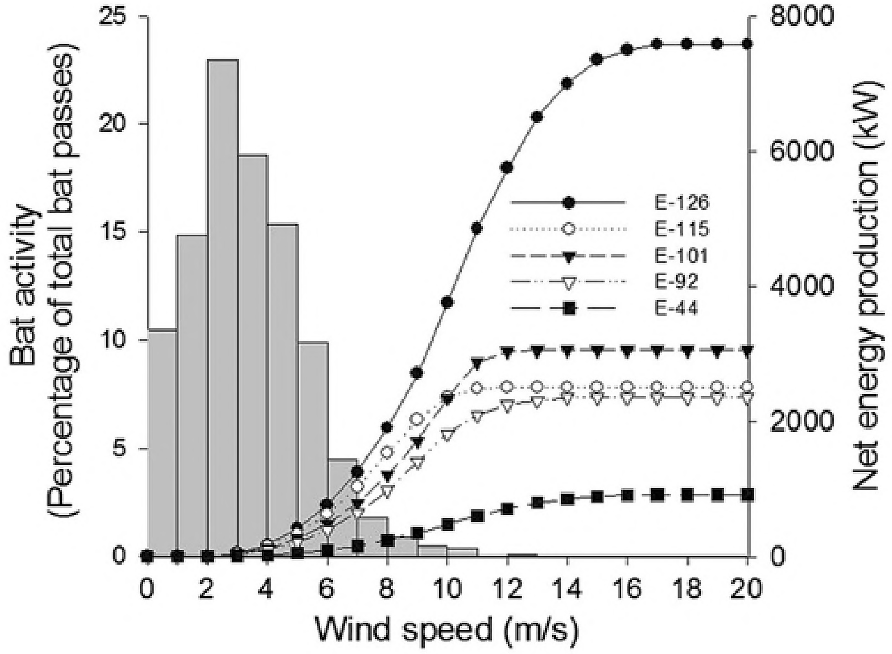

Figure 8. Bat and net energy production in relation to wind speed [21] (E - rotor diameter).

Active methods to deter bats from wind turbines may also be applicable. The Ultrasonic Acoustic Bat Deterrent System for the Wind Industry, developed by the NRG Systems Company, has shown a 32-67% reduction in bat fatality from 15 wind turbines in Illinois (USA) [23].

13. Conclusions

Thus, a comparison of the data obtained in 2010-2021 concerning the study of foraging behaviour and vocal activity of bats allows us to draw the following conclusions:

(i) The total number of registered voices is 43938 signals, 4177 of which were recorded in 2019.

(ii) Index of bat activity depending on the research methodology ranged in the interval 4.62 (on transects) – 10.81 (at a stationary vantage point), and was in average 8.76 signals per hour (for comparison: the Myrne wind farm (the Kherson region) – 7.14 signals per hour; the Kalanchak wind farm (the Kherson region) – 6.62 signals per hour; the Overianivka and the Novotroitsk wind farms (the Kherson region) – 10.53 signals per hour; the Prymorsk wind farm (the Zaporizhzhia region) – 7.07 signals per hour; the Prymorsk wind farm-2 (the Zaporizhzhia region) – 8.10 signals per hour; the Botiievo wind farm (the Zaporizhzhia region) – 6.70 signals per hour).

(iii) Forage and migratory behaviour of bats, calculated by determining the index of their activity, shows the average values.

(iv) The distribution of bats in the project area, defined as the difference between the number of recorded signals in individual habitats, indicates the attraction of animals to settlements and open waters, while the wind farm area is less attractive to them.

(v) The species composition of bats, identified for 6928 signals recorded in the territory of the projected wind farm, is stable and represented by widespread at least 10 species belonging to 7 taxonomic ranks. The undisputed dominants were Pipistrellus kuhlii+ Pipistrellus nathusii, the part of which was more than 50% of the whole complex.

(vi) There are no species of the category "endangered" among the identified bats. The distribution areas of all species of the project area are quite wide. Within the Zaporizhia wind park there are no endemic species or unique habitats of their existence.

(vii) Analysis of the bat distribution, carried out by the Kernel Density method, revealed several areas of the increased activity of animals. Most bats were attracted to the settlements and to open waters. There were revealed some wind turbine generators near which the implementation of minimization measures is required. In total, according to forecasts, there are 7 such wind turbine generators within the Zaporizhia wind park. Another 24 turbines are in the zone of average negative impact on bats.

(viii) August and September are the most dangerous for bats. Methods for changing the start-up speed and ultrasonic bat deterrence are effective and can be recommended as environmental management.

Monitoring the state of bats in the project area both during the construction of the wind farm and its operation is mandatory for the development and implementation of measures to minimize the possible negative impact on bats.

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Information concept of the human health phenomenon as a guarantee of bioecosystem stability

To cite this article: V E Pyurko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012070

Information concept of the human health phenomenon as a guarantee of bioecosystem stability

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Abstract. The current idea of the phenomenon of human health is strongly associated with a harmonious, well-developed personality. A healthy person in all respects can be called one who adequately responds and adapts to the changing conditions of the ecological, biological and social environment. The main prerequisites for health are the stability of the bioecosystem and sustainable resources. Aim/tasks is the theoretically substantiate the information-structural model of human health and the characteristics of its components. The theoretical and methodological basis of the work was the synergistic use of the principles of science and a systematic approach, which led to the choice of research methods: general scientific (analysis, synthesis, systematization, generalization of literary sources); interdisciplinary (structural-system approach, axiological method). Based on the use of the method of information-structural modeling, the modern trend of natural science is substantiated, which is the key to the stability of the bioecosystem - the information model of human health. It consists of the following blocks: information field of knowledge of the main subject areas; information and technological base of research; information and organizational management tools. The basics of a new interdisciplinary approach to the formation of a generalized idea of the phenomenon of human health from the standpoint of information-structural modeling: systematized information concept of integrated health as a unity of physical, mental and social health, verified it, obtained information about the system in as a whole by translating verbal-qualitative information into quantitative assessments. Conclusions. It is emphasized that the information space of individual health statuses is a holistic multidimensional dynamic system of a certain structure, in which the system-hierarchical homeostasis of interaction of physical, mental and social health statuses at different hierarchical levels is realized. It is proved that the information concept of the phenomenon of human health promotes the further integration of various data, builds constructive ways to formalize complex natural objects, and determines the stable functioning of the bioecosystem.

1. Introduction

The current view of the human health phenomenon is transversally associated with a harmonious, well-developed personality. A healthy person in all respects can be called one who is able to adequately respond and adapt to changing conditions of ecological, biological and social environment, systematically improves himself, maintains a high personal capacity [1, 2].

Relative stability of the bioecosystem and sustainable resources are considered to be important predictors of health, the presence of which allows everyone to realize their health potential [3]. The bioecosystems balance is considered not only in terms of stabilizing normal environmental conditions where they have not been damaged by previous anthropogenic activities, but also the restoration of damaged bioeconomy in order to prevent further disturbance of the ecological balance of the planet. Only consolidated efforts and active restoration and conservation activities can ensure the achievement in the future of a stable planetary ecosystem with optimal physico-chemical parameters for human existence [4].

The concept of sustainable resources involves not only the prevention of depletion of energy resources, minerals, raw materials. It is much larger and involves prudent management, taking into account the financial and material resources of countries, communities, individuals, unused resources of production, materials and tools, intellectual resources, the potential of public and private initiatives. The more different resources are in the assets of a certain structural entity (person, community, organization, region), the greater the potential for directing these resources to health measures.

At the present stage of the study of the multifaceted phenomenon of human health use the idea of health as an integrated system that allows to perform the main function of the viability of the organism and human life in society [5]. When it comes to the level of integral health, its high degree should be characterized by a functional balance of the body with the environment in the presence of physical, mental and social comfort [6, 7].

The modern information paradigm of the human health phenomenon concept is presented as the unity of physical, mental and social aspects [8]. Recently, it has become clear that further productive solutions to health problems are possible not only through the universalization of the definition of health, but also through new approaches, principles of its study, where sustainable development and information technology are special [9]. Thus, there is a clear approach to the study of the information concept of the phenomenon of human health as a guarantee of stability of bioecosystems.

The research aim is to theoretically substantiate the information-structural model of human health and to characterize its components.

2. Methodology

The theoretical and methodological basis of the work was the synergistic use of the following components: the scientificity principle to reveal the causal links in a complex system of integrated health and balance of the body with the environment in the presence of physical, mental and social comfort, and a systematic approach finding out the real difficulties that have arisen in the process of studying the phenomenon of human health and developing options for their elimination. This approach has led to the choice of certain research methods: general - analysis, synthesis, systematization, generalization of scientific content on the information concept of the phenomenon of human health from literary sources; interdisciplinary - axiological method was used to study the achievements of the scientific community in the field of information concept of integrated health; the method of information-structural modeling involved a multifaceted study of integrated health and the creation on this basis of information-structural model of human health, characterization of its components and relationships with the environment as a guarantee of stability of the bioecosystem. The combination of research selected methods is justified by the complexity and ambiguity of the studied problem and the need for in-depth knowledge, which is not limited to analysis and systematization of a wide range of scientific sources, but reaches the level of worldview generalizations.

3. Results

The use of information-structural modeling involves a deductive way of dividing a complex problem into qualitative blocks that contain information about the structure and functioning of the subject of modeling, as well as a description of the overall organization of these blocks and their problem-oriented verbal components [10, 11]. Based on this method use, the current trend of natural science, which is the key to the stability of the bioecosystem, is the information model of human health. It consists of at least three blocks: the information field of knowledge of the main subject areas; information and technological base of research; information and organizational means of management (figure 1).

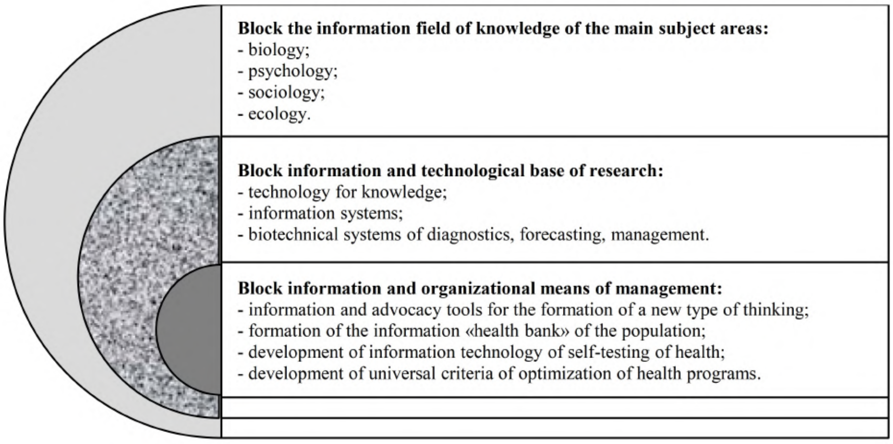

Figure 1. The information model of human health

The first block is the information field of knowledge of the main subject areas which is divided into such subject areas that constitute the necessary knowledge of interdisciplinary research and are basic for the category of human health: biology, psychology, sociology, ecology. It provides basic knowledge for shaping health concepts as a guarantee of bioecosystem stability. It is through these disciplines that a systematic synergistic approach to the problem of health from the standpoint of the unity of physical, mental and social aspects in the functioning of biosystems, implements interdisciplinary research methodology, conceptual exchange of constructive information. The criterion for the separation of knowledge in these subject areas is the criterion of compliance of knowledge with the global goal of research on the phenomenon of health, namely:

(i) human health in different environmental environments from the standpoint of physical, mental and social status;
(ii) the dependence of health on the interaction of major factors: genetic, environmental and lifestyle;
(iii) the formation, maintenance and development of human health in a single intrasystem (human) and system-environmental (human + environment) information space.

Biology, formulating patterns of functioning of individual organs and physiological systems of the body, makes it possible to determine individual deviations or features of these manifestations in the body of a particular person in the range of norms in the form of appropriate normative indicators. Biological sciences gain knowledge about the structural and functional organization of the brain, individual characteristics of the central and peripheral nervous systems, higher nervous activity. Psychology, the object of study of which is a person, his personality, social relations, belongs to the humanities. She studies the patterns of manifestation and development of the psyche, mental phenomena that are divided into mental processes, properties and states. This division is conditional, because all mental processes are interdependent. The course of mental processes always occurs against the background of certain mental states, and individual differences in mental processes act as characteristics of mental properties.

Sociology studies the social mechanisms of the relationship personality-society, specific forms of manifestation of general laws in the field of social interaction of people in historically formed forms of communication. More important for the problem of health is the aspect of phenomena and processes that occur when people interact with society, group interactions with other people in accordance with generally accepted moral and ethical values in this society. The nature of moral relations, conflict or comfort of social behavior of the individual as a member of a social group affect the mechanisms of its systemic and environmental homeostasis.

Ecology as a science studies the patterns of formation and functioning of biological systems in their interaction with the environment. In the complex of environmental problems of human health is a central system-forming factor that combines various studies aimed at studying the patterns of influence of various external influences on the human body. Nowadays, the issue of environmental conditionality of the population is very important. To solve it, one must learn to objectively assess not only human health, but also the health of the environment. It should be noted that the environment is diverse, unstable and multifactorial.

Within the studied focus of the problem in this subject area requires knowledge of the econorm as a systemic-environmental homeostasis of human interaction with different environments - natural (environment), social, informational and spiritual. Equally important is knowledge of methods and techniques for diagnosing the functional state of man in extreme environments, its ultimate ability to adapt to them, as well as knowledge of methods and tools to maintain systemic and environmental homeostasis of the human body in various extreme environments.

Logically related to the latter is the knowledge of diseases treatment methods of various environmental environments that surround man. By diseases treatment we mean the creation, if possible, of such an eco-environment (natural, social, informational, spiritual), which would not harm human health and contribute to the disclosure of all its potential: physical, spiritual, intellectual, etc.

The second block of the health problem is the information technology research base. Today, each of the sciences described above has its own methods and diagnostic tools that assess the indicators of mainly their side of human health (body, brain behavior) in changing environmental conditions. The current level of development of new information technologies with their methodology, methods, tools of analysis and synthesis allows to reach a new level of awareness and presentation of already known and new knowledge. However, the development of such a unified technology for integrated health research, taking into account its complex bioecosystem nature, is just beginning.

This unit is conventionally divided into the following components: information technology for knowledge; information systems; biotechnical systems of diagnostics, forecasting, management. The first component includes the following components:

(i) technology of data awareness - obtaining information;
(ii) information awareness technology - obtaining knowledge.

Note that this division of the first component is consistent with the main idea of information technology, namely the awareness of the triad data - information – knowledge. The component Information Systems, in turn, is divided into:

(i) information and reference systems;

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(ii) information-analytical systems (diagnostic, forecasting, control, and monitoring, working in different time slices: continuous monitoring of the state of the object of study and discrete-continuous);

(iii) information and consulting systems;

(iv) expert and polyalgorithmic expert systems of diagnostics, forecasting and management.

The separation of biotechnical systems of diagnostics, forecasting and management as a separate unit of information systems (because sometimes a biotechnical system can be considered as a type of information system) is due to its direct connection with man (healthy or sick) as opposed to information system with a person both directly and indirectly. In addition, information systems also deal with the information field of knowledge about the human environment.

The block isolation of information-technological base of research with its components provides facilitation and streamlining of work with large flows of information in the multifaceted field of knowledge. The purpose of this block is to collect, store and analyze the information field of knowledge of the subject areas of biology, psychology, sociology, ecology, as well as the transformation of this knowledge to solve problems of maintaining and promoting health.

The third block consists of information and organizational tools for health management: information and advocacy tools for the formation of a new type of thinking (development of healthy lifestyle skills, fashion for health); formation of the information health bank of the population according to the unified technology of bioecomedicine; development of information technology of computer self-testing by the user of the integrated health index; development of universal criteria of adequacy and optimization of health programs aimed at the formation and maintenance of health at all ages of human life.

Health as the most important process of life of the human body and personality is influenced by a whole range of environmental factors - physical, spiritual and social. It follows that it is absolutely necessary to distinguish the physical, mental and social aspects of health, which are equally represented in the overall structure of health as a holistic bioecosocial system. At the same time, it is possible to form an informational idea about the block structure of the health category by decomposing it as a whole.

The health information structure can be represented as a hierarchically branched tree with five levels. Each level, in turn, contains a different number of information models that reflect its current state.

The first level of health structure is individual integrated health.

The second level is formed by certain aspects of health - the so-called statuses: physical, mental and social.

The third level consists of the health status components, each of which has its own structure and function. The components of physical health are: the body's internal physiological systems and the body's control systems. The components of mental health are: intelligence, emotions and character. The components of social health are: personal-environmental and personal-moral aspects.

The fourth level is formed by the component elements. For components of the internal physiological system of the body - these are individual physiological systems of the body, such as cardiovascular system, respiratory system, blood system. For the governing system of the body - the nervous system, immune system and endocrine system. The components of the intellectual component are: properties of thinking, memory, attention and perception. The components of the emotional component are the subjective experiences of the individual - the impressive and expressive components. The components of character are the qualities of the individual responsible for maintaining and maintaining health. The following are accepted as components of the social component: adaptation to physical living conditions; adaptation of personality to working conditions; adaptation to the moral and ethical norms of society. The personal and moral component is formed by: honor, conscience, dignity, responsibility, charity.

The fifth level of the structure of health is formed by separate indicators of all components of health. Thus, for the cardiovascular system as a component it is: heart rate, systolic blood pressure, diastolic blood pressure, cardiac output, etc. Values of physical health indicators are obtained by clinical-diagnostic and laboratory methods or by calculations. Indicators of mental and social status are determined by methods of field and laboratory observation, testing, surveys, questionnaires, etc. We describe the principles on which the concept of the human health phenomenon as a guarantee of stability of the bioecosystem.

The generalization principle of the information knowledge field. The general picture of the information field of interconnected flows of knowledge in the subject areas of biology, psychology, sociology, ecology, which are changing dynamically, is represented by the function of a specific task of interdisciplinary research to be solved.

The principle of systematic research. In order to optimize the solution of complex problems of different fields of knowledge, it is necessary to consider the object as a holistic system, identifying the diversity of types of connections in it and reduce them to a single theoretical picture.

It should be noted the relationship between the principle of systematic research with the principle of generalization of the information field of knowledge. Systematics directs the researcher to a comprehensive intrasystemic study of the interconnected functioning of physiological systems of the body, on the one hand, and systemic-environmental interaction of man with the environment - on the other, which allows to distinguish between general and specific patterns of environmental impact as the unity of physical, mental and social statuses. The systems approach prompts the researcher who solves a specific problem to be included in the general picture of the information field of knowledge in the subject areas of biology, psychology, sociology, ecology.

The principle of homeostasis at different levels of biosystems organization. For the harmonious evolutionarily adequate functioning of the complex object man + eco-environment it is necessary to maintain a dynamic balance of system-environmental interaction in changing eco-environments, onto- and phylogeny. Thus, the observance of this principle as an attribute of systematics pursues the goal of forming the harmony of the bioeco-object.

The adequacy principle of system-environmental interaction. To ensure the adequate functioning of the object of study in the comprehensive diversity of its conditions in terms of human health - its physical, mental and social status, and the state of eco-environments, including extreme, with which man interacts, it is necessary to individually objective adaptation of system-environmental interaction, ie intrasystemic adaptation of a specific complex object of functioning man + eco-environment.

The internal systemic adaptation of such a complex object should be understood not only as the mutual adaptation of man - eco-environments, but also the adaptation of only man to eco-environments or only eco-environments to man. In this case, individual-object adaptation can be carried out due to both the evolutionary mechanisms of adaptation, and introduced external control actions.

The principle of adequate optimality of system-environmental interaction makes it possible to understand that in the formation, maintenance and development of human health should rely not only on its ability to adapt to environmental conditions, but also on the transformation of ecosystems in the interests of human health, physical, spiritual, intellectual and social needs. Thus, compliance with the principle of adequate optimality of system-environmental interaction is a necessary condition for the implementation of the principle of homeostasis at different levels of organization of bioecosystems.

The principle of evolutionary compensation. Evolution-appropriate management actions are a priority to ensure individual-object adaptation. In this case, evolutionary adequacy is

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determined by the specific object of study.

The humanization principle. To ensure the comfortable functioning of man in the environment, regardless of the state of his physical, mental and social status, it is necessary to create such eco-environments that are adequate to the capabilities of the individual, meet his physical, spiritual, intellectual and social needs and contribute to its potential.

The principle of ethics and aesthetics of human interaction with eco-environments. In order to form, maintain and develop health as an alternative to the endless treatment of human diseases and eco-environments, it is necessary to cultivate consciously caring attitude to eco-environments and consciously caring eco-environments, remembering that the main commandment of medicine Do no harm directly, but also indirectly, through the eco-environments that surround it.

The principle of the information space intellectualization. In order to optimize the process of solving complex problems in a single information field of knowledge of the subject areas of biology, psychology, sociology, ecology should use the latest information technology, including methods, algorithms, mathematical, informational and verbal models, hardware and software, resulting in information product, the power of information intellectualization which is determined by the ability of the researcher to form it and gain new knowledge, including those that go beyond the task. The ability to generate new knowledge and generalize them depends on the intellectual component of the researcher: logical, associative, algorithmic thinking.

4. Conclusions

It is established that the information space of individual health statuses is an integral multidimensional dynamic system of a certain structure, in which the system-hierarchical homeostasis of interaction of physical, mental and social health statuses at different hierarchical levels is realized. It is proved that the information concept of the phenomenon of human health promotes the further integration of various data, builds constructive ways to formalize complex natural objects, and determines the stable functioning of the bioecosystem. The basics of a new interdisciplinary approach to the formation of a generalized view of the phenomenon of human health from the standpoint of information-structural modeling: systematized information concept of integrated health as a unity of physical, mental and social health, verified it, obtained information about the system in as a whole by translating verbal-qualitative information into quantitative assessments. The main purpose of this approach is to learn to assess the limits of harmonious human interaction with the environment and to learn the mechanisms that ensure this harmony. To achieve this goal requires information integration and transformation of knowledge accumulated in the subject areas of biology, psychology, sociology, ecology - building an information space using the latest information technology to develop adequate and optimal measures, including diagnostic, treatment, rehabilitation, prevention. This space is the only field of knowledge of these subject areas, which is focused on the formation, maintenance, development and restoration of human health, which operates in different environments. The algorithm for achieving the global goal in the form of a set of principles reflects the essence of a systematic approach to solving specific problems. Today, as never before, people are increasingly realizing that the formation, maintenance and development of their health depend on a single field of knowledge in different subject areas. Combining knowledge of the subject areas of biology, psychology, sociology, ecology as the most important for human health is the first contribution to the formation of a healthy society of the future as a guarantee of bioecosystems stability.

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To cite this article: O E Pyurko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012071

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012071 doi:10.1088/1755-1315/1049/1/012071

Endo-adaptive mechanisms of mesophytic plants' functioning as a component of ecosystem resistance

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Abstract. The ecological state deterioration of the biosphere contributes to the formation of structural-functional mechanisms of plants' adaptation to the synergistic influence of negative factors at different levels of living systems' organization. A complex algorithm of the plant organism reaction response to any adverse factor includes a wide range of histological-metabolic adaptive mechanisms that provide a nonspecific reaction and are responsible for increasing the plant organism resistance. Aim is the investigation of endo-adaptive specificity of mesophytic plants' formation as an ecosystem resistance component. Methods are experimental research, quantitative and anatomical analysis, mathematical and statistical processing of the obtained data. The article presents the histological-functional specificity of Portulaca oleraceae L. vegetative organs under chloride load and without it in the Ukrainian south conditions. It is proved that the various parameters study of plants' metabolism and anatomical-morphological reconstruction plays an important role in studying the salt resistance mechanisms, which determine the existence of mesophytic plants under stressful environmental changes. It is shown that adaptability is an equal component of two interdependent processes (the development of damage caused by stressors and the restoring the values of structural-functional parameters), which generally forms an endo-adaptive mechanism of plant functioning and ensures steadiness of ecosystem stability.

1. Introduction

The south of Ukraine forms a zone of risky agriculture, which is characterized by a temperate–continental climate with hot summers, high solar insolation and significant water shortages, and soil salinity causes poverty and specificity of natural flora [1–3]. Salt resistance of plants is an urgent problem of crop production, attracts the attention of many researchers and practitioners of agriculture due to the need to increase yields on saline soils and the development of new lands. Soil salinization causes great damage to agriculture, reducing crop yields [4–7]. The study of the relationship of plants with the environment is of theoretical interest in terms of understanding the mechanism of action of salts on the plant organism and the corresponding reactions of the organism. In addition, under natural conditions, the toxicity of salts depends on a number of other reasons: soil moisture, its mechanical composition, the presence of nutrients [8–12]. However, despite the enormity and complexity of the problem of salt tolerance, its solution largely depends on knowledge of the nature of salt tolerance, knowledge of the adaptability to salinization of the soil of various herbaceous and woody plants, and the effectiveness of methods to increase salt tolerance. Thus, the problem of salt resistance is an important aspect of the dynamic evolutionary ecology of plants [13–17]. Therefore, salt resistance should be understood as an ecological and physiological phenomenon, which is formed mainly on the study of its own mechanism of stability and understanding of the active adaptation that characterizes the plant. Mesophytic plants fight overheating and salinization by vertical arrangement of leaves, folding and folding of leaf blades, increasing the intensity of transpiration [8, 18]. More heat–resistant mesophytes are characterized by increased cytoplasmic viscosity and cell juice concentration, increased synthesis of heat–resistant enzyme proteins. Heat–resistant plants are characterized by specific morphological and anatomical features of the structure of individual organs, have a reduced level of metabolic processes, have high viscosity of the cytoplasm, high content of bound water in the cell, etc. In order to derive sustainable cultivated plants, this issue is becoming increasingly important [19–21]. Using this ability, especially at a young age, you can change the nature of the plant and create high–yielding forms, able to withstand various types of salinity, soil and air drought and bring in these conditions a larger harvest, which is very important for humans.

Aim is the investigation of endo–adaptive specificity of *Portulaca oleracea L.* mesophytic plants' formation under chloride loading and without salinization during ontogenesis as a component of ecosystem resistance.

2. Methodology

During the theoretical study of the problem, research and experimental work, general scientific research methods were used: theoretical analysis and generalization of scientific and methodological literature on morphology, anatomy and ecology of plants, periodicals; experimental method, quantitative anatomical analysis, mathematical and statistical processing of the obtained data [8, 19]. Determination of the vegetative organs size of experimental plants was carried out according to generally accepted morpho–anatomical methods [4,6], physiological characteristics were studied according to generally accepted physiological methods [19]. The data statistical analysis was performed using Microsoft Excel and Statistica 8.0. The average measurement error does not exceed 5%.

3. Results

The data analysis showed that the *Portulaca oleraceae L.* root has the following structure: bark (71,02%), periderm (15,26%), cambium (0,96%), wood (3,13%), xylem bundles of three levels (9,63%): the first – 2,43%, the second – 3,2%, the third – 4,0% (figure 1). At the root of the cortex parenchyma does not perform a water–retaining function. Here, probably, some important substances are synthesized, as well as spare substances accumulate. Here, in the vacuoles of the cells of the parenchyma of the cortex, salts are deposited, which come in excess to the plant. Elements of a phloem are very weakly traced in a parenchyma of bark. Our studies have shown that in saline proportions of *Portulaca oleraceae L.* root tissue acquires the following values: bark (71,3%), periderm (14,88%), cambium (0,87%), wood (3,21%), the xylem bundles of three levels (9,74%): the first – 2,5%, the second – 3,23%, the third – 4,01%. It has been proven that in *Portulaca oleraceae L.* the tips of the roots are damaged and brown, and this leads to the intensive appearance of lateral roots of the 2nd and 3rd levels. This changes the spatial structure of the root system, which on saline soils is located in the surface layers of the soil. NaCl salts significantly accelerate the lignifications of the inner walls of epidermal cells and cause their thickening. Regardless of the root growth conditions, the rate of woodiness of their cells does not change. This process is a specific protective reaction aimed at creating a barrier that limits the entry of salt ions into the plant.

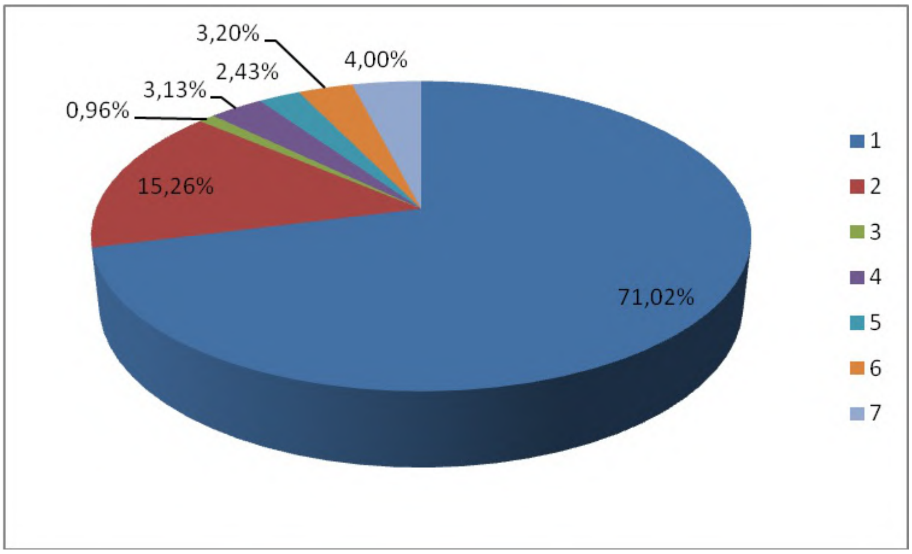

Figure 1. Histological ratio in the *Portulaca oleraceae L.* root: 1 – bark, 2 – periderm, 3 – cambium, 4 – wood, xylem bundles of three levels: 5 – first, 6 – second, 7 – third.

The study of the internal structure of the *Portulaca oleraceae L.* stem showed that the epidermis is 0,15% of the stem total thickness. Under the epidermis is a small layer of collenchyma – 2,39%. Behind it is the cortex parenchyma – living, large cells that perform a water-storing function, which accounts for 2,39%. And in general the bark is 7,32%, which is also 3 times less than at the stem top. The bark is followed by meristematic tissue – cambium, which is 0,16% of the total cut. The layer of wood here is represented by sclerenchyma and vascular–fibrous bundle. The sclerenchyma lies in a continuous layer, as it accounts for 11,36% of the total ones. Behind the sclerenchyma are collateral vascular–fibrous bundles located in a circle. They are larger than in the upper part and make up 11,36% of the total cut size, and in total wood occupies 19,13%. The xylem vessels are directly adjacent to the core cells, which ensures the unimpeded transition of the required amount of water and minerals immediately into the bundles, and from there to the desired parts of the plant. The core is represented mainly by round or medium water–storing cells. Round cells of the 3rd level, their size is 5,53% of the total thickness; 2nd level cells – 3,29; 1st level cells are not even observed.

After the NaCl action, the plant *Portulaca oleraceae L.* formed a characteristic morphological structure, and this corresponds to the anatomical features: bark – 4,85%, collenchyma – 2,32%, bark parenchyma – 2,32%, cambium – 0,16%, wood – 19,34%, sclerenchyma – 11,37%, VFB – 11,37%, core – 39,51%: cells of the 2nd level – 3,22%, cells of the 3rd level – 5,54% (figure 2) . It is shown that assimilation shoots are sluggish, translucent, pale green; epidermis cells, parenchyma, cortex parenchyma and vascular bundles decreased significantly in size.

Of all the plant organs, the leaf is most closely connected with the environment in the process of intensive metabolism – photosynthesis and transpiration. Therefore, its structure much more strongly reflects the impact of changing environmental conditions. The external morphological diversity of the leaf is accompanied by the same diversity of its anatomical structure. Above and below the leaf is covered with a single layer of epidermis. The epidermis is represented by large, thin–walled cells that are tightly pressed together. The main cells form a cover that protects the cells from drying out, mechanical damage, and infection. The leaf epidermis is 2,58% of the total thickness of the leaf. Compared with the control of the epidermis for salinity decreased in size and amounted to 1,5%.

Using morpho–anatomical methods Zakharevich S.F. [6] in the study of the main cells of the

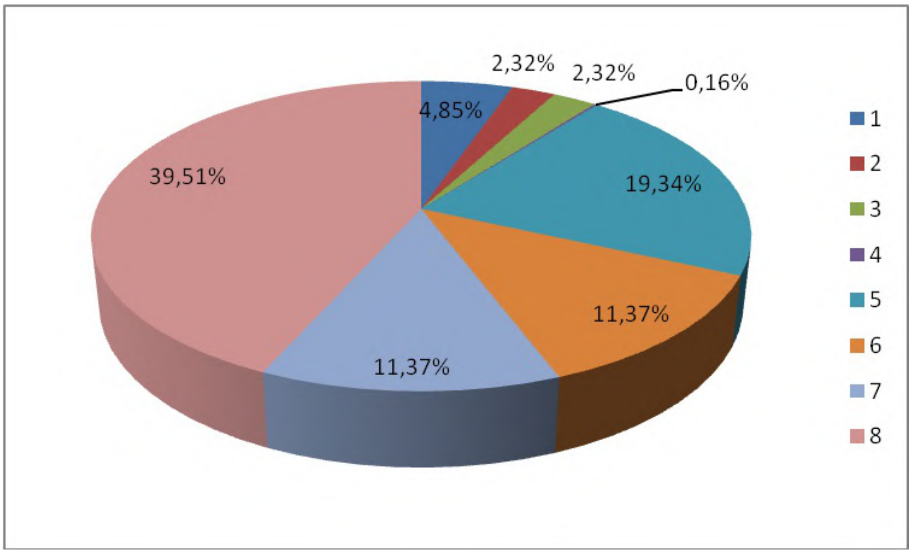

Figure 2. The tissues ratio of the *Portulaca oleraceae L.* stem: 1 – bark, 2 – collenchyma, 3 – the bark parenchyma, 4 – cambium, 5 – wood, 6 – sclerenchyma, 7 – VFB, 8 – core.

leaf integumentary tissue, we identified two types of cells that differ in size, projection: – 240 *pcs.*, cell size along the long axis – 720 *microns*; S = 4800 μm^2; type II – projection of cells 5–6 angular, angles – pointed and obtuse, the number of cells per 1 mm^2 – 150 *pcs.*, cell size along the long axis – 360 μm; S = 1200 μm^2. The type of respiratory system is anomocytic.

Under the NaCl action there are the following anomalies of the respiratory complexes: type I – two stomata are in one polygonal cell, the contours of the cell – rectilinear, sharp, obtuse angles; type II – the stomata are surrounded by two cells, on the one hand a hexagonal cell, on the other a 5–cornered cell, cells with rectangular faces, with pointed and obtuse angles; type III – stomata are accompanied by two cells, one of which is much larger than the other; type IV – the stomata are surrounded by a pair of epidermal cells, whose common walls are at right angles to the closing cells (diacytic type of the respiratory tract). According to some authors [3, 5–7, 9–12, 14–17, 20] abnormal respiratory complexes occur under the influence of stress, in this case under the NaCl action.

On average, the short axis of the respiratory cell is 240 μm, the long – 300 μm. The stomata number is 140 $pieces/mm^2$.

After the epidermis is the mesophile, which is differentiated into photosynthetic and aquifer parenchyma. The photosynthetic parenchyma is 54,22 % of the total thickness. The aquifer parenchyma is represented by large water–storing cells and is 32,27 % of the total leaf thickness.

As a result of the constant shortage of water, the plant, receiving excess water, tries to keep it on a rainy day in the maximum amount and wherever possible. In this case, in the *Portulaca oleraceae L.* leaf such a storage tissue becomes the aquifer parenchyma. The aquifer parenchyma is surrounded by lining cells. In the center of the leaf is a vascular–fibrous bundle, and is 9,89%. It consists of the beam xylem zone, located farther from the stem, and the beam phloem zone (closer to the stem).

It was determined that the leaf under the NaCl action became sluggish, pale green, inanimate, acquired a characteristic morphological structure, and this corresponds to the anatomical features: cuticle (0,94%), epidermis (2,44%), photosynthetic parenchyma (54,39%), aquifer spongy parenchyma (32,45%), the leading bundle (9,78%) decreased significantly in size, there were multifaceted friends of rectangular shape due to stress.

Analyzing the data on the weight of one seed and the number of seeds in plants, a pattern is observed (table 1). In *Portulaca oleraceae L.* on saline soil the seeds are small, and in *Portulaca oleraceae L.* in control more. It was found that 75% of seeds germinate in the control of *Portulaca oleraceae L.* plants, and 58% in saline plants.

Adaptation of *Portulaca oleraceae L.* can be assessed according to the variability level of physiological–biochemical parameters and anatomical–morphological adapted changes at different levels of the organization during ontogenesis, which characterize the "reliability" of a particular genotype. In this case, the plant productivity, as the final integrated indicator, finally shows the influence degree of the active factor on the plant, and the analysis of the productivity components, to some extent, allows determining the main directions and magnitudes of this impact.

Table 1. *Portulaca oleracea L.* productivity (SP – Seed productivity; CSP – Coefficient of seed productivity).

Experiment option	Seed diameter, μm	Seed weight, mg 1000 pcs	Mass one seed, mg	SP Potential	SP Real	CSP
Salinity	875,6±1,3	360±0,9	0,36±0,9	500±100	50±0,7	0,58±0,5
Control	908±1,4	390±1,2	0,39±1,1	250±40	120±1,2	0,75±0,7

Full realization of the *Portulaca oleraceae L.* potential productivity is possible only in the presence of favorable conditions for its vital activity. Features of individual plant development are determined by genotype, response rate and level of its implementation in the phenotype, which largely depends on environmental conditions, including water supply during the growing season.

Accordingly, finding out as many reasons for reduced productivity, identifying the main directions and depth of stress, in this case – salinity, are a necessary prerequisite for the development of scientifically sound technologies for growing plants for rational and efficient use of saline and plant resources in specific areas.

4. Conclusion

The learning of a complex of histological–functional changes, coordinated by self–regulation of the plant organism, in particular *Portulaca oleraceae L.*, is important for studying the mechanisms of salt resistance of mesophytic plants in southern Ukraine. Than higher the level of biological organization (cell, organism, population, biogeocenosis) that greater the number of mechanisms involved in the adaptation of plant organisms to stressful environmental conditions. Histological and functional characteristics of *Portulaca oleraceae L.* allow a clearer understanding of the plant adaptation mechanism to environmental conditions, which forms a correct conception of endo–adaptive mechanisms of mesophytic plants' functioning as part of ecosystem resilience.

Generalized structural analysis of the obtained data showed that the *Portulaca oleraceae L.* root has the following structure: bark (71,02%), periderm (15,26%), cambium (0,96%), wood (3,13%), bundles xylems of three orders (9,63 %): the first – 2,43%, the second – 3,2%, the third – 4,0%. It is proved that at salinity the root tissues ratio of this plant acquires the following values: bark (71,3%), periderm (14,88%), cambium (0,87%), wood (3,21%), xylem bundles of three orders (9,74%): the first – 2,5%, the second – 3,23%, the third – 4,01%.

It was found that the internal structure of the *Portulaca oleraceae L.* stem is represented by the following components: epidermis of the bark (0,15%), collenchyma (2,39%), the bark parenchyma (2,39%), cambium (0,16%), wood (19,13%), sclerenchyma (11,36%), VFB (11.36%), core (8,82%). After the NaCl action this plant formed a characteristic morphological structure, which corresponds to the anatomical features: bark — 4,85%, collenchyma — 2,32%, the bark parenchyma — 2,32%, cambium — 0,16%, wood — 19,34% , sclerenchyma — 11,37%, VFB – 11,37%, core — 39,51%.

It is shown that the epidermis forms 2,58% of the total leaf thickness of *Portulaca oleraceae L.* compared with the control of the epidermis in salinity decreased in size and amounted to 1,5%, and also had anomalies of the stomatal complexes. The leaf under the NaCl action became sluggish, pale green, lifeless, acquired a characteristic morphological structure, and this corresponds to the anatomical features: cuticle (0,94%), epidermis (2,44%), photosynthetic parenchyma (54,39%), aquifer spongy parenchyma (32,45%), the leading bundle (9,78%) decreased significantly in size, there were multifaceted friends of rectangular shape due to stress.

These researches show that in *Portulaca oleraceae L.* on saline soil the seeds are small, and in control more ones; in control 75% of seeds germinate, and on saline – 58%.

Thus, adaptability is an equal component of two interdependent processes – the development of damage caused by stressors, and the restoration of structural–functional parameters, which generally forms an endoadaptive mechanism of plant functioning and ensures the ecosystem stability.

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To cite this article: I A Maltseva *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012072

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012072 doi:10.1088/1755-1315/1049/1/012072

Ecological determinants of algal communities of different types of ecosystems

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Abstract. The results of studies of the environmental regularities of the formation of algal communities in soils of various ecosystems in the south of Ukraine are presented. 26 forest, 11 steppe and 3 saline ecosystems were investigated. The research has established the species richness of algae in each ecosystem and produced a multidimensional ordination of algal communities based on the analysis of the main components to clarify the factors that determine the composition of algal communities. The research has established the species richness of algae in each ecosystem and produced a multidimensional ordination of algal communities based on the analysis of the main components to clarify the factors that determine the composition of algal communities. Predictors determined by edaphic conditions and phytocenotic interactions associated primarily with edificators of ecosystems were used for the analysis. The ecological space of the studied ecosystems was formed by four main factors with eigenvalues greater than one, which explained 81.4% of the total variance. PC1 (34.82% of variance) is associated with the type of ecosystem and such edaphic parameters as pH, the availability of moisture in the habitat, and soil mineralization. PC2 (21.98%) reflects changes in the gradients of trophicity (humus content) and granulometric composition of soils. PC3 and PC4 additionally explain 16.04% and 9.27% of the total data variance, respectively. Their values mainly depend on the mineralization, trophicity, and moisture supply of edaphotopes, which, at the level of the composition of algae, is obviously associated with the heterogeneity of the ecological preferences of the algal species themselves, as well as the variability of ecological niches of ecosystems, due to which there are species more typical for other types of ecosystems in the communities. The use of the factor rotation procedure by the Varimax normalized method made it possible to concretize the taxa most associated with the main components: PC1 indicates the various Cyanobacteria species, PC2 – Chlorophyta, Streptophyta and Eustigmatophyceae, PC3 – Xanthophyceae and Euglenozoa, PC4 – Bacillariophyceae.

1. Introduction

From the perspective of the general theory of systems, the internal structure of ecosystems is determined by the nature and way of interaction of elements [1]. The forest and herbaceous ecosystems have different abilities to influence the formation of their internal phytocenotic environment and the composition of the organisms that inhabit them [2–5]. The various studies have shown the specific features of algal communities in forest, steppe, desert, and other ecosystems [6–11]. This is consistent with the definition of the essence of the ecosystem, where it is represented by a set of interconnected organisms that function in the same territory and interact with the environment in such a way that the flow of energy forms clearly defined biotic structures and the circulation of substances between the living and nonliving components. At the same time, ecological factors are not only interrelated and determine the nature of plant communities, but the latter also acts as a powerful ecological factor that forms the specificity of the ecotope [12–15]. Therefore, there is no linear relationship between vegetation and environmental conditions and their change [16]. It has a more complex character [17, 18]. Even more complex nature of interactions is expected at the level of individual organisms and their communities that occupy a subordinate position relative to the edificators that determine the structure and functioning of a particular ecosystem [19,20]. This fully applies to microscopic algae inhabiting the upper soil layers. Many works have been devoted to the study of factors affecting the composition and structure of microalgal communities [21–24].

2. Research aim and objectives

However, given the contemporary understanding of the priority of the conservation and maintenance of natural diversity, there is considerable interest in microalgae, not only as organisms that provide a wide range of ecosystem services [9, 25, 26] but also sources of biotechnologically valuable compounds [14, 23, 27–30], further continuation of these studies is necessary.

The aim of this work was to identify the influence of phytocenotic and edaphic factors on the structure of algal communities in various forest, steppe, and saline ecosystems.

3. Material and methods

The analysis was carried out on the basis of material collected in 2000-2013 in the south and southeast of Ukraine in oak (5 ecosystems), alder (4), aspen-birch (3), and pine (6) forest ecosystems in the floodplains of the Samara, Severskiy Donets, Vovcha, Molochna rivers, in oak (8) forest ecosystems in gullies (ravine oak forests), in the steppe (11) and saline (3) – in flat habitats. Within each ecosystem, 5 soil samples each with a volume of 25 cm^3 were randomly selected to determine the species composition of microalgae, as well as a number of physicochemical parameters of the soil: pH (water), humus (%), the sum of salts (dry residue, %), particle size distribution (content of physical clay, %). The selection of soil samples for research in each ecosystem was carried out in 3–6 fold replicates. For each ecosystem, moisture conditions (hygrotope) were determined, depending on both on the climatic conditions of the study region and on the location in the relief. They were ranked from "0" to "5", respectively, from very dry habitats to wet habitats. The type of ecosystem was distinguished taking into account edificators – arboreal and herbaceous. The species composition of algae was determined based on methods of working with crops. We used soil cultures with fouling glasses, agar on BBM medium for the growth of green algae, and some Heterokontophyta (Ochrophyta), G11 – for Cyanobacteria [31], WC liquid medium – for Bacillariophyceae [32]. When setting and working with crops, standard procedures were used [31]. The cultivation was carried out at a temperature of 20°C and a light intensity of 35 mmol m^{-2} s^{-1}. The alternation of light and dark periods was 12 hours / 12 hours. The determination of algae was carried out with an optical microscope "XSP–128" at a magnification $\times$ 1000, and using oil immersion. The referential system of Cyanobacteria was used in accordance with the reports of I. Komarek and A. Anagnostidis [33, 34], the rest of the groups – according to "Syllabus of Plant Families" [35]. The literature used for identification included Ettl and Gärtner [36,37], and other [36,38–45]. The particle size distribution of the soil was determined by the method proposed by N.A. Kaczynski, the humus content – according to I.V. Turin, pH of water extract by potentiometric method [46]. The analysis of the dependences of the composition and structure of algal communities on soil and phytocenotic parameters was carried out by the method of principal components.

4. Results and discussion

The Algae of various divisions were found within the studied ecosystems (table 1). A wide variety of Chlorophyta and Heterokontophyta species are noted in forest ecosystems. They account for 39.7–59.7% and 28.9–45.3%, respectively, of the total number of algae species in forests. The majority of Heterokontophyta is represented by species from the classes Xanthophyceae, Bacillariophyceae: 17.5–27.4% and 7.9–16.9% (respectively, of the entire diversity of species). The diversity of Eustigmatophyceae from Heterokontophyta, Streptophyta, and Euglenozoa is low and limited to a few species. Cyanobacteria in forest algal communities range from 2.7% to 15.7% of the total number of species. The data obtained are generally consistent with the results of other researchers of algae in forest ecosystems, which indicate that the main forest communities of algae are Chlorophyta and Xanthophyceae [47–49].

Table 1: The number of algal species in various ecosystems, units (%).

Ecosystems	Flood plain oak forests	Ravine oak forests	Alder forests	Birch and aspen–birch forests	Pine forests	Steppe ecosystems	Salt marshes
The quantity and sequence numbers of the studied ecosystems	5 (1–5)	8 (6–13)	4 (14–17)	3 (18–20)	6 (21–26)	11 (27–37)	3 (38–40)
Cyanobacteria	16 (13.8%)	13 (15.7%)	2 (2.7%)	12 (10.0%)	9 (7.9%)	40 (31.3%)	20 (48.8%)
Eustigmatophyceae (Heterokontophyta)	5 (4.3%)	3 (3.6%)	2 (2.7%)	5 (4.2%)	4 (3.5%)	4 (3.1%)	–
Xanthophyceae (Heterokontophyta)	25 (21.6%)	17 (20.5%)	20 (27.4%)	21 (17.5%)	20 (17.5%)	20 (15.6%)	7 (17.1%)
Bacillariophyceae (Heterokontophyta)	10 (8.6%)	14 (16.9%)	11 (15.2%)	15 (12.5%)	9 (7.9%)	14 (10.9%)	3 (7.3%)
Chlorophyta	55 (46.6%)	33 (39.7%)	32 (43.9%)	61 (50.8%)	68 (59.7%)	46 (36.0%)	10 (24.4%)
Streptophyta	5 (4.3%)	3 (3.6%)	4 (5.4%)	5 (4.2%)	4 (3.5%)	4 (3.1%)	1 (2.4%)
Euglenozoa	1 (0.8%)	–	2 (2.7%)	–	–	–	–
In total	116	83	73	120	114	128	41

It should be noted that the role of green algae and Xanthophyceae in the formation of communities differs in various types of forest. Also among the studied forest ecosystems, there are those where pronounced participation of diatoms and cyanobacteria was observed. For example, a wide variety of diatoms was characteristic of oak forests in gullies (ravine oak forests) and alder forests growing in the lowlands of the floodplain part of river valleys. In general, Cyanobacteria, which are not numerous in forest ecosystems, were common in oak forests growing both in river floodplains and in gullies. It is believed that Cyanobacteria play an insignificant role in forest ecosystems [50]. It is also suggested that the abundance of forest litter and other decomposable biomass in forest ecosystems can provide a sufficient amount of mineral nitrogen and this leads to the absence of nitrogen-fixing Cyanobacteria [50]. Our research does not support this. There are forest ecosystems for which the development of Cyanobacteria is a

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stable trait. These are deciduous and oak forests, including those growing in a temperate arid climate [51]. There is also evidence that in the composition of microorganisms of the forest litter (pine and oak forests), the number of bacteria assimilating mineral nitrogen is maximum in spring, the peak in the number of nitrogen fixers in oak forests occurs in summer, and in pine forests – in autumn [52]. Thus, these regularities still require further study, taking into account the emerging interactions between the organisms inhabiting the soil and forest litter, the processes occurring in them, the physicochemical properties of the soil, moisture conditions, phytocenotic conditions determined directly by edificators. For the studied steppe ecosystems, the predominance of Chlorophyta and Cyanobacteria algal communities was noted. In salt marshes, the role of Cyanobacteria becomes even more pronounced (table 1). A wide variety of Chlorophyta and Cyanobacteria was also noted for other xerophytic ecosystems [53–55], as well as saline soils and salt marshes [6, 11, 56, 57]. Thus, within each ecosystem, a specific ecological space is formed, which is assimilated by various taxa of microalgae. Using principal component analysis, four main factors with eigenvalues greater than one were identified, which explain 81.4% of the total variance (table 2).

Table 2: Eigenvalues and the proportion of the explained variance of the selected factors.

Factor	Eigenvalues	Percentage of total dispersion, %	Cumulative eigenvalues	Cumulative percent, %
1	4.18	34.82	4.18	34.82
2	2.56	21.29	6.73	56.12
3	1.92	16.04	8.66	72.16
4	1.11	9.27	9.77	81.43

When calculating the factor loadings matrix, the rotation of factors was used by the Varimax normalized method. It is an orthogonal rotation method that minimizes the number of high load variables per factor and simplifies the interpretation of factors [58]. In this case, the factor loadings were subjected to the normalization procedure, i.e., dividing by the square root of the corresponding dispersion. The obtained values are presented in table 3.

Table 3: Factor loadings matrix.

Variable	PC1	PC2	PC3	PC4
Cyanobacteria	**0.91**	0.04	–0.13	0.11
Chlorophyta, Streptophyta	–0.16	**–0.81**	0.42	–0.01
Xanthophyceae	–0.22	–0.32	**0.78**	0.16
Bacillariophyceae	0.43	0.01	0.35	**0.60**
Eustigmatophyceae	0.01	**–0.75**	0.06	0.05
Euglenozoa	–0.11	0.03	**0.81**	0.20
Humus	–0.20	**0.55**	0.37	**0.75**
Acidity	**0.82**	0.29	–0.14	–0.29
Mineralization	**0.56**	**0.33**	0.17	**–0.74**
Granulometric composition	0.25	**0.79**	0.44	0.12
Moisturizing	**–0.62**	0.29	**0.64**	–0.08
Ecosystem type	**–0.92**	–0.15	0.14	0.12

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The strongest connection is reflected by factor loadings above 0.7 [58]. However, taking into account the peculiarities of the studies being carried out, we took into account the values of factor loads starting from 0.5, which reflect a weaker relationship between the variable and the factor and have a meaningful interpretation. The first factor, which explains 34.82% of the dispersion, is associated with the type of ecosystem and such edaphic parameters as pH, the availability of moisture in the habitat, and soil mineralization. Along the first axis (figure 1), on one side there is a transition from swampy to xerophytic steppe ecosystems, from ecosystems without signs of salinity with weakly acidic pH to saline ones with alkaline pH values. The second factor reflects changes in the gradients of trophicity (humus content) and particle size distribution of soils. It accounts for 21.98% of the total dispersion. Along the second axis, there is a transition from ecosystems with low-humus soils of a lighter particle size composition to ecosystems with highly humified soils of a heavier particle size composition. The third and fourth factors additionally explain 16.04% and 9.27% of the total data dispersion, respectively. Their values mainly dispersion on the mineralization, trophicity, and moisture supply of edaphotopes. Among the significant factors affecting soil algae, pH, organic matter, particle size distribution, and moisture content were also indicated [50, 59–63].

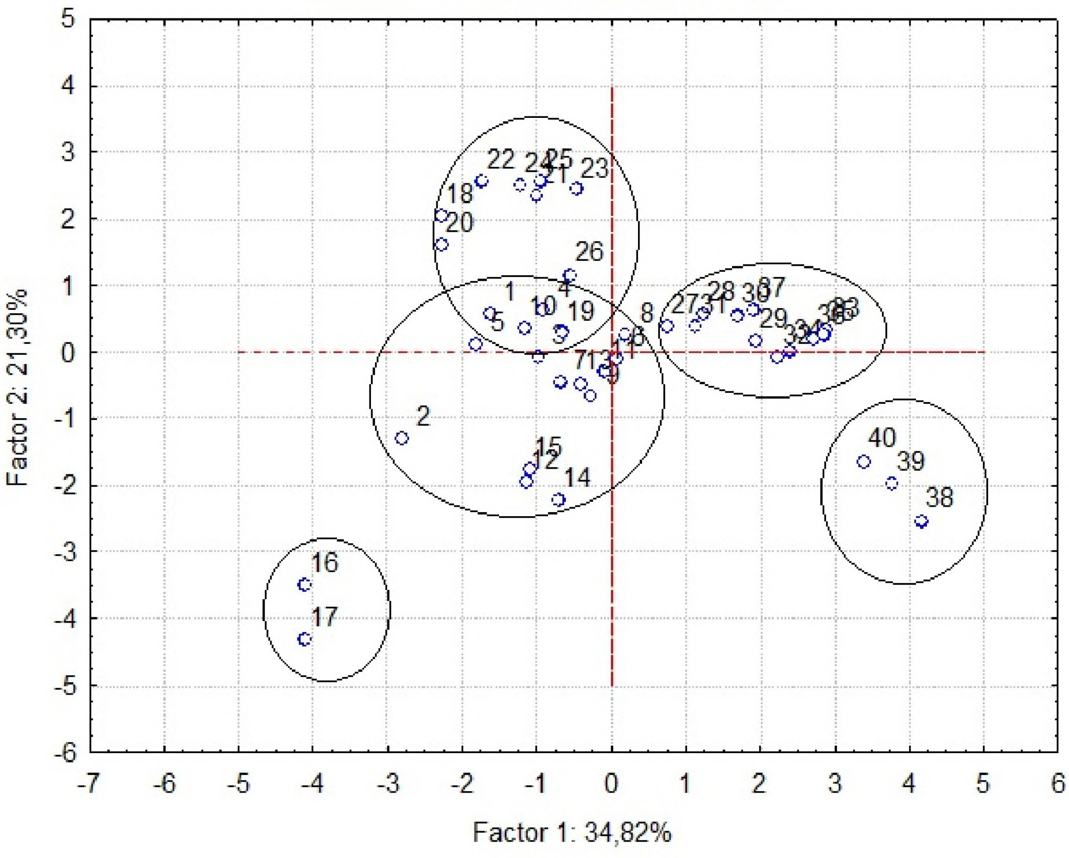

Figure 1: Main ecological gradients of algal communities in different ecosystems. Ecosystem numbers correspond to table 1.

In terms of the composition of microalgal communities, the first main component is indicated by the diversity of Cyanobacteria species, the second is Chlorophyta, Streptophyta, Eustigmatophyceae from Heterokontophyta, the third is Xanthophyceae and Euglenozoa, and the fourth is Bacillariophyceae. Due to the factor rotation procedure, it was possible to reduce the number of taxa in the diagnostic groups to two. This also made it possible, despite the sufficient diversity of ecologically non-equivalent species within each large taxon, to display their preferences within the ecological space allocated by the main factors. For Cyanobacteria, the most significant characteristics of the edaphotop were found to be pH, mineralization, providing moisture, and the type of ecosystem. At the same time, Cyanobacteria are associated with negative values of the coefficients with pH and mineralization, and positive ones with providing moisture and the type of ecosystem, which indicates their multidirectional influence. Green algae (Chlorophyta, Streptophyta) and Eustigmatophyceae exhibit similar requirements for the ecological parameters of their habitat. Such edaphotop characteristics as trophicity and particle size distribution are of particular importance for them. The provision of the habitat with moisture is of particular importance for Xanthophyceae and Euglenozoa, and for Bacillariophyceae – the trophicity and mineralization of the edaphotope.

5. Conclusion

The ecological space within which communities of algae are formed in ecosystems is determined by edaphic conditions and phytocenotic interactions, determined primarily by edificators of ecosystems. In a multidimensional coordinate system describing the ecological space of algal communities, four main factors are determined that explain 81.4% of the total variance. The type of ecosystem, pH, and particle size composition of the soil has the greatest contribution to the dispersion of PC1 and PC2. A somewhat lesser relationship is observed with such characteristics of the edaphotop as mineralization, trophicity, and providing moisture of the habitat. 3 and 4 mainly depend on mineralization, trophicity and providing moisture of edaphotopes. At the level of the composition of algae, this is obviously associated with the heterogeneity of the ecological preferences of the species of algae themselves, as well as the variability of the ecological niches of ecosystems, due to which there are species more typical for other types of ecosystems in the communities. The use of the factor rotation procedure by the Varimax normalized method made it possible to concretize the taxa that are maximally associated with the main components: PC1 is indicated by a variety of Cyanobacteria species, PC2 – Chlorophyta, Streptophyta and Eustigmatophyceae, PC3 – Xanthophyceae and Euglenozoa, PC4 – Bacillariophyceae.

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To cite this article: A Zymaroieva *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012073

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012073 doi:10.1088/1755-1315/1049/1/012073

Analysis of the spatio-temporal trend of sugar beet yield in Polissya and forest steppe ecoregions within Ukraine

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Abstract. Ukraine has all the preconditions to increase the sugar beet yield, but, at present, comprehensive studies of spatio-temporal variation in the yield of sugar beet in the country have not been conducted. Though, such research is essential for the formation of crop management and yield forecasting in the future. The study aim is to analyze the general spatio-temporal dynamics of sugar beet yield within 10 regions of Ukraine, to identify the determinants of this trend and to characterize the areas of Ukraine regarding the sugar beet yield. Several statistical methods have been applied to the average sugar beet yields data which were provided by the State Statistics Service of Ukraine. The Akaike Information Criterion (AIC) was used to estimate the likelihood of a statistical model to the observed data. To calculate the global spatial autocorrelation coefficient, I-Moran statistics were computed using the Geoda095i program. A spatial database was created in ArcGIS 10.2. The average sugar beet yields within the study area ranged from 154.5 dt/ha to 495.7 dt/ha. The spatio-temporal trend of sugar beet yield has been described by a fourth-degree polynomial. It was determined that the overall trend of sugar beet yields is determined by agroeconomic and agro-technological factors, whose contribution to the yield variation is 72-96%. The areas where high sugar beet yields are ensured by favorable natural conditions, such as soil fertility, were identified, as well as areas with high crop yield potential provided that agricultural and breeding techniques are adequately used.

1. Introduction

A high crop yield potential is decisive for the efficient use of available arable land [1–4]. An yield potential is defined as the yield of a variety grown under the conditions to which it is adapted, without any restrictions in water or nutrients, and under the effective control of pests, diseases, weeds, and other stresses [5–7]. In recent decades, the annual increase in the yield of sugar beet varieties in European countries has been about 1.5% [1, 8, 9]. This increase in yield is due to an increase in the average temperature at the beginning of the growing season [10–12] and the improvement of agricultural technology, in particular, the optimization of fertilizer use [13–15] and crop protection [16, 17]. Also, the increase in crop yield potential in European countries is achieved by the improving crop management systems and is not due to the increased production intensity, but rather to the better usage of available natural resources and growth factors [9, 18, 19]. However, the key driver for increasing sugar beet yield potential is breeding progress [1, 20], which allows the increase of sugar content from 4% at the beginning of crop cultivation to over 18% today [21, 22]. Thus, about 50% of the increase in yield and quality of sugar beet was achieved by the progress of selection [23], which, in turn, led to an increase in its yield potential [24]. Currently, some studies claim that the yield potential of sugar beets in developed countries is approaching its limit. Hoffmann and Kenter [1] estimated the yield potential of sugar beet at 24 t sugar ha^{-1}.

Nevertheless, the actual yield is always lower than the potential one, since many factors limit sugar beet yields, such as non-optimal weather conditions (water supply, length, and temperature of the growing period) and management practices [4, 25, 26]. The climate change is one of the most pressing issues confronting agronomy today [19, 27, 28]. Most likely climate change will result in significant increases in sugar beet yield potential (due to accelerated growth during warmer springs) as well as losses due to drought stress [29].

Even though the production of sugar beet in Ukraine has been growing rapidly over the past 10 years, the yield of sugar beet in our country is low compared to EU countries. Thus, in 2019, the average yield of sugar beet in Ukraine was 461.1 ha^{-1}, and in European Union countries was 738.1 ha^{-1} [30, 31]. The average yield potential of sugar beet hybrids in Ukraine is realized only by 50–60% [32]. Due to the increasing crop yields Ukraine can double its sugar production and become a significant exporter.

The sugar beet cultivation is focused in Ukraine's central area, where the soil conditions, water supply, and temperature are all suited for the optimal crop yields and sugar content in beets. This is also due to the proximity of sugar beet processing plants in the same region. Vinnytsia, Poltava, Kyiv, Khmelnytskyi, and Ternopil are the five leading sugar beet cultivation regions in Ukraine, accounting for 61% of total sugar beet production [33]. However, the productive potential of other regions of the country for sugar beet cultivation has not yet been assessed. It should be noted that Ukraine has all the prerequisites to increase the yield of sugar beet, but, at present, comprehensive studies of variations in the yield of sugar beet in the regions of Ukraine in spatial and temporal aspects have not been conducted. And such research is essential for the formation of crop management and yield forecasting in the future.

2. Research aim and objectives

Thus, Ukraine has all of the prerequisites for increasing sugar beet yield, but comprehensive studies of sugar beet yield variations in Ukraine's regions in spatial and temporal aspects have yet to be conducted. And such research is essential for the future development of crop management systems and yield forecasting.

The aim of our work was therefore to solve three tasks:

(i) to analyze the spatiotemporal variation of sugar beet yield in 10 regions of Ukraine (206 districts);
(ii) to determine the nature of the general trend of sugar beet yield;
(iii) to identify areas with the most favorable growing conditions for this crop.

3. Material and methods

3.1. Data of crop yield

Crop data were obtained from the Ukrainian State Statistics Service and its territorial offices (http://www.ukrstat.gov.ua/). The time-series datasets include annual yield averages by the administrative district for 10 regions of Ukraine, which include 267 administrative districts, over 27 years from 1991 to 2017. The research area is divided into two natural vegetation and climatic zones: the Polissya Forest Zone and the Forest Steppe Zone (Zymaroieva et al., 2020). From 1991 to 2017, data on soybeans were available for ten administrative regions (Cherkasy, Chernihiv, Khmelnytskyi, Kyiv, Lviv, Rivne, Ternopil, Vinnytsia, Volyn, Zhytomyr). FAO provided information on the annual yield of soybeans in Ukraine [31].

3.2. Yield trend analysis

As an analytic form of the trend, we chose between polynomials of a different order [34]. Yield trends were analyzed using parsimonious regression models of increasing order for: an intercept-only model, a linear model, a quadratic model, a cubic model, and a quartic model [35, 36].

The Akaike Information Criterion (AIC) [37] was calculated for each of the five regression models to estimate the likelihood of a statistical model to the observed data. A good model has the lowest AIC of all the models and was chosen as the best representation of the yield trend for a specific administrative district. R 3.0.2 was used for all calculations and data analysis.

A fourth-degree polynomial best describes the total yield trend within the investigated area. As a result, the yields trends in all administrative districts were described by fourth-degree polynomials in the next analysis phase for quantitative comparison. As a result, we chose the following characteristics of fourth-degree polynomials: constant, the maximum rate of yields decreases in the range between the first maximum and the minimum, and the maximum rate of yields increases in the range between the minimum and the second maximum [38] (Figure 1).

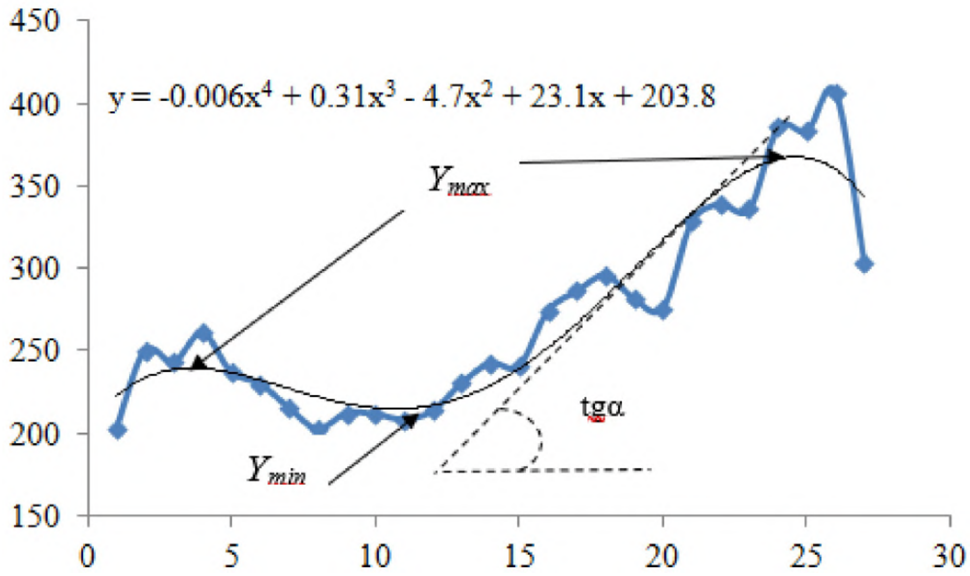

Figure 1. The typical sugar beet yields dynamics during 1991-2017 and approximation of the trend by fourth-degree polynomial: axis of abscissas – time (1 – 1991, 27 – 2017); ordinate axis – yields, dt/ha; b is an absolute term of the polynomial equation; Y_{Min} – the value of the polynomial at the point of the local minimum; Y_{Max} – the value of a polynomial at the points of local maxima; $tg\alpha$ – the maximum rate of increasing crop yields in time between the minimum and maximum, the tangent of the angle of inclination of the tangent to the curve of the polynomial at the inflection point (similar to the maximum rate of yields decline in the downstream branch).

A spatial regularity of the crop yields and trend parameters variation were investigated by I-Moran statistics [39]. The global Moran's statistics were calculated using Geoda095i (http://www.geoda.uiuc.edu/) [40]. A spatial database was created in ArcGIS 10.2. The statistical analysis was performed by Statistica 10 software.

4. Results

To assess the representativeness of the obtained data, we compared them with the average sugar beet yields throughout Ukraine, which were presented by the Food and Agriculture Organization of the United Nations (FAO) (figure 2, a). It was found that between the average yield of sugar beet in general in Ukraine and the yield in the study region there is a statistically significant correlation ($r = 0.97$, $p < 0.001$) (figure 2, b), which indicates the high accuracy of our data and the synchronicity of yield fluctuations throughout Ukraine. Such synchronicity is the result of a constant external factor, which in our opinion has an agro-economic origin.

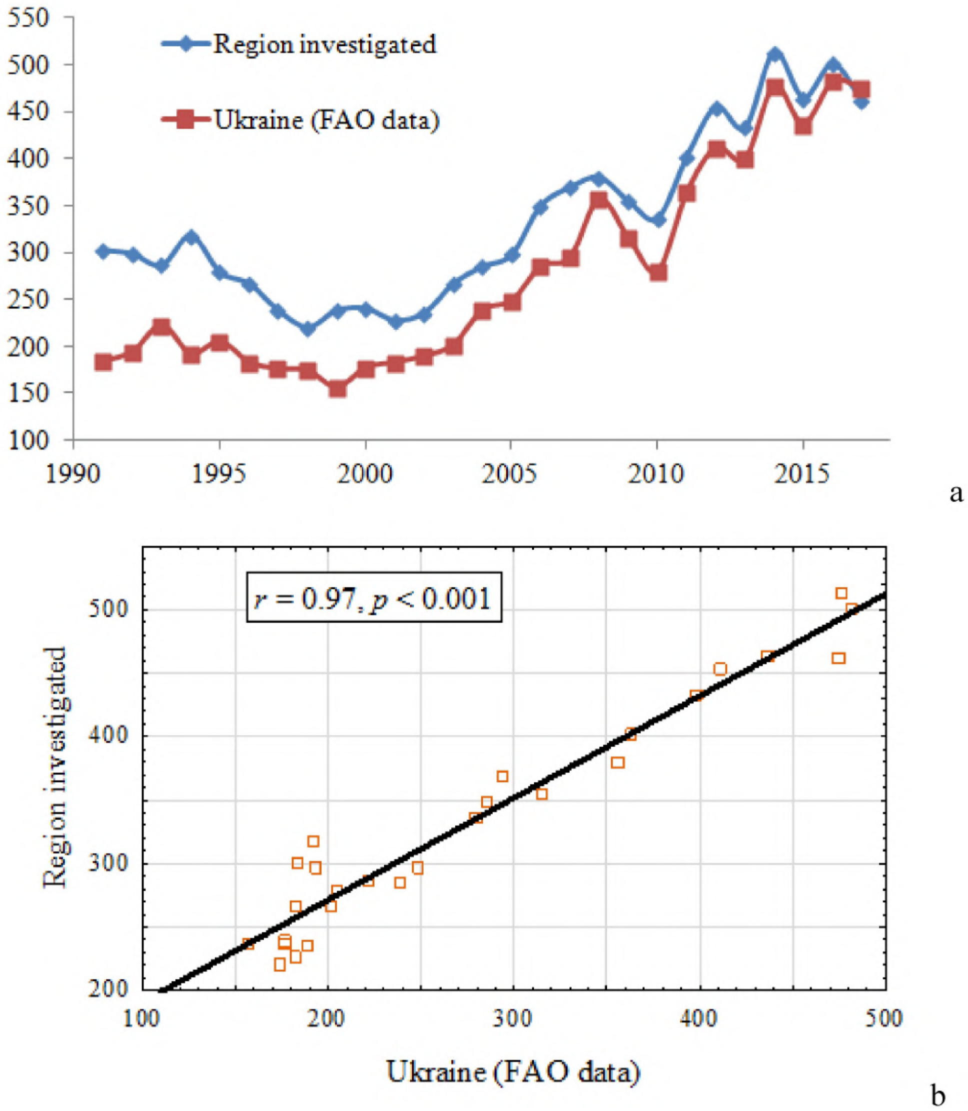

Figure 2. The sugar beet yields dynamics during 1991–2017 total in Ukraine (dt/ha, left y-coordinate) and in the region investigated (dt/ha, right y-coordinate) (a) and a scatter plot of sugar beet yields total in Ukraine against sugar beet yields in the region investigated (b).

The average yield of sugar beet in the study region ranged from 154.5 dt/ha to 495.7 dt/ha (figure 3). The highest average yields are in the central and southern regions of the region, and the lowest in the north. The coefficient of variation is the highest in the southwest (29.4–32.7%), for the rest of the territory, the coefficient of variation at the level of 20.14–29.3% is predominant.

There is a weak negative correlation between the average sugar beet yield and the coefficient of variation at the probable level (r = –0.19, p $<$ 0.007) (figure 4). This suggests that areas with higher yields tend to have a lower coefficient of variation, i.e., are more stable to external factors.

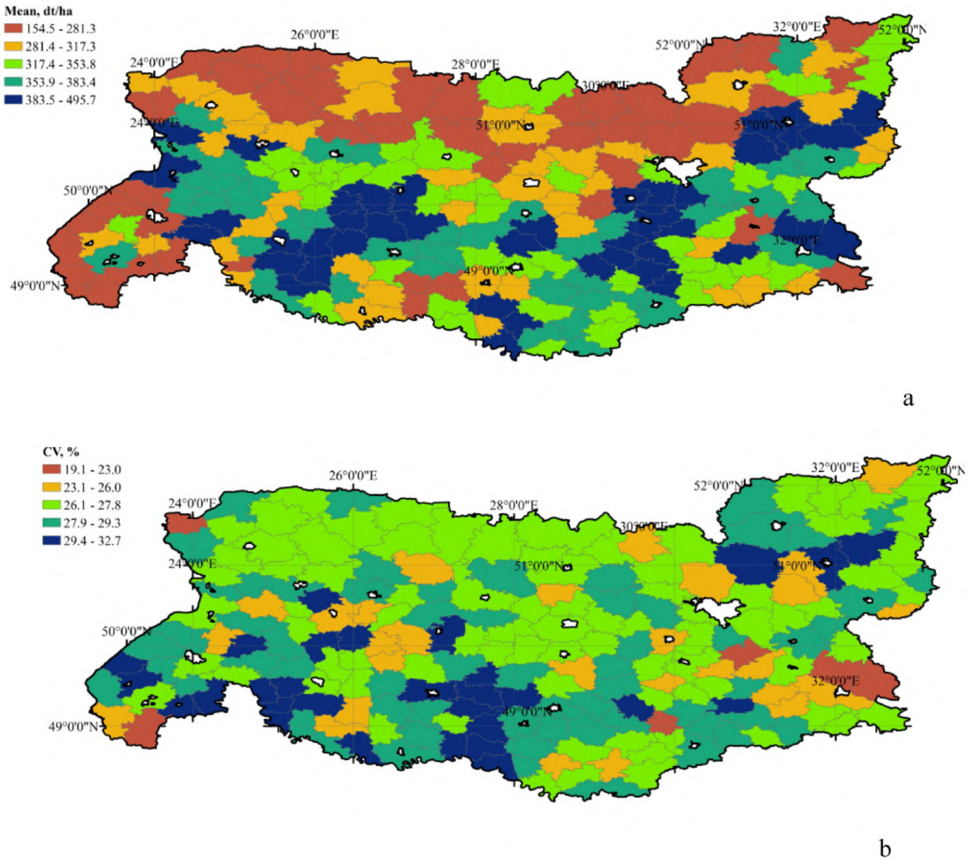

Figure 3. Average yield (A) and coefficient of variation of sugar beet yield (B).

The average yield and its coefficient of variation are spatially dependent (Moran's I-statistics 0.36, $p < 0.001$ and 0.17, $p < 0.001$, respectively). The dynamics of sugar beet yield in 144 administrative districts (70% of the total) is best described by a fourth-degree polynomial (figure 5). Therefore, according to the Aikake information criterion (AIC), we have identified this type of trend as the main one. Since the chosen model is a fourth-degree equation, the sugar beet yield trend can be classified as "yield stagnation" [41].

Since the final dynamics of the averaged data of sugar beet yield in the study region can be characterized by a fourth-degree polynomial, the yield dynamics can be described and interpreted using the following characteristic points and indicators: maximum and minimum points, inflection points (figure 1). The trend of sugar beet yield is also described by the constant term of the polynomial equation, the maximum rate of yield decrease, the maximum rate of yield increase occurring at inflection points, and the coefficient of determination of the regression model.

The general trend of sugar beet yield is characterized by two local maxima (Y_{Max}) and one local minimum (Y_{Min}) (figure 1). In our case, the local minimum reflects the lowest yield over the entire research period and occurs in 2010. Local maxima fall in 1993 and 2016 correspond to the highest crop productivity during the study period.

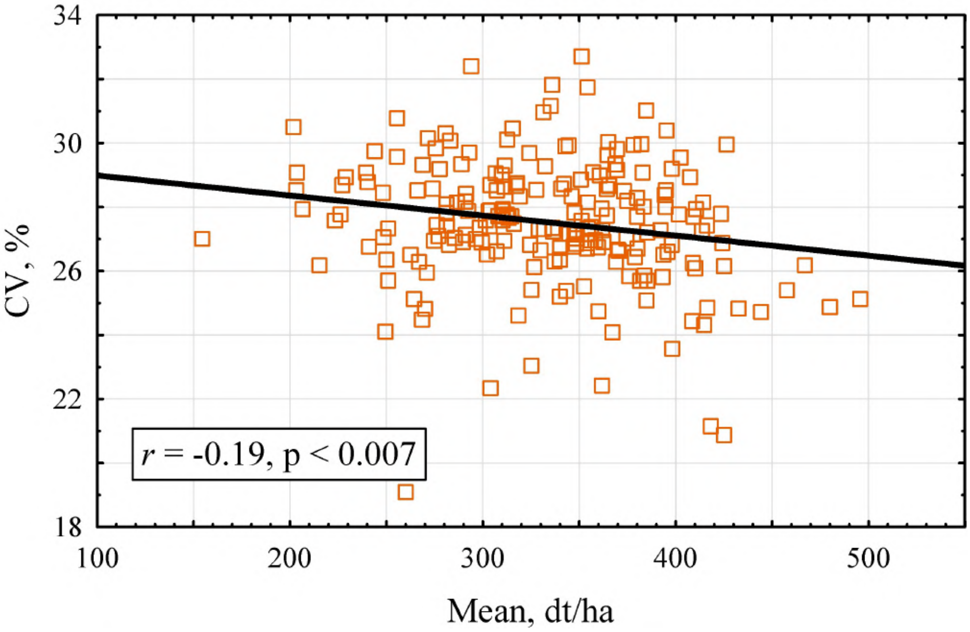

Figure 4. The relationship between the average sugar beet yield and its coefficient of variation.

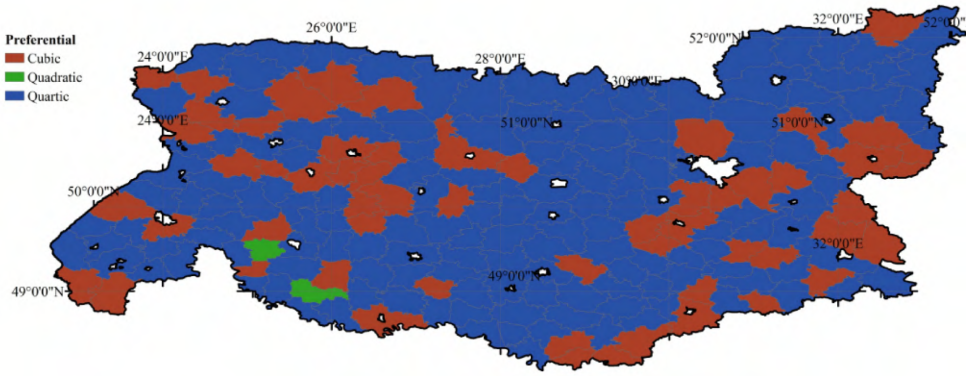

Figure 5. Spatial variations of the sugar beet yield trend types.

Since local maxima occur at the edges of the studied range, their further study is questionable.

Another indicator used in the study of the general yield trend is the absolute term of the polynomial – the constant b, which indicates the yield of the crop in the initial period (figure 1). Thus, the constant b indicates the initial conditions for describing the course of the process and is an independent parameter of the temporal dynamics of crop yields over time. The initial level of sugar beet yield varies from 175 dt/ a to 421 dt/ha (figure 6). This indicator allows identifying areas with the most favourable soil conditions for sugar beets cultivation.

The average yield level for the study period and the initial yield level (coefficient b of the polynomial equation) were significantly positively correlated ($r = 0.98$, $p < 0.001$). This explains the fact that the spatial variation of the values of coefficient b (figure 1) is spatially dependent, which is confirmed by the Moran test (Moran's I-statistics 0.42, $p < 0.001$). Between the local maximum and minimum on the one hand and the minimum and maximum yield on the other, there is an inflection of the polynomial curve, where the second derivative is zero (figure 1). At these points, the rate of decline or increase in yield becomes greatest, and the corresponding

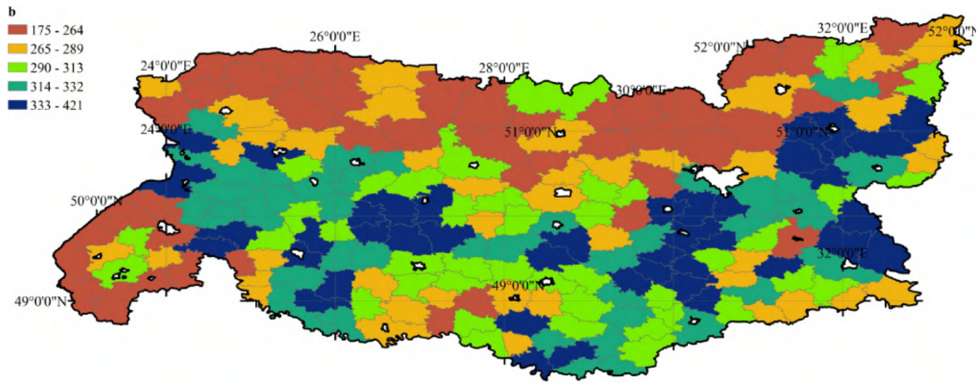

Figure 6. Spatial variation of the sugar beet yield in the initial period of research (constant b of the regression equation).

dynamics can be described by a linear relationship. The angle of inclination of the tangent to the regression line at the point of intersection indicates the maximum rate of yield decline or increase, respectively, so it can be a characteristic indicator of yield dynamics [42].

The indicators of the maximum rate of decrease and the maximum rate of yield increase can be used as indicators of the resilience of the agroecosystem to external factors (figure 7, 8). Areas, where sugar beet yields decline rapidly during the transition period, are in the north of the study region (figure 7), and areas, where yields tend to increase rapidly, are in the south (figure 8).

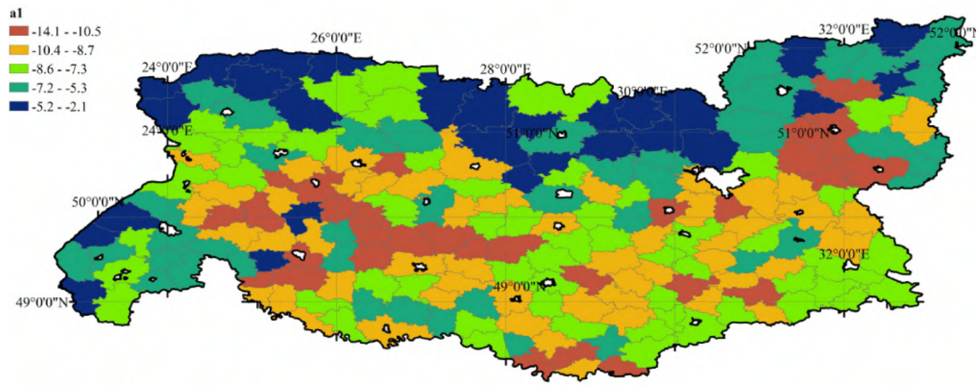

Figure 7. Spatial variation of the maximum rate of sugar beet yield decline.

The initial yield level is negatively correlated with the rate of decline in crop yield in the first stage of research ($r = -0.72$, $p < 0.001$). The rate of yield decrease (figure 7) is spatially dependent (Moran's I-statistics 0.33, $p < 0.001$). The rate of yield increase is proportional to the intensity of the previous decrease ($r = -0.57$, $p < 0.001$). The rate of yield increase (figure 8) is also spatially dependent (Moran's I-statistics 0.28, $p < 0.001$).

The coefficient of determination indicates how accurately the model described the overall yield trend. The fourth-degree polynomial explains 72–96% of the sugar beet yield temporal variation (figure 9). This indicator is spatially dependent (Moran's I-statistics 0.29, $p < 0.001$).

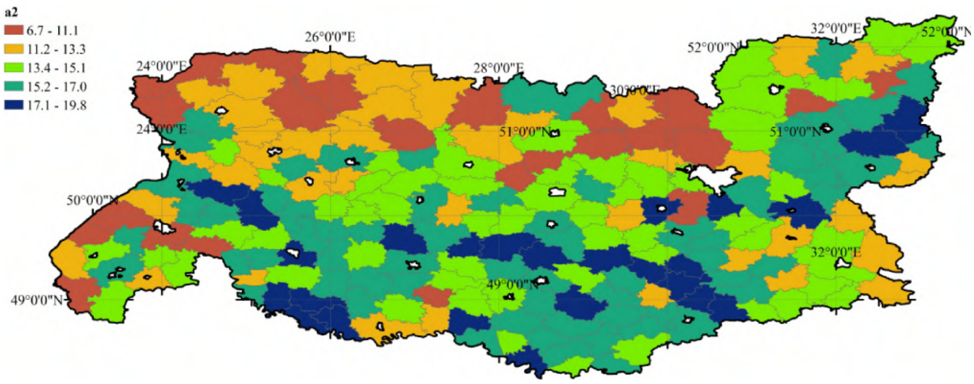

Figure 8. Spatial variation of the maximum rate of sugar beet yield increase.

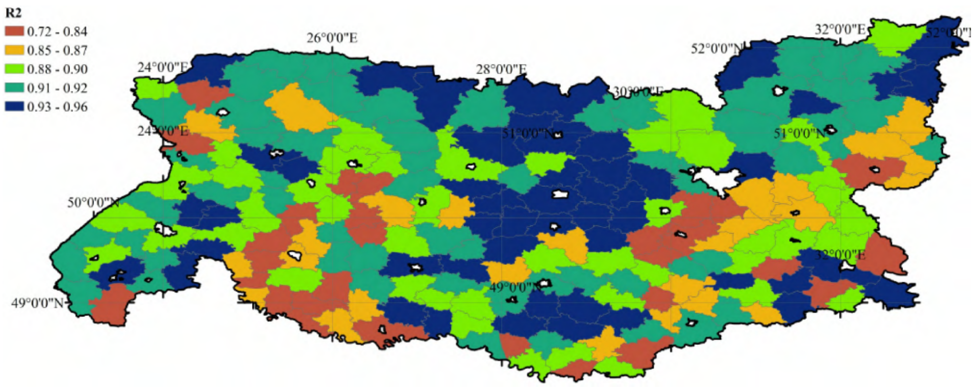

Figure 9. Spatial variation of the coefficient of determination of the sugar beet yield regression model.

5. Discussion

The high level of correlation between the average yield of sugar beet in Ukraine (FAO data) and the sugar beet yield in the study region (our data) indicates the high accuracy of our data and the synchronicity of yield fluctuations throughout Ukraine. Such synchronicity is the result of a constant external factor, which, in our opinion, has an agro-economic origin. This assumption is confirmed by the general form of the trend, which has the form of an economic cycle with ups and downs [43, 44]. Thus, according to the Food and Agriculture Organization of the United Nations, in Ukraine, there was a sharp decline in sugar beet yields in the period after the collapse of the Soviet Union. The "bottom" of yields dates back to the early 2000s [33]. After 2010, the increase in yield is almost linear and reaches a local maximum in 2016. It is known that agroecological factors are closely related to agro-technology and selection [45], so these factors can be combined into one group. Despite the general increase in sugar beet yield in the last decade of the study period, the general trend can be described as "stagnation of yield", which indicates that the increase in productivity is still quite slow.

With the help of the "initial yield" indicator, we can identify areas that have the most fertile soils and are characterized by high sugar beet yield potential. The high correlation of this indicator with the sugar beet average yield indicates that these conditions (soil fertility) are a decisive factor in achieving high yields [46]. Thus, the highest average yield and initial level of yield geographically correspond to Ternopil, Vinnytsia, Khmelnytskyi, and Cherkasy regions (figure 3), which are the main producers of sugar beets in Ukraine [32]. The research is also valuable because it allows for district differentiation of crop yields.

By mapping the indicators of the maximum rate of decline and maximum rate of yield increase, we can identify areas that respond to rapid decline or increase in yield to changes in management conditions, as well as areas with more stable yields (figure 7, 8). It was also found that the higher the initial yield, the slower it decreases, even in adverse conditions for sugar beets cultivation. Since we determined that the general trend is of agro-economic and agro-technological origin, the coefficient of determination can be interpreted as an indicator of these factors' role in the dynamics of sugar beet yield. The obtained data indicate that these aspects of yield are of paramount importance (72–96% of the contribution to the overall variation in crop yields). The central and northern regions are the most sensitive to agro-technological and agro-economic factors, and the southern regions are the least sensitive.

6. Conclusion

According to the findings of the study, the general trend of sugar beet yield within the study area is best described by a fourth-degree polynomial. The existence of a trend of this form is due to the influence of agro-economic factors, whose contribution to the overall variation in yield is from 72 to 96%. We have also identified areas that have the best soil and climatic conditions for growing sugar beets. Spatially, they coincide with the regions with the highest crop yields. Indicators of the maximum rate of decline and maximum rate of increase in yield can be used as markers of resistance of the agroecosystem to external factors, including agro-technological and agroeconomic. Regions with initial high yields are more stable in transition periods. The yield in areas with favorable soil and climatic conditions for sugar beet cultivation is less dependent on the impact of agro-economic and agro-technological factors. Thus, Ukraine has all the prerequisites for increasing the yield of sugar beet, especially in areas where the impact of agricultural technology and breeding is crucial.

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To cite this article: T Pinkina *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012074

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012074 doi:10.1088/1755-1315/1049/1/012074

The growth characteristics and survival rates of great pond snail (*Lymnaea stagnalis* L.) juvenile under the heavy metal impact

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Abstract. The study of the long-term effects of toxic substances, in particular, heavy metals, on aquatic organisms is currently a topical issue, due to the increase of anthropogenic pressure on the hydrosphere. The embryonic and juvenile stages of mollusks are more sensitive to toxic effects than adult ones. Consequently, the effects of different concentrations of heavy metal in the aquatic environment on the growth and survival rates of *Lymnaea stagnalis* juveniles were evaluated. In a chronic toxicological experiment, we used chronic lethal, sublethal, and subthreshold concentrations of heavy metals. We conducted 12 toxicological chronic experiments, lasting 60 days, with 1070 specimens of *L. stagnalis* juveniles. The toxic effect of heavy metals exposure in the aquatic environment in young individuals is manifested at much lower concentrations than in adults. The heavy metals ions affect the shell height of *L. stagnalis* juveniles even at the embryonic stage, which is manifested in some cases in the acceleration of their growth, in others – in its slowing down. The chronic experiment indicated that the values of shell height growth of juveniles in most cases correlate with the values of the total body weight growth. Under the influence of sublethal concentrations of heavy metal ions, the survival rates of juveniles are 3–4 times lower than the control. In solutions containing chronic lethal concentrations of Co^{2+} and Mn^{2+}, up to 80–90% of juveniles die. The sharper and more rapid response of young snails to toxic effects compared to adult animals can be explained by embryo intoxication.

1. Introduction

In recent decades, anthropogenic factors have accelerated the cycle of geochemical elements, resulting in increasing metal imports into water systems [1,2]. The heavy metals such as Copper (Cu), Cadmium (Cd), Zink (Zn), Cobalt (Co), Manganese (Mn), and Nickel (Ni) are potentially hazardous in combined or elemental forms [3,4]. Most are on the U.S. Environmental Protection Agency's list of priority metals for monitoring and assessing their harmful effects on aquatic ecosystems [5–8]. Since heavy metals chlorates are highly soluble in water, they are readily absorbed by living organisms [9] and accumulate in the gills, liver, and muscle tissues of various species in a contaminated water ecosystem [10]. Drinking water contaminated with heavy metals becomes one of the main problems for human health [11–13].

Snails are among the invertebrates that could accumulate significant quantities of heavy metals in their tissues, making them suitable test animals for researching the kinetics of metal accumulation and detoxification [7,14–17]. Understanding how metals influence freshwater snails can help scientists better comprehend the ecotoxicological impact of metal contamination on snails' populations and design water-quality guidelines that sufficiently safeguard protect water organisms [18–21]. According to several studies, freshwater snails' early life stages have been found to be among the most vulnerable aquatic organisms to inorganic pollutants, including heavy metals [22–25]. Thus, Wang et al. [26] found that juvenile freshwater mussels are more sensitive to acute and chronic copper exposure than most other freshwater organisms tested, such as cladocerans (*Daphnia magna* and *Ceriodaphnia dubia*), an amphipod (*Hyalella azteca*), fathead minnow (*Pimephales promelas*), and rainbow trout (*Oncorhynchus mykiss*). Therefore, young individuals of freshwater mollusks were used for our study.

A rising number of studies have been published that measure the effects of known lethal concentrations on aquatic organisms [27–30]. The study of acute poisoning of aquatic species with the survival rate as the primary criterion is the main focus of researchers [31–34]. Growth processes are quite sensitive to the slightest changes in any environmental factor, so the size and mass characteristics of animals placed in a poisoned environment are among the parameters that characterize the body's response to changes in water quality [35,36]. The freshwater pulmonates are one of the most commonly used taxonomic groups for toxic experiments because acute effects may be observed within a very short time [37, 38]. Although chemical spills and other point sources of toxins can cause localized mortality in aquatic animals, freshwater snail populations may be declining as a result of the pervasive impacts of chronic, low-level contamination (Strayer et al., 2004). A number of research have examined the acute toxicity of metals to freshwater mussels, but little is known about the sub-lethal effects of long-term exposure to low-level, environmentally relevant concentrations [24]. Recently, it was shown that the great pond snail is either the most sensitive or the second-most sensitive freshwater animal in chronic exposures to Co, Cu, Ni, and Pb, making it particularly important for the creation of future water quality requirements [39–43].

2. Research aim and objectives

Lymnaea stagnalis was chosen for this study because of its widespread prevalence throughout Ukraine, its sensitivity to heavy metal impact, and its success in laboratory culture [44,45]. We studied the features of heavy metals chronic exposure effect on the size-weight characteristics and survival rate of juvenile great pond snails.

3. Material and methods

3.1. Experimental animals

Juvenile great pond snails (*Lymnaea stagnalis*, Linnaeus, 1758) were obtained from the clutches (eggs) of adult snails, which were placed in solutions of heavy metal chlorides and kept for 70 days in laboratory culture. In three years, 12 toxicological chronic experiments lasting 60 days, were performed, in which 1070 young specimens of great pond snail were used.

3.2. Chronic toxicity tests

Toxicological tests were carried out using the Alekseev method, which was developed by Stadnichenko [46]. Chlorides of 6 heavy metals (copper, cadmium, nickel, zinc, cobalt, manganese) were used as toxicants. The content of toxic substances was calculated by cation. *L. stagnalis* juveniles placed in clean (non-toxic) water were controls. The water temperature was measured three times a day. The optimum temperature (19–23°C) was maintained due to the periodic ventilation of the room. The illumination close to that the snails are used to in natural reservoirs was created, as well as the daily rhythms of activity (respiratory, nutritional), for this purpose the indicators were taken at regular intervals.

The concentration ranges for the toxicological studies were chosen according to a fishery-toxicological approach, which distinguishes four concentrations (table 1). In the chronic toxicological experiment, we used chronic lethal, sublethal, and subthreshold concentrations.

Table 1. Concentrations of heavy metal ions (mg dm^{-3}) used in the experiments.

Ion	Level of toxic impact			
	Acute	Chronic lethal	Sublethal	Subthreshold
Cu^{2+}	4	0.04	$4{\cdot}10^{-5}$	$4{\cdot}10^{-8}$
Cd^{2+}	5	0.05	$5{\cdot}10^{-4}$	$5{\cdot}10^{-6}$
Ni^{2+}	10	0.05	$5{\cdot}10^{-3}$	$5{\cdot}10^{-6}$
Zn^{2+}	15	0.5	$5{\cdot}10^{-3}$	$5{\cdot}10^{-5}$
Co^{2+}	25	2.5	0.25	0.03
Mn^{2+}	110	30	0.3	0.03

In a chronic toxicological experiment, we used chronic lethal, sublethal and subthreshold concentrations of heavy metals. The range of acute lethal concentrations (as well as other ranges) was determined by us empirically, but it is not discussed in the text of the article due to the short duration of the molluscs' survival in this range (3-5 days). And in this study, a chronic experiment was set up.

3.3. Determining the dynamics of changes in the size-weight characteristics and survival rates of mollusks

The size and weight measurements (shell height, body weight) of juvenile mollusks were taken every 10 days. The weight of mollusks was determined by direct weighing (weight VLR-200) with an accuracy of 0.0005 g. The height of the shell was determined using a micrometer (accurate to 0.01 mm). The survival rate was determined by counting (every 10 days) the surviving individuals and comparing this number with the total number of individuals taken into the experiment at the beginning.

3.4. Statistical methods

The concentrations measurements were log-transformed. The normality of the sample's distribution was determined using the Kolmogorov-Smirnov test. The student's t-test was used to assess the significance of the differences between the two mean values of the samples in case of normal distribution. Wilcoxon Matched Pairs Test was used to test for differences between samples if they are not normally distributed. Equality of variances was tested by ANOVA. The regression analysis was carried out to determine the dependencies between body weight and shell height. The significance level of 5% was accepted in the study. The difference between the means was considered probable if $p < 0.05$. The statistical analysis was performed by Statistica 10 software.

4. Results and discussion

It is known that juvenile gastropods are much more sensitive to heavy metal impact than adults [47, 48], although it would be more appropriate to speak not about sensitivity, but about a much higher dose load that juveniles receive at the same concentration (due to the difference in biomass) compared to adults. That is why the toxic effects of these pollutants are manifested in young individuals at much lower concentrations. The influence of heavy metal ions on the shell height of juvenile great pond snails during hatching suggests that mollusks perceive toxic effects at the embryonic stage, which is manifested in the lower average shell height of mollusks hatched in metal solutions compared to the control (table 2). Shell height distribution is not normal for all metals. The differences in shell height compared to the control values are significant for Cobalt ($Z = 4.2$, $T = 49.5$, $p < 0.05$), Copper ($Z = 2.11$, $T = 84$, $p < 0.05$), Zinc ($Z = 2.3$, $T = 2515$, $p < 0.05$), Nickel ($T = 2.0$, $Z = 3.2$, $p < 0.05$).

Table 2. The shell height of juvenile mollusks (mm) at the moment of hatching.

Heavy metal ion	N	Mean ± Stand. Error	Minimum	Maximum	Std.Dev.	Coef.Var
Cd^{2+}	86	1.47±0.017	1.16	1.78	0.16	10.97
Co^{2+}	34	1.38±0.019	1.11	1.62	0.11	8.08
Cu^{2+}	26	1.48±0.018	1.30	1.70	0.10	6.29
Mn^{2+}	43	1.53±0.017	1.28	1.75	0.12	7.70
Zn^{2+}	88	1.50±0.015	1.24	1.86	0.14	9.58
Ni^{2+}	14	1.32±0.044	1.11	1.63	0.17	12.68
Control	41	1.56±0.022	1.10	1.80	0.14	9.07

The largest range of variation and the lowest average shell height have juveniles mollusks that were kept in different concentrations of Nickel ions (CV = 12.7%), which indicates that this metal ions significantly affects the embryonic development of the gastropod pond snail [49]. In addition, the freshwater pulmonate snail, *Lymnaea stagnalis*, is believed to be the most sensitive aquatic organism tested to date on Ni [41]. According to the ANOVA results, the shell height of juvenile great pond snails is significantly dependent on the concentrations of all heavy metals studied ($p < 0.05$). The effect of different concentrations of heavy metal ions on the shell height is manifested in some cases in accelerating their growth, in others - in slowing it down (figure 1).

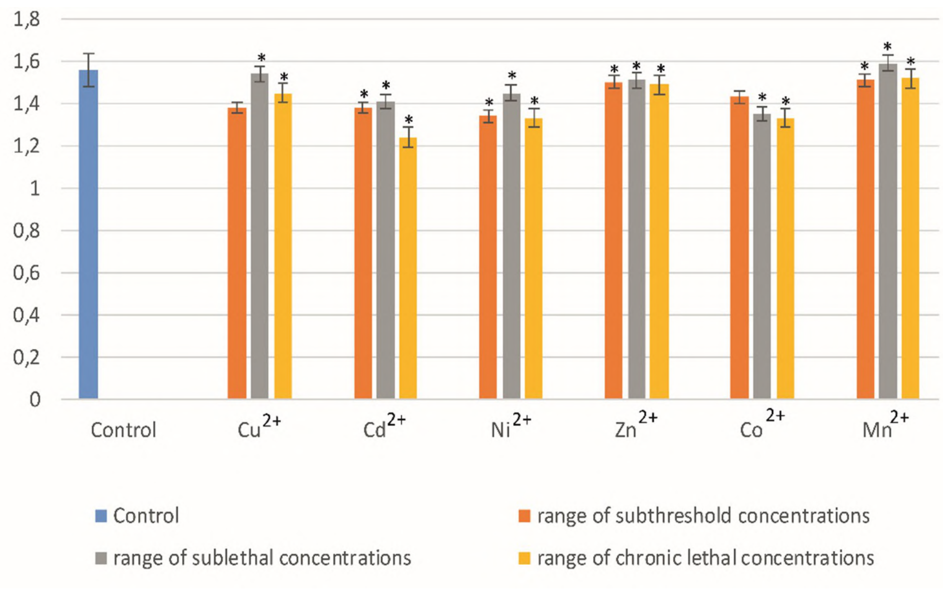

Figure 1. Influence of heavy metal ions on shell height (mm) of juvenile *L. stagnalis* at the moment of hatching. * – differences compared to the control values are significant.

Copper ions at subthreshold concentrations did not affect the shell height of newborn mollusks; however, at sublethal and subthreshold concentrations of copper ions, the average values of shell height were statistically significantly higher than those of the control. The average shell height of juvenile snails at hatching is significantly less than the control ones only when exposed to cadmium ions at chronic lethal concentrations ($p < 0.05$). Under the influence of nickel ions at sublethal concentrations, the size of the embryos is significantly larger ($p < 0.05$) than in the control group. In the remaining studied concentrations of Ni^{2+} the values of the shell height are significantly lower than the control values ($p < 0.05$).

Under the influence of zinc and manganese ions, the shell height of juveniles at the moment of hatching is statistically significantly higher than the control values. And under the influence of cobalt ions, juvenile shell height decreases with increasing concentration of the solution, which indicates an increase in toxic effects with increasing Co2+ concentration in the medium (figure 1).

Heavy metals' impact on snails' survival is well documented, but their sublethal effects on the growth process are gaining traction [28]. When studying the size-weight characteristics of juvenile mollusks during prolonged (60 days) stay in a medium poisoned with heavy metals, it was found that, as in adult mollusks [50], the shell height growth rate of juvenile mollusks in most cases correlates with the growth of total body weight. Changes in the shell height of juveniles under long-term toxic exposure generally repeat the dynamics of changes in the same parameter in embryos, but there is a clear tendency to a decrease in the growth rate of juvenile great pond snails in the toxic environment (figure 2, 3).

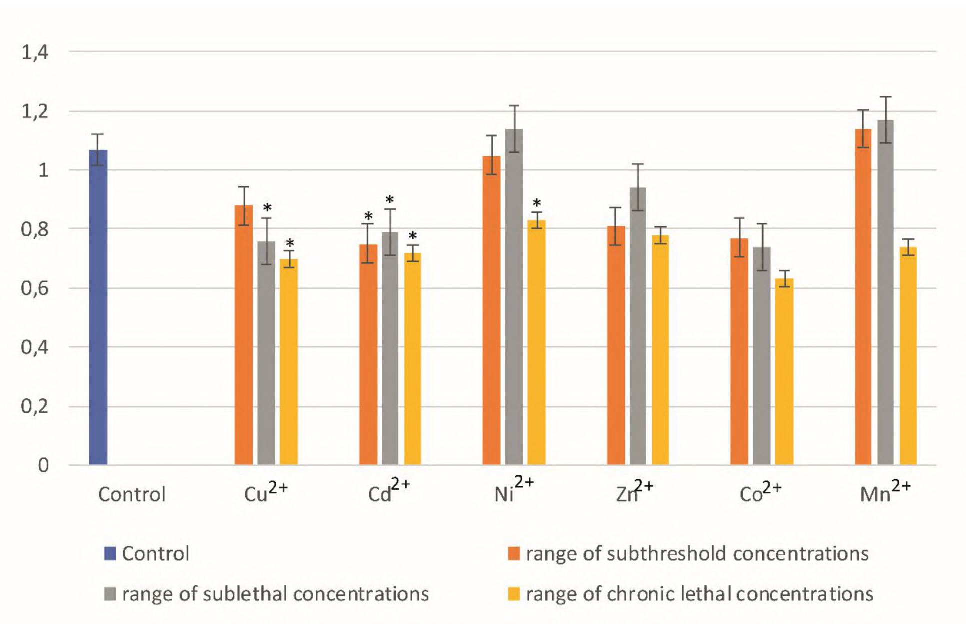

Figure 2. Increase in shell height (growth) of juvenile *L. stagnalis* during the 60-day experiment, mm. * – differences compared to the control values are significant.

All the average increases in shell height of juveniles obtained in the experiments are lower than the control values, except for the indicators obtained in solutions of sublethal concentrations of Ni^{2+} and subthreshold and sublethal concentrations of Mn^{2+} (figure 2). Inhibition of shell growth by heavy metals can be explained by the juvenile-snail development suppression was a particularly sensitive end-point, possibly due to Ca homeostasis disruption [51]. Since, *L. stagnalis* need a lot of calcium to keep up with its quick shell creation and rapid growth rates in the early stages of its life (around 20 percent of body mass per day) [40].

The water balance in the body of juvenile great pond snails at first becomes positive when the concentration of heavy metals in the environment increases (which probably allows at least to some extent to compensate for the toxic effect), but gradually and smoothly shifts to the negative side as the concentration of the toxicant increases [52]. It can be assumed that dehydration of young animals at chronic lethal concentrations of pollutants subsequently leads to their death.

In most of the studied solutions containing heavy metals, under the influence of subthreshold and sublethal concentrations there is no statistically significant difference in weight from control values ($p < 0.05$), which indicates a certain resistance of these indicator to toxic effects (Fig 3). However, with increasing concentrations of heavy metals, there is an increase in intoxication, which is reflected in the size-weight values. In chronic lethal concentrations, deviations from the weight of control animals can, in some cases, reach 49%, and in shell height, up to 30%.

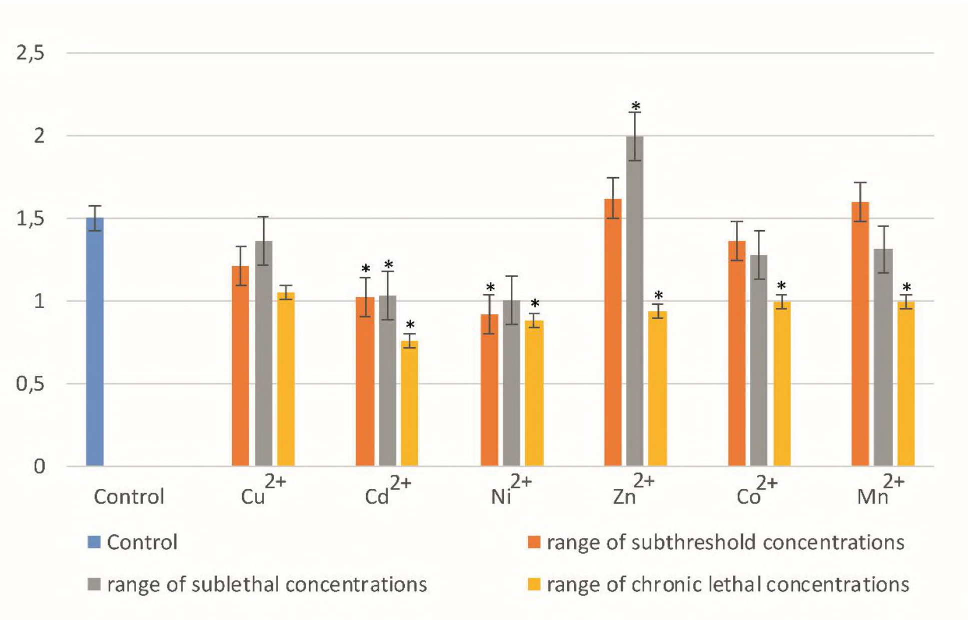

Figure 3. Influence of heavy metal ions on the total body weight (mg) of juvenile *L. stagnalis*. * – differences compared to the control values are significant.

The juvenile pond snails are the most sensitive to the influence of Cadmium ions in terms of size- weight parameters. In solutions with Cd^{2+}, the values of these indicators are the lowest among all those obtained under the influence of the other five studied metals (figure 3).

Individual survival has been discovered to be one of the criteria for the organism's stability, which is considered in time [53]. When studying the survival of juvenile pond snails exposed to heavy metals, we found that they do not respond to intoxication in the same way that adults do [50]. In adult pond snails there is a stimulation of vital functions under the influence of sublethal concentrations of pollutants, and the values of snails' survival in solutions of subthreshold concentrations are very close to control values, which suggests that they are immune to toxic effects. Heavy metal ions greatly affect the survival of juveniles. The percentage of juvenile specimens that survived in a toxic environment during the chronic (60 days) experiment is always below the control values, regardless of the concentration of pollutants in the environment. Only when juveniles are exposed to sublethal concentrations of Ni^{2+} and subthreshold concentrations of Mn^{2+} do survival rates approach 50%, and exposed to other metals, juvenile survival rates are 3–4 times lower than control values in some cases.

The presence of juveniles in solutions of chronic lethal concentrations of heavy metals leads to persistent suppression of their viability, which is manifested in high values of snails' death. At the same time, a paradoxical situation arises: juveniles react less strongly to those metals that were diagnosed as highly toxic in the acute experiment and more strongly to those that were determined to be slightly toxic [3]. Thus, in solutions of chronic lethal concentrations of Co^{2+} and Mn^{2+}, up to 80–90% of juveniles die (figure 4).

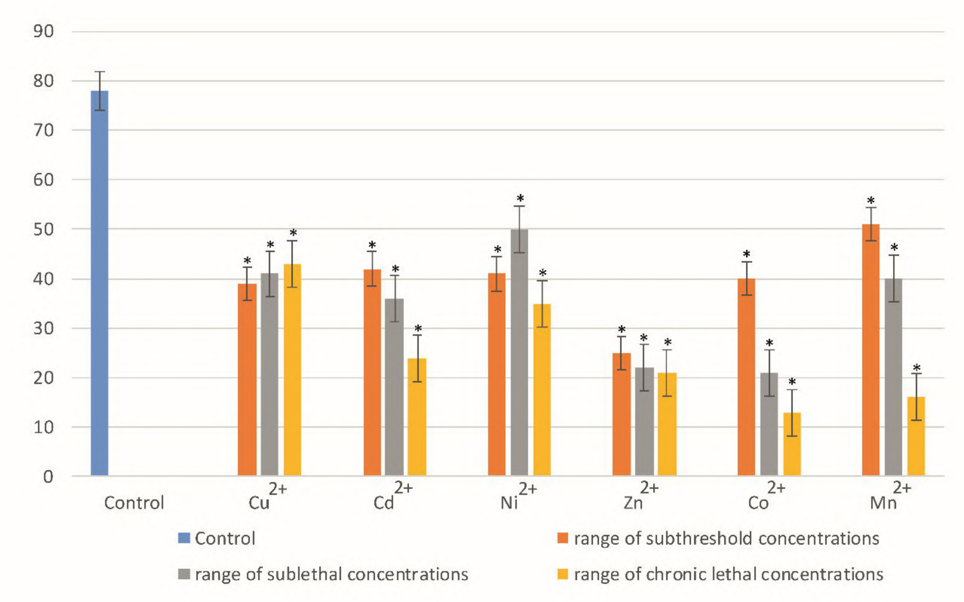

Figure 4. Influence of heavy metal ions on the survival rates (%) of juvenile *L. stagnalis* in the first 30 days of life. * – differences compared to the control values are significant.

A possible explanation for this phenomenon is the following: when a juvenile organism is exposed to highly toxic substances, it immediately experiences severe stress, reparation mechanisms are activated, and this makes it possible to resist the toxic effects to some extent [54–56]. In the case of prolonged exposure to low-toxic substances intoxication of organisms increases slowly, the body initially reacts less rapidly, untimely adaptation mechanisms and slowly increasing negative changes in the functioning of body systems make it unable to resist the toxic effects of heavy metals [57–59]. Under the influence of Zn^{2+}, which has a moderately toxic effect on great pond snails, the survival rates of juveniles in solutions of all its concentrations differ little from each other and range from 20–25% (figure 4).

Thus, the study of the shell height and body weight of juvenile *L. stagnalis* under the influence of heavy metal ions in the aquatic environment showed that the determining factor for changing these parameters is time of exposure. In the first 30 days of the experiment, regardless of the solution concentration and the nature of the metal ion, there were no statistically significant differences in changes in shell height and body weight of great pond snail juveniles compared to control specimens. Only when the animals are kept in a poisoned environment for a longer period of time do the size and weight parameters undergo significant changes in relation to the control values. The dynamics of changes in the shell heidht and weight of juveniles within a toxic environment indicate that juvenile mollusks are extremely sensitive to heavy metals impact. In general, the size-weight indices decrease with the increasing concentration of pollutants.

Biomonitoring of water bodies is the use of aquatic species, to measure the extent of human influence on aquatic ecological balance. Our research confirmed that the early juvenile stages of Lymnaea stagnalis are extremely sensitive bioindicators, allowing even very low levels of the heavy metals to be detected. The quantitative characteristics of the growth and survival rates of the lake pond juveniles reflect the toxicological situation of the environment and can be recommended as biological criteria of toxicity in biotesting in the system of environmental monitoring of natural water pollution by heavy metal ions.

5. Conclusion

The influence of heavy metal ions on the shell height of juvenile great pond snails at the moment of hatching suggests that mollusks perceive toxic effects at the embryonic stage, which is manifested in the lower average shell height of mollusks hatched in metal solutions compared to the control. The largest range of variation and the lowest average shell height have newborn mollusks that were kept in different concentrations of Nickel ions. Although, in terms of shell height and weight growth, the juvenile pond snails showed the greatest vulnerability to the influence of Cadmium ions during the chronic experiment. In solutions with Cd^{2+}, the values of these indicators are the lowest among all those obtained under the influence of the other five studied metals. Under the influence of sublethal concentrations of heavy metal ions, the survival rates of juveniles are 3-4 times lower than the control. In solutions containing chronic lethal concentrations of Co^{2+} and Mn^{2+}, up to 80-90% of juveniles die. As a result, it is possible to suggest that poisoning already affects mollusk embryos, as evidenced by the fact that juvenile great pond snails react more sensitively to the impact of the studied pollutants than adult mollusks. The growth and survival rates of L. stagnalis juveniles reflect the environment's toxicological state and can be considered as biological toxicity criteria in biotesting of natural water pollution by heavy metals.

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To cite this article: I V Kholoshyn *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012075

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012075 doi:10.1088/1755-1315/1049/1/012075

Territorial assessment of the ecological and social comfort of the population living environment of large industrial cities (by the example of Kryvyi Rih)

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Abstract. Providing a favourable and comfortable living environment for the population is one of the main tasks of optimising urban development. The level of comfort is formed with the territorial interaction of natural and socio-economic conditions for the region's development. This interaction is especially manifested in large industrial centres, characterised by a strong negative anthropogenic impact on the environment. The territorial assessment of the comfort of the living environment involves a comprehensive spatial analysis of the population comfort main factors. The purpose of this work is a spatial analysis of the population living comfort of one of the most industrialised regions not only Ukraine, but also Europe – the city of Kryvyi Rih.Functional zoning was carried out using GIS Map Info with the allocation of the following areas: residential zones, public and business zones, industry and warehouse zones, resort and recreation zones. The distribution of the residential area according to the level of comfort of the population living environment was carried out according to 3 groups of factors: transport accessibility, development of social infrastructure and ecological state. The first group characterises the habitat from the point of view of the city's provision with transport routes for various types of public transport. The second group characterises the population's social conditions, namely the number of educational, cultural and medical institutions. The third block includes the ecological state of the territory according to the criterion of atmospheric pollution. The method of scoring made it possible to compare individual parts of the area under study across the entire range of natural, ecological and social population comfort. The combination of indicators of the totality of all three groups factors was carried out using overlay operations. As a result of the research, a map characterising the spatial differentiation of indicators of the living comfort in the city of Kryvyi Rih has been created. The specialisation of the city as a large industrial centre has determined the leading role of the group of environmental indicators in the situational model of the living environment comfort in the region.

1. Introduction

Ensuring a favourable and comfortable environment is one of the main tasks of optimising urban development. The level of comfort is formed by the territorial interaction of natural and socio-economic conditions of the region's development. This interaction is especially evident in large industrial centres, which are characterised by strong negative anthropogenic impact on the environment. An essential feature of such cities is the territorial differentiation not only in terms of environmental indicators, but also in terms of development of social, transport and engineering infrastructures. As a result, in industrial cities there is a significant heterogeneity of the urban environment in terms of living conditions.

Therefore, spatial analysis of habitat comfort, which takes into account a set of conditions and their parameters meeting the basic needs of the population, becomes important for such regions. It provides an opportunity to develop measures optimising the interaction of the living environment with the functioning of the industrial sphere of a large industrial region.

The concept of "*comfort of the living environment*" is interpreted as a measure of subjective feelings and objective state of well-being, formed under the influence of a set of different conditions most favourable for human life and economic activity [1].

It is taken into account that the set of optimal natural and ecological conditions for life forms *ecological comfort*, and the one of favourable for population's economic activity forms *social comfort* of living. Studying ecological comfort, a set of conditions and their parameters that meet the basic physiological needs of living in the investigated area (including natural and climatic, geological and geomorphological, the degree of pollution of the atmosphere, soil, etc.) is taken into consideration. Examining social comfort involves the analysis of various social factors that affect primarily the livelihood of the population (development of services, the degree of development of the territory, transport accessibility, etc.).

In general, ecological and social comfort of the population living is a complex, multifactorial system that is an element of a large anthropogenic urban ecosystem. The structural elements of this system are urbanised, industrially changed landscape, transport and social infrastructure, and environmental situation. Thus, the territorial assessment of living comfort involves a comprehensive spatial analysis of the main factors of living comfort. Such research is of particular importance for objects with high technogenic load.

The purpose of this work is a spatial analysis of population'sliving comfort in large industrial cities, and the object of the study is one of the most industrialized regions of Ukraine and Europe – the city of Kryvyi Rih.

2. Methods

The traditional practice of modern urban planning is the functional zoning of the territory. When planning urban areas for different functional purposes, experts take into account the type and purpose of the territory.

There are different approaches to the allocation of urban functional zones [2–10]. For example, there is a division of functional zones into: residential areas, public and business areas, industrial and warehouse areas and resort and recreational areas [8]. Often production zones are divided into transport infrastructure zones, engineering infrastructure zones, communal warehousing, production and special zones.

However, as practice shows, the more zones, the more complex the zoning structure is and it is more difficult to manage such a city. In addition, it is more difficult for the local population to adapt to more complex zoning structures, to understand the purpose of each of them and to develop a system of restrictive measures. Therefore, the desire to generalise the functional structure of large cities seems obvious.

In this paper, the basis of functional zoning of the city (by the example of Kryvyi Rih) is the classification defined by the current state building codes DBN B.2.2–12: 19 "Planning and development of territories".

According to these norms, the territory of the city as for functional purpose and nature of use in general is divided into: residential, industrial, landscape recreational ones, within which individual land plots should be planned into functional zones: residential and public buildings, industrial buildings, communal and warehouse buildings, landscape and recreational, health and wellness, green areas, environmental protection, historical and cultural purposes, transport communications (transport infrastructure), engineering communications (engineering infrastructure), special purpose [5].

Residential zone is the territory where there are zones of housing, public buildings, green areas of common use, adjacent areas of residential buildings, objects of daily and periodic service, public centres, green areas of general and limited use, special purpose, main and street-road network, sites for utilities, engineering support of residential areas, fire stations, garages and parking lots, bicycle parking lots, etc. [5].

Industrial zone is the territory of enterprises, facilities, utilities and facilities, transport infrastructure, warehouses, innovation development (technology parks, industrial parks) as the part of industrial zones, industrial areas, enterprises located separately or the groups of enterprises [5].

Landscape-recreational zones are the ones of green and other open spaces for various purposes, located in the settlements and suburban areas, and in inter-settlement areas, including landscape complexes, recreational areas, resorts and health areas, cultural heritage sites and tourist zones, territories of nature reserve and water funds, water and field protection zones, transport-distribution green strips and other objects of green economy [5].

The zoning is based on the general plan of the city of Kryvyi Rih on a scale of 1:25 000, executed by SE SDI Kryvbasproekt in 2011, generalised to a scale of 1:100 000. It should be noted that clear differentiation of urban areas by type of functional use is difficult in a large industrial city due to the close intertwining of different functions of one area, so to clarify the spatial data additional cartographic materials [11] and current satellite images have been used.

Methodology features for determining the level of the population living environment comfort of the city's residential area should be vcharacterised separately. Comfort and quality of life have been evaluated by many researchers. There are a number of methods for determining various aspects of quality of life, based on various indices, indicators and opinion polls [6, 8, 12–17]. In general, these approaches reflect the socio-economic living conditions of the population and the degree of satisfaction with them, or the degree of environmental safety of the territory.

In this work the population's living comfort is determined by three **groups of factors**: transport accessibility, development of social infrastructure and ecological condition of the territory. *The first group* characterises the territory of residence in terms of providing the city with transport routes of various types of public transport. *The second group* characterises the social living conditions of the population, in particular the number of educational, cultural, health care institutions, etc. The factors of *the third group* include the ecological condition of the territory by the criterion of air pollution.

The choice of these factors as the main ones in assessing the living comfort of the city population is confirmed by the results of a survey of city residents conducted by the Institute of Urban Development (Kryvyi Rih). Thus, among the comfortable factors of living, the indicator of developed transport infrastructure (62.4% of respondents), developed trade infrastructure (44%), presence of playgrounds (37.1%), presence of park areas and squares (31.6%) and proximity of educational institutions (31.6%), services (28.7%), satisfactory environmental situation (25.2%), availability of cultural and entertainment facilities (21.1%) and sports grounds (16.3%) received the largest number of elections.

In order to quantify the population‘s living comfort, the method of *scoring* the territory of the city of Kryvyi Rih has been chosen. The scoring system is characterised by simplicity of calculations and allows: to correlate the existing level of comfort and identify its territorial imbalances; to include in the system of assessments any kinds of indicators of natural-ecological and social purpose; to derive an integrated indicator of comfort of a certain territory and carry out a comparative analysis of integrated indicators of comfort of different urban areas.

In order to perform the scoring, the territory of Kryvyi Rih on the city master plan is covered with a regular grid, the cell size of which is 500×500 m, which is determined by the mapping scale (1:100 000). For each pixel of the grid, the scores of the factors of living comfort of the population are determined. In order to interpolate the conditional surface, the coordinates of the centroids of each cell are determined and a layer of points from the weighted averages is created. The Geo Info geographic information system has been used to process the weighted averages. The result is a series of maps illustrating the spatial differentiation of each of the comfort indicators.

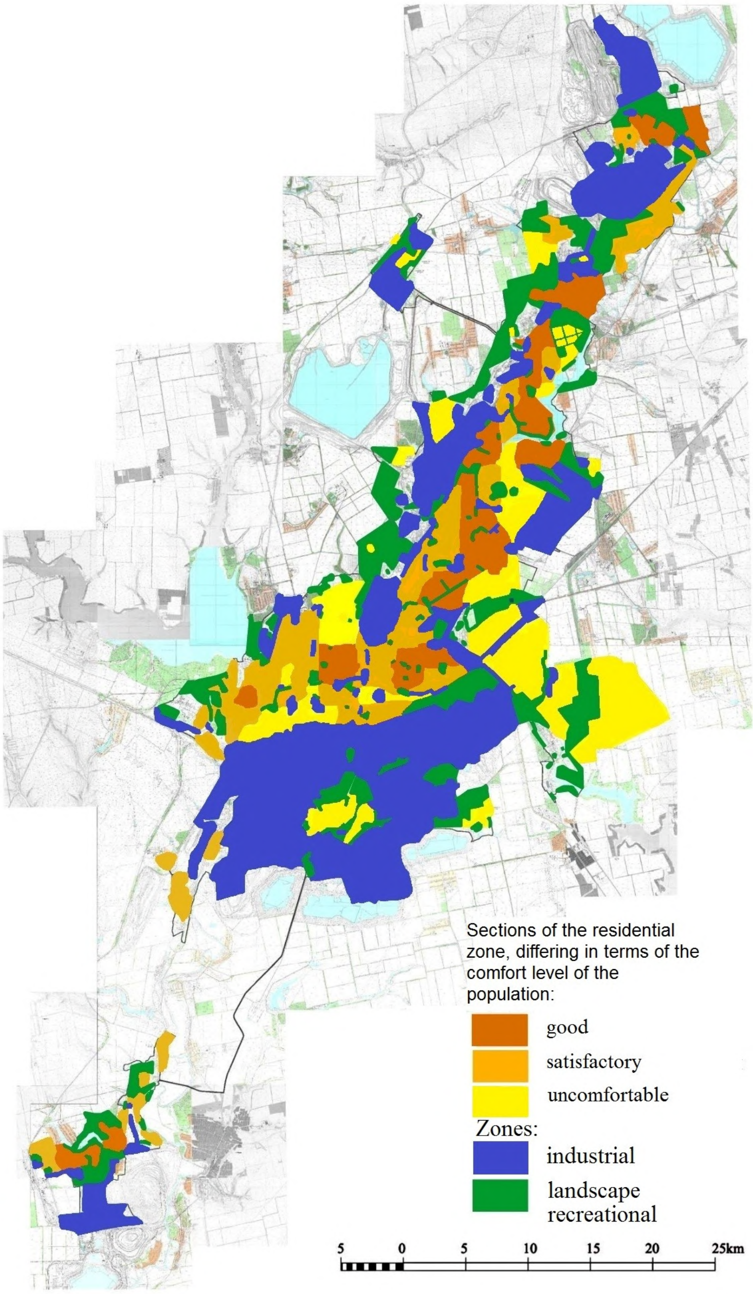

Figure 1. Map of ecological and social comfort of the living environment of the population of Kryvyi Rih.

The determination of the integrated indicator of the population's living comfort of the city of Kryvyi Rih has been carried out by averaging all estimates for each of the pixels.

The obtained total scores have been ranked according to the principle of natural gaps. This allows to distinguish within the statistical series of the integrated indicator of living comfort of the population of Kryvyi Rih three groups of *conditions of comfort of the population living environment* (ranging from the highest to the lowest ones): *good* (more than 3.8 points), *satisfactory* (from 2.3 to 3.7 points) and *uncomfortable* (less than 2.2 points).

Based on the principle of spatial combination of indicators of cells in polygons, a map of population living comfort in the city of Kryvyi Rih has been constructed (figure 1).

3. Results and discussion

Kryvyi Rih is the eighth most populous city in Ukraine (612.8 thousand people as of January 1, 2021), the largest of the cities which are not regional centers. It is a multifunctional centre with a dominance of industrial functions. More than 100 large industrial enterprises are located on its territory, which provide about 10% of the total industrial production of Ukraine. The negative result of the industrialization of Kryvyi Rih is serious environmental problems: the city is one of the most environmentally unfavourable regions for the population. Therefore, the study of quality of life in the current urban conditions is an important and urgent task.

The analysis of the zoning scheme of the territory of Kryvyi Rih performed in the framework of this study (figure 1) allows to determine *the linear type of functional zoning* of the urban area. It is natural for a city longer than 100 km.

A unique feature of such a structure is the lack of a clear urban "core" in Kryvyi Rih, which is typical of most large cities. As a result of the dispersed location of individual industrial facilities, the central part of the city has the shape of a central axis that crosses Kryvyi Rih from the south to the north. As a powerful centre of the mining and metallurgical industry in the historical perspective, Kryvyi Rih was formed along the ore body of the Kryvyi Rih iron ore basin, so industrial enterprises tend to iron ore deposits.

Residential areas have been formed around these facilities, gradually creating a single urban infrastructure. Today it significantly increases the time for moving from the suburbs to the central part, the cost of engineering and transport infrastructure of the city, etc. Inconveniences also occur due to the stretching of the entire system of public and cultural services, as well as the growing tendency to monotony of urban landscapes.

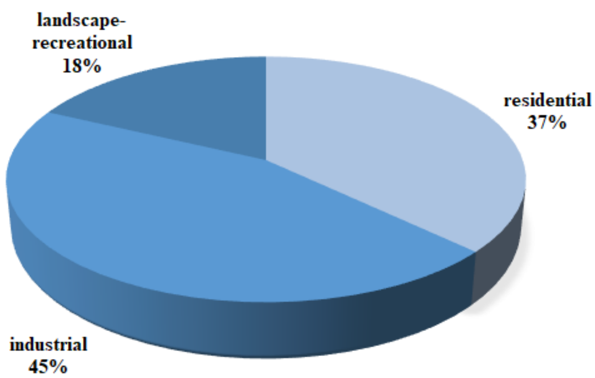

Figure 2. The ratio of functional areas in the structure of the city of Kryvyi Rih.

A characteristic feature of the functional zoning of large industrial centers is the dominance of industrial zones in the structure of their territories. In Kryvyi Rih, ***industrial areas*** occupy a significant part – about 45% of the city (figure 2).

The largest industrial area is located in the southern part of the city (figure 3) and is represented mainly by large enterprises of the metallurgical industry: PJSC "ArcelorMittal Kryvyi Rih", JSC "Southern MPP", PrJSC "Ingulets MPP". In the general structure of the territory of this city's part, the industrial zone covers more than 70%, among which quarries, dumps and tailings dominate.

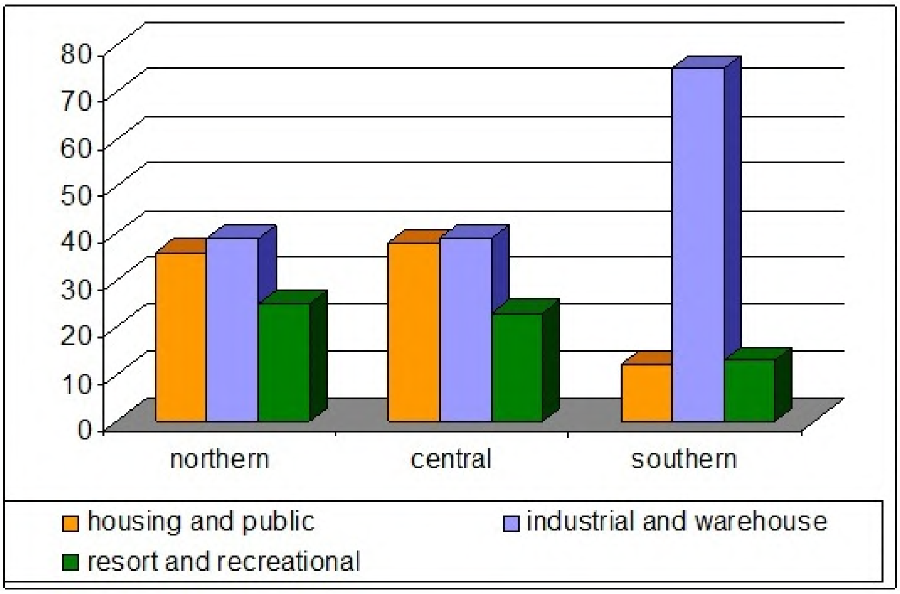

Figure 3. The ratio (in %) of the areas of functional zones in the different parts of Kryvyi Rih.

In the central and northern parts of Kryvyi Rih, industrial areas cover less than 40% of the territory (figure 3). In addition to large industrial enterprises (PrJSC "Central MPP", PrJSC "Northern MPP"), there are enterprises of trade, utilities, consumer services, food industry and others.

Landscape-recreational areas occupy only 18% of the city and are represented by parks (Fedir Mershavtsev, Bohdan Khmelnytsky, Jubilee and others), squares, beaches. The location of the Kryvyi Rih Botanical Garden of the National Academy of Sciences of Ukraine, which belongs to the zone of the Nature Reserve Fund is of great importance for the city. In the southern part of the city the share of landscape- recreational areas is the smallest one (12%). Due to the significant anthropogenic pressure on the environment, the city does not have enough recreational facilities.

Residential areas occupy 37% of the city's territory, with a significant predominance in its central part (67%). They occupy the smallest area (12%) in the south of Kryvyi Rih (figure 4).

The basis of the residential area of Kryvyi Rih is occupied by manor buildings, the other part of it is covered with the areas of medium and multi-storey buildings. The last also include public and business zones: city government agencies, organizations, educational and health care institutions, etc.

According to the analysis, in Kryvyi Rih the residential areas are as close as possible to the industrial ones, they often fall into the sanitary protection zones of enterprises, which violates the state building norms.

Characteristics of the population's living environment comfort of the residential area of the city requires analysis of indicators of each of the three groups of factors: transport accessibility, development of social infrastructure and environmental condition of the territory.

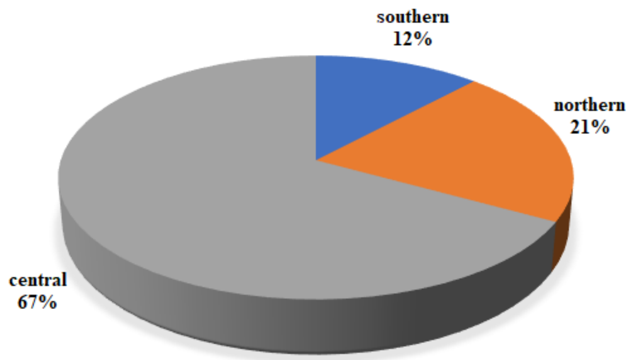

Figure 4. Distribution of the territories of residential zones (in %) s in different parts of Kryvyi Rih.

Transport accessibility, or accessibility of transport services for the population, is an important socio-economic condition for the development of the city. Availability of transport services means the ability of different groups of population to use transport infrastructure to realise their movements, the ability of people to reach jobs, study, purchase goods and services, as well as the implementation of other life functions.

In the work, transport accessibility is assessed by the following criteria: the number of transport routes (according to the site Easy way), distance from the city centre, proximity to high-speed tram stations and land transport stops

As in the other large industrial regions, the most favourable for the livelihood of the population are urban areas with the highest rates of transport accessibility. In Kryvyi Rih they are naturally located along the central axis of the city along its entire length.

Urban areas, characterised by a sufficient number of transport routes for the normal functioning of the population have a satisfactory rate These large areas are usually located between the central part and the outskirts of the city.

The most separated from the main highways areas of Kryvyi Rih are unfavourable for the population's livelihood. This category includes areas with a small (1–3) number of urban transport routes, as well as areas with zero transport coverage. There are no high-speed tram lines in these areas either. These unfavourable areas are located in the outskirts of Kryvyi Rih.

In the work territorial development of ***social infrastructure*** is assessed by the number (within a certain area) of institutions of *education* (preschool, general secondary, extracurricular, higher, etc.), *culture* (cultural-artistic, entertainment, art education, museums, theatres, libraries, etc.), *health service* (primary, secondary, tertiary link, pharmaceutical, etc.).

The highest scores were given to about 10% of the residential areas of Kryvyi Rih. Mostly these are the territories of the old and new central parts of the city, as well as separate plots of its northern part.

The largest share (about 55% of the residential area) falls on the territory with a satisfactory indicator of social infrastructure development. These are the areas of large and the most populated Saksahan and Pokrovskyi administrative districts of the city. In the other districts the areas with the average value of the indicator are distributed locally. Social and healthcare facilities predominate among the social infrastructure facilities here.

About 35% of the territories have the worst assessed social characteristics. They are classified as socially disadvantaged due to the small or zero number of social infrastructure facilities. Mostly they are the territories of the residential areas distant from the central axis of the city.

The assessment of ***the ecological condition*** of urban areas is based on the nature protection scheme of Kryvyi Rih, in which the areas are differentiated by the total indicator of air pollution.

There is a significant territorial differentiation of Kryvyi Rih in terms of air quality. The most polluted is the air basin of the east of the central and southern parts of the city. The most favourable one is removed from the contaminated areas of the extreme southern and northern parts of the city. Other urban areas have intermediate values for air pollution.

The introduction of an integrated indicator of comfort as a set of indicators that characterise individual factors of comfort with their territorial affiliation, has allowed to build a map of ecological and social comfort of Kryvyi Rih population (figure 1), which reflects the territorial differentiation of three levels of residential area of the city: favourable (good), satisfactory and uncomfortable.

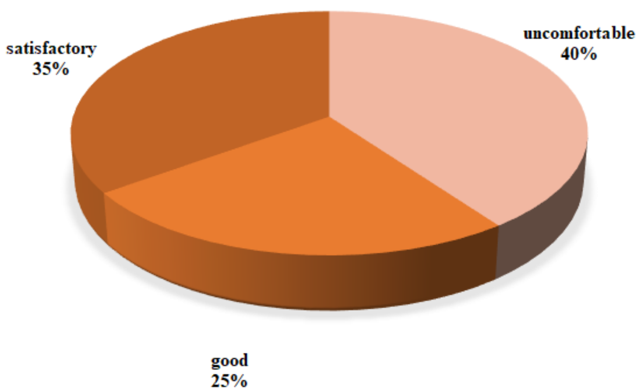

Figure 5. The ratio of areas of the residential zone with different levels of ecological and social comfort of the living environment of the city population in Kryvyi Rih.

The spatial position of the comfort areas of the residential zone together with the localization of the industrial and landscape-recreational zones form the basis of the spatial-planning organisation of the city, its "*framework*". The framework divides urban spaces according to the intensity of their development and the degree of population's comfort of life and, in general, significantly complements the functional zoning of the city.

Presented on figure 5 the ratio of the areas of the residential zone with different levels of ecological and social comfort of the population's living environment of Kryvyi Rih shows the dominance of uncomfortable areas (40%) in the city.

There are significantly fewer urban areas favourable for life in Kryvyi Rih.Their share does not exceed 25%. Almost twofold exceedance of the share of areas with extremely uncomfortable living conditions is a characteristic feature of large industrial cities. This is due to the link between the development of urban infrastructure and the industrial development of the region. Whereas social demand is of secondary importance here.

Analysis of *the spatial differentiation* of the habitat comfort indicator revealed that about 63% of the territories with favourable comfort are concentrated in the central part of Kryvyi Rih (figure 6), while in the north of the city there are only 7% of such territories. However, the vast majority (82%) of areas with uncomfortable living conditions are in the central part of the city; they also significantly dominate in the east. The share of these territories in the north and in the southern part of Kryvyi Rih is insignificant (20%).

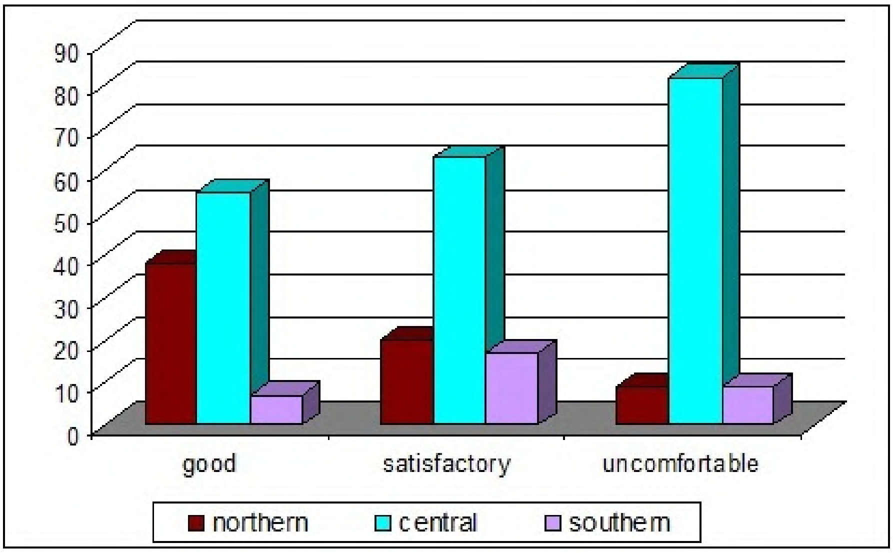

Figure 6. Spatial distribution of territories with different levels of ecological and social comfort of the living environment of the population of Kryvyi Rih.

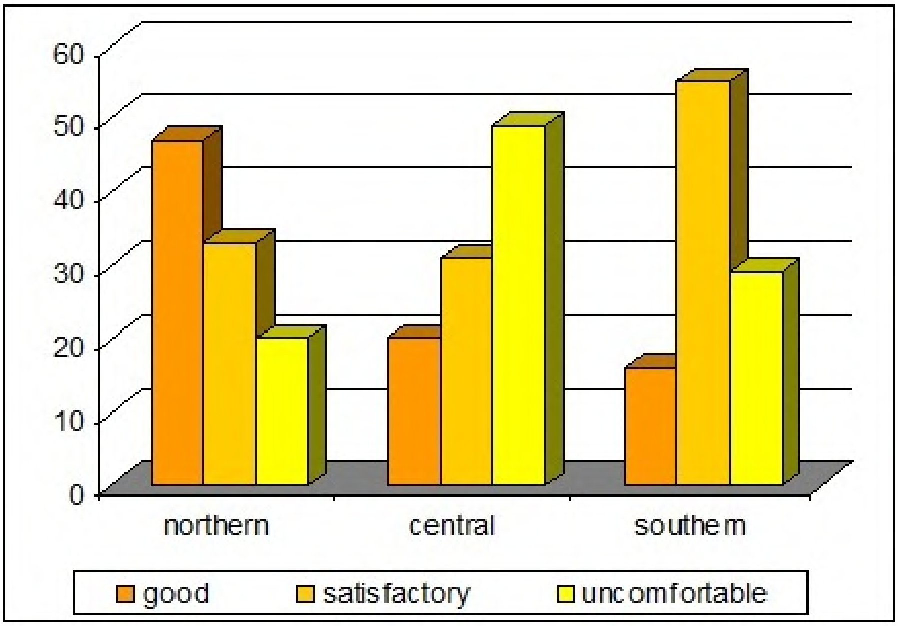

Figure 7. Quantitative ratio of territories with different levels of ecological and social comfort of the living environment of the city population of Kryvyi Rih.

The analysis of *the quantitative ratio* of territories with different levels of the ecological and social comfort of the population living environment of the city of Kryvyi Rih shows somewhat different values compared to the spatial analysis (figure 7). In the context of quantitative analysis, the northern part of the city is the most comfortable to live in, while the southern one and the east of the central part of Kryvyi Rih are the most unfavourable. The revealed destructiveness is caused by excessive (more than 2/3) concentration of territories of the residential zone in the central part of the city.

Table 1. Distribution (in %) of territories with different levels of ecological and social comfort of the population living environment by administrative districts of Kryvyi Rih.

Comfort indicator group	Districts						
	Terny	Pokrov-skyi	Saksahan	Central City	Dovhint-sevsky	Metalur-hiynyi	Inhulets
good	24	33	18	7	7	4	7
satisfactory	15	12	17	30	1	11	13
uncomfortable	7	13	8	9	51	05	7

The regularities revealed during the research were reflected in the differentiation of the living comfort indicator by administrative districts of the city (table 1). Significantly more than half (57%) of the territories with favourable living conditions are in Terny and Pokrovskyi districts of Kryvyi Rih, located in the north and in the northern part of the city centre, respectively. More than half (51%) of the area considered as uncomfortable is located in Dovhintsevsky district, situated in the east of the central part of the city. In the other areas of the city this figure varies in the range of 5–13%.

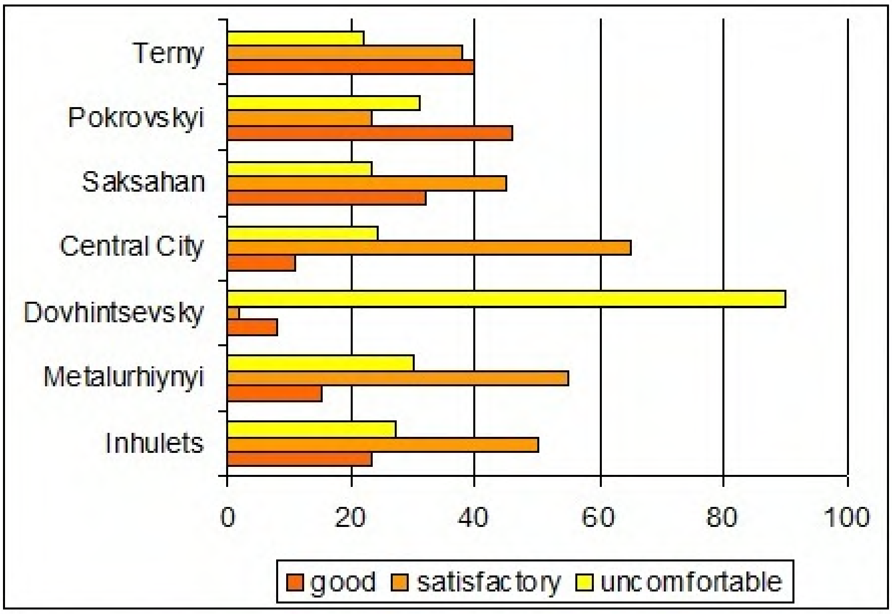

Figure 8. Quantitative ratio of territories with different levels of ecological and social comfort of the population living environment by administrative districts of the city of Kryvyi Rih.

Thus, according to the set of criteria of ecological and social comfort of the population's living environment (figure 8), the most favourable are Terny, Pokrovskyi and Central City districts, the most uncomfortable is Dovhintsevsky district. Indirect confirmation of the obtained results is their correlation with the results of the survey of city residents conducted by the Institute of Urban Development (Kryvyi Rih). Thus, in the distribution of city districts by comfort through the eyes of respondents, Central City District was in the first place (28.8% of respondents), and Dovhintsevsky district was in the penultimate one (6.3%). Respondents defined rather low assessments of living comfort for Terny (7.8%) and Ingulets (4.6%) districts, because of the remoteness of the place of residence from the administrative centre.

4. Conclusions

1. An important result of the study has become the development of methods for spatial assessment of ecological and social comfort of the population living environment of large industrial cities by the example of Kryvyi Rih, which includes a set of criteria and evaluation indicators using mathematical and cartographic modelling based on geo-information technologies.
2. For the first time for the city of Kryvyi Rih a series of thematic maps of the main factors of formation of ecological and social comfort of the population living environment has been built, which made it possible to form an integrated map of the comfort of the urban environment.
3. The obtained results make it possible to identify territorial imbalances in the development of socio-economic policy of the city.
4. In order to ensure a balanced comfortable living of the population of all residential areas of the city it is necessary to systematically develop social infrastructure, improve public transport, increase the area of recreational areas, implement measures for enhancement of the ecological condition of the territory, etc.

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To cite this article: O V Bondarenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012076

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IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012076 doi:10.1088/1755-1315/1049/1/012076

Visualization of demographic statistical data

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Abstract. In this publication, the authors address the content and objectives of demographic data visualization, generalize the most common techniques and tools for demographic data visualization, and share their own experience of testing various statistical visualization practices, namely World Population Dashboard of United Nations Population Fund and Population Reference Bureau. Special emphasis is placed on the implementation of Trendalyzer software, developed by the Swedish Gapminder Foundation, and the experience of demographic statistics visualization via interactive infographics made by Oxford Martin School (a structural unit of the Department of Social Sciences at Oxford University). The presented article evaluates the contribution to the visualization of statistical data made by such Ukrainian organizations as State Statistics Service, public organization "Ukrainian Center for Public Data", BusinessViews and Top Lead. Outlining the advantages and disadvantages of various visualization practices, the authors argue that "dry" statistics being represent by means of visualization tools such as Trendalyzer and Our World Data may constitute a clear and expressive language of convincing facts that contribute to a holistic demographic worldview.

1. Introduction

1.1. The problem statement

Professionals specializing in the population issues permanently deal with challenges related to comprehension, systematization, analysis, generalization and presentation of large data sets that characterize the number, composition, movement and location of the population in terms of a separate administrative-territorial unit (country, county, region) and globally. Statistical data are dynamic, thus their presentation in text format complicates the cause-and-effect identification, and establishment of trends and patterns existing between demographic phenomena and processes. Visualization itself particularly facilitates the process of analysis, presentation and comprehension of complex demographic data, as human brain perceives and processes visual information faster and better than textual one [1].

The scientific literature review indicates that the research topic we are studying is not new. Several attempts have been made to address particular aspects, that is: data visualization in sociology [2]; exploring the demographic history of populations with enhanced Lexis surfaces [3]; reaching the potential of visualization of statistical data on the POWER BI platform [4]. There is a growing body of literature that recognizes the importance of data and statistics visualization to a wide audience [5], and explores some aspects of visualization of statistical and scientific data [6]. Existing research recognizes the critical role played by methods of visualization and their perception [7]; and demographic data visualization [8].

More recent attention has focused on manuals and guides, i.e. Open manual on open data [9]; Pro Tableau: a step-by-step guide [10]; and 10 Demographic Infographic Templates to Share Population Data and More [11] and others.

Meanwhile, the analysis of the data visualization background highlights not only significant breakthrough in comprehension of the issue studied, but also indicates certain gaps in some important aspects of it. On the one hand, according to [8], good visualization, applied in a scientific context, improves the understanding of the underlying data without sacrificing truth for the sake of beauty. “Visualizations can be employed to efficiently explore and discover patterns in demographic data, to help viewers gain a better understanding of magnitudes, intensities, durations, changes, and differences, and to communicate these to large audiences” [8]. On the other hand, the current state of data visualization often does not meet societal needs, as the amount of statistical information is rapidly growing and constantly changing. It follows from the above that it is not enough for the visualization tools to visualize and illustrate the data, as it is also essential to update the information to the current state corespondingly.

1.2. The objective of the article

This publication overviews the current state and the analysis of the authors experience of visualization of demographic data. To achieve the declared objective, we apply the following research methods: systematization and analysis of the scientific literature and the method of visualization, which is considered as a systematic, rule-based, dynamic and / or static graphical representation of information, which helps to identify cause-and-effect relationships between demographic phenomena and processes.

2. Results and discussion

2.1. Visualization techniques

Visualization is a graphical presentation of information, which can concisely represent large arrays of data in an image. There are many visualization techniques presently, among the most common are graphs, diagrams, spectrograms, tables, infographics, charts, interactive storytelling, maps and cartograms, etc. Whatever the visualization technique, the data “speak” itself. The choice of a specific data visualization technique depends on the specifics of the data to be illustrated and the purpose of the visualization.

The advantages of visualization are:

- emphasis on different aspects of the data;
- analysis of a large data set complex in structure;
- reduction of human information overload and focus of human attention;
- unambiguity and clarity of the derived data;
- allocation of the links and relationships contained in the information [12], [13].

We can define the following visualization objectives based on the scientific literature review:

- to represent visually quantitative information in schematic form;
- to present data in an objective and relevant way without distortion and curvature (each visual indicator is presented unambiguously);
- to generate automatically visual product from the data set;
- to present predominantly the most significant elements correctly (not to overload the user’s attention with redundant information);

- enable the user to draw independent conclusions or verify the correctness of the author's conclusions.

2.2. Visualization tools

Common knowledge is talking about the complex in a simple and accessible form is not an easy task, that is why talking statistics so they come to life, to observe the cause and effect of demographic phenomena and processes beneath the numbers, to reveal trends and patterns, makes an extremely difficult task. Nevertheless, digital technologies presently offer many tools for data visualization. Let us consider some of them in more details.

Addressing the interactive visualization of relevant demographic data, the World Population Dashboard of United Nations Population Fund and the Population Reference Bureau are worth referring to.

World Population Dashboard [14] is an interactive dashboard that demonstrates population data, key demographics globally, regionally and locally (by country). Presented data provided by the United Nations Population Fund and other UN agencies is updated annually and can be downloaded in PDF and XLSX formats. The main indicators to filter information are Population, Maternal and Newborn Health, Family Planning, Education, Fertility, Life Expectancy, Harmful Practices.

The Population Reference Bureau (PRB) [15] is a private non-profit organization founded in 1929 that specializes in collecting and providing statistics necessary for research and / or academic purposes related to the environment, health and population structure. The PRB website presents relevant demographic information summarized in the World Population Data Sheet and visualized in the form of interactive maps, charts, graphs, etc.

The advantages of the above mentioned web resources are the relevance of information, its prompt updating, free of charge access to data, the information dissemination capacity, convenient format back-up. However, the proposed mode of data presentation fails retrospective analysis, a choice of user-friendly format for data presentation, etc. The latter opportunities are extensively provided in the Trendalyzer software and on the Our World in Data website.

Trendalyzer [16]. The software was developed at the initiative of Hans Gösta Rosling, who is a Swedish physician, a professor at the Carolingian Institute of International Health, and a founder of the Gapminder Foundation. Hans Gösta Rosling, being an internationally acclaimed TEDster and statistician, introduced an extremely powerful web service for retrospective visualization of the global, regional and country statistics by means of Google Motion Charts. The current version of Trendalyzer – **Gapminder World** – is a visually attractive product that provides users with socially relevant information. The amateur users can take advantage of such tools as Bubbles, Maps, Trends, Ranks, Ages, Dollar streer, etc., whereas professional users may benefit from visualization of statistics with their own data input to the Gapminder Tools Offline. Trendalyzer software components, including the Flash-based animation charting gadget, are currently available for public use as part of the Google API visualization. The picture below is an example of demographic data visualization via Gapminder World using Bubbles technology – an interactive bubble chart (figure 1, figure 2).

In the above example diagram, bubbles show several variables by default: two numerical variables on the X (number of children per woman) and Y (world population), bubble size (country population) and bubble color (region). The time variable controlled by a slider or a so-called timeline reflects the retrospective and projected development of a demographic phenomenon or process. Thus, a user, moving along the timeline, can observe the dynamics of the total fertility rate in the interim between 1800–2021, as well as the demographic forecast until 2100. The analysis of interactive data permits the characterization of the main quantitative indicators of birth rate, proving population birth rate to be the main driver of demographic development. Bubble diagram let identify the main factors effecting the birth rate; reveal the

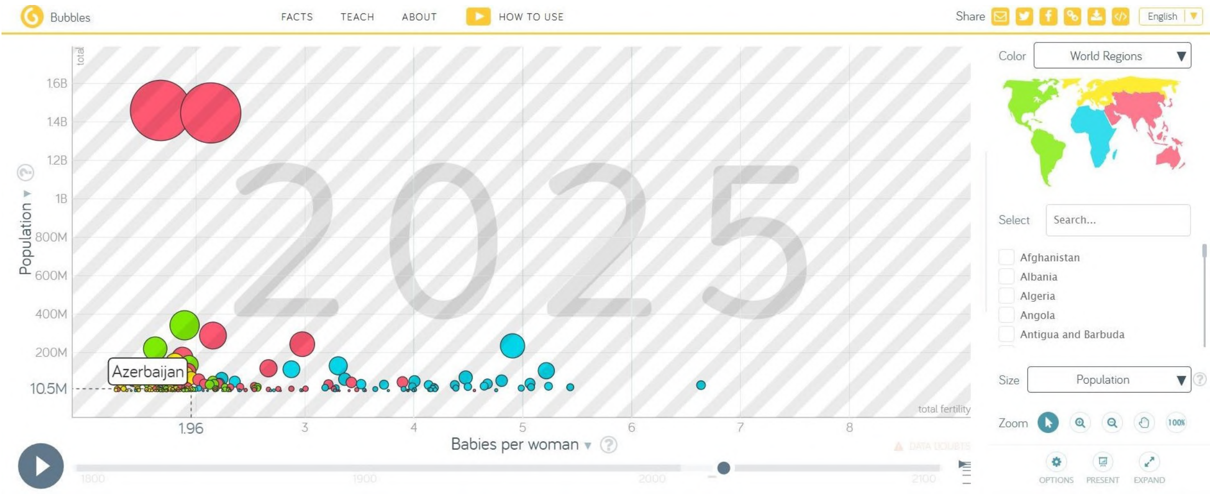

Figure 1. Demographic forecast of the dynamics of the total fertility rate.

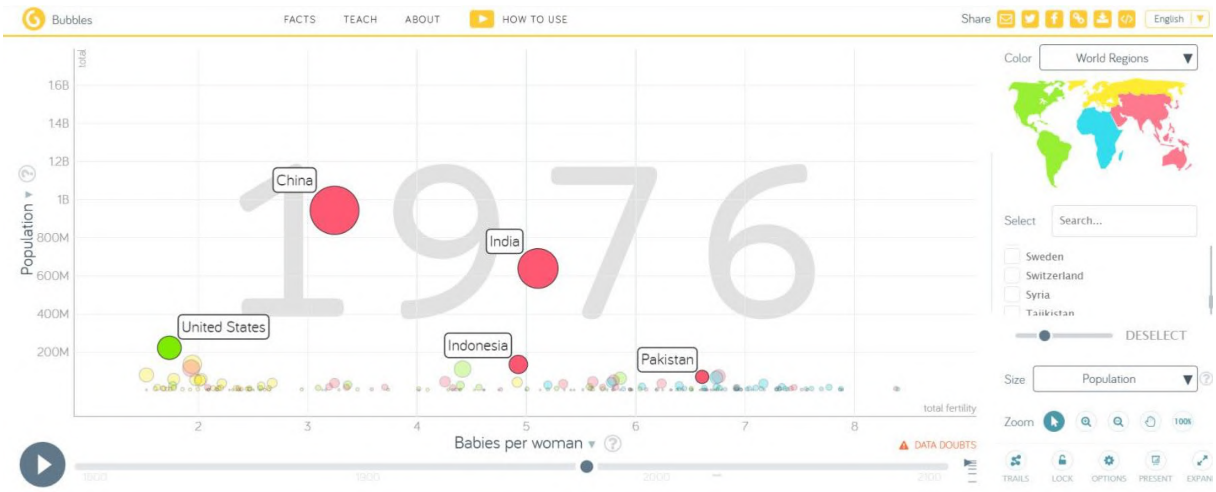

Figure 2. The comparative analysis of the total birth rate of distinct countries.

historical peculiarities of changes in this process; and analyze current demographic trends. The software can filter data and thus perform a comparative analysis of territorial features of fertility and its indicators globally and regionally (figure 3). Interactive graphs, maps, ratings of global demographic processes, proposed by Gapminder contribute to the change in perception of world development and help to overcome the "planetary ignorance". In his interview, Hans Gösta Rosling emphasizes that Gapminder World exposes the world as it is, not as it is thought to be. "When people see the world to be the same as it was 10 or 50 years ago, it means that they see neither the direction in which we are all moving, nor the speed of change, nor the potential for development" [13].

Our World in Data [17]. The visualization of demographic statistics via interactive infographics from The Oxford Martin School at the University of Oxford is equally interesting and exciting.

Our World in Data is the result of collaboration between the non-profit Global Change Data Lab and Oxford University researchers who study global human problems based on empirical analysis of global statistics. The website provides data visualized in the form of numerous

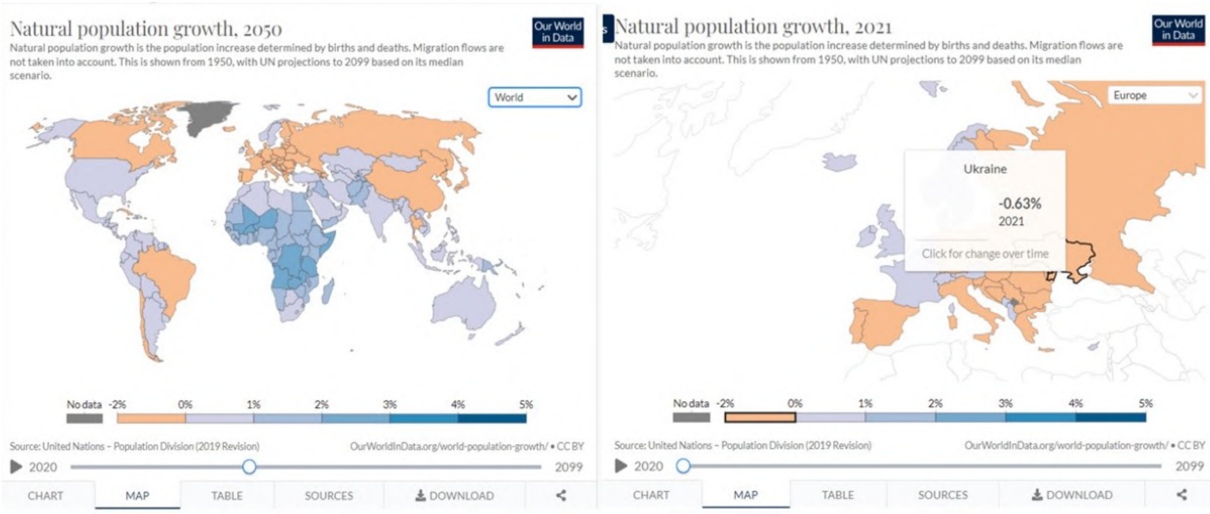

Figure 3. Natural population growth: global demographic forecast until 2050 (left), Natural population growth of the Europe region with illustrations of data for each country (right).

interactive graphs, maps, tables on topics, grouped into 11 sections: Demographic Change; Health; Food and Agriculture; Energy and Environment; Innovation and Technological Change; Poverty and Economic Development; Living conditions, Community and Wellbeing; Human rights and Democracy; Violence and War; Education and Knowledge; Sustainable Development Goals Tracker.

Among the advantages of Our World in Data are the following:

- analytical information is demonstrated by various visual tools – tables, graphs, charts, maps;
- convenient interactive format for presenting the same information enables the dynamic nature of the studied demographic phenomena and processes to be reproduced;
- different levels of data visualization (global, regional, local) (figure 3);
- extension of the CCBY license for the use of visualized products (graph, table or map) which allows to adapt the information conventionally;
- the implementation of statistical reports of authoritative world organizations (United Nations Population Division, Food and Agriculture Organization of the United Nations, World Bank, Gapminder and others) as sources for creation of visual products;
- tables, graphs and maps are available in several formats (Image PNG, Vector graphic SVG, Full data CSV);
- visualized information can be disseminated on social networks (Twitter, Facebook) and site embedded.

In addition, the site offers explanations, comments and some instructions on how to use the interactive graphs, tables and maps.

We might suggest the following work procedure with the content available in the World Population Growth section.

The analysis of the content of interactive maps presented in this site section leads to the conclusion that the peak of world population growth is characteristic for the middle of the last twentieth century. Comparative analysis of the set of maps responds to a number of questions, including:

- How have natural growth and population growth changed in different regions of the world with times?
- What is the demographic forecast for the dynamics of natural growth and population growth?
- Which regions of the world and which countries demonstrate the highest and lowest natural increase?
- Why is natural growth the highest in Africa? Will this trend continue in the near future and why?
- What year was the negative natural increase recorded in? Why?
- Why is population growth declining every year?
- What are the reasons for countries with the same population growth rates in the last century (such as India and Nigeria) to grow population at different rates now?

Thus, a convenient interactive format for presenting the same information makes it possible to reproduce the dynamic nature of the studied demographic phenomena and processes (figure 4).

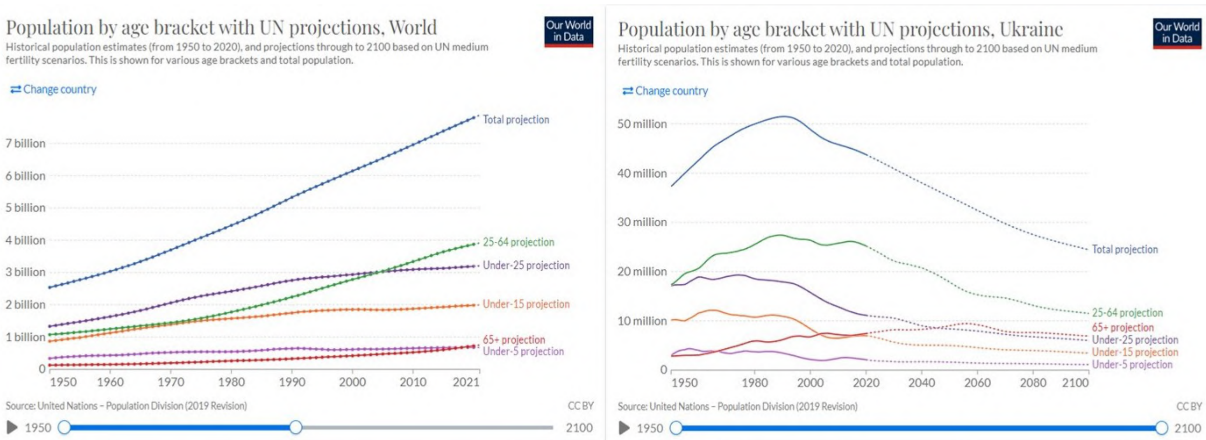

Figure 4. Population by age bracket with UN projections World and Ukraine.

The data visualization by Our World in Data covers not only large amounts of information, but also makes the perception of complex information more comprehensive, the comparison of quantities faster, and the identification of data patterns easier. For instance, the analysis of Population by age bracket with UN projections, World and Population by age bracket with UN projections, Ukraine (figure 5) lets trace age-related historical estimates of the population within 1959–2020 based on UN scenarios with average birth rates. Moreover, in order to detect the content of the current demographic trend, there is no need to compare the figures, as the nature of the dynamics of the studied demographic process is apparent. The salient feature of the data visualized with Our World in Data tools is persuasiveness, as such visualization format provides an objective outlook on age imbalances in the population and instant assessment of the ratio of children, people of reproductive age and the elderly. Regardless of the visualization technique used in Our World in Data, the data presented are objectified which is of extreme importance.

Consequently, our experience of practical testing Gapminder World and Our World in Data in delivering the courses of Population Geography and Fundamentals of Demography convincingly proves their reliability and feasibility in use, as exploiting the software makes it possible to:

- systematize and visualize data;

- present data in the form of simple and visual animation;
- receive the latest information, promptly observe the dynamics of data;
- publish data in the necessary hierarchy, carry out data comparative analysis;
- optimize the study of large data sets, highlight the most important ones;
- compare blocks of information, receive information in a customized form quickly.

The most important thing about the software observed is that "boring" statistics become clear, vibrant, eloquent, impressive and fascinating.

In Ukraine the state of demographic data visualization is not up to the mark compared to the Gapminder World and Our World in Data, presented above, despite the fact that the population is studied thoroughly and comprehensively. Systematic demographic research is carried out primarily on the basis of Ptoukha Institute for Demography and Social Studies of the National Academy of Sciences of Ukraine. The latter is a reputable scientific institution in the international scientific space, which collaborates with a number of international organizations and foreign scientific institutions (UNDP, UNFPA, UNICEF, European Commission, The World Bank, ILO, IOM, World Health Organization, National Institute for Demography of France, Max Planck Institute for Demographic Research and others). Meanwhile, the rapid growth of available data overelaborates for professionals and users the search for the information necessary for grounded decisions. Therefore, there is a need to visualize a significant array of demographic data in an interactive format with up-to-date (systematically updated) content. As Seema Acharya and Subhashini Chellappan emphasizes "data visualization is visual communication" [10].

In Ukraine, among the individual organizations engaged in data visualization, we can mention the State Statistics Service, the Ukrainian Center for Public Data (UCDS) [18] and BusinessViews [19], all of which specialize in visual content. We would like briefly describe their contribution to the visualization of statistics.

The State Statistics Service, apart from presenting data via infographics, complimentary developed an application "Statistics in Smartphones", which provides quick and convenient access to public information from the State Statistics datasets posted on the Unified State Web Portal of Open Data data.gov.ua. Convenient interface provides access to up-to-date statistical information; visualizes the information of data sets on selected parameters (indicators, classifications, territory and period); groups data sets by topics (branches of statistics); visualizes information in the form of graphs and histograms; download data sets to the "My sets" section; disseminate information via messengers and social networks.

UCD experts collect and systematize data sets; develop systems (geoinformation systems included) for convenient and visual presentation of data, online tools for working with data; prepare analytical reports based on comprehensive data analysis; share the data processing experience among the professionals and the public. Among the latest projects developed by the UCD is the interactive visualization "Mortality rate in Ukraine 2018–2020" (figure 5), which is distributed under a Creative Commons (CC BY) license, and can be copied and disseminated in any form or format and modified (edited, etc.).

BusinessViews release annual infographic guides (figure 6), which publish employment, business, finance, technology and other aspects of social life in a simple format and language of the target audience.

Apart from the above-mentioned data visualization services, there are available numerous cloud services for creating customized visual products in the varied formats, that is infographics, interactive maps, graphs, charts, etc.

Among the most popular services, which are equally suitable for obtaining a quick clear result as well as for advanced use, there are the following: Canva, Chart.js, ChartBlocks, Crossfilter, D3.js, DataHero, Datawrapper, Dygraphs, Ember Charts, FusionCharts, Google Charts,

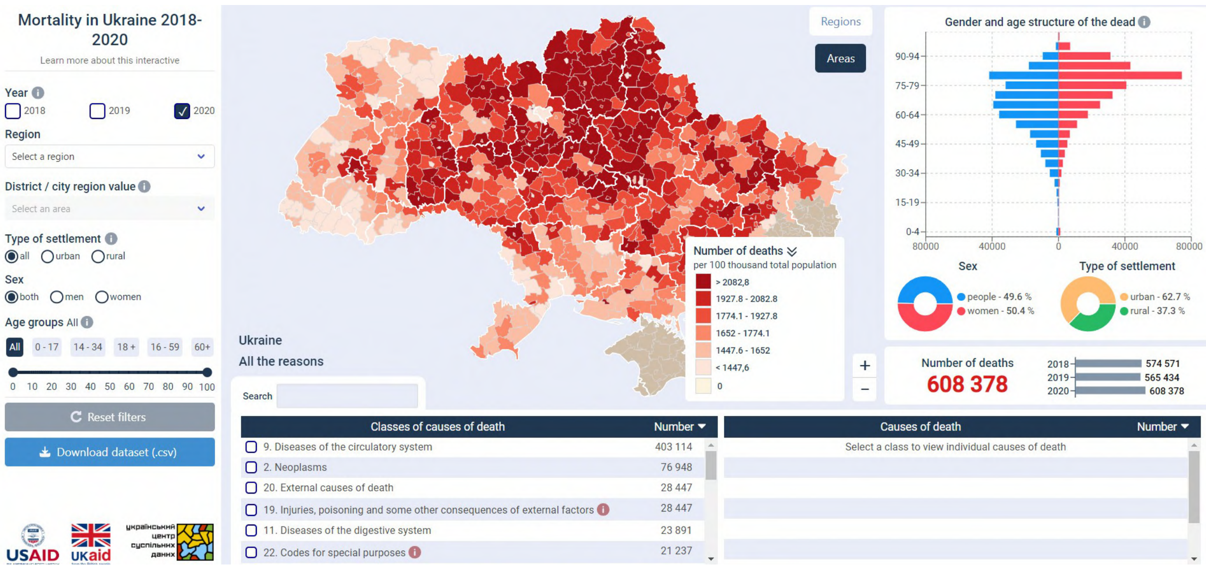

Figure 5. Interactive visualization “Mortality rate in Ukraine 2018–2020”, developed by the Ukrainian Center for Social Data [18].

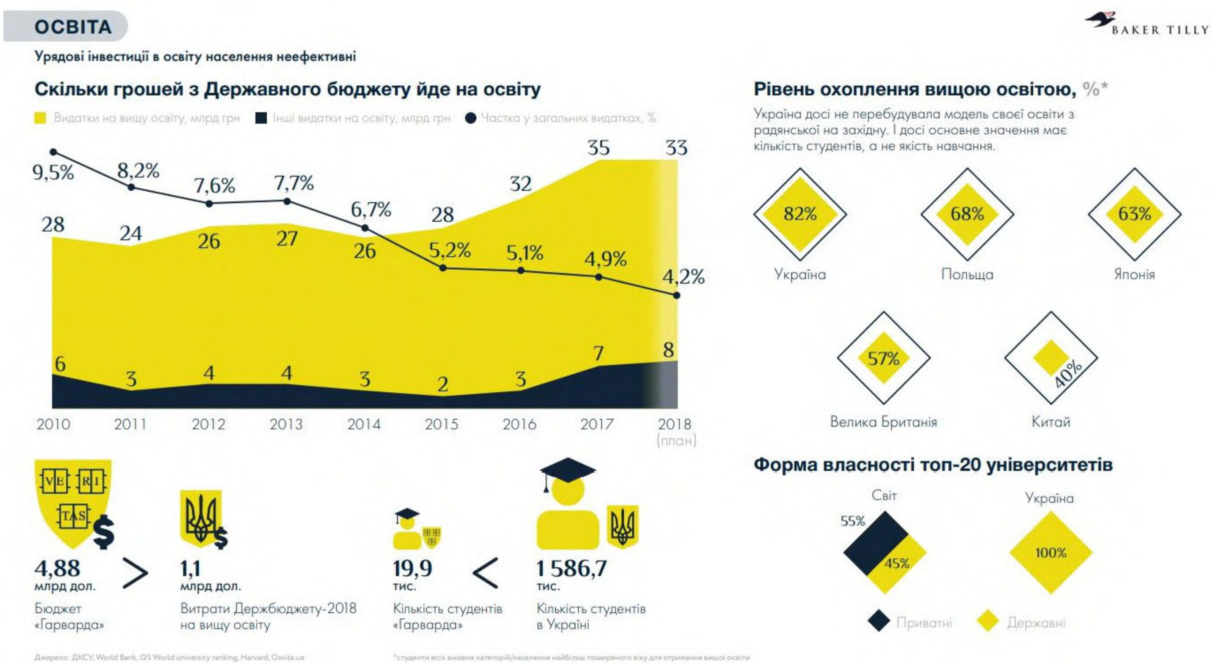

Figure 6. Infographics “Expenditures on higher education in Ukraine” (2018), presented by BusinessViews [19].

Highcharts, Infograph, InstantAtlas, Kartograph, Leaflet, Modest Maps, NVD3, OpenLayers, Plotly, Polymaps, Raw, Tableau Public, Timeline, Visual.ly, Visualize Free, ZingChart.

The analysis of the advantages and disadvantages of the latter is beyond the scope of this publication, but we consider their further perspective revision.

3. Conclusion

The scientific literature review and the analysis of the practical state of demographic data visualization have confirmed the conclusions that visualization is a powerful tool for presenting large data sets, with certain advantages and can be implemented using certain techniques (graphs, charts, spectrograms, tables, infographics, diagrams, interactive storytelling, maps and cartograms) and tools.

Among the currently available visualization tools, based on the authors' positive practical experience, we can recommend the use of Trendalyzer (Gapminder), Oxford Martin School, World Population Dashboard (United Nations Population Fund) and World Population Data Sheet (Population Reference Bureau).

One of the findings of this research is that among the Ukrainian means of visualization of demographic data, the services developed by the State Statistics Service and the public organization "Ukrainian Center for Public Data" deserve attention. These tools can visualize the impact of various factors on the world's population in the interactive mode, identify common demographic trends that occur globally, regionally or locally, reveal causal links between demographic phenomena and processes.

We anticipate the prospects for further research in the analysis of the advantages and disadvantages of a number of cloud services available for data visualization and coverage of the experience of their use aimed at demographic forecasting.

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Traditional water supply systems at lack of water regions and their modern situation (cases of M’zab Valley, Algeria and Miyakojima Island, Japan)

To cite this article: N H Rezig and G V Shevtsova 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012077

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012077 doi:10.1088/1755-1315/1049/1/012077

Traditional water supply systems at lack of water regions and their modern situation (cases of M'zab Valley, Algeria and Miyakojima Island, Japan)

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Abstract. The historical development of water supply systems for portable and irrigation water gathering is traditional for lack of water regions of the world. The diversity of such systems can be observed at Middle East and Asiatic cultures. Some of them are still in use or partly in use now. The study cases of the work are traditional distribution systems of rainwater in the deserted M'zab Valley, Algeria and tropical Miyakojima Island, Japan. The research is aiming to precise the modern situation of traditional water supply systems estimating the possible ways of theirs sustainable development and revitalization. The research conducted on the case grounds mainly with field studies and interview methods. The water supply system of M'zab has been implemented more than eight centuries ago and is still in use. It is a complex hydraulic system based on the principle of total utilization of torrent water and on the equitable division of this water over the entire oasis. Local people now beginning to understand its cultural significance aiming to popularise it. Miyakojima Island medieval water supply underground system consist of the network of cave sources integrated with architecture. Now it is in decay not using like a source of potable water but still preserving some sacral significance with not pointing on popularization. For the sustainability and revitalization of the traditional water supply systems now it is not enough to preserve their initial function but also need to develop the potency of tourist attraction with reservation as cultural property.

1. Introduction

The historical water supply systems is an interesting scientific topic connecting architectural, engineering, ecological, sustainable development, revitalization and other aspects. Mostly they shaped in lack of water regions of the world, including well-known medieval irrigation water systems of Middle East deserted regions (the foggara in Algeria, the Qanat in Iran, Khettara in Morocco, Falj in Oman and so) as well as city potable water supply underground systems of Middle East. We can observe medieval water supply systems also in other regions of the world, including some tropical regions of Okinawa, Japan. The significant amount of such ancient water ways are used until now, some of them are already out of use but currently obtained touristic and educational attraction. There also the cases of preserving both direct water supply and touristic options. Several of such system are designated as UNESCO cultural property.

In our work we tried to concentrate mostly to the topic of modern situation of provincial ancient water supply systems located in small historical settlements in connection with the current proses of theirs preserving and popularization aiming to estimate the possible ways of theirs sustainable development and revitalization. The study cases are traditional distribution system (foggara) of rainwater based on horizontal drainage galleries in the deserted M'zab Valley, Algeria and ancient network of cave sources and wells (uriga) for underground water gathering at tropical Miyakojima Island, Japan.

The research is based on the own authors field studies of M'zab Valley foggara (Algeria) and Okinawa Miyakojima Island uriga (Japan) concerning observation, photo fixation and interview methods of the investigation of foggara and uriga sites including municipal government and local people's attitude to the point. The part of the work at Miyakojima Island was conducted within Kyoto University (Japan) and supported by Grant of Hakuho Foundation Japanese Research Fellowship program 13th (2018-2019).

2. M'zab case

The city of Ghardaïa, like all Saharan areas feels a lack of water due to low level of precipitation and high temperature and evaporation. Since the Mozabite people settled in the region, they have suffered from the scarcity of water, they have used water wells to irrigate their crops and for daily domestic use. After enormous damage caused by the unexpected floods of the valleys, the Mozabite sages put in place a system of defense against floods and use its running water in periods of drought. This efficient and undoubtedly the most sophisticated system has been designed to capture and distribute water and has resistance to the effect of time. From here was born the traditional system of sharing and collection of water, and it has been established for seven centuries and a half. The water sharing and collection system has been classified as a World heritage site in 1982, it works until today thanks to the people who made it, and also to the regular maintenance work that succeeded kept it in good condition.

2.1. Historical overview on the traditional water supply system in M'zab

Due to the location of the M'zab Valley in a dry, desert region, the Mozabite thought deeply in an efficient way that enables them to use the available water sagely. Initially, they dug wells to exploit the groundwater until it numbered more than a thousand, they did not stop there but rather they searched for methods to exploit the torrential water that used to pass through the valley from time to time, leaving behind some damages without actually benefiting from it.

The precursor Bahmed Abu Sahaba, who died in 1273, was the first who established all the bases of the traditional system.

Then it was improved and renewed by Hamou Oulhadj after a great flood in 1306. He opted for the construction of the bouchene dam which receives the surplus of waters of the bouchemdjene channel and which also replenishes the groundwater table and the surplus is directed again to the course of the M'zab Valley. This important achievement took years to complete, which indicates ingenuity despite the lack of means at the time.

Later, a commission called the trustees Al'umana was formed to monitor and divide the torrents and maintain their facilities in view of the fact that water is rare, and the difficulty of obtaining it in the M'zab area [1–3].

2.2. The functioning of the traditional water supply system

The system of dividing the water in the M'zab Valley is based on the principle of Total and optimum utilization of rainwater and on equitable division for this water on the total oasis. Here we can set two types of irrigation system in the oasis of Ghardaïa:

In ordinary days: the irrigation is done through wells khottara excavated along the M'zab Valley, in the oasis, and inside the settlement, so called ksar, to extract ground water from varying depths between 10m and 80m approximately. The water is extracted using a bucket held by two cords and pulled by animals. Its capacity is between 40 and 50 liters. Then the water is stored in basins that precede the well, it contains a slot in one of its corners that allows the passage of water to the second basin which is larger in size. Then the extracted water is distributed by streams flow seguia towards the palm orchard. The main function of these basins is to store water, reduce its momentum, and maintain the constant flow of water in the streams during the process of irrigation. Their number varies according to the number of owners. The ownership of each well is from five to ten people. The exploitation of the well's water is divided between them in the periods of time where each one takes his share of time according to his contribution to the process of drilling and preparing the well [4–6] (figure 1, figure 2, figure 3).

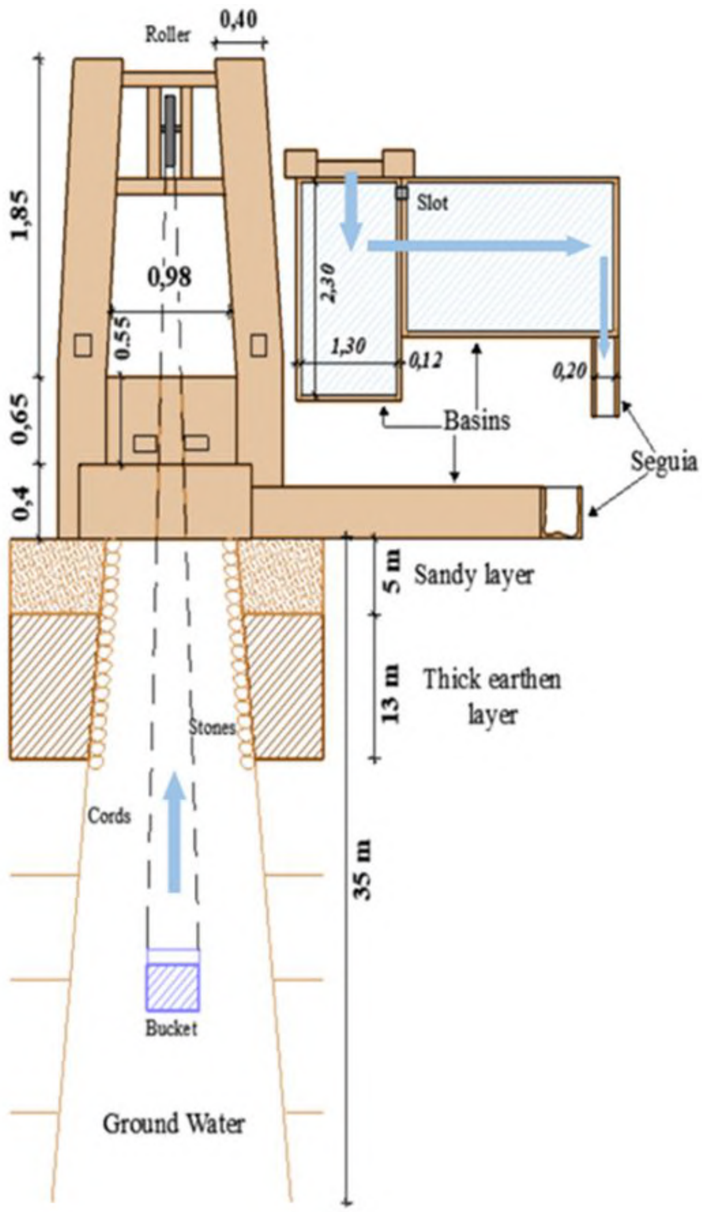


Figure 1. The functional diagram of the wells during the irrigation process in ordinary time (by author).

Figure 2. The well of ksar (by author).

Figure 3. The well of oasis (by author).

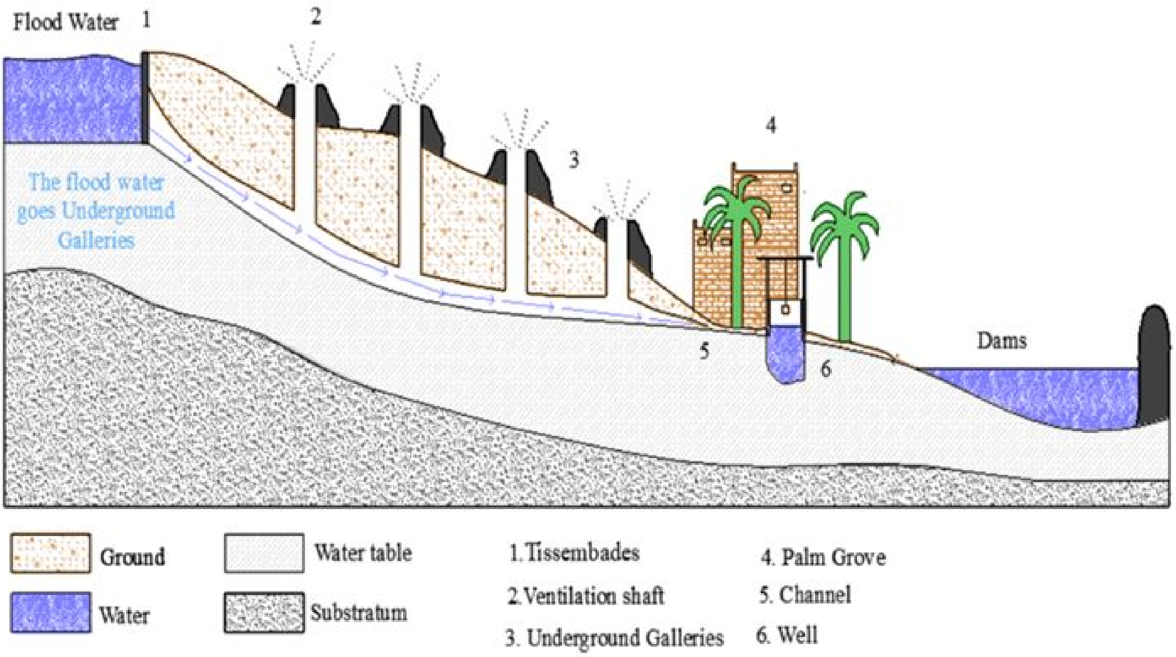
In the flood days: the flood is divided into 3 parts depending on the priority: irrigation, recharge of the water table, and the evacuation of excess water to the valley

The floodwater is directed from the valleys towards the distribution point tissembath, it has openings that help to regulate and reduce the flow of floodwater before entering the underground galleries (tunnels). Each gallery (drain) is sized according to the flow to be conveyed for the irrigation of the oasis (depending on the number of palms needed to irrigate), it contains also a metal flat valve for closing or opening the slot, its dimensions are from 85cm to 40cm on the surface (figure 4).

There are 5 underground galleries along 170 m equipped with ventilation shafts with a diameter of about 90cm, and length varied according to the distance between the wells and the tissembath, the main role of these shafts is the aeration, control, and maintenance of underground galleries. The water reaches the oases trough the underground galleries and then through the channels that are serving lake paths for human circulation in ordinary time and became water transporters during the flood days.

The water infiltrates the palm orchids through koua, which is a small opening located on the wall of the orchid, each orchid has a single koua, and its thickness varies from one palm grove to another, according to several parameters: the surface of the orchid, the number of palm trees and the distance between the underground canal and the orchids.

Inside the palm grove, the distribution of the water is promoted by an earthen network of seguia of variant dimensions (figure 4, figure 5, figure 6, figure 7, figure 8). When the palms are flooded, the surplus water flows through openings in the walls then directed automatically to the various dams, which in turn feed the layer of groundwater for later use by irrigation wells scattered in an oasis, and the excess of that water is automatically directed into the stream of the valley [1, 2, 6–8].



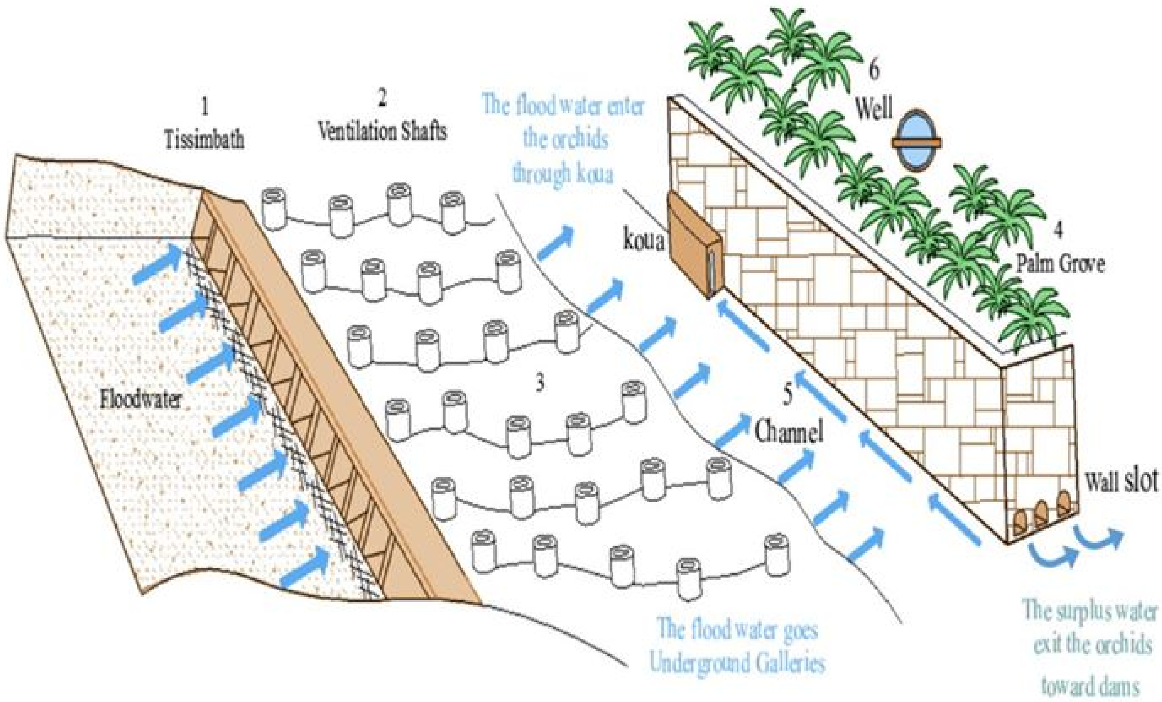


Figure 4. The functional diagrams of M'zab foggara in the flood time: vertical and horizontal projections (by author).

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Figure 5. Tissembath and ventilation shafts.

Figure 6. Channel during the Flood.

Figure 7. Channel during ordinary time.

Figure 8. Koua.

Figure 9. Seguia.

Source:
`http://www.atmzab.net/index.php?option=com_content&view=article&id=1265&It`

2.3. The modern situation of the traditional water supply system of M'zab Valley

To date, the system of distribution of floodwaters has worked perfectly for 7 centuries. It has been renewed several times. The last repairs were carried out after the great flood of 2008 at tissembath level, and also the underground tunnels.

The credit goes to the people who created it, their traditional customs, and to the committee of Al'umana who set a regular maintenance work that has kept it in shape, and its good performance, such as:

- Covering the canals with plaster.
- Cleaning the system by removing waste before the arrival of irrigation water.
- Verification of the state of the wells and canals regularly.
- The permanent cleaning of the orifices, to avoid damage caused by the ascent water level.
- Usage of pumps in traditional wells, to promote easy and immediate irrigation and provides water all the time without the need for workers. However, this has disadvantages also such as making changes to the traditional system by replacing the bucket with the pump and exposing it to the risk of rising water levels over time, which may cause degradation and disturbance in its function.

As for now, the traditional water supply system considering also a tourist attraction due to its unique and genius structure. The local people volunteer organize tours inside the ksar settlement and the oasis for the visitors in all the seasons, and the traditional water system has a share from these tours [2, 9].

2.4. General regulations in the traditional customs about the water supply system

The precursors in the M'zab Valley set customary rules and regulations, so called "customs", inspired by the Islamic religion that contributed to preserve the Mozabite architecture over centuries.

The supply water traditional system has a share of general rules in the traditional customs can be set in the following:

- Respecting all water streams, valleys, reefs, wells, and others.
- Respecting the width of M'zab Valley, where it must be 20 meters and 10 meters on both sides and it is not permissible to construct any building there.
- In order to preserve the canals, it is forbidden to build any natural or artificial barriers over them, such as the road, building, trees, or to plow them.
- Not to make any change to the water transporting system because it will expose people to water danger.
- No one is allowed to open the barriers of dams or canals, whether during torrential rains or otherwise, except for the trustees Al'umana.
- The dividing of the torrent water between partners should be according to the number of palms, without counting other trees.
- The process of clearing the torrent water from dust inside the oasis is the responsibility and at the expense of all the partners as well as the restoration, but must be under the supervision of Al'umana and technicians.
- It is prohibited for any citizen to interfere in the maintenance of dams, waterways, and all stream channels, except under the supervision of those concerned, since it requires careful study of the supply system [2, 3, 5, 10].

3. Miyakojima case

Miyakojima is a small coral reefs archipelago in a group of Okinawa Islands, Japan. Now it is widely known in Japan as a popular sea resort.

3.1. Geological and historical overview of Miyakojima water supply

Miyakojima archipelago is a very interesting example of historical water supply methodic starting to develop from 13th c. Natural water supply circumstances of Miyakojima Island are quite unusual: there is almost no sources of surface water. Nevertheless of rich tropical green forests covering the islands of Miyakojima, it has only one quite short (just for about 3 km long) Sakida-ga, river and is suffering of potable water shortage, depending mostly of underground water sources. The annual rainfall amount of Miyakojima is about 2,250 mm although nearly a half of rainwater quickly penetrates underground, and the rest is evaporating by subtropical sunshine leaving on the surface almost nothing [11]. The reason is a special geological structure of Miyakojima Islands where under the soil locates the layer of porous Ryukyu limestone that easily allows the rainwater to penetrate in. Beneath the limestone is lying a bedrock of impermeable mudstone. Tectonic forces of the archipelago created underground valleys with groundwater flows, where penetrated rainwater easily moves into the ocean [12]. Although there is abundant groundwater at Miyakojima, getting it is not an easy task. From ancient times, the people of Miyakojima either dug wells in hard limestone or obtained domestic water from naturally created caves called uriga in local language. These caves were up to 20 m deep places accessing with long down steps. The sources usually located in the bottom of the caves and it was the duty for the women and teenagers to get the water from them. From the 19th c., the population of Miyakojima increases and water selling business arose. At the beginning of 20th c. people started to collect rainwater in reservoirs and in 1924, there was the first case of manpowered circled treadmill water-for-cell lifting from a deep well.

From the middle of 20th c. there were several series of water supply aqueducts constructions leading the water pumped from the wells to the different places of the island finally covering almost all territory of Miyakojima [12]. In 1973, Miyakojima suffered from a big drought that leads to looking for new water distribution possibilities including creating huge underground water reservoirs as well as Fukuzato and Sunagawa underground dams' construction completed in 1998 [11]. This point finally led to the completely stop of natural cave sources using for daily life water supply.

3.2. Uriga cave sources and wells of Miyakojima: current situation, preserving and revitalization efforts

According to 18th c. document "Yosei-Kyuki", there were for about 60 wells and natural cave sources at Miyakojima Island [12]. Not all of them survived until now. According to the cultural and historical sites list of Miyakojima, currently are preserved for about 20 ones [13]. Although a very attentive attitude to historical waterways' of agricultural, industrial and potable water supply [14, 15] preserving and revitalization in Japan, there are not much information about Miyakojima's uriga cave sources in touristic internet resources or booklets as well as in the scientific field. Nearly single extensive notice of the Miyakojima cave sources could be find on the desk map installed in the center of Miyakojima city (figure 10) as well in the list of Miyakojima local historical property designated sites [13].

We investigated four of survived historic sources situated at the site of old Hirara city (now Miyakojima city) area. As a result, it became evident that they are currently in different situation and their level of preserving is not equal.

The first and the second of them: Yamatoga and Butoraga sources are situated nearly in the northeastern part of old Hirara city and both designated as National important cultural property [16].

Figure 10. The desk map with uriga cave source marking installed in the centre of Miyakojima city (by author).

Butoraga (figure 11) is a typical popular place of cave water source used by common people to get the water accumulated in the limestone of natural cave bottom with narrow entrance that now is hiding under the banyan tree branches. The villagers carved the stairs in the ground to make water lifting easier. Although this cave source is not actually used in daily life, the groundwater still collects at the bottom of the basin deep inside the cave. The atmosphere of the place is simple and solemn, making the little image of abundance.

Figure 11. The desk map with uriga cave source marking installed in the centre of Miyakojima city (by author).

Yamatoga (figure 12) is a deep well spring believed to have been excavated around 1720 as it comes from the contents described in “Yosei-Kyuki” ancient historical document (1727) [16]. According to local folklore, this source was limited only for official service people belonging to Shuri royal government (the capital of Ryukyu kingdom) and Satsuma domain, and was not open to the public. The spring is surrounded with the mixture of large and small curved stones erected with splendor high-level masonry technology of the time. The massive stone steps are leading down to a flat stone paved rectangular place with source water basin. There used to be two gates leading up to the source, and it is said that there was also a water guard. There are various theories as to why the name “Yamato” is given to this source, whether because the artisan involved in its construction was a person from central part of Japan (Yamato region), or because it was used by officials dispatched from the Shuri royal government that associated with central political power of Yamato lands. Currently, Yamatoga well is evidently the most known and good maintained source of Miyakojima, but even with this, it attracting only random tourists.

Figure 12. The desk map with uriga cave source marking installed in the centre of Miyakojima city (by author).

An interesting example of natural cave spring is Muikaga (figure 13). This is the largest and deepest historical cave source of the island having 103 stone steps leading down to the water source. The archeology of the nearest shell and porcelain mound witness that in ancient times there was large settlement around the source, but now Muikaga cave is surrounded with abandoned jungle spot locating at the western suburb of Miyakojima (Hirara) city and has a small local sanctuary (so called utaki) near the entrance. Muikaga historical cave source is designated as a Municipal Historic Site but seems to be visited very seldom [17].

Also in the northwestern part of Miyakojima city, we can find an interesting and rare ground water source called Upuka that was used before mostly for farm animal (cows and horses) drinking water (figure 14). The date of its discovering is not clear, but as it is described in “Yosei-Kyuki” historical document (1727), the repair work of the source was conducted in 1717, so it can be said that Upuka spring already existed at the beginning of the 18th c. After the Second World War, due to the spread of water supply and the decrease of cattle and horse breeding, the source was no longer used and was buried with the earth and sand. But it was re-excavated in 2004 as a cultural development project, enabling people to view Upuka spring for the first time in 50 years. Now it is designated as a Municipal Historic Site [18].

Generalizing, it can be noticed quite low engagement of Miyakojima historical water sources in the touristic attraction infrastructure of the Island. Although Miyakojima Archipelago is a

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Figure 13. The desk map with uriga cave source marking installed in the centre of Miyakojima city (by author).

Figure 14. The desk map with uriga cave source marking installed in the centre of Miyakojima city (by author).

popular sea resort of Japan with developed transportation, housing and excursion network, the touristic and educational function of local historical cave sources' is not fully developed. At the same time, the cave springs also are not in use any more as resources of potable water. One of the reasons is bad natural quality of local hard water polluted with metallic mixtures. This problem now resolving by softening the water in centralized water supply system of Miyakojima so the cave sources became inconvenient for use as drinking water. Nevertheless, in some cases the cave water is still used now for local rituals preserving at Miyakojima theirs own iniquity [19]. Judging from the interview with local people, the image of uriga cave sources is closely associated here with small homeland warm feelings and "childhood" local life traditions. All historical sources of Miyakojima have appropriate marking and nearby desk information that also witnessing the interest of local authorities to this topic (figure 11, figure 12, figure 13, figure 14).

4. M'zab and Miyakojima cases: comparing discussion

We tried to compare the foggara water supply system of M'zab and Miyakojima uriga cave sources network in two main parameters: basic historical features and current situation of functioning, preserving and revitalization.

The both operating with underground water resources water supply systems are products of local geographic situation, climate and culture. Foggara of M'zab is similar with other desert Middle East irrigation systems formed at the same circumstances, but it has original distinguishing points capturing only floodwaters and not using other water resources [7]. Uriga of Miyakojima is an original cultural phenomenon resulting from Miyakojima coral island non-ordinary geology and connected with local beliefs and rituals [19].

The initial function of foggara is irrigation water supply and preventing floods, uriga has a function of potable water supply also often serving as utaki – integrated in the nature sacral place of local deities worshiping.

The age of the both systems is nearly the same. Miyakojima's uriga sources and wells are in use mostly from 13th c., M'zab Valley's irrigation history also starts from 13th c. M'zab Valley foggara system is much more complicated and elaborated than Miyakojima uriga, but some uriga sources are integrated in interesting stonework architecture. The way of water extraction from foggara and uriga wells are different. While in M'zab is practicing mechanic water lifting from vertical wells, at Miyakojima the wells and cave sources are the places of people visiting for hand lifting of the water. The underground sources are often provided with elaborated inner space additionally used for water deities worship.

Nevertheless, it can be argued that uriga is similar to the initial stage of foggara development. In some meaning, uriga system started to follow the same as foggara way of development at the end of 19th – the beginning of 20th cc., when human powered mechanisms of water extraction from the wells appeared at Miyakojima. From the middle of 20th c., this system was replaced by pumped water lift up from the wells starting centralised water distribution at some parts of the island. Finally, this way of development was replaced by more progressive and original water supply system of underground dam and pre-oceanic cat-off walls system elaborated there at the end of 20th c. [11].

The current situation of M'zab foggara and Miyakojima uriga systems also is quite different. Foggara is still fully used in traditional way (just animal force of water lifting from the wells is replaced with the pumps) and professionally maintained by strong local community. There no modern water supply systems to replace or duplicate it. The touristic and educational function of foggara are complimenting and now are in developing stage. As a result – the preserving of historical water system in M'zab is excellent in all meanings.

Miyakojima's uriga completely lost its initial function as a source of potable water due to the developing of a new modern water supply system and partly preserving only its ancient sacral function. Touristic and educational functions are aiming to develop in the frame of some revitalization efforts of municipal authorities (designating as historical sites and placing nearby the information desks marking uriga touristic sites, realization of some small projects of sources renovation and preserving) but seems not to meet enough enthusiasm from local community and business.

This effect may be directly connected with natural environment, local customs and traditional way of living preserving situation of the researched cases. While in M'zab Valley all three aspects (the natural environment, local customs and traditional way of living) are fully preserved, in Miyakojima Island only the aspect of natural environment is preserved, the local customs are preserved only party and the local community traditional way of living is in the study of decay due to modernisation and globalization (figure 15).

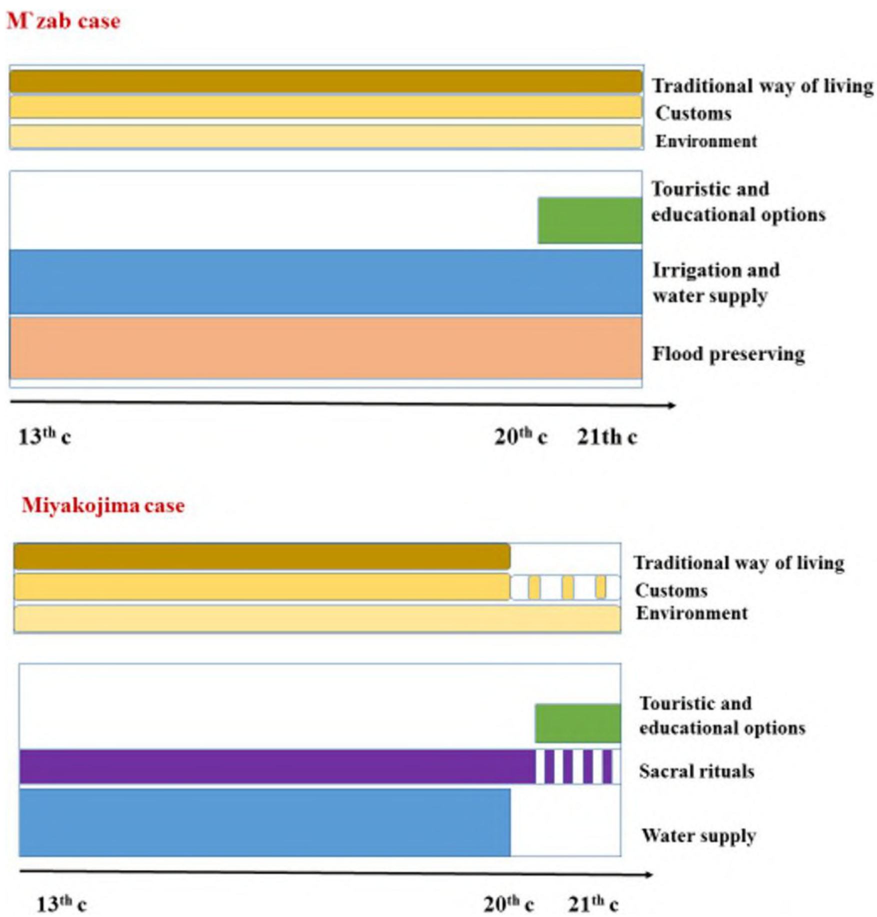

Figure 15. The desk map with uriga cave source marking installed in the centre of Miyakojima city (by author).

5. Conclusion

The situation with preserving and revitalization of historic water supply systems at some area supposed to be directly connected with the surviving of local natural environment, customs and traditional way of living of the area. In this point, the natural environment and traditional way of living preserving leads to the preservation of the needs in historical water supply system functioning as it is clearly seen in the case of M'zab. It also important to preserve the possibilities (experience and ancient techniques) to operate and maintain such water system that is provided by preserving of local culture customs transmitting the experience of centuries to the new generations. The loss of some of the aspects named above usually causes the interrupting of historic water supply system operating that in most cases leads to its decay as we can clearly see at the case of Miyakojima. In other words, only in the case of all three these aspects presence, the historical water system may currently remain in use that create a best condition to its sustainable development.

It is also evident that the best way to preserve ancient water supply systems are joint efforts of local authorities and community. At the same time for the sustainable development and revitalization of the traditional water supply systems now it is not enough only to preserve their initial function but also needs to develop theirs potency as tourist attractions and educational hubs as well as to popularize and designate these extremely interesting objects of human civilization history as cultural property cites.

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Lake Biwa Canal at Kyoto Japan: sustainable development and revitalization

To cite this article: G V Shevtsova and M S Parkhomchuk 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012078

Lake Biwa Canal at Kyoto Japan: sustainable development and revitalization

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Abstract. Lake Biwa Canal (engineer Tanabe Sakuro) connects Lake Biwa and Kyoto. It was built in the end of the 19th c. in order to revive Kyoto, which decayed after the transfer of the capital to Edo (Tokyo) in 1868 and served to supply Kyoto with drinking and industrial water, as well as for cargo transportation. The aim of the work is to determine the historical periods of Lake Biwa Canal's existence and to highlight its significance for ensuring the sustainable development of Kyoto. The research was conducted at Kyoto mainly with field studies and interview methods. As a result, three historical periods of the Lake Biwa Canal existence were identified. In the first period (1885-1951), the canal combined water supply, transportation and landscape-shaping functions and was fundamental to the sustainable development of Kyoto. In the second period (1951-1990th), the transport role of the canal became unclaimed, and its role in sustainable development of the city significantly decreased. In the third period (since 1990th), the canal was designated as National Historic Site, and a campaign of its revitalization began. The Canal acquired touristic and educational functions and increased its role in the sustainable development of Kyoto. Thus, at the time of its construction, the Lake Biwa Canal was the main driving force that saved Kyoto from decline. Now, we can talk about the opposite process, when Kyoto City supports the sustainable development of the Canal.

1. Introduction

Lake Biwa Canal is an interesting and original industrial project completed in Kyoto in the end of 19th c., at the time of Industrial Revolution. It was constructed for transfer the industrial, agricultural and potable water from Lake Biwa to Kyoto, used also for cargo and passenger boats transportation. In the time of its creation, the Canal played a great role for revitalizing Kyoto that declined due to decreasing of population caused by the transfer of the capital to Tokyo after Meiji Restoration in Japan. It was the period when Japan, that delayed its technical progress due to the centuries of isolationist policy of Tokugawa shogunate's governance finally opened its borders to the world. Japan quickly gained new technical experience sending the young people to study technical sciences, medicine and architecture to the progressive countries of Europe and America. Lake Biwa Canal construction was the first Japanese big industrial project completed only by local engineers with no foreign forces. Lake Biwa Canal is still more than 130 years in use, now playing not only its direct role of water supply to the Kyoto but also becoming a great touristic and cultural attraction of the city. The history of the Canal was not so smooth and in the second part of 20th c., there was a period of its decline when the industrial role of the

Canal was diminished and its touristic significance was not developed yet. The revitalization of the Canal namely started from the end of 20th c. and is now in process.

The aim of the article is to determine the historical periods of Lake Biwa Canal existence estimating its significance for ensuring the sustainable development of Kyoto.

Japan has quite interesting diversity of historical waterways with theirs preserving, popularizing and revitalization experience. Some of them, like the revitalization experience of historical Hachiman-bori Canal at Omi-Hachiman city now designated as Japanese Important Cultural Landscape property is lightened in the scientific literature [1]. At the same time, Lake Biwa Canal revitalization experience is not so good described in scientific field. Thus, the sources of the research became a grate historic material base of Biwa Canal Museum [2–4], internet resources [5, 6], booklets [7] and some conference materials [8, 9]. Mainly the indispensable information was gained from author's personal field research as well as from interviews provided with Lake Biwa Canal Museum scientists, Kyoto city officials, local volunteers, members of Lake Biwa Canal Line Charm Creation Committee and other peoples engaged in the process of Lake Biwa Canal revitalization. During the research, we explored the structure and modern condition of the First Lake Biwa Canal and Kyoto incline, experienced the excursion-boat transportation and examined the revitalization events of Keage Filtration Plant.

The research was conducted at Kyoto (Japan) under Hakuho Foundation Japanese Research Fellowship program 13th (2018-2019) at the base of Kyoto University.

2. Lake Biwa Canal structure and history

The Lake Biwa Canal structure is consists of two mains canals. The construction of the First of them was started in 1885 and completed in 1890. It begins from Biwa Lake at Kannon-ji area (Otsu city) and runs until Fushimi area of Kyoto (figure 1). It is approximately 20 km long (for about 11 km to Keage point) and consist of the system of open-water sections interleaved with 4 tunnels, the longest First (Nagarayama) tunnel is 2440 m long and the shortest Second one is just about 124 m long (figure 2), all works were fulfilled mostly by manpower [7]. The Second Canal was completed 20 years later to increase the volume of Kyoto water supply. It is only 7.4 km long but is deeper and running completely in the tunnel constructed near the First Canal.

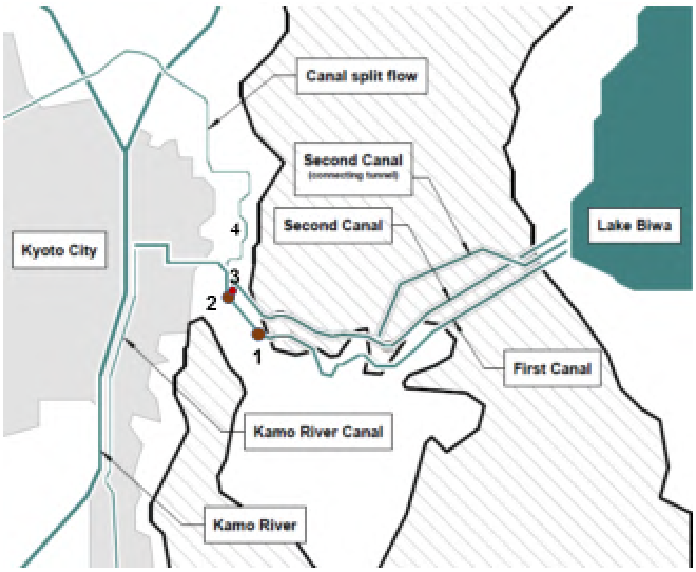

Figure 1. Lake Biwa Canal: general scheme. 1-2 – Keage Incline, 3 – Lake Biwa Canal Museum, 4 - Nanzenji Suirokaku aqueduct (by author).

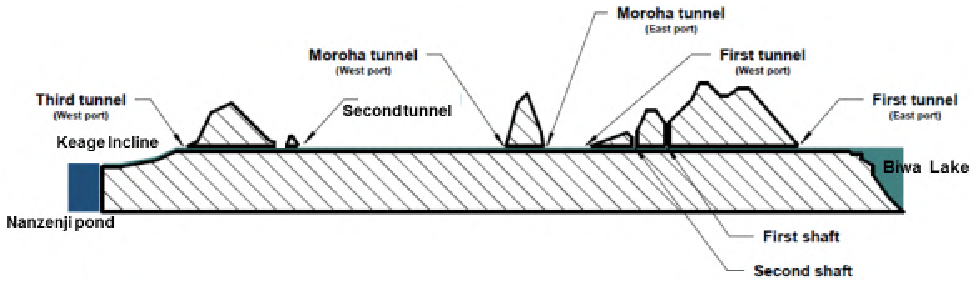

Figure 2. Lake Biwa Canal: longitudinal section of the First Canal (by author).

The idea of Canal construction for water delivering from Lake Biwa to Kyoto was popular there from the middle ages but of course, at that time it was impossible to fulfill it technically. But in the end of 19th c. when Japan start to adopt quickly the foreign industrial skills this ancient idea was refreshed by Kunimichi Kitagaki, the 3th Kyoto Prefectural Governor. He planned to build new factories that needed energy of water for the electricity, as well to develop the boat transportation trough the Canal [5]. The expenses of construction were partly covered by Emperor and partly by Kyoto city [5]. The executor and senior engineer of the project became Sakuro Tanabe, quite young specialist who graduated from Imperial College of Engineering in Tokyo (a precursor of the University of Tokyo's Faculty of Engineering) where he studied under the direction of Henry Dyer, a Scottish engineer who do a lot for establishing Western-style technical education in Japan. The graduation thesis of Tanabe Sakuro was concerned of Lake Biwa Canal construction, so Kyoto's authorities decided to invite him immediately for the project fulfilling. The construction of the First Canal started in 1885, took for about 5 years and was completed in 1890. During the construction, there were used many new for Japan technical skills such as vertical shaft tunnel construction method used for the longest Nagarayama (the First) tunnel [8]. The two constructive shafts (47 and 20 m deep) are still preserving and visible as from inside the tunnel the same as in the mountain forest over the tunnel where can be found the heads of these vertical shafts now using for emergency exit and ventilation of the tunnel (figure 2, figure 3).

Figure 3. The beginning of Lake Biwa Canal, the entrance to the First tunnel and the head of the first tunnel shaft (by author).

At the same time, Canal construction required big works of soil and stone transportation as well as development of grate production complex of instruments and materials including brick and shaft factories erection. With the completion of the First Canal, the first in Japan business-use hydraulic power station was constructed at Keage area for generating electricity using water from the Canal [7]. This emerge was utilized for electric lighting and factories of Kyoto in realizing so called "Electric Power Project" of Kyoto authorities. At the same time, the Canal became a waterway for charcoal, wood, rice and so cargo boat transportation as well for the people transportation and many of them used this way for sightseeing ("Ship Transportation Project" of Kyoto authorities).

The two very interesting features of Lake Biwa Canal can be seen in the area of Keage – the point where the First Canal is entering Kyoto. Here was constructed for about 3 km long Branch Canal (see figure 1) passing upon Nanzenji temple grounds though special brick construction similar with Ancient Rome aqueduct known as Nanzenji Suirokaku. The second interesting feature is the way of boats transportation from Keage point to nearby Nanzenji moorage pond where was impossible to complete waterway because of 36 m height differences of Lake Biwa and Kyoto watersheds. Therefore, the boats reached to the Kyoto using so called Keage Incline – a 582 m long slope equipped with rails [7]. Namely, from Keage point, the boats were loaded on small open railway cars moved down the incline with the principle of cable car to Kyoto's Nanzenji pond where the Canal continued at Kyoto area (figure 4). Lake Biwa Canal Museum poses a unique video of Keage incline boat railcars running from the end of 1940th.

Figure 4. Keage Incline and Nanzenji Suirokaku aqueduct (by author).

The water from the Canal also was used for rice milling and spinning factories ("Hydraulic Power Project" of Kyoto authorities) as well as for fire prevention of Imperial Palace and surrounding big temples and shrines such as Higashi-Honganji, Nanzenji and so. A special feature is also the utilization of Canal water for the creation of several temple and aristocratic villas' water-pond landscape gardens (Honen-in temple, Heyan-jingu shrine, villa Murin-an and so), the most interesting of them are the masterpieces of famous Japanese garden designer Shigemori Mirei [10] (figure 5).

Figure 5. Honen-in temple, Heyan-jingu shrine and villa Murin-an landscape gardens using the water from Lake Biwa Canal, the beginning of 20th c. (by author).

Several years after, the water flow of the first Canal become insufficient for increased electricity needs of Kyoto. To resolve this problem, the second Kyoto Mayor, Kikujiro Saigo fulfilled several big projects including the Second Lake Biwa Canal construction, road-widening project and municipal electric railway creation [5, 7]. The Second Canal construction was started in 1908 and completed in 1912. The 7.4 km long Second Canal was constructed completely in the tunnel nearly to the section of the First Canal from Lake Biwa to Keage where Keage Filtration Plant was erected. This filtration plant purifying potable water from the Second Canal had improved gravelly the quality of Kyoto potable water and is still in use until now. In addition, there were constructed three new power stations (are still in operation now) giving energy to electric railway of Kyoto. Later it turned fatality for lake Biwa Canal development: the railway finally gained main role for cargo and passenger transportation of the area initiating gradually decreasing of Canal boats transportation. Due to this, in 1948 Keage Incline was closed, and in 1951 boat transportation of Lake Biwa Canal was interrupted completely for the long time. Industrial and potable water supply role of the Canal constantly remained. Lake Biwa Canal was renovated several times; the largest renovation of the both Canals was fulfilled in 1968 – 1974 and is known as Showa's Major Renovation of Lake Biwa Canal.

3. Further existence and revitalization process of Lake Biwa Canal

In the end of 1960th – the beginning of 1970th Lake Biwa Canal gained some attention from Kyoto authorities mostly in the meaning of water-landscape arrangement of surrounding touristic area. A small canal branch flowing from Keage was improved as landscape "Philosophers' Path" with sakura-trees growing on the both sides. This allowed to create a pleasant walking area from Nanzenji to Ginkakuji touristic attractive temples. At the same time, the former Keage Incline with preserved rails was restored as Sakura Garden [9]. At Yamashina area along the Canal way from Biwa Lake was created Higashiyama Ryokuchi Park flourishing now with very interesting species of local flora and fauna (figure 6) [9]. Recently it became evident the grate role of historic canals for aquatic ecosystems [11] that could be seen also in this example. Local senior people Sawa Minoru and Mita Takahashi reminding that at hot summertime the children from Rakoto School located near the Canal at Higashiyama Ryokuchi Park used to swim in the water calmly flowing in the shallow section of the First Canal.

Figure 6. City recreation landscaping of Lake Biwa Canal: "Philosophers' Path" and Keage Incline sakura-trees blossoming, Higashiyama Ryokuchi Park, the second half or 20th c. (by author).

In 1983 Nanzenji Suirokaku brick aqueduct and Keage Incline were designated as Kyoto City Historical Sites [9]. In 1996 Lake Biwa Canal was designated as National Historic Site [5]. Connectively to this event, at Keage area near the former Nanzenji pond (finishing point of Keage Incline, see figure 1) was constructed Lake Biwa Canal Museum that is gathering artefacts, archive and scientific materials of the Canal history (figure 7), but the Canal itself in this time still gave the impression of a partly abandoned place.

Figure 7. Lake Biwa Canal Museum and its collection (by author).

In 2015 according to Kyoto City and Otsu City Majors' agreement there was created the "Trial Project of Restoration of Lake Biwa Canal Boat Traffic" with "Lake Biwa Canal Boat Ride Planning Committee". That leaded to the creation of "Lake Biwa Canal Boat Traffic Project" that renewed in 2018 after 67 years long interruption the tentative (touristic) boats transportation of the First Canal. This activity was started by "Lake Biwa Canal Line Charm Creation Committee" and is not in full scale yet [12]. Namely, the navigation of Biwa Canal is active only for several month in spring and autumn periods – the seasons of sakura blossoming and red momiji maple leaves along the Canal (figure 8). The small boat excursions are limited with several (8-10 per day) quite expensive courses requiring previous reservation [12]. Usually all places for navigation season are booked in 2-3 days after the reservation opening for about 2 month before the start of the event.

Figure 8. Current touristic boats operation of the First Canal (by author).

Keage Filtration Plant also practices some popularization activities. Namely in May, when on its territory blossoms many azalea bushes, it organizes the days of "open visit" when everybody can observe the modern and historical facilities of water filtration process (figure 9). The event is accompanied with children educational classes getting know more about water distribution and filtration system of Kyoto, including filtration plant field orientation concourses, quizzes and competitions as well as pipe running water degustation. Everybody is proud there of the fact that Kyoto's running water is one of the most pure in the world and might be drunk with no boiling having nearly the same quality as bottled water. To emphasize this achievement, the Waterworks Bureau of Kyoto City designed the image mascot of a firefly, the tiny insect that lives only near pure flowing water.

Figure 9. Keage Filtration Plant and its popularization activities, azalea blossoming and firefly mascots (by author).

According to the information from Dr. Shirakawa Tetsuo, a scientist of Lake Biwa Canal Museum, they also looking for the possibilities to present Lake Biwa Canal industrial and landscape area for UNESCO Heritage tentative list.

4. Historical periods of Lake Biwa Canal development

Thus analysing the historical perspective of Lake Biwa Canal it can be determined the existence of three historical periods of its development (figure 10). The First period took place from 1885 until 1951; it can be characterized as a period of construction and primary flourishing of the Canal. At this time, the Canal obtained and reinforced all its main functions like industrial and potable water supply, transportation and garden-landscape shaping functions (see figure 10). In this time, the Canal became the main revitalizing force for Kyoto city.

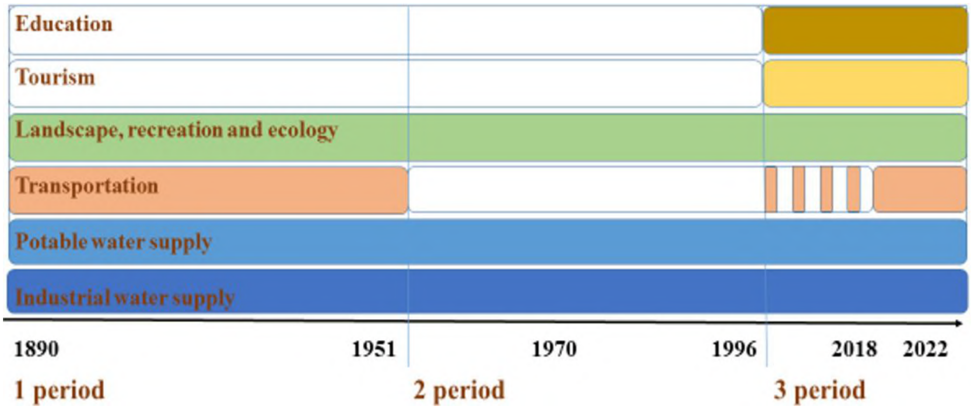

Figure 10. Lake Biwa Canal: the diversity and changing of functions during the time (by author).

The Second period can be determined from 1951, when the transportation function of the Canal was lost and until the end of 20th c., when Kyoto City started the program of Canal revitalization. During this period, the transportation function of the Canal was ceased due to historical circumstances (such as rail and car roads development), its revitalizing role for Kyoto city seriously diminished and the Canal felt some decline (see figure 10). At the same time, the landscape-recreation and ecological function of the Canal intensified.

The Third period has begun in the end of 1980th, when the Canal was designated as National and Kyoto City Historic Sites, and Lake Biwa Canal Museum was constructed. It is the time when Kyoto authorities and local people realized attractive potential of Lake Biwa Canal starting to develop this resource as a place of touristic, educational, ecological attraction and historical heritage also trying to revitalize its lost a half century ago transportation function (see figure 10).

Up at the Nejirimanpo small tunnel leading under the Keage Incline it is still preserved a memorial plaque showing the autographed hierologic inscription of Kunimichi Kitagaki, the 3rd Kyoto Prefectural Governor, who inspired the idea and started the construction of the Canal: "Enjoy the 100-year dream". These worlds probably can characterize the effectivity and the significance of Lake Biwa Canal project in the best way.

5. Conclusion

Grate historical project of Lake Biwa Canal construction has determined in the end of 19th c. the urban development of modern Kyoto. Its existence led in the end of 19th – the beginning of 20th c. to the great vitality of Kyoto's industry and trade boat transportation shaping the new significance of Kyoto. Lake Biwa Canal continues to supply potable and industrial water to Kyoto for about 130 years adapting recently new functions and getting new values as a Historical Heritage, touristic attraction, educational hub and recreation zone of the city. In the beginning of 20th c. Lake Biwa Canal became the main drawing force that saved Kyoto from decline providing its sustainable development. It could also be seen the opposite process of Canal revitalization by Kyoto City authorities and local volunteers that took place from the end of 20th c. and is currently in the progress.

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The influence of socio-demographic and external factors on the change of urban parameters of the Luhansk region

To cite this article: K V Sokolenko *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012079

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012079 doi:10.1088/1755-1315/1049/1/012079

The influence of socio-demographic and external factors on the change of urban parameters of the Luhansk region

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Abstract. The scale and nature of changes in the urban planning parameters of the Luhansk region under the influence of socio-demographic and external factors are studied. The actual development trends of the Lysychansk-Rubizhne-Sievierodonetsk agglomeration, the evolution of the regional settlement system, the state and problems of the urban development of the region are determined. To conduct the study, methods of system analysis, analytical comparisons, statistical analysis, urban planning analysis were used. The information base consists of literary and archival sources, cartographic materials. Quantitative and qualitative changes in the main territorial and urban planning parameters of the Luhansk region have been studied. A methodology for assessing and making urban planning decisions is proposed. The urban planning tasks and directions of transformation of the residential environment of the Luhansk region, controlled by Ukraine, are analyzed. Lugansk region in modern conditions is an outsider of socio-economic development. The occupied territories of the Lugansk region of the so-called ORLO (separate districts of the Luhansk region) are in a state of crisis. Industrial, ecological, social degradation is intensifying. This trend can lead to the devastation of settlement systems. The tasks of rational transformation of the territorial-planning organization of the Lugansk region remain relevant. From the intermediate conclusions, it is advisable to single out: the region has significantly changed its functions. The border and the line of demarcation of the JFO will still indefinitely be the determining factor influencing the state and development of the region. The task of the territorial development should be considered at the level of the Lysychansk-Rubizhne-Sievierodonetsk agglomeration and the structure of the region as a whole to ensure the growth of its potential. It is expedient to implement priority tasks according to unconditionally effective options that give a quick and demonstrable result. It can be education, transport infrastructure, anything that raises social standards. It is necessary to achieve a consensus of different groups of the population in the implementation of urban planning tasks and projects.

1. Problem statement

Since 2015, the JFO has been ongoing in the territories of the eastern regions of Ukraine. By the decision of the National Security and Defense Council of Ukraine, it is recommended to use the terminology [1], which indicates the intention of the goverment to specify the actual state of the conflict situation. The active phase of hostilities was replaced by the stabilization of the demarcation line. (term - the line of hostilities we will not avoid yet). The task of social and economic development, improvement of the territorial organization of the Lugansk and Donetsk regions, bringing the planning structure of the region in line with modern conditions and the needs of populated areas remains relevant. [2–10] The industrial cities and territories of the east of Ukraine - the Lugansk and Donetsk regions were in a pre-crisis state, due to the outdated industrial structure. The Russian external aggression, the occupation of the part of the regions led to circumstances, the consequences of which are difficult to assess in economic categories. From the point of view of the engineering and planning organization, the territories of the regions are "cut" by military operations. The relevance of the topic is determined by the curtailment of the settlement system under the conditions of external influences and the depressed economic state on the territory of the Luhansk region. Among certain tendencies of the beginning of the XXI century, one can point to a decrease in the population of the region; deterioration of the economic situation in the industrial region; excessive environmental load on the territory and cities of the region; technically and technologically outdated industry, infrastructure. Primary and separate are the political factors of the state of the situation - the occupation of the part of the territory of the regions. For a detailed analysis of the situation, the development of optimal urban planning solutions, it is necessary to solve a number of scientific problems. It is necessary to find the main territorial and town-planning characteristics. Develop and propose methods and methodologies for making urban planning decisions. To analyze urban planning methods for transforming the living environment of the Luhansk region controlled by Ukraine.

The uncertainty of external influence factors is proposed to be assessed using a multifactorial classification using a stepwise dichotomy.

A comprehensive analysis will make it possible to develop options for forecasting the prospective development of the Lysychansk-Rubizhne-Sievierodonetsk agglomeration, the functional and planning structure of settlement.

2. Purpose, idea and research methodology

2.1. The goal of the research

Study of the scale and nature of changes in urban parameters of the Luhansk region under the influence of socio-demographic and external factors. Determination of current trends in the development of the Lysychansk-Sievierodonetsk agglomeration, the evolution of the regional settlement system, the state and problems of urban development of the region.

2.2. The idea

In the context of the armed conflict that has been going on for 8 years in the territory of the East of Ukraine – the Lugansk and Donetsk regions, a border region is being formed. The total length of the border with the Russian Federation within the Luhansk region is 737 km (39% of the total length of the Ukrainian-Russian border). The demarcation of the JFO has a length of more than 410 km. A new type of regional classification is emerging, which is characterized by restrictive functions - fixing the border, legislative regulation of the regime for crossing the demarcation line, etc. The latest functions of regional typology should be taken into account in the tasks of improving the territorial planning organization of the Lugansk region and urban development. The study of quantitative and qualitative changes of the main factors and factors of urban development is an urgent task.

2.3. Methodology

To conduct the study, methods of system analysis, analytical comparisons, statistical analysis, urban planning analysis were used. The paper studies the quantitative and qualitative nature of the influence of socio-demographic and external factors on the change in the urban planning parameters of the Luhansk region. The information base consists of literary and archival sources, cartographic materials.

2.4. Results

Quantitative and qualitative changes in the main territorial and urban planning parameters of the Lugansk region have been studied. A methodology for assessing and making urban planning decisions is proposed. The urban planning tasks and directions for transforming the living environment of the Luhansk region, controlled by Ukraine, are analyzed. Luhansk region in modern conditions is an outsider of socio-economic development. The occupied territories of the Lugansk region of the so-called ORLO (separate districts of the Luhansk region) are in a state of crisis. Industrial, environmental, social degradation is intensifying. This trend can lead to the devastation of settlement systems. The tasks of rational transformation of the territorial-planning organization of the Lugansk region remain topical. From the intermediate conclusions, it is advisable to single out: the region has significantly changed its functions. The border and the line of demarcation of the JFO will still indefinitely be the determining factor influencing the state and development of the region. The task of territorial development should be considered at the level of the Lysychansk-Rubizhne-Sievierodonetsk agglomeration and the structure of the region as a whole to ensure the growth of its potential.

3. The research results

From the point of view of the tasks of the modern planning organization of the Lugansk and Donetsk regions, it is impossible not to take into account the influence of the functional potential of the town-planning form. [7,10–13] We can assume that there are relevant planning goals that require balanced and timely regulatory actions. The reason and condition is the armed conflict and the occupation of part of the territories of the regions. Military conflicts have their own internal logic, and they are also characterized by unpredictability. However, history has enough examples when the processes of territorial development go hand in hand with an unresolved conflict. The term of the environmental protection has been going on for 8 years, and experts and politicians cannot give an adequate forecast for its completion [2]. System-statistical analysis makes it possible to determine the main parameters that determine the functional development of the territory. Lugansk region has an area of 26.7 thousand km^2 or 4.4% of the territory of Ukraine. ORLO occupies 8.4 thousand km^2, about 31.5% of the region. Currently, the territory of the Lugansk region is 18.3 thousand km^2 or 3.1% of the territory of Ukraine and is divided into 4 districts - Svatove, Sievierodonetsk, Starobilsk and Shchastia. Alchevsk, Dovzhansk, Luhansk and Rovenky districts (figure 1) are temporarily not controlled by Ukraine. [14]

The region has 37 cities and 109 urbanized settlements, about 780 rural settlements. On the territory controlled by Ukraine there are 12 cities (32%), 26 urban settlements (24%) and 507 rural settlements. (65%) The population of the region is 2121.3 thousand people. (according to the State Statistics Service of Ukraine as of 01.01.2021). The presence of the population in the territory of the region controlled by the Ukrainian government is 666.3 thousand people (31.4% of the population of the region). 280.4 thousand internally displaced persons (13% of the region's population) have been registered. [4,14]

The level of urbanization of the region reaches 87%. The population density was 83.9/km^2 in 2014. Due to the lack of reliable statistical data, it is difficult to determine the population density separately for the territories of the region. If we use outdated indicators, then in the territory of the Lugansk region, controlled by Ukraine, the population density is 35/km^2 , in the territory of the ORLO, the density can reach 152-177/km^2 and less, depending on the actual population.

ORLO has 25 cities, 83 urbanized settlements, 273 rural settlements. The population is difficult to calculate correctly, according to various sources it is 1.2-1.4 million people. 280.4 thousand people received the status of a temporarily displaced person.

Laws of Ukraine cannot operate in the temporarily uncontrolled territory of the region. The problems of regions and internally displaced persons are dealt with by the Ministry of

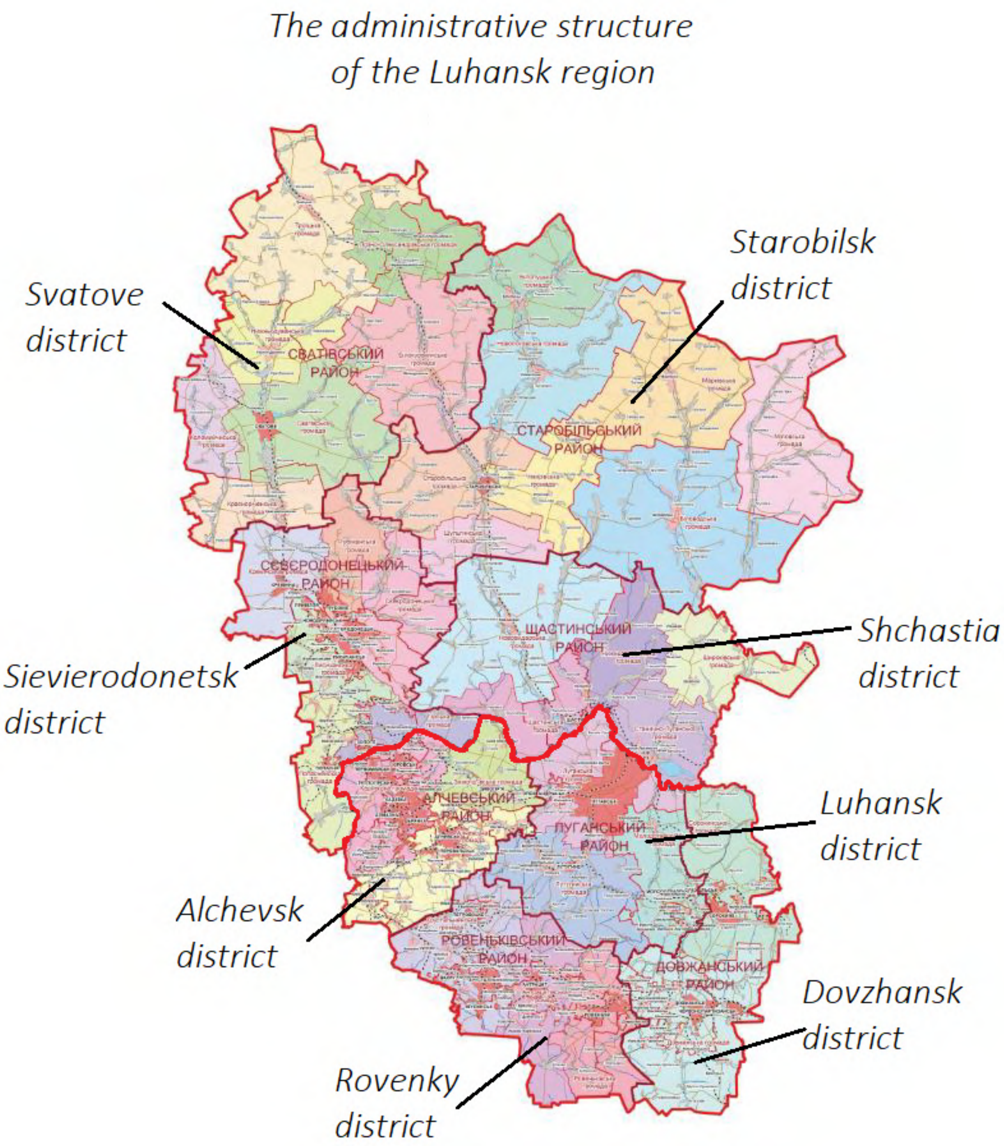

Figure 1. The administrative structure of the Luhansk region.

Reintegration of Temporarily Occupied Territoriesof Ukraine.

The most urbanized territories remained in the uncontrolled part of the region. Central Luhansk (Alchevsk-Kadiivka-Holubivka-Pervomaisk), Luhansk, South Lugansk agglomeration (Khrustalny-Antratsyt-Rovenky-Dovzhansk), and Sorokyne-Molodohvardiisk agglomerations remain outside the influence of the government. Thus, the region "lost" most of the coal mining enterprises.

The administrative and urban center of the region is the Lysychansk-Rubizhne-Sievierodonetsk agglomeration. The functions of the regional center are performed by the city of Severodonetsk. The demarcation line partially coincides with the imaginary line dividing the agricultural north and the industrially urbanized south.

From the industry that gave rise to the industrial Donbass, PJSC "Lysichanskugol" and SOE "Pervomaiskugol" remained in the Lugansk region, the number of operating mines is 12. The production capacity of the mines is from 100 to 700 thousand tons of coal per year, coal is mined at depths of 55-900 m. The availability of commercial coal reserves in operating mines varies widely - from 30 to 133 years.

Figure 2 gives an idea of the industrial planning framework of the coal industry of the Luhansk region. Mines are concentrated in coal mining sites. Railway and road communication are subordinated to the tasks of delivery and freight turnover of enterprises. The presence of a transport network determines the possibilities of operation or development of industries with a significant turnover. The conditional demarcation line gives an idea of the scale of the problem.

The structure of industrial production in the Luhansk region at the beginning of the armed conflict indicates a focus on the mining and processing industries. That is, the industry relies on

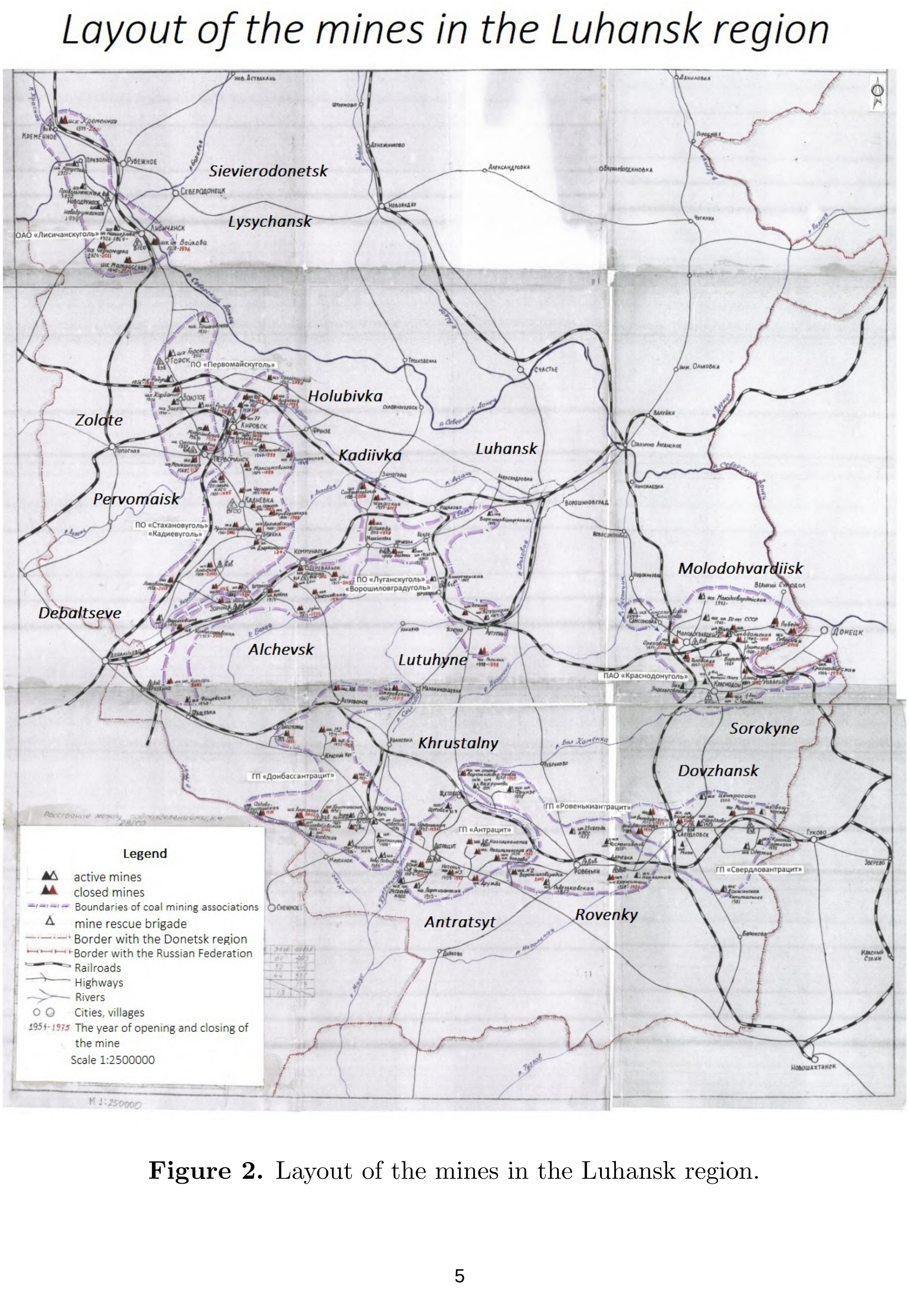

Figure 2. Layout of the mines in the Luhansk region.

Table 1. Structure of industrial production in the world and Ukraine, %.

	World	Developed countries	Russia	Ukraine	Luhansk region	Luhansk
Industry:	100	100	100	100	100	100
- Mining industry	10.4	5.9	24.4	8.2	12.8	9.7
Processing industry, in particular:	81.9	87.7	66.7	-	80.1	55.0
- Food industry	10.9 (10.7)	9.5 (9.1)	11.1	15.5	3.3	11.4
- Consumer goods manufacturing	5.5 (7.8)	4.6 (6.5)	1.7	1.1	0.3	1.3
- Chemical and petrochemical industry	13.2 (11.2)	13.3 (11.6)	8.4	6.4	9.4	4.3
- Metallurgical industry	5.8 (6.9)	4.2 (6.9)	21.6	21.9	22.0	14.8
- Machinery	35.9 (29.1)	45.3 (34.3)	8.0	12.5	5.7	15.3
- Production of gas, water and electricity	7.7	6.5	8.9	18.3	7.0	35.5

the resource base. (Table 1). As a result of the armed conflict, the region's industrial production has shrunk by almost five times. Without bias, the obsolete coal and metallurgical industry was in crisis even before the conflict. The coal industry was largely supported by targeted transfers from the state budget - grants and subsidies. [1,2] In the expert community, there is a view that the service life of an average mine does not exceed 100 years. This term predetermines many factors and conditions. The mines of Donbass that are closed have an average service life of 77 years

Ukraine has pledged until 2035 to throw up the consumption of coal at state-owned power plants as part of the decarbonization of the economy. Thus, the trend to close the mines is determined. It is clear that the process will be lengthy, profitable mines with large balance reserves of coal will work for some time.

For the mono-industry, this will mean a reduction in the territories used, the release of many zones. The consequence of this is a decrease in the population and a decrease in the standard of quality of life. At the same time, the economic crisis does not reduce the amount of infrastructure needed to service housing and utilities infrastructure, social institutions, and commercial establishments. Cities of Ukraine falling into decay face numerous problems in the field of spatial planning [4, 5, 8, 10, 12, 15] in particular:

- The decline of cities, the reduction of population and territories requires the development of projects for new activities in abandoned or abandoned areas. This requires well-balanced decisions from planners aimed at creating new jobs.
- Redundant areas, primarily industrial areas, require master plans to be revised to account for changes in the size of activities or their reduction.

- The reduction of cities also leads to a change in the territorial planning structure. Managerial staff do not have the necessary experience, the methodology for developing planning solutions is practically absent.
- It becomes economically unprofitable to keep the infrastructure focused on a larger scale. There is a need for a planned reduction in urban infrastructure in accordance with a decrease in population and a decrease in economic activity, which puts forward additional requirements for the urban planning system.

Different countries have different approaches to solving the problems of declining cities. [8, 12, 15] However, urban planning must ensure a methodological approach and consensus reached by the local community.

Of course, the urbanized south of the region fully faces all these problems. But how are they resolved? The state of the economy of the occupied districts of Luhansk region is difficult to describe in detail due to lack of information. One can evaluate the existing trends. Let's try to highlight the most important and indisputable. Lost economic potential, production volumes need to be analyzed not only in terms of absolute indicators. The qualitative influence of conditional or specific indicators should be taken into account.

The narrow sectoral focus of the coal-mining region cannot secure sustainable and efficient development. The coal and steel industry existed relatively efficiently in the form of vertically integrated corporations. The destruction of the structure caused problems in marketing, certification, supply of raw materials and components. In 2013 coal production in the mines of Donbass amounted to 26.3 million tons, and this accounted for 76% of the total coal production in Ukraine. There are 85 mines left on the territory of ORDLO (separate districts of the Donetsk and Luhansk region) . There are 42 mines in the occupied part of the Luhansk region. In particular, all the mines producing anthracite, which is the most valuable type among the coal of the energy group and for which five out of 12 thermal power plants in Ukraine are designed, ended up in the occupied territories. That is, anthracite and a significant share of coking coal are mined in ORDLO. Since 2014, the process of closing mines has been ongoing. So far, less than 40 mines are operating. In ORDO for 2020 19 mines were closed. Figure 2 illustrates the closed mines in the Lugansk region. On social networks residents of ORDLO publish information on wage arrears. The total unpaid wages of ORDO miners exceeded 1.5 billion rubles.

Almost all mines have wage arrears, and debts have also been accumulated for large city-forming enterprises. But the average level of wages remains very low - up to 15 thousand Russian rubles. There are practically no investments in the restoration of production capacities and the modernization of production. Settlements for which closed mines performed a city-forming function are rapidly degrading. There are numerous cases when the railroad rails that unite the enterprises of the coal industry are dismantled. At the same time, the processes of dismantling power lines and electric power substation of stopped mines are ongoing. The processes are both spontaneous and organized in nature - under the slogan of infrastructure optimization. In fact, all mines do not work in Alchevsk and Lugansk districts. Work in the mode of drainage and in some places local illegal coal mining - the so-called "kopanki" are an indicator of new problems. More or less stable work is demonstrated by anthracite mines in the south of the region.

The metallurgical complex is in a state of crisis. First of all, the instability of the work of enterprises is recorded, which is a depressing problem for nonstop production. The work level of productive capacity reaches 18-20%. In 2013, the cargo turnover at the Kommunarsk station (Alchevsk city) amounted to 6.5 million tons. The metallurgical complex shipped 4.5 million tons of products. The crisis at the plant leads to the crisis of related enterprises. Qualified personnel are leaving - accidents, failures of units are becoming more frequent, the level of spoilage in production is growing. Troubles are partly covered by regular reorganizations. Leadership changes unpredictably. Consequently, the economic state of the ORLO is characterized as a crisis. If negative trends persist, a catastrophe could be expected in a few years.

It should be noted that a significant part of the resources is consumed as a loan. Natural gas is supplied at reduced rates, almost free of charge to the people. Electricity and water are partly supplied from Ukraine for humanitarian reasons. The debt of ORDLO (to all suppliers) for the consumed electricity as of 08/01/2021 amounted to UAH 23,876,311,000. The debt of ORDLO for consumed water and water supply services (to Ukraine) as of 08/01/2021 reaches UAH 2,098,243,000 [16].

Utility tariffs at ORLO are growing. A characteristic sign is the fact that the cost of natural gas and electricity is growing slightly, and the cost of water has increased many times over - which indicates the source of the resource supply. The low cost of natural gas is due to supplies from the Russian Federation at non-market prices.

Problems in the planning and organizational structure of the territory of the Luhansk region at the current stage:

(i) Controlled part of the Luhansk region:
- Urban planning documentation should be updated taking into account the actual situation
- The development strategy takes into account the border nature of the region and the presence of an armed conflict (JFO zones and lines of demarcation)
- The communication network needs to be updated and upgraded. Reconstruction of the configuration of roads and railway communication is needed
- Persist and has potential for growth in agriculture
- The recreational resource of the region is preserved and has the potential for growth
- The water resource of the region is preserved and has the potential for growth - provided it is used economically
- The forest resources of the region are preserved and have the potential for growth - provided it is used economically
- The mining industry needs to be developed and optimized in accordance with the needs and objectives of the industrial sector of the region
- The Luhansk power station (Shchastia city) provides generation in the region, but the power transmission network needs to be upgraded
- The engineering protection of the border needs to be strengthened
- The industrial development of the region is based on the potential of the existing agglomeration Lysychansk-Rubizhne-Sievierodonets, which should be considered as a regional territorial entity
- There is a process of adaptation of citizens who have received the status of a temporarily displaced person. Some people change place of residence, some people get housing and job
- As a result of the high level of unemployment, there is a migration of labor resources - partly to the regions of Ukraine, partly to the EU countries, partly to the Russian Federation
- Reverse migration to ORLO is almost non-existent

(ii) ORLO (separate districts of the Luhansk region):
- ORLO is outside the influence of the Ukrainian government. The existence (development) of the territory occurs separately, independently
- There is no integration with the Ukrainian economy (impossible)
- It is impossible to determine the timing of the restoration of control
- Social and humanitarian ties predominate
- Possible military escalation (provocation)
- The mining industry is degrading
- The energy branch is degrading

- The railway line is deteriorating
- The ecological state is uncontrollable and deteriorating
- Agriculture remains relevant, but not competitive
- There is no development strategy
- Urban planning documentation has lost its relevance. Upgrading and development is not possible
- The socio-economic condition is deteriorating
- The demographic situation is aggravated at an accelerated pace
- Formed dependencies - 1. from Ukraine, 2. From the Russian Federation
- Dependence on Ukraine is formed in the following areas: power supply (may be reduced at the expense of the Russian Federation); water supply (dependence is critical and cannot be compensated); the direction of coal sales (partially, we are not talking about the stability of supply volumes); social payments - pensions and other types. The general trend is to reduce payments. The reduction in payments means a deterioration in the social standards of the population. (The number of temporarily displaced persons is decreasing. The number of pensioners receiving Ukrainian pensions is decreasing. The scale of payments is decreasing)
- Dependence on the Russian Federation, are formed in the following areas: social payments; gas supply; Material and technical supplies - ensuring the needs of the armed formations; fuel and lubrication materials; compensation for economic losses by infrastructure elements; consumer goods (food, medicines); Reorientation of trade relations
- The ORLO ommunication network is sufficient
- A few more years of the existence of ORLO will cause a complete restructuring of the mining industry. Uncontrolled and without compensatory and mitigating measures. The consequence for the region will be a significant deterioration in social standards of quality of life

A separate problem remains the ecological state of the territories and districts of the Luhansk region. Mines, quarries, mining of building materials, manufacturing facilities caused changes in the landscape. Industrial areas of Donbass have accumulated about 40% of man-made emissions. Water and air basins are polluted, large areas have been disturbed and undermined, soil erosion is progressing, the regimes of groundwater and rivers have been violated. The colonial type of exploitation of the natural resources of the region had extremely negative consequences for the environment. The high level of urbanization adds to the problems with the disposal of municipal solid waste and with the preservation of the quality of water sources.

The largest amount of industrial waste has accumulated in the area of activity of coal mining enterprises. Only on the state-controlled territory of the region there are 44 rock waste disposal areas, covering an area of more than 900 hectares. The total amount of waste accumulated in them is more than 38 million m^3 and continues to grow every year.

Threats from the temporarily occupied territories, where the coal industry is in a catastrophic state, remain a significant environmental problem for the region. The closure of mines occurs haphazardly, without any projects and environmental assessments of the possible impact on the natural environment. At least, there are no announcements of environmental protection projects after the liquidation of mines.

Thus, the situation has frozen into bifurcation points. The situation may break into an uncontrollable crisis with catastrophic consequences, or a program of gradual development of the region's territory may be implemented. Actually, for both parts of the Lugansk region, the problems are generally similar. However, the difference is in scale, availability of resources and development potential. Table 2 contains an analysis of problems in the planning and organizational structure of the territory in terms of development tasks.

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The end of the long Leontief cycle should be taken into account. A change in the technological structure makes it inexpedient to restore obsolete production. It seems more expedient to create new innovative capacities and enterprises. Therefore, it is necessary to create conditions for investors and preserve the infrastructure. The modern economy relies primarily on human potential. The resource base is no longer decisive. Developed territorial infrastructure - ommunication networks, power lines, pipelines are able to attract modern production - with a favorable state policy to support the region.

The return of control over ORDLO will set a number of tasks that will need to be solved under uncertain conditions:

(i) political and legal uncertainty, including conditions for resumption of control;
(ii) uncertainty of the transition period;
(iii) paragraphs 1 and 2 are likely to provide for the conditions of compensation and rehabilitation of the region, identifying the sources and characteristics of the damage to the region;
(iv) it is impossible to predict whether the significant external factor that will determine the functions of the region will change - that is, the region will either remain a borderland, or it will be possible to establish cross-border cooperation in conditions of softening of relations and no territorial claims;
(v) Urban planning documentation, territorial development will be based on the problems of paragraphs 1, 2 and will be irrelevant or absent;
(vi) The Luhansk region does not have the resources to restore control - administrative and technical;
(vii) there will be a question of compensation (replacement) of resource supply which is now provided by the Russian Federation;
(viii) A significant proportion of temporarily displaced persons will not wish to return;
(ix) One should not expect labor migration to the liberated territories;
(x) Reconstruction of the infrastructure will take a long time, except for critical emergency units;
(xi) One can expect stability from agricultural companies, companies that have maintained economic efficiency. Some mines can operate at the level of profitability;

The objectives of the study, aimed at determining and analyzing public demand for the parameters of changing the urban environment, are based on the generalization of an analytical survey that displays a list of citizens' requests according to the characteristics of the urban environment.

(i) Safety. For the Luhansk region, first of all, safety from hostilities. Any exacerbation causes a complex of reactions - explicit or hidden
(ii) Housing problem. Temporarily displaced persons actually decide on their own. Many of those who have lost their homes have not been able to obtain or purchase another one.
(iii) Workplaces. Having a paid stable job is an important requirement.
(iv) Social and medical service. It can be noted that social services, the pension fund as a whole have reached a high level of organization of their activities. Medical care is less than satisfactory. This is due to the loss of the base of medical institutions, the problems of the Covid pandemic.
(v) Public transport - convenience, availability of work needs
(vi) Intercity transportation. The requirement to provide multi-vector long-distance communication is important.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012079 doi:10.1088/1755-1315/1049/1/012079

(vii) Communal area. The list of requirements for the maintenance of a residential environment is quite clear

(viii) Trade and retail

(ix) Recreation, rest, tourism.

Table 2. Determination and analysis of public demand for characteristics of the urban environment configuration. Conditions and factors determining the quality of the urban environment.

1	security[1, 9]	Completely not provided
2	Housing[4]	Demand is not completely met. There is people who are not provided with their own housing
3	Working places[2, 8]	The condition is unsatisfactory. High unemployment, low wages, wage arrears, labor migration
4	Social services[3, 4, 5]	Partially satisfactory condition
5	Medical service[3, 5]	Somewhat unsatisfactory condition. Insufficient base of medical institutions. High cost of medical services.
6	Public transport[5, 6]	Partly satisfied. In need of urban planning solutions
7	Intercity transport[5, 6, 7, 9]	Partly satisfactory. Insufficient rail links. The situation is partly saved by private intercity transportation
8	Housing services and utilities[5, 7, 8]	Partly satisfactory. Unsatisfactory ratio of price to quality of services. A comprehensive program is required.
9	Commerce[7]	May be considered sufficient
10	Recreation, leisure, tourism[5, 6]	Partially satisfactory. There is potential for growth, subject to stringent environmental restrictions

Notes to the table 2

(i) §1 is the determining and deterrent factor for the development of the region

(ii) §3 depends on the sustainable development of the region. Growth is provided by agglomerations and cities. State and regional policy should be aimed at the creation of new jobs

(iii) §4, 5 should ensure balanced and professional actions of the central and local authorities

(iv) 2, 4 do not satisfy the demand

(v) §4, 5, 6, 7, 8, 10 determine the quality of the living environment, and the actual directions that require development and improvement

(vi) §6, 7, 8, 10 the source of development is domestic demand, fair competition, creation of conditions for business, demonopolization of the service market.

(vii) §6, 7 the level of development of transport communications affects the satisfaction of the needs of §2, 3, 4, 5, 9, 10

(viii) §3 has a significant impact on solving the problems of §2, 5, 6, 7, 8, 9, 10 (solvency contributes to the development in this industry)

(ix) §7 The development of an integrated scheme of external transport, intercity communication depends on §1 and the time factor.

(x) It should be noted that in those segments where the competitive environment and private business operate, positive changes or development problems are resolved by the consumer. Yes, it can be noted that in cities there are no problems with mobile communications, Internet services, a network of gas stations, etc.

If we consider the tasks of rational transformation of the territory of the Luhansk region, its spatial-planning structure, it is necessary to determine the factors of influence, restrictions, conditions. Restrictions determine the parametric framework of the object of study - namely, the territory of the Luhansk region, controlled by Ukraine. Conditions affecting restrictions:

- Armed Conflict (JTO);
- Political uncertainty - it is impossible to predict the time and format of the conflict;
- Administrative and territorial reform, outdated and partly obsolete urban planning documentation.

At this stage, the effect of the time factor can be ignored. Urban development is a process, so it is advisable to determine the directions of development and planning guidelines. It is important to take into account the time factor if the development of the two parts of the Luhansk region follows different political vectors. East and West Germany once existed in different political formats, but in a European paradigm of development. South and North Korea are one nation with one language in one region - two different worlds and civilizations.

It is advisable to carry out the primary classification according to the principle of dichotomy - the primary feature is control (political, administrative, zone of validity of the legislation of Ukraine) over the territory. Any urban planning documentation is based on the regulatory and legislative framework. We consider the following restrictions on the basis of whether there will be significant harm or benefit if ignored or taken into account? Changes in the ecological state, changes in the social structure in the ORLO may have an impact on the parameters and objectives of the development of the Lugansk region. In the paradigm of here and now, for example, the problems or tasks of the functioning of public transport or medicine in the ORLO are insignificant. Ecological safety is one of the limiting factors. Any development must secure the stability of ecological indicators. In this sense, it is advisable to conduct environmental monitoring, including the involvement of international organizations to record the actual state of the environment throughout the Lugansk region.

4. Conclusions

The basic directions for the prospective development of the Lysychansk-Rubizhne-Sievierodonetsk agglomeration and the functional planning structure of the settlement have been developed. The uncertainty of external influence factors is proposed to be assessed using a multifactorial classification using a stepwise dichotomy. Urbanized areas are developing more actively than rural areas. Agglomerations and cities have greater potential for development. From a socio-economic point of view, it is more expedient to plan investments in the development of jobs or infrastructure, which contributes to the economic development of the territories. The Lugansk region in modern conditions is an outsider of socio-economic development. The occupied territories of the Lugansk region, the so-called ORLO, are in a state of crisis. Industrial, environmental, social degradation is intensifying. This trend can lead to a deterioration in the quality of life. The surplus population will independently solve migration issues, since the resource of the territory cannot provide modern environmental quality standards for a high density of people. The loss of a resource (coal mining) will lead to the devastation of settlement systems. The Lugansk region retains the potential of agricultural production and recreation. The industrial potential of the Lysychansk-Rubizhne-Sievierodonetsk agglomeration has prospects for further development. The tasks of rational transformation of the territorial-planning organization of the Lugansk region remain topical. From the intermediate conclusions, it is advisable to single out: the region has significantly changed its functions. The border and line of demarcation of the JFO will still be an outstanding factor influencing the state and development of the region for an indefinite time. The task of territorial development should be considered at the level of the agglomeration formation Lysychansk-Rubizhne-Sievierodonetsk and the structure of the region as a whole to ensure the growth of its potential. It is expedient to implement priority tasks according to unconditionally effective options that give a quick and demonstrable result. It could be education, transport infrastructure, anything that raises social standards. It is necessary to achieve a consensus of different groups of the population in the implementation of urban planning tasks and projects.

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Reconsidering the concept of sustainability: personal adaptability dynamics as predictor of positive change

To cite this article: P V Lushyn and Y V Sukhenko 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012080

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012080 doi:10.1088/1755-1315/1049/1/012080

Reconsidering the concept of sustainability: personal adaptability dynamics as predictor of positive change

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Abstract. The article deals with the attempt to reconstruct the concept of sustainable development in the context of the COVID-19 pandemic. The literature review supported the idea that the studies devoted to the features of sustainability in social systems are extremely fragmentary. The authors provided a holistic vision of the process of sustainable development in terms of a dialectical self-organization of open living systems. To accomplish this goal, a number of studies have been conducted at different stages of the COVID-19 pandemic. The findings confirmed a strong relationship between the psychological and social level of adaptation (as a manifestation of the adaptability/sustainability of the individual) to the conditions of the pandemic. This helps considering indicators of psychological stability as a predictor of social sustainability. The prospect of the further research consists in the reinterpretation of the current world in terms of a rhythmic, emergent, hybrid and innovative (REHI-world) self-organization of open living systems.

1. Introduction

Currently we are witnessing the emergence of novel models of the world as well as the concepts of sustainability integrated into them. In particular, understanding of the world changed at least three times over the span of 20 years: SPOD-, VUCA-, BANI-world. The traditional idea of sustainability is challenged by the VUCA world model (volatile, unpredictable, complex and ambiguous) [1], [2], [3]. Analyzing the concept of sustainability, it is assumed that psychological and social processes constitute a shared ecosystem in which every individual element has a certain impact on the whole system, and vice versa. On the one hand, global crises are often human-made, in particular, the origin of COVID-19 pandemic has still been problematic ("…these elements indicate that there is no evidence to support the hypothesis of a man-made origin of SARS-CoV-2" [4]) but there are very few who are hesitant as to the fact that its spread and transmission could be attributed to some artificial impact. On the other hand, the global events of the ongoing pandemic cannot but influence the individual who may bear the signs of external turbulences and environmental change. Further we will study the perspectives of reconstructing and redefining the concept of sustainability in terms of its personal correlate – individual adaptability during the COVID-19 pandemic.

2. The COVID-19 pandemic literature review

Recent theoretical findings reveal the complex impact of COVID-19 pandemic on (a) the progress of reaching the goals of sustainable development [5], (b) on the resource potential – which has turned to be dualistic and ambivalent – within social and economic spheres of life. The pandemic displayed the fundamental deficiencies and fragilities of current systems as well as fostered the post-pandemic change of thinking and practice towards accepting ambiguity, unpredictability, and variability into options of economic, social and political transformation [6]; it enables the formation of the collective vision of alternatives in detecting the principal roots of risks, and in building nondiscriminatory perspectives for sustainable social and economic development [7]. The research has underlined the resourcefulness of the corona-crisis for the future policy of social transformation in predicting, assessment and generating adequate response to the climate change problem [8]. New data were collected to prove that utilitarian and capability approaches to nature may be among prominent sources of the corona-crisis. To eliminate its negative consequences the humanity needs to stay more non-manipulative, constructive and pro-ecological [9]. It has been found that the COVID-19 outbreak opened up the alternatives to broaden the sphere of common mobility [10], [11], emphasized the role of long-term investment to youth organizations which proved to be efficient in preparation for natural disasters by providing first aid options especially during the COVID-19 pandemic [12]. Being aware of the problems caused by the COVID-19 pandemic, as well as understanding the growing complexities (consistent with Kondratieff's wave theory), a group of authors formulated an alternative approach to sustainable development in terms of transformative learning paradigm. It presupposes an adequate change in thinking, formation of new competencies for harmonious administration and management of life problems, which concern nature and building life perspectives [13].

There is a growing field of research dedicated to predictors, dynamics and resources of sustainable development under COVID-19 pandemic. They are such personal qualities as openness to experience, conscientiousness, extraversion, agreeableness, emotional stability. The drivers of sustainability are family and social status, conditions of work during the pandemic. The health predictors, that mitigate the outcomes of COVID-19 could be anxiety, depression, life satisfaction [14]. Compliance, diligence are most likely to prevent certain behaviors, while such maladaptive qualities as negative affectivity and psychological detachment correlate with markers of depression, anxiety, suicidal risks and symptoms of COVID-19 [15]. Honesty, obedience, life satisfaction, tolerance for ambiguity and hope are the most prominent drivers and predictors of personal safety and alleviation of COVID-19 outcomes [16], [17]. A special longitudinal study revealed a strong correlation between faiths, science mindset and anxiety related to COVID-19: science mindset has increased during the first period of the pandemic, while religious mindset showed the signs of a certain decrease [18]. Positive and negative psychological states under the pandemic correlate with extraversion and negative affectivity, at the same time life satisfaction is determined by the parameters of economic threat, unrealistic optimism and trust in governmental decisions [19]. It is through the action of community members, via the majority of people adhering to social distancing, respiratory and hand hygiene recommendations, that the spread of a disease is attenuated [20]. In the context of the unprecedented and long-term corona-crisis the population displayed high level of personal and social resilience and health restoration [21]. The major resource of personal resilience came from social support, strong marital relations and caring attitude of the loved ones [22], [23]. An illustration of the centrality of family processes in buffering against risk in the context of COVID-19, as well as promoting resilience through shared family beliefs and close relationships, is provided [24]. Flexibility of psychotherapeutic assistance has been considered relevant in increase of subjective well-being [25].

3. On the emergence of a psycho-social sustainability model: theoretical substantiation

The sustainability is a phenomenon of economic, social and psychological self-organization which also constitute a basic quality of living open systems [26]. The open systems are defined as those capable of transcending from one context to another by which they survive, renovate the existing potential. The other quality of a living open systems is that their transitions are characterized by a certain rhythmical flow of different states, among which are critical periods. This flow or periods of transcending are–in terms of dialectics–a marker of sustainability of development process (thesis-antithesis-synthesis [27]).

This research is based on the assumption that the ability to psychological and personal change could constitute a precondition for administration of social and even global self-organization. This precondition lies in a reassessment or reinterpretation of a role of negative (antithetical) factors/critical destabilizations (which is the sphere of ecology).

During the latest decades ecology criteria and its understanding has critically changed in psychology. Formerly, a certain state or phenomenon was considered ecologically valid on condition it proved its non-adversarial nature. The latest research of the second wave of the Positive Psychology supported the idea that a critical and even a traumatic event may promise positive results in the course of personal development (which is "post-traumatic growth"). The task of a psychologist or a clinician is to support/facilitate personal self-organization which transcends the stages of negative and/or even "abnormal" response as being temporal and, thus, transient by nature [28]. By this the start of a new understanding and practice of ecology criteria in the context of social and political system's sustainability is marked.

We assumed that the positive personal response to adversity (especially through the dialectical lens of the COVID-19 pandemic evolution) can determine an adequate social response and, thus, be the predictor of system's stabilization. Consequently, the ongoing COVID-19 global crisis may support the paradoxical nature of system's sustainability within the emerging REHI-world model (R-rhythmical, E-emerging, H-hybrid and I-innovative [29]).

Research goal is to study the perspectives of reconstructing and redefining the concept of sustainability in terms of its personal correlate during COVID-19 pandemic.

4. Methodology

In order to verify the hypothesis, we examined the adaptability potential mostly in young adults, 25-44 years of age. The overwhelming majority of them are master students with a professional experience in the spheres of education, social services, economy, finance, IT-business, medicine and the military. The research period is ranging from April, 2019 till February, 2022. During the period we had four assessment sessions. First psychodiagnostics or assessment – April, 2019 (N=117 the average age 31,3±7,6), second – April, 2020 (N=70 the average age 34±6,7), third – October, 2021 (N=87 the average age 32,4±6,2), fourth – February, 2022 (N=117 the average age 33,4±6,6). Total – 350, male – 129, female – 221.

The study of personal and behavioral changes in young adults during the pandemic was carried out by the following psychological referents. *Basic coping strategies* were analyzed through the study of a coping strategies indicator (D. Amirkhan, adaptation by N. Sirota, V. Yaltonsky). The problem-solving strategy is defined as an active use of personal resources in dealing with problems; search for support – active search for communicative resources among referent others (family, friends, etc.); avoidance – escape from the contact reality, certain flight from solving problems [30]. *Personal readiness for change and different aspects of the uncertainty tolerance (TU)* was administered with the PCRS "Personal change-readiness survey" (S. Rodnyk, R. Heather, T. Gold, M. Hal, adapt. N. Bazhanova, G. Bardier). If defines some general and specific targets: passion as energy and vitality level, indefatigability; resourcefulness – cognitive component of TU, a capacity to find solutions and utilize new resources; optimism

– hope, faith in the ability to succeed, orientation on solving problems; adventurousness – motivational aspect of TU, craving for something new, the unknown, rejection of the formerly tested and reliable; adaptability – resource-based component of TU, ability to change plans, decisions, to adjust to unexpected situations; confidence – trust in oneself and the ability to reach goals when needed; tolerance for ambiguity – activity and emotional component of TU, confidence in dealing with "no-clear-answer" or ambiguous situations [31]. *Meaningfulness of life, meaningful goals* were measured with the test of meaningful life orientations (D. Leontiev): life goals – having meaningful goals that open up life perspectives; process – process of life that brings interest and emotional richness to life; result – life effectiveness and self-realization satisfaction, appreciation of productivity of a certain life period; locus of control I – self-confidence, an ability to take care of life and to build it in accordance with her/his own goals, tasks and meaning; locus of control life – a measure of taking control over life and making decisions as well as independently putting them to life [32].

In scientific and experimental terms, the situation of the COVID-19 pandemic is a unique natural laboratory that provides an opportunity to study the peculiarities of the development and response of the individual and the community to global challenges and environmental transformations. We consider the COVID-19 pandemic as a factor whose varying degree of spread and manifestation affects and changes a person. Clarification of psychological patterns of this process will allow us to deepen the idea of sustainable systemic development of the surrounding (external) environment, socio-psychological environment of the individual, relevant socio-psychological resources and technologies (psychological and pedagogical including) as well as to determine their applied importance for the sustainable development of cities and society.

Each period, when diagnostic sections were carried out, was specific in terms of the degree of spread of the COVID-19 pandemic and its impact on the development and psychological state of the individual:

1. *April 2019*, the first assessment. We associate it with the zero level of impact or the pre-pandemic situation in the world and in Ukraine. It is eight months before the COVID-19 coronavirus outbreak (December 2019, China); the key event of this period in Ukraine is the end of the presidential elections (other background events we consider more or less predictable and could be qualified as the zone of actual development, i.e., existing within accessible resources of the population). Generally speaking, the humankind hasn't yet faced the threat of a global and catastrophic nature, so further we mark this stage as a *stable pre-pandemic*.

2. *April 2020*, the second assessment. We associate it with the shock level of impact associated with the announcement of the COVID-19 pandemic (March 2020, WHO), the introduction of the first hard lockdown in Ukraine; this period is characterized by the maximum level of discomfort and threats due to the uncertainty of the situation, a minimum of knowledge about the infection, the course of the disease, lack of medical resources, a sharp change in the way of life in all spheres, at all levels. So, we mark this time as a *shock stage of the pandemic*.

3. *October 2021*, the third assessment. We associate it with the expected or "normative" level of impact in the context of the third wave of the COVID-19 pandemic in Ukraine; opportunities for vaccination are accessible, the population is provided with more or less sufficient information for making personal decisions. It gives grounds for characterizing this stage of the pandemic as *adaptive or stabilizing*.

4. *February 2022*, the fourth assessment. We associate it with a predictable impact of the pandemic in the context of the spread of a new strain called "Omicron". There is a radical increase in the spread of the virus and a relatively mild course of the disease. On the one hand, this period is characterized by the strengthening of quarantine measures, on the other hand – an unpredicted activation of the influence factor of another kind – the threat of Russian military aggression, and massive information campaign in the media. This situation encourages us to designate the factors of influence at this stage as hybrid, and the stage itself as *hybrid or*

transient. It lasts from the "normative" phase of the pandemic (on the ground of predictability, variability in decision-making and implementation of the coping strategies by the individual) to the stage of sudden threats of the military crisis.

Statistical processing of the data included ANOVA analysis, a posteriori estimation was carried out with Bonferroni and Tamhane's tests, the details are provided in interpretations below. Data processing was administered via SPSS.17 statistical package.

5. Results and discussions

Thus, diagnostic measures were carried out at the pre-crisis, crisis, stabilization and hybrid stages of the pandemic. Dispersion data analysis (ANOVA) is represented in the table below (table 1).

Table 1. Personal development of young adults in the context of COVID-19 pandemic (2019-2022).

Researched parameters	2019	2020	2021	2022	F	Sig.
Passion	19.0	18.8	19.2	18.5	0.45	0.720
Resourcefulness	20.1	19.5	22.6	21.6	10.01	0.000
Optimism	19.8	17.7	20.0	18.9	5.65	0.001
Adventurousness	15.0	15.2	15.3	14.6	0.52	0.669
Adaptability	15.8	15.2	15.7	14.8	1.18	0.317
Confidence	19.2	18.7	20.2	19.7	2.04	0.108
Tolerance to ambiguity	15.7	13.9	14.3	12.2	12.34	0.000
Readiness for change Overall	124.6	119.0	127.3	120.3	6.25	0.000
Life goals	27.8	26.2	33.3	32.8	21.06	0.000
Process	27.7	26.4	31.0	30.4	7.65	0.000
Result	23.3	22.2	26.7	26.3	14.26	0.000
Locus of Control – I	19.9	18.0	21.5	21.3	10.57	0.000
Locus of Control – Life	31.4	26.1	31.4	31.3	10.37	0.000
Meaningfulness Overal	97.1	87.5	106.5	105.9	17.68	0.000
Problem-solving	23.6	23.9	24.2	24.5	1.13	0.338
Search for support	20.9	19.9	21.1	21.1	1.05	0.369
Avoidance	17.0	19.3	16.3	17.9	10.69	0.000

During the excessive spread of the pandemic and the first lockdown in Ukraine people responded with "psychological closure". According to the posterior comparisons between the first and the second assessments (April 2019 to April 2020) there was a decrease in their overall readiness for change (124.6–119.0, 0.006), including optimism (19.8–17.7, 0.001) and tolerance for ambiguity (15.7–13.9, 0.025). This means that people's hope and faith in success have been noticeably shaken; it has become more difficult for them to be balanced about the lack of clear answers; to regulate and master themselves in situations where it is not clear what is happening and what will come out in the end, when goals and expectations are blurred or uncertain, and the work cannot be completed. A marker of psychological tension of a person is fixation on problems with an increased coping strategy avoidance, as well as avoiding contact with the surrounding reality in general (17.3–19.3, 0.001). The overall comprehension of life in this period decreased (97.1–87.5, 0.002). This was not so much due to changes in life goals, depreciation of the present and the past but due to disbelief in one's own freedom of choice and the control of life (19.9–18.0, 0.003), manifestations of fatalism, the belief that life cannot be consciously controlled, that freedom is an illusion, that there is no point in trying to take care of and think about the future (31.4–26.1, 0.000).

Between the second and third diagnostic assessments (April 2020 – October 2021), Ukrainians experienced two waves of the pandemic. During the period they largely developed individual and herd immunity to new strains of coronavirus at both biological and psychological levels, and practically returned to a sustainable way and rhythm of a novel life style. Over the year and a half they have gained the unique and paradoxical experience of living in conditions of isolation, self-isolation, pressure, threats and losses nobody could have imagined in pre-pandemic years.

There arises a question – how did all this affected the psychological portrait of Ukrainians and in what psychological state did they enter the third wave of the pandemic? Being in difficult conditions, people managed not only to adapt to them, but also to increase their own psychological, personal capital. Compared to 2019, in 2021 they became more inventive (21.1–22.6, 0.001); Ukrainians acquired a clearer-than-pre-pandemic comprehension and meaning of life (97.1–106.5, 0.002). The goals of life (27.8–33.3, 0.000) became more understandable, the process of life – according to the "here and now" principle (27.7–31.0, 0.006), its experience, and the result (23.3–26.7, 0.000) – became more valuable. People began to trust themselves more, to also believe in their own strength, to appreciate their understanding of freedom of choice and building their own goals and meanings (19.9–21.5, 0.012). Thus, the October 2021 pandemic situation seems more stable and predictable, especially on psychological level of young adults in Ukraine.

However, in February 2022, on the background of the fourth and almost normative wave of the pandemic, Ukraine faces a powerful military threat from a neighboring country. Significant psychological markers of hybrid pandemic-military challenges at this time were the lowest for the entire study (2019-2022): indicator of tolerance to ambiguity range is 13.9–12.2, 0.000. This is a clear evidence that to tolerate the synergistic effects of uncertainty, to calmly treat the lack of clear answers, to show self-control in incomprehensible, unpredictable situations, and at the same time to be in limbo related both to the pandemic and the military threat is extremely difficult... Against the background of a significant decrease in tolerance to ambiguity and general readiness for change (127.3–120.3, 0.043), the strategy of avoiding problem solving (16.3–17.9, 0.009) has also intensified. In general, these markers are associated with the deployment of a new phase of "psychological" closure, similar to the one that took place in April 2020.

The results of the study are consistent with the conclusions of other authors about the relevance and role of personality traits, their ability and contribution to amortizing the effects of the COVID-19 pandemic. The latter manifest themselves as a prognostic potential regarding the state of health [14], adaptation, recovery from situations of a high degree of uncertainty [16], optimization of behavior patterns at different stages of the spread of the pandemic [17], perception of a threat to health and the economy, unreasonable optimism, lack of control, trust in government regulations and approval of the conspiracy [19], as well as a generalized orientation that allows to perceive the world as understandable, manageable and meaningful, providing various means to cope with the situation of the pandemic [21].

6. Conclusion

Theoretical analysis of the problem has shown that the studies of the pandemic period are actually extremely fragmentary describing the negative and positive aspects of its influence, predictors and factors that determine the stability of social and economic systems. In this regard, we have attempted to reveal a general picture of their relationship and dynamics over time in the context of the Covid-19 pandemic.

We have put forward the hypothesis that the self-organization of systems at the personal level is inextricably linked with the level of social self-organization and exerts a certain influence on the signs of stability of the latter. Hence, it seems logical to consider personal self-organization and stabilization as a predictor of the sustainability of social systems.

Having conducted a special study of the influence of pandemic on the properties of personality adaptation, we have established a stable or, more precisely, rhythmical nature of the stabilization of the personal system. Moreover, we have found that the diverse phenomenology of personality manifestations in adversity (COVID-19 pandemic) fits into and corresponds to the dialectical sustainability model of development (thesis-antithesis-synthesis).

This can also support the emergence of an original understanding of the world in terms of a rhythmical, emerging, hybrid and innovative self-organization (REHI-world [29]), while the concept of sustainability being – facilitation of the rhythmical change of self-organization in any open living system, such as social or/and psychological by nature.

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The concept of sustainability of the urban realm and community as the key feature of the utopia

To cite this article: A Y Fedak and S M Linda 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012081

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012081 doi:10.1088/1755-1315/1049/1/012081

The concept of sustainability of the urban realm and community as the key feature of the utopia

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Abstract. The aim of this paper is to demonstrate the topic of sustainability as a key basis for the formation of utopia on the example of the work of utopians (architects, politicians, etc.) in the historical context, and to compare their approaches to environmentalism with those prevalent and implemented today.The authors identify three conditional periods of utopia formation from the point of view of urban planning, which clearly demonstrate the shift in the approach to solving relevant problems, namely: spreading the idea of an ideal city (on the example of Franciscus Patricius, Ludovico Zuccolo); rejection of the city as a desirable model of human settlement and an attempt to return to nature (works by William Dean Howells, William Morris, Anatole France); a period of active implementation of environmental technologies in projects since the early 20th century (the work by Ernest Callenbach).

1. Introduction

The concept of sustainability implies a change in people's living standards, taking into account their current needs, and eliminating the negative impact on the future. A 1987 report by The United Nations General Assembly states that the concept includes two main ideas: taking into account the needs of the poorest sections of the population and limiting excess to the consumption and use of natural resources to conserve them [1].

In the historical context, the idea of transforming society by taking into account the needs of the poorest sections of the population is reflected in utopian ideas that depict an ideal society in which all residents are often equal. The concept of "utopia" is described as "an imagined place or state of things in which everything is perfect" [2]. The authors of utopias proposed verbal or visual authorial models of an improved society where peace and harmony prevail, and all citizens are happy and satisfied with the conditions of their lives. Utopia researcher K. Mannheim, describing different historical periods of utopias, notes that utopian ideas spread from the poorest and most oppressed centres. For example, the idea of the utopias of the orgastic chiliasm stems from the poorest part of the population - the peasants; liberal humanist utopias - from the middle classes, namely the bourgeoisie and the intelligentsia; the conservative idea - from the opposition segments of the population, etc [3].

A common theme of sustainability was observed in the work of utopians, who believed that the ideal community could realize its potential only in a certain stable environment. Utopian ideas reflect the hyperbolized desire to improve the social order by changing the political model and improving social conditions, establishing equality among the population, imposing significant restrictions on the use of resources and territories, and so on. It is worth noting that utopias are characterized by the idealization of human capabilities, for example, almost all authors of utopias note that the inhabitants of their cities are less sick or not sick at all. The theme of happiness in the utopian was global, but in fact, did not provide any possible alternatives. People who, according to utopians, will live in a state with the appropriate structure and conditions, must meet specific criteria: their behavior, thoughts and feelings are clearly regulated. "Utopia has never offered options" [4]. There is no unemployment or hunger in utopias, all basic human needs are met, there are no poor and needy, and so on. Utopias exaggerate the aspirations of the authors and idealize the possibilities of transformation, because they exist exclusively on paper. As a result, the study of the idea of sustainability through the analysis of utopias is quite significant in the historical context, as they are not burdened with issues of implementation, economic problems and quite clearly reflect the changing approaches to this issue over the centuries.

The concept of sustainability includes a significant number of different aspects. For example, the author of a significant number of books on sustainable development, John Elkington, identifies three main aspects of sustainability: social, economic and environmental [5]. Ignacy Sachs cites eight types of sustainability, social, economic, ecological, spatial, territorial, cultural, national and international policy [5]. Given that utopias contain an idealized socio-political system (all inhabitants have equal opportunities and living conditions) and mostly describe states and cities formed from scratch, it is worth emphasizing the spatial aspects of such models. For a clearer analysis of approaches to sustainability in the works of utopians, the authors of the article identified several specific components that were analyzed: the socio-political model; the choice of the territory where the state or city was formed; the approach to the formation of the urban environment; access and attempts to influence the population to natural resources.

The aim of this paper is to demonstrate the idea of sustainability as a key basis in the formation of utopia, which is realized through the representation of different approaches to site selection and urban strategy, through a specific understanding of "sustainable community", through the relationship between sustainability and historical context. To achieve this goal, it is useful to compare the ecological approach present in the texts of utopians with today's understanding of new technologies and their potential for environmental impact. This article for the first time analyzes the urban structure of the utopia of A. France and W. Dean Howells, clarifies the features of approaches to land selection and city formation in the context of forming a sustainable community in the works of F. Patricius, L. Zuccolo and W. Morris.

2. Research methodology

The authors of the article analyze six utopian works written from the 16th to the 20th century inclusively. The author went over not only classical examples of architectural utopias, but also works of fictions that are new to the study of utopias.

To present the results of the analysis, the authors propose three conditional periods of utopias, based on the change in the utopian approaches to the choice of territory and structure of populated cities, their attitude to technology and opportunities for environmental impact. It should be noted that this division is conditional, and focuses on the generalization of many different concepts.

The first period covers the period from the 16th to the 18th century and the concept of the ideal city, which presupposes: symmetrical planning and selection of sites that contain everything necessary from the beginning; landscaping through a clear functional division; use of simple technologies and means to change the natural environment. Within this period, the authors have analyzed the utopian works of Franciscus Patricius [6], Ludovico Zuccolo [7], as they most clearly describe the consideration of natural conditions in site selection to minimize anthropogenic transformations.

The next period, which spans the late 18th and early 20th centuries and is characterized by the abandonment of the city as a desirable model of human settlement and an attempt to return to nature, is based on the desire to transform large settlements into more flexible and adaptable ones. Such utopias are often accompanied by an attempt to abandon the development of industry and a desire to return to traditional lifestyles. This is the result of people's inability to provide all workers with proper living conditions in the real world. Features of approaches to the formation of the city are highlighted in the example of the utopias of William Dean Howells [8], William Morris [9], Anatole France [10].

The third period is the stage of active implementation of technologies in projects (since the beginning of the 20th century), which is characterized by more active development of technologies and attempts to use them to improve the environment and so on. For this period, Ernest Callenbach's [11] utopia was chosen, which describes in detail the transformation of existing cities, taking into account the concept of green energy, the introduction of traffic jams and more.

The peculiarities of the urban planning approach to the organization of settlements were analyzed by the method of content analysis of textual and graphic works, and the methods of environmental friendliness and sustainability proposed by the utopians were singled out. The comparative method allowed us to compare the behavioural habits predicted for the inhabitants of the utopias with the described environment.

3. Literature review

The first two periods proposed by the authors of this article resonate with the research of Tessa Morrison, in which the architect, studying utopian urban projects until the early 20th century, divides them into two blocks - the ideal cities of the Renaissance and the cities of the Industrial Revolution [12]. Tessa Morrison's works are devoted to the study of the utopian component of the concept of ideal cities, for example, the ideal cities by Filarete, Albrecht Dürer and other authors [13]. Helen Rosenau described the historical aspects of the formation of ideal cities from antiquity to the Enlightenment, analyzing the architectural features of Sforzinda by Filarete, Charles Fourier's utopian colonies, the concepts of Ebenezer Howard's garden city and other authors [14]. Political scientist Marius de Geus analyzed the practicality of the utopian approaches regarding the interaction with nature on the example of the analysis of works by such authors as E. Howard, E. Callenbach etc [15]. A detailed analysis of the peculiarities of the ecological utopia of E. Callenbach is described in the article by Fedak A., which also summarizes the vision of environmental society in the works of Plato, T. More, T. Campanella, Cyrano de Bergerac, Denis Vairasse, V. Odoyevsky [16].

4. Results and discussions

4.1. The model of cohesive community as a social basis for sustainable development in the concepts of Renaissance ideal cities

In Italy in the Middle Ages, city-states served as centers of cultural, social and political development. The spread of the concept of the ideal city, which was characterized by proportionality and correctness of the structure, became popular because it allowed to form a clear urban fabric, with predictable functional zoning. The concept provided not only an aesthetic solution to the image of the city, but also the transformation of the social order, which also had to be subject to the proposed scheme.

Ancient Roman engineer and architect Vitruvius in his treatise "Ten Books on Architecture" describes recommendations for choosing a city site, designing public and residential buildings, selection of materials and more. Vitruvius notes that when building a city, it is important to design the streets taking into account the direction of the winds, as people living in unfavorable locations are more likely to get sick and need appropriate treatment. The treatise mentions eight winds, which are named according to the direction from which they blow, which corresponds to the wind rose (for example, northeast wind). Vitruvius proposes to orient the city around the world and design 8 main radial streets, the first of which deviates by 22.5 degrees from the north, and each subsequent deviates from the previous one by 45 degrees. Thus, the city has an octagonal shape, and all streets are designed to be protected from the main winds [17].

Vitruvius' ideas for regulating the city's space have been popular since the 15th century, when architects and statesmen tried to settle the chaotic city of the Middle Ages after the plague pandemic. The anti-epidemiological measures that are gaining popularity include: control of clean air through the disposal and processing of sewage, including waste and residues from the food industry, regular cleaning of sewage systems, etc.; organization of cemeteries outside the city; increasing the network of medical colleges, which provided professional training for physicians and persons who could provide medical care; construction of special infirmaries, hospitals (a special type of building with porches) on the outskirts or outside cities; introduction of quarantine for ships that had to stand on the roadstead (anchor stop) for a certain number of days before entering the harbor [18]. All these attempts to regulate the fabric of the city in order to improve the quality of life of people influenced architects and politicians, who tried to regulate the activities of city-states, to improve them. The architectural designs of the ideal city were designed by Italian architects Filarete and Francesco di Giorgio Martini, described in the treatise by Leon Battista Alberti. They also gained popularity in the works of utopian philosophers who used the right urban structure to form ideal states.

In the Renaissance, the idea of forming a friendly community of the city was more than just a desire to reach an agreement among the inhabitants. The inability to travel long distances and the lack of means of rapid transmission of information limited people and the circle of their constant communication to a certain area, community. Utopian projects of the Renaissance were aimed at organizing relations within such communities, providing a favorable environment for the formation of a sustainable community.

The English writer Sir Thomas More in his socio-political satire "Utopia" (1516) and the Italian philosopher Tommaso Campanella in his treatise "The City of the Sun" (1623) offer special containers for collecting rainwater that can then be used. The French writer Denis Vairasse in his utopia "History of Sevarambes" (1675) describes a system of land irrigation, which will allow the use of a significant number of territories that were previously considered infertile [16]. The correct shape of the city (a circle in T. Campanella, a square in T. More and D. Vairasse) and a fictional location with favorable natural conditions, allowed the authors to visualize the ideal city, which would be provided with everything necessary. The inhabitants of such a city were also portrayed as endowed with idealistic traits of character, and the relationship between them was clearly regulated and did not go beyond what was permissible. This approach was too abstract from the real conditions, as the authors of these utopias did not give recommendations on the choice of site or ways to interact with the environment.

The Italian philosopher Franciscus Patricius in his treatise "The happy city" in 1551 when choosing a site for a new city recommends avoiding: wetlands and forest areas with evergreen trees such as ivy, cypress, spruce, etc.; locations where there are often east or south winds. Part of the city should be located on an elevated, for better ventilation, otherwise part on the plain. Given the need to protect the city from external enemies, Patricius also proposes to build a defensive wall and moat around the city. The city should be divided into a "happy" part (focused on soldiers, magistrates, priests) and "unhappy" (inhabited by farmers, artisans and merchants). All city residents must meet certain standards, including external attractiveness. The buildings are designed to protect against excessively scorching sun and low temperatures; shaded areas under the loggias can be used as terraces; the rooms on the first floor will also serve as a salvation from the sun [6]. All residents should have some property near the outer border of the city and in its central part - this will encourage them to defend the city borders in case of attack [6]. There is no detailed information about the architectural or engineering features of the city organization, which distinguishes this utopia from the works of T. More or T. Campanella, but the functional division of the city, which affects the formation of the community is described quite clearly (figure 1).

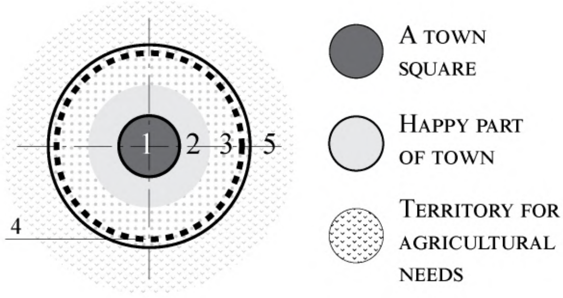

Figure 1. Schematic representation of city planning. 1 A town square; 2 “Happy” part of city (focused on housing of soldiers, magistrates, priests); 3 “Unhappy” part of city (focused on housing of farmers, artisans and merchants); 4 Every resident should have property near the city limits (this will encourage them to defend the city in the event of an attack); 5 Large enough area for agricultural purposes [drawn by author according to the description in “The happy city” by Franciscus Patricius].

The Italian theorist Ludovico Zuccolo in his work “Aromatario, or the Republic of Utopia” (1625) criticizes the work of T. More ”Utopia”. The author singles out insufficient detail of T. More’s work on various aspects of the organization of public life, the idealization of people and their behavior; notes impossibility to implement the proposed model. Zuccolo believes that it is not necessary to decide whether the country will be mainland or island - it is much more important to take into account climatic and natural resources. The site should be located in an area with good climate conditions and clean (“healthy”) air; the way of life should correspond to the terrain. The described political ideology has the features of democracy - individual freedoms; election of power; no communal property [7].

4.2. The first pre-ecological utopias of the Industrial Revolution: concept of abandoning of cities and returning to nature

Since the end of the 18th century, aesthetic utopias have been spreading, which preserve the humanistic ideal and the desire to rebuild the Golden Age [19].During this period, urban planning is becoming an increasingly organized process, subject to certain general rules and laws. Cities that were formed in the previous period are subject to reconstruction (for example, the reconstruction of Paris by Baron Haussmann between 1853 and 1870). The development of industrialization and the active development of cities contributed to the deteriorating living conditions of residents who came to certain industrial centers in search of work and, as a result, lived in inadequate conditions. Characteristic of many authors of utopian works of the late 19th century are images of countries that do not have large cities, and residents prefer to live in rural areas planted with trees. The inhabitants of such utopias mostly have equal living and working conditions, living in harmony with their neighbors and the environment.

For example, the American writer William Dean Howells in his utopian novel “A Traveler from Altruria” (1894) describes the fictional island nation of Altruria, whose inhabitant is in the United States and marvels at the social restrictions on the rights and freedoms of some citizens. The territory of the country is divided into districts, each of which has a capital, and cities and villages in the usual sense are absent. Cities, some of which were quite large (some could hold up to a million people), were considered economically unviable: they did not provide citizens with the necessary resources, but used those produced in villages and provinces as a result, negatively affecting the economy; all cities were completely destroyed. The author describes anthropogenic climate change: to improve conditions, the country's inhabitants separated from the island a peninsula (20 miles wide and 93 miles long), located in the southeast of the country. It is proposed to use natural energy sources: wind and water power; the inhabitants of the country completely abandoned the use of classical energy sources; power lines cover the entire territory of the country, connecting villages and capitals [8]. It is noted that the country's residents do not play sports as such, as all are involved in agricultural work and other types of physical labor for at least 3 hours a day. Thus, the counterurbanization of the territory contributed to changes not only in the characteristics of buildings, but also in the daily habits of citizens.

Another example of counterurbanization is the utopian work of the English writer and art theorist William Morris, who in his novel "News from Nowhere (or An Epoch of Rest)" (1890) describes a society of the future in which cities that served as industrial centers disappeared. The main administrative unit is a community or district, which is formed by villages. The author proposes a change in the functional purpose of outstanding buildings. For example, Windsor Castle has been preserved, but now it performs a different function: most of the rooms have become living rooms where anyone can live; a part of the premises serves as a museum. Phalanstery by Charles Fourier is mentioned in the work as one of the steps in the organization of an ideal society, which is still considered obsolete and imperfect. In the described future, the area of forests and various plantations increases and the population of birds of prey increases. The political ideology described by W. Morris has signs of communism: there is no private property in the state; no money and no payment for work, all goods are received free of charge; all residents live in separate buildings, but the doors of their apartments are always open [9].

The French writer Anatole France describes the events of the future in his 1905 novel "The White Stone". The author describes the Great Union of Several European States - "European Federation". Cities that have been formed are historically degrading; most settlements are villages. The city's population decreased as most people began to live in villages [10]. Settlements of any shape, most buildings are located along roads (figure 2).

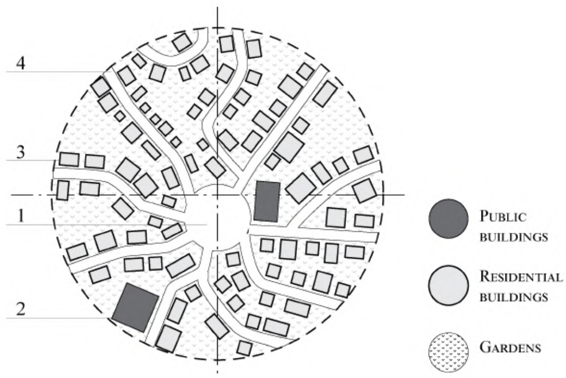

Figure 2. Schematic representation of city planning. 1 Round area- a town square; 2 Public buildings; 3 Residential buildings; 4 Arbitrary network of streets; motorways, streets and roads focused on motor vehicles and trams [drawn by author according to the description in "The White Stone" by Anatole France].

Despite the rejection of the urban way of life, France describes a variety of industrial plants and factories in which all processes are automated. The author does not pay much attention to natural resources, and the described political ideology has signs of collectivism: lack of private property); lack of money: employees receive vouchers for a certain number of hours worked; these vouchers are exchanged for food, clothing, etc [10].

The architectural utopias of reurabnization include the idea of the garden city by Sir Ebenezer Howard [20]. This is the concept of a self-sufficient city, which is formed by low-rise buildings surrounded by a lot of greenery. A city of 32,000 inhabitants was proposed, and in the event of an increase in population, another city would have to be formed for new residents. E. Howard founded in 1899 the Town and Country Planning Association, which operates to this day and is engaged in improving urban planning and environmental policy.

4.3. Introduction of eco-technologies in utopian projects

Since the beginning of the 20th century, active urbanization, the proliferation of motor vehicles and the increase in the number of plants and factories have contributed to increasing problems, both in the organization of urban spaces and in the field of environmental protection. These negative transformations have contributed to the emergence of new urban planning practices, such as New Urbanism and Sustainable Architecture, which are focused on the introduction of means to protect the environment and improve the living conditions of residents. Utopians, who previously proposed the formation of new cities on conditional islands, now go beyond the planet Earth, describing ideal societies on Mars or the Moon. Some authors describe utopian societies in today's cities, offering a significant number of changes in the urban fabric, the approach to nature conservation and behavioral habits of residents.

For example, the American writer Ernest Callenbach in his novel "Ecotopia: The Notebooks and Reports of William Weston" describes in detail the community living in an ecological environment: there are waste recycling stations, renewable energy sources are used, and so on [11]. Callenbachs work is characterized not only by an attempt to introduce an ecological economy, but also to restore damaged rivers and the spaces around them (figure 3).

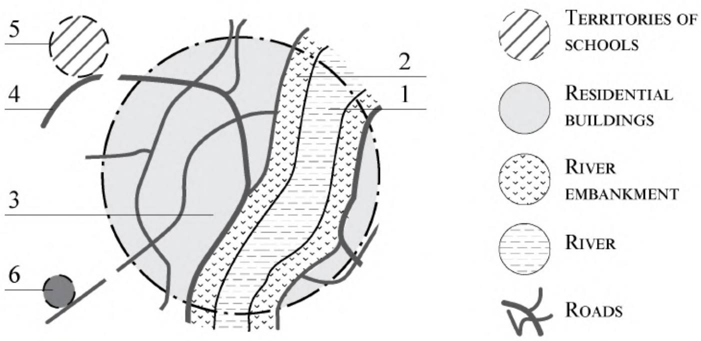

Figure 3. Schematic representation of city planning. 1 Restored river, which was previously turned into a sewer; 2 Embankment with public areas; 3 Buildings; 4 Roads are focused on electric vehicles, cyclists, pedestrians; 5 Territories of schools; 6 Factories and power stations [drawn by author according to the description in "Ecotopia: The Notebooks and Reports of William Weston" by E. Callenbach].

Callenbach depicts the country Ecotopia, formed not on a conditional territory, but on the site of existing cities in the United States, which are subject to some reconstruction. Preserved historic cities have a typical US street network, planned according to the grid street plan. At the same time, new cities are formed by a network of winding streets that have different names, not numbers. This work depicts a state where the laws of sustainable development have been implemented, which has had a positive impact on clean air and the region's ecology. Residents, although they have to follow certain rules (sort garbage, wear only clothes made of natural materials) are still not subject to such clear restrictions as it was provided by the utopias of previous centuries [11].

4.4. The result of the analysis of the selected utopias of the three periods
Summary of the analysis of the selected utopias is given in the table 1, where the leading characteristics of all three periods are singled out according to the choice of the territory on which the state or city was formed; approach to the formation of the urban environment; access and attempts to influence natural resources.

Table 1. Summary table of approach features for all three periods.

Period	The concept of the ideal city as a model of a close-knit community	Utopias of abandonment of cities and return to nature	Introduction of eco-technologies in utopian projects
Timeline	By the 18th century	End of the 18th - beginning of the 20th century	From the first half of the 20th-century
Analyzed works	F. Patricius “The happy city” (1551);L. Zuccolo “Aromatario, or the Republic of Utopia” (1625)	W. Morris “News from Nowhere (or An Epoch of Rest)” (1890); W. D.Howells“A Traveler from Altruria” (1894); A. France “The White Stone”(1905)	E. Callenbach “Ecotopia: The Notebooks and Reports of William Weston” (1975)
Choice of territory	Conditional location	Conditional location; reconstruction of existing cities	Reconstruction of existing cities (Northern California, Oregon and Washington, USA)
Approach to building the territory	Urbanization	Deurbanization of the territory	Deurbanization of the territory
The urban structure	City	Small towns, villages	Small towns, villages
Anthropogenic impact on the environment	Minimization of environmental impact; taking into account climatic conditions and clean air; the way of life must correspond to the terrain	Minimization of environmental impact; approach to nature - active gardening and spread of agriculture; attempts to use natural energy sources	Use of natural energy sources; garbage processing stations are operating; implementation of the principles of sustainable development; use of the latest technologies for cleaning the river, etc

5. Conclusions

Analysis of the works of utopian writers of the 16th-20th centuries. demonstrated that the idea of sustainable development in the context of the environmental approach has become the basis for the formation of utopias Utopian concepts stated that the cleanliness of the city and the ability to improve the physical characteristics of space are important aspects of comfortable living that shape the behavioral habits of residents.

Until the 18th century, the authors of utopias operated with the concept of an ideal city, striving to organize the territories of cities that were formed chaotically. They suggested using physical means to increase the level of involvement of residents in the public life of the city and reduce the incidence. For example, a responsible approach to choosing a site for the construction of a new city, which would create a healthy comfortable environment, due to the required strength and direction of winds, which improves the health of citizens ("The happy city" by Franciscus Patricius, "Aromatario, or the Republic of Utopia" by Ludovico Zuccolo). The city-states they describe are self-sufficient and orderly, their structure is clear and the population is evenly distributed throughout the territory. At the same time, the main means of anthropogenic ascent to nature are attempts to irrigate the land and collect rainwater. In these concepts, the model of a cohesive community that works for the common good to improve living conditions is central.

The industrial revolution of the second half of the 18th century led to the development of industrialization and active urban development. This contributed to the migration of the working class, who gathered in cities that were industrial centers, and the uncontrolled increase in population density, a significant deterioration in their living conditions. As a result, in the 19th century a number of projects emerged to reurbanize territories by destroying large cities and forming a network of settlements with a good-neighborly community of people (garden cities; concepts of rural utopias). Such projects aimed to restore the well-being of neighboring communities and strengthen people's connections with nature, improve the level of the environment, which has deteriorated significantly as a result of the growing number of plants and factories. The main means offered were a return to the rural way of life, a reduction in the percentage of mechanized production, and so on. Such utopias were pre-ecological in nature.

Since the 20th century, the topic of finiteness of natural resources, the state of the environment and the decline of social interaction between people has been more actively raised. These problems are reflected in the work of utopians who try to visualize cities with alternative energy sources, or offer models of communities that abandon non-organic products in favor of natural products.

Thus, the analysis of utopias in the works of selected writers of 16-20 centuries. demonstrates that the idea of sustainable development is one of the leading in the formation of utopia. Writers, statesmen and architects, using fictional societies or images of cities of the future, offer their vision of solving many problems. The ideas of solving the problems of social equality and ensuring social justice are most acutely reflected in their works. However, the formation of such an ideal society is impossible without a healthy environment. The ecological component occupies a leading place in utopias. It is provided by various measures at different times: cohesive, consolidated action of residents to ensure the cleanliness of the environment, escape from the city and merge with nature, the use of the latest technologies.

Thus, the desire to shape the sustainability of the environment, as a guarantee of sustainability of the community, is one of the leading signs of utopias.

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To cite this article: V S Patsiuk *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012082

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012082 doi:10.1088/1755-1315/1049/1/012082

Revitalization of the industrial heritage: guidelines for Kryvyi Rih

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Abstract. The post-industrial stage of development determined a significant reduction of the importance of industrial production, which led to restructuring the economy. An active process of revaluation has begun – reassessing the value of industrial heritage and finding options for its further use. Kryvyi Rih is the most powerful industrial center of Ukraine and despite the fact that the industry is in an active stage of operation, the issue of diversification of the city's economy and further transformation of industrial facilities is raised in a timely manner. The tasks of this research are theoretical analysis of the concept of revitalization", the essence of this process, the study of practical experience of revitalization in Ukraine and abroad, the result of which should be an analysis of prospects for the implementation of this process in the industrial heritage of Kryvyi Rih. The analysis of the possibilities of Kryvyi Rih industrial heritage revaluation was carried out through the prism of an interdisciplinary approach based on research in architecture, ecology, economics, geography and culturology. Disclosure of this issue took place at two levels of research: theoretical and empirical. Theoretical research was based on the use of general scientific systems approach, analysis and synthesis, structural-functional analysis, comparative analysis, modeling methods, design, SWOT and PEST-analyzes of the probable effectiveness of revitalization in Kryvyi Rih. Empirical research was expeditionary methods, observations, the method of field visual inspections. The study has structured the concept of "revitalization", revealed promising areas of industrial facilities revitalization. The world tendencies and the best national examples of transformation of industrial territories into various innovation spaces have been analyzed. An assessment of the potential of the city's various objects in terms of revitalization opportunities has been given. Conceptual models of creation of the Industrial Culture Park "SHAKHTA" on the place of the preserved mine "Artem-2", and also industrial and landscape park on the place of Burshchitsky dump have been prepared, futuristic possibilities of their use in the tourist activity have been allocated. Intensification of efforts of specialists in various related fields to ensure the sustainable development of the urban environment of old industrial areas is the key to a qualitative revival of industrial spaces, harmonization and ecological optimisation of the former industrial environment, solving a number of socio-economic problems.

1. Introduction

Postindustrial processes influence the entire modern world – economies of industrial, industrial-agrarian and agrarian countries, since all countries are interconnected by a complex system of ties. All advanced and economically developed countries of the world have passed the stage of industrial development. Significant industrial areas resulted from it require now not just utilization, but revision of their functions and revival.

In the era of industrialization, cities were planned and built presuming the fact that industrial zones and enterprises would be located on the outskirts, and residential areas would be beyond the negative influence of enterprises but at a convenient transport distance for commuting with necessary objects of social infrastructure and cultural life for the workers in the center rather far from industrial zones. However, over time, with the growth of urbanization and the rise in births, it turned out that industrial enterprises became surrounded with residential areas. In the course of time, natural resources – the basis of industry – fell short, production volumes declined and depressed post-industrial zones replaced powerful industrial giants.

Thus, there has arisen a question of changing the functional planning of areas of industrial cities. The problem of industrial areas in urban zones is typical of many developed countries. Gradually, the idea of revitalization of industrial zones and objects or their relocation outside cities has come into being. Such post-industrial zones continue to develop based on the cluster principle, which implies a combination of business, science and production in the form of industrial parks.

Revitalization is a term used in scientific practice to refer to the processes of reproduction, revitalization and restoration of the urban space. Revitalization of existing industrial complexes located within the city is very popular now, which is associated with contradictions between the needs of society and the established structure of the urban environment.

However, revitalization of industrial zones and objects should be treated with caution. First, it is necessary to determine the purpose and function, then carry out partial reconstruction to preserve historical technical features of industrial architecture. Revitalization of city industrial objects aims to optimize the use of industrial facilities and territories, improve architectural and spatial characteristics and aesthetic qualities of the urban environment, and most importantly, identify, preserve and use monuments of industrial architecture and technical culture, protect and restore the natural landscape [1].

Revitalization of industrial facilities and zones is a sign of society's transition to the post-industrial stage of its development. Revitalization of industrial heritage in developed countries is manifested on a total scale. Ukraine is trying to follow the world's mainstream trends, so there are successful examples of revitalization in the country. Sooner or later, all industrial areas face the need to raise questions about the future of industrial objects. The city of Kryvyi Rih is no exception to this historical evolution in Ukraine. The city is still characterized by availability of powerful operating enterprises of the mining and metallurgical complex. However, some of the objects of the iron ore industry are already abandoned or mothballed, which logically sets the task of their revitalization.

2. Publication overview

The issue of studying ways of transforming abandoned industrial facilities is treated in many works by foreign scientists. In the USA and Europe, revitalization projects were implemented in the early 50s of the XX century. Accordingly, attention of scientists has been focused on this issue for a long period and it is still topical nowadays [2].

In Ukraine, this issue is also gaining significant popularity, but it is only covered by journalists, public figures, analysts, bloggers, etc., but not by scientists. Studies and publications on this subject very often apply somewhat different terminology. Therefore, it is worth differentiating between a number of concepts that are sometimes used as synonyms when disclosing the issue of revitalization. The most used terms in scientific publications are the following:

Conversion is the process of restoring, reconstructing or rebuilding production facilities that have a historical load, with their modern use for other purposes [3].

Reorganization is transformation of the organizational structure and the structure of enterprise management while preserving fixed assets and production potential of the enterprise. In this context, it is a kind of radical complex innovations, consisting in the organizational restructuring (of the system, goals, relations, norms) of any object [1]. This concept mainly appears in Russian scientific publications.

Reconstruction is rebuilding a duly commissioned construction object: change of its geometric dimensions and/or functional purpose that results in changed main technical and economic indicators, improved operating conditions and quality of services. It provides for complete or partial preservation of elements of bearing and enclosing structures [4].

Renovation (from Latin renovatio – renewal, restoration) is a technical and economic process of replacement of machines, equipment, tools that are out of production due to physical and moral wear by new fixed assets at the expense of the depreciation fund [1].

Redevelopment of industrial zones is a process that consists in improving the industrial zones planning structure that involves more rational use of an industrial territory with an increase in operative efficiency; identification of territorial reserves, an increase in their exploitability degree due to increased density of their development; improvement of transport links and liquidation of low-performance industrial enterprises; improvement of the architectural qualities of the development, reduction of harmful effects of enterprises on the environment [5].

Brownfield is a type of reorganization of urban industrial zones that means creation of industrial parks on preexisting production sites (former factories, plants, shops, port docks). As a rule, in such places there are already structures that undergo further reconstruction and finishing building; there usually exists appropriate infrastructure, utilities and ready-made warehouses [6]. This term is mainly used in analytical commercial research rather than in scientific sources.

Revalorization provides for priority changes (scale of transformation, preservation) of volumetric-spatial and planned characteristics in order to increase the aesthetic and artistic value of urban environment, implementation of fragmentary restoration works and possible compensatory construction in order to restore the lost dominants with preservation of functional type of the object to be transformed [7].

However, after analyzing these definitions, we have opted for the concept of **revitalization**, although its interpretation in many sources highlights various aspects. Revitalization means "return to life". In the Cambridge Dictionary, revitalization is defined as *the process of making something grow, develop, or become successful again* [8].

Based on the research of Polish scientists, it can be argued that revitalization is "a certain sequence of planned measures aimed at restoring the economy and changing the spatial and functional structure of degraded areas of a city. This is a process that can be applied to urban areas of various intended functions, such as industry, military, ports, residential buildings, transport infrastructure" (courtesy translation) [9].

Revitalization in a broader sense implies a moral and spiritual revival which is the result of a purposeful social and urban planning policy. Revitalization is the highest content, a super-task of conversion and concerns not only specific objects, but also the urban area in general, the environment in which man exists. According to M. Stratton, "philosophy" of revitalization implies that cities are historically endowed with different resources and many other benefits that can be grown or revived; and the benefits of improving urban environment and the increased number of new jobs are followed by stable strategic benefits for the whole society [10].

O. A. Sych defines revitalization as a process of spatial, technical, social and economic changes, as well as activities that are carried out for the greater public good and aimed at overcoming the crisis in the region, restoring its former functions and creating conditions for further development using its endogenous features [11]. According to A. P. Bronevytskyi, revitalization is a complex of organizational, technological, architectural and economic measures aimed at partial or complete reconstruction of an industrial facility with a further change in its intended functions [12].

3. Methods

The study of possible revitalization of the industrial heritage of Kryvyi Rih is conducted on the basis of the interdisciplinary approach underlaid by a thorough analysis of numerous studies on architecture, construction, urban science, ecology, economics, geography, tourism and cultural studies. When disclosing these problems, a combination of the following general scientific methods and approaches is used: analysis and synthesis of all available information on the problems of research; the system approach to prospects for implementation of revitalization of industrial facilities in accordance with the concept of sustainable development; comparative analysis – comparison of the best revitalization practices of European countries and Ukraine; system-functional analysis in the study of a complex of relationships in the system of "non-operating industrial facilities" – "the city as a territorial entity within which these objects are located" – "the city population interested in creating new jobs, and obtaining new facilities for leisure and self-development".

Theoretical research is impossible without applying a complex of empirical methods, in particular, on-site visual examinations of the objects described during field expeditions. In addition, the authors of the article have been organizers of multiple excursions to these objects and had the opportunity to both observe tourists' reaction to the objects to be revitalized and attract tourists to the visual and aesthetic assessment of these formations.

Besides general scientific theoretical and empirical methods, a number of applied techniques are used in the study, in particular, the design method in describing and assessing potential efficient revitalization of the Burshchytsky dump and the underground mine "Artem-2", modelling their territory and marking future locations, and assessing potential efficiency of revitalization in Kryvyi Rih using SWOT and PEST-analysis techniques.

4. Results

Revitalization is one of the elements of development policy aimed at preventing degradation of urban areas, crises, as well as contributing to protection of national heritage, development, and qualitative changes occurring through increasing social and economic activity, improving the living environment with simultaneous adhering to the principles of balanced development [13].

The need for revitalization arises when degradation and decline of landscapes, complexes or individual objects, previously actively used in industry or everyday life, take place. However, an important requirement for revitalization is the need to preserve the authenticity of the object. That is, if it is a mine headframe room, it must retain the industrial atmosphere given to it.

After analyzing the existing approaches to the definition of revitalization, the attempt has been made to formulate the author's definition. Thus, in our opinion, revitalization is a process aimed at the complex transformation of depressed industrial facilities and territories for their functional reformation in order to improve the social living conditions of the population.

As a basis for revitalization, the premises of former factories or other industrial facilities which already contain special structures, design and technical equipment that can be used in the future as an element of interior, exterior, or, in general, be involved in an active use are usually chosen.

The results of the revitalization of old industrial facilities are impressive, because, if they are commercialized, they bring significant profits due to their authenticity, uniqueness, certain exoticism and, of course, the brand, which is usually formed around the main attraction of the institution.

After analyzing a number of different publications we can identify the classification of the main types of revitalization projects: 1) creation of food establishments; 2) creation of accommodation facilities (both temporary and permanent); 3) creation of educational and scientific space; 4) creation of leisure and recreation facilities (including active ones); 5) creation of sports facilities; 6) creation of business centers; 7) multifunctional projects (combining all or several of the above types) [14].

The tasks of revitalization are: socialization of space and creation of conditions for urban development; improving the environment and forming creative elements of infrastructure; creation of new space for leisure and recreation of the population; increase of tourist and cultural potential; stimulating economic development; protection of industrial and architectural heritage; investment attraction, etc.

The practice of revitalization in European countries has already gained considerable momentum, but the worldrenowned classic of giving "a second life" to industrial facilities is the Zolferine mine in Essen, Germany, one of UNESCO's most visited industrial sites. Today it is a cultural and creative center where you can visit the Coal Path Museum, the Ruhr Museum, the North Rhine-Westphalia Design Center, the Margaretenhöh Ceramics Museum, and the exhibition of contemporary art at the former coke plant [15].

Successful examples of revitalization in Europe include: the ABS Museum in Madrid (Spain) on the site of an old brewery, where a modern art center with the latest architectural forms has been created; the park on the site of the metallurgical plant in Luxembourg; Wunderland Kalkar amusement park, founded on the territory of an unfinished nuclear power plant, which was built in Kalkar (Germany) in 1972 – this park was opened in 2001 and includes a hotel, gastronomic and leisure complexes; Duisburg-Nord Landscape Park, one of the largest in the world (formerly Meiderich Metallurgical Plant, which now houses a diving center in the former gas storage facility, a concert hall in the former power plant, and an open-air cinema in the former steel melting shop); Kunststad Shipyard in Amsterdam (Netherlands), which has been transformed into a festival district and is the workplace of artists and cultural managers (now in the harbor there are artists' and designers' studios, theater stages, record companies, cafes, restaurants and even a skate park) [16]; Culture Factory Polymer in Tallinn (Estonia) – a multidisciplinary art center set up in the premises of a former Soviet toy factory; Trzczyna Factory is an art and educational complex located in the building of the former factory in Warsaw (Poland), where marmalade and canned food were made; "Sapnu Fabrika" in Riga (Latvia), which is a cultural and communicative space created in the building of the former glass factory built in 1911 and many others.

Lithuania belongs to countries with a noticeable industrial component of the economy. Some industrial facilities are operating and some are closed. Closed industrial enterprises are now partially revitalized. The main direction of revitalization is creation of various museums. Non-operating defence-industrial objects include Plokštinė missile base with 40-meter-deep silos located in northwestern Lithuania (Žemaitija National Park), where the Cold War Museum was created to preserve its authenticity. This site is one of the most unique and visited in Western Lithuania.

In the central part of Vilnius, the first industrial power plant built in 1903 is located. Currently, its premises are transformed into the museum of power engineering. A complex of the 19th and 20th century fortifications can be found in Kaunas. The complex is a complicated engineering system of nine forts; each of them is very individually adapted, from a theriological reserve (protection of bats) to a museum of military equipment or the Holocaust.

The Ignalina nuclear power plant, which is no longer on operation, has a great potential for revitalization, but in the context of development of the Baltic states, it is a unique object of this type, where educational excursions are organized. Thus, the experience of Lithuania shows its own national practice of revitalization of industrial facilities of different ages and purposes.

Such practice is beginning to be introduced in our country only in recent years. The first large enterprise revitalized in Ukraine was the insulation materials plant in Donetsk, which was transformed into the Art Foundation "Izolyatsia" in 2010. The first project implemented by this fund was the exhibition about miners' life "1040 Meters under Ground", which was realized by world-famous Chinese artist Cai Gotsiang, who was the artistic director of visual and special effects of the Olympic Games in Beijing. However, due to the beginning of war in eastern Ukraine in 2014, the fund was evacuated to Kyiv [17].

The next project, implemented in 2014, was the Art Factory “Platforma”, located on the territory of a former Darnytsya Silk Factory. It is a complex that combines business, festivals, coworking, art, IT sphere, fashion, education and other industries of creative economy.

“UNIT.City” was also created in the capital on the territory of a former Kyiv Motorcycle Plant. It positions itself as the first innovation park in Ukraine, a place where ecosystem and infrastructure for business development in the field of high technology and creative industries are built. There are plans to equip 25-hectare area with co-working spaces, a dozen research centers and even a housing estate with a developed infrastructure. There is a free programming school “UNIT.Factory” in the park.

A well-known example of revitalization is the National Art and Culture Museum Complex “Mystetsky Arsenal”, located in the building of the Old Arsenal - a former workshop for the manufacture, repair and storage of ammunition and parts for guns.

Another project is “Pivzavod” in Kyiv. The aim of this project was to transform the territory of a former brewery into multifunctional environment with domination of a new educational cluster in the historic building of a former brewery. There are also small offices, a hotel and residential buildings there [18].

In Kharkiv on the site of a former locomotive plant, founded in 1985, Art Plant Mechanica was established, which is multifunctional cultural and creative space. Its revival began in 2016. Concerts and festivals are regularly held on the site of the “plant”.

Western Ukraine has made significant progress in revitalizing industrial facilities. In Lviv the most successful examples of revitalization are: “Lem Station” on the basis of a former tram depot, “! FESTrepublic” - on the site of a former plant “Halychsko”, “ReZavod” - formely a plant of electronic medical equipment. The most successful project in Ivano-Frankivsk is the innovation center “Promprylad. Renovation” (formely a Soviet instrument plant). This is one of the first examples of transforming an abandoned enterprise into a modern business cluster with the involvement of public investment in Ukraine. It focuses on four areas of region development - new economy, urban design, contemporary art, and education. This is a project in the field of impact investment, where investors simultaneously invest in the social impact on the region and receive a return on investment in the form of dividends [19].

In the south of Ukraine, the most successful example of revitalization is “Urban CAD” in Kherson, which was created on the site of the former ventilation shop of the machine-building combine plant.

The city of Kryvyi Rih, the most powerful industrial center of Ukraine, has a huge potential for revitalization of industrial facilities. But instead of the fact that the city has more than 200 different types of industrial heritage sites, in our city there are a number of deterrents for implementation of revitalization: 1) the Soviet heritage, as a rule, is not perceived as a value, and most industrial facilities belong to the Soviet period; 2) misunderstanding the value of objects and approaches to their preservation by the residents; 3) the low interest of investors in such projects due to the difficulty of restoring old industrial premises; 4) the neglected condition of buildings and significant need for investment [14].

At the same time, at the initiative of the public, namely the public organizations Kryvyi Rih Foundation of the Future, Urban Development Agency, with the assistance of the Metinvest group of companies, on November 15-16, 2019, the city held “Urban Hackathon”. During this event the leaders of the “Urban CAD” project from Kherson presented their experience of giving a second life to the industrial heritage. In addition, five objects of the city promising for revitalization were put forward for discussion. They were the mine “Artem-2”, the premises and dill of the mine “Ventylyatsiyna-3”, the premises of the former management office of the Lenin mine, the abandoned greenhouse and Burshchytsky dump.

Expert groups have prepared options for revitalization of these facilities. In particular, 2 projects were proposed for the revitalization of the greenhouse. Within the first one the creation of a thematic complex where it will be possible to place a museum, a photo area, a restaurant and gift-shops for selling thematic souvenirs is planned. Another project proposes to grow vine and make wine from it, as well as to breed snails in these vineyards and use them in cooking, as the main concept of this project is to create a restaurant of French cuisine.

On the site of the former management office of the Lenin mine it is proposed to create a youth center, on the roof of which it is planned to create an observatory with a relaxation area. Four floors of the building may be made thematic ones, where there will be rooms for work and rest, an art hub, a hostel, a multifunctional center, a thematic museum with the involvement of moving and interactive elements, exhibition halls, etc. Another option was to create a social center "InTerny" on the basis of this building. The task of the center is to help the most affected categories of the population - the elderly and people (especially children) with special needs, where they will be offered professional help and temporary, or even round-the-clock care.

On the territory of the mine "Ventyliatsiyna-3" there is a complex of buildings connected by outlet shafts with a diameter of 2 m and a small metal headframe. On the basis of this object it is proposed to create an active leisure center "StreetTown", the main purpose of which is to provide active leisure for children and youth of the city. The buildings offer the following locations: an administrative zone, a food zone, a sanitary zone, an indoor skate park, a trampoline, dance floors. It is also planned to place speleological training locations in the mine shafts and a climbing wall on the wall of one of the buildings. Near the buildings a small parking, a skate park, a bicycle area and a fountain with iron fish as a symbol of the iron ore basin are planned to create.

During "Urban Hackathon", the authors of the study participated in the development of projects for revitalization of the Burshchytsky dump and the mine "Artem-2". The hackathon outlined the guidelines by which these objects can be developed, the opportunities and directions of revitalization of these objects were also determined. So let us have a more detailed look at them.

The Burshchytsky dump is one of the three panoramic observation points of Kryvyi Rih. This is an object of industrial heritage resulted from disposing waste rocks by the former Novokrivorizkyi mining and processing plant in the early 1970s. The area of the dump itself makes 35 hectares (0.35 sq.km), its length is 0.9 km, the largest width is 0.5 km. The relative height of the dump (from the foot on the Inhulets River side to the top) is 68 m. The highest absolute mark above sea level is 138.2 m.

The dump is located in close vicinity to the left bank of the Inhulets River. It has a steep terraced part facing the river valley side and the hilly part that consists of one tier and borders on the mine allotment of open pit No. 2-bis of the PJSC "ArcelorMittal Kryvyi Rih". The type of the dump is rocky, partially reclaimed. The main types of rocks are non-metallic quartzites, schists, oxidized quartzites. The reclaimed areas are covered with a thin layer of loesslike loam. The dump structure is complex, fragmentary tiered with a top plateau. The surfaces of the plateau and tiers are flattened due to technical reclamation. There are remnants of an entrance motorway leading to the top of the dump. The largest number of tiers (five) face the Inhulets River (figure 1).

The degree of overgrowth with tree and shrub vegetation is insignificant and makes 20 percent. Many surfaces are just covered only with thin herbaceous vegetation.

The top plateau of the dump is an excellent observation point which offers a panoramic view of the western, central and southern parts of the city. From its highest point, turning around, one can see:

- a chain of underground mines that go far northwards;
- the historical part of the city;

Figure 1. The Burshchytsky dump (photographed by V. Kazakov).

- pipes and workshops of the metallurgical plant of the PJSC "ArcelorMittal Kryvyi Rih";
- open pit No. 2-bis of the PJSC "ArcelorMittal Kryvyi Rih" and a new very high dump of pit No. 3 of the same enterprise;
- the open pit and dumps of the Pivdennyi GZK in the distance;
- numerous old and new dumps and working heavy mining equipment – excavators, 130-t BeLAZ trucks, powerful drilling rigs;
- the canal of the Inhulets River sandwiched between dumps and open pits (figure 2);
- a high pre-revolutionary (1884) Beleliubskyi bridge and Katerynivska railways (figure 3);
- numerous objects of industrial heritage of the old mine Hdantsivskyi and iron foundry Hdantsivsky (1892);
- concentrating plants of the Pivdennyi GZK and "ArcelorMittal Kryvyi Rih".

Figure 2. The canal of the Inhulets River and panorama of man-made landscapes from the Burshchytsky dump (photographed by A. Orlova).

Figure 3. Panorama of Beleliubskyi bridge and the city from the Burshchytsky dump (photographed by V. Kazakov).

In the immediate vicinity of the dump there are several objects of industrial heritage: the ruins of surface facilities of underground mines No. 5 Nova and Valiavka-Pivdenna of the former Ilyich mine administration (built in the 1950s); open shafts of these mines that go as deep as 60 and 380 meters respectively.

Breathtaking is the panorama of the city from the height of the Burshchytskyi dump at night, when Kryvyi Rih turns into a constellation of lights.

Since 2014, the dump has been the all-season tourist attraction of numerous excursions at the daytime and at night.

Based on the above, it can be stated the territory of the Burshchytsky dump is diverse in nature and promining in terms of revitalization of this object and as a tourist attraction. In the study, an attempt is made to create the concept of the author project of the industrial and landscape park "VIDVAL". The project is aimed to build a creative area at the industrial heritage object in order to expand the range of leisure activities and improve the tourist image of the city.

This project is suggested for implementation in three stages: the first stage involves area beautification, creation of the most necessary infrastructure and basic non-capital-intensive leisure facilities; the second stage provides for a more fundamental modernization of the object with attraction of investments to create capital-intensive locations; the third stage involves filling this territory with creative trendy objects and holding various events regularly at this location.

Thus, at the first stage, it is planned to create a parking area at the foot of the dump in the place closest to the main road. It is appropriate to place the main monetized infrastructure nearby: catering facility, a stall for of selling souvenirs and renting equipment (they will be of a modular format initially), an information stand with the layout of the object.

Also, at this stage it is planned to:

- gravel and strengthen paths;

- build stairs in steep areas;
- mount several benches at the top and in the most panoramic places;
- create multiple selfie zones;
- create a rope adventure park on one of the dump slopes;
- build an alley of gabions with stones specific for Kryvyi Rih (one of the gabions will be in the form of a horn – the tourist logo of the city of Kryvyi Rih;
- create a food zone and a water equipment rental zone near the Inhulets River to provide the opportunity to run a boat, a kayak or catamaran;
- create a dirt – a specialized track for BMX or mountain bikes in the dirt jumping style on one of the slopes;
- install a sundial at the top of the dump in addition to observation points in order to create a certain brand and reveal the ideological concept of the project developers.

At the second stage, after the suggested industrial landscape park has become a specific attraction core for the city residents and tourists, it should be made as safe as possible to visit by arranging an underground walkway under the railway, and fence the railway track itself. Also, it is suggested to create a stationary administrative and information zone with free Wi-Fi and a medical center that will be located at the entrance; a stationary all-year catering facility, and a tent camp. On one of the slopes facing the railway, it is planned to install the letters VIDVAL and build a staircase and an observation point nearby. It is also possible to place an aerolift – a hot air balloon tied to the surface. This balloon can rise up 50-100 meters and it offers a magnificent panorama of the industrial city.

At the third stage, there are all relief and technological possibilities to build a funicular to connect the Burshchytsky dump with one of the two opposite dumps across the Inhulets River and arrange an indusrial-style soft play area.

In the future, this object can be used to organize a variety of events. In particular, in 2017, the city launched the festival "Night of Industrial Culture" (a similar festival is also held in Germany and Poland), which has transformed into IndustrialFEST in Kryvyi Rih. The venue for the festival has been one of the most pressing issues for the organizers. Creation of a thematic site for such events would solve this problem. The site location far from the main transport system and absence of a convenient access are the only obstacles. However, this problem can also be solved through additional investment in creating the access road and powerful promotion.

Besides, this object can be used for holding a variety of events: sports competitions, artistic plein airs, thematic festivals, wedding ceremonies, etc. In the process of promoting this object, it is reasonable to create thematic legends that will add to the brand of the location.

In general, entrance to the park is planned to be free, the leisure area and renting the territory for events are monetized.

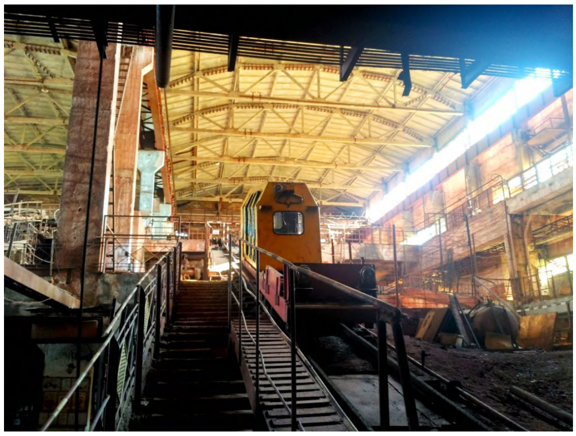
One of the city's closed underground mines may become another promising object for revitalization. However, implementation of such a project is much more capital intensive. In Kryvyi Rih, there are several promising objects for possible revitalization of underground mines: "Hihant Hlyboka", "Ventliatsiina V-4", "Peremoha" (all three are the former mine named after Dzerzhynskyi), "Pivnichna" and "Ventliatsiina No. 1", "Ventliatsiina No. 2", "Ventliatsiina No. 3" of the former mine named after Kirov, "Pershotravneva 1-2" and others. However, at the moment, in our opinion, the underground mine "Artem-2" could become the most successful project.

"Artem-2" is an underground mine for producing rich iron ores in Kryvyi Rih iron ore basin. It was part of the mine named after Kirov (figure 4). In the mid-1970s, the mine included 4 underground mines: "Artem-1", "Artem-2", "Klitiova named after Kirov", "Pivnichna"; the open pit "Pivdennyi", a crushing and sorting plant, a mechanicalrepair and other shops.

Figure 4. External view of the underground mine "Artem-2" (photographed by V. Kazakov).

"Artem-2" is unique, even within Kryvyi Rih because ore was transported on the daylight surface not by the traditional vertical skip mechanism, but by two belt conveyors installed in inclined (not vertical) shafts (figure 5). In addition to them, the deposit named after Kirov was also opened by a number of vertical shafts.

(*a*)



(*b*)

Figure 5. Internal view of the underground mine "Artem-2", (*a*) and (*b*) (photographed by V. Kazakov).

Since 2010, due to liquidation of the enterprise, "Artem-2" has been operating in the mode of retaining equipment and pumping out mine waters.

The authors have conducted a study and identified a number of prerequisites favorable for revitalization of "Artem-2" and development of the project "Industrial Culture Park "SHAKHTA" (the ICP "SHAKHTA").

(i) **Sufficient degree of preservation of the on-surface and underground structures of the industrial object**, including wide opportunities for their involvement in revitalization:

(a) Preserved mining equipment, subject to its restoration and filling with new mining artifacts, can become the basis for creating the Museum of Mining Equipment. This

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012082 doi:10.1088/1755-1315/1049/1/012082

museum can be equipped with various installations and modern exhibits: a 3-D model of the mine, stands with pictures of technological processes, sculptures from mining equipment spare parts, etc.

(b) The existing outdoor area (free courtyard) can become the basis for creating a skansen (exhibition) displaying rocks and minerals. It is expedient to form a promotion advertising and training career guidance center for young people by organizing various events on the basis of the created museum and the skansen ("SkillCity", "Geology Lecture Hall", "Mining Master Class", etc.).

(c) The mechanisms to go down and underground levels of "Artem-2", preserved in the good working condition, subject to careful preparation, can be used for implementing the main edutaining attraction of the ICP "SHAKHTA" – "Descending into the mine". Before descending, visitors are instructed on safety, and dressed in working suits of miners. During the descending, visitors get acquainted with the mine history and peculiarities of iron ore mining in Kryvyi Rih basin in different historical periods. The descending is supplemented by multimedia presentations located on both sides of the descending and brief stops on different levels.

At least one underground level can be prepared for visiting by tourists in order to illustrate the real process of underground iron ore mining with involvement of working equipment, etc. Interactive activities for tourists may include borehole-drilling, imitation of blasting, ore loading and transportation on the level to the conveyor. On other underground levels, there can be located exhibition halls, underground cafes, souvenir shops. Such an attraction tour will be a good alternative to visiting operating underground mines that are reluctant to receive tourists.

The maximum depth of descending for potential visitors is 550 meters.

(d) The on-surface facilities (buildings of the engine room and auxiliary shops) that are available on the territory can be distributed according to the functional content and used for exhibitions, forums, fairs, quests, seminars; partially equipped offices for craft manufacturers and small production complexes, photo studios, etc.

(e) The industrial site of "Artem-2" is functionally planned: a park area with a modern playground, a rope adventure park, a climbing center, an art installations site, etc.

(ii) **Favorable geographical position** "Artem-2" is located in the part of the city without well-developed edutaining complexes but with convenient access roads (Volodymyr Velykyi Street, Bykov Street, Ivan Avramenko Street, the city roundabout road). Within a 10-minute travel by car, there are large residential areas with potential visitors to the ICP "SHAKHTA" (Artem, microdistricts Skhidnyi I, II and III, Vechirnii Boulevard, microdistricts Yuvileinyi, Hirnytskyi, Soniachnyi, the 95th quarter area (Gorkyi Square)), as well as the malls "Metro" and "Epicentr".

Subject to sufficient landscaping and designing an open area, the following structures can be created in the future: artificial ponds and recreation areas near them, ecological paths for excursions to other places of interest.

(iii) **The object belonging to the PJSC "Tsentralnyi Mining and Processing Plant"** which is part of the structure of the international mining and metallurgical company "Metinvest". This is the most powerful holding structure in Ukraine that could invest in revitalization of this object by itself. In addition, such proposals in the format of a political program were articulated by one of the candidates during the mayoral elections.

The project of revitalizing the mine "Artem-2" and creating the ICP "SHAKHTA" is aimed to preserve identity and authenticity of the industrial object (the mine) by creating conditions for modern rethink of industrialization processes. The implementation of the project is possible subject to a flexible planning structure. To achieve the purpose, the following is proposed:

(a) Creation of locations on mining (historical) themes:
   1. The Museum of Mining Engineering and a skansen of rocks and minerals located outdoors;
   2. An exhibition hall for changing expositions (photos on industrial themes, art objects made of metal, etc.), a training geological laboratory placed in the premises of the on-surface facility on the first level;
   3. The attraction-excursion "Descending into the mine".
   The second level can host a free recreation area, divided into: a souvenir shop of the ICP "SHAKHTA", a hall "Free microphone", a café "Tormozok".

(b) Creation of post-industrial tourist locations:
   1. A tourist information center (TIC) and the branch of a children tourism center - on the first level;
   2. A rope adventure park; a climbing wall, a sports ground; a free art-zone and information stands on industrial tourism in Kryvyi Rih – in the yard.

(c) Creation of locations for small-scale and private functions (administration offices, tenants' offices in a separate room.

(d) Creation of an open space. The project provides for "soft" planning of the courtyard – we suggest preserving its function of the central space from where all buildings can be entered. It will be adapted for lectures, movie screening, performances, exhibitions, community meetings, hackathons, etc.
   Since the main territory of the ICP "SHAKHTA" is already planned and does not provide for parking (due to seasonality of mass events), parking is provided in the parking area of the mall "Metro" which is located opposite the mine area.

(e) Use of the ICP "SHAKHTA" as a location for development of event tourism: *Industrial FEST* (a festival of industrial culture that introduces diversity of industrial Kryvbas through demonstration of mining equipment, master classes, photo-exhibitions, etc.); *IndustrialWeek* (the Week of industrial culture that provides for preferential visits to attractions of the ICP "SHAKHTA", lectures by tourism activists, etc.); IRON BIKE (the international biker festival), etc.

The universality of the project consists in the fact that it can be both social and commercial; in general and partly, the project may comprise financing at the expense of the city budget funds, investments of individuals and funds; providing an opportunity to lease land to small and medium businesses with the purpose of commercial activities and tax collection to the city budget.

Currently, "Artem-2" revitalization project has no competitors within Dnipropetrovsk region and in Ukraine. Operation of the ICP "SHAKHTA" will ensure preservation of the industrial heritage of Kryvyi Rih and sustainable development of industrial tourism in the city. Visualisation of "Artem-2" revitalization model was performed by "Metinvest" in 2020 (figure 6). However, at the moment, there are no practical changes in implementation of this project.

In order to confirm or refute the need to revitalize industrial facilities as one of the factors of the city's cultural development and attract tourists, it is worthwhile to conduct additional analysis. We have chosen two methods: a SWOT analysis and a PEST analysis. The former characterises the object through characteristics of four main sides – "strengths", "weaknesses", "opportunities" and "threats". The latter allows conducting a marketing analysis to identify political, economic, social and technological aspects of the environmental impact.

The SWOT-analysis of possible revitalization potential of industrial facilities in Kryvyi Rih:

"S" – strengths

(i) The city has a rich industrial heritage and, accordingly, a large number of promising objects for revitalization.

Figure 6. Project of creating an interactive industrial museum and scientific and educational Experimentarium [20].

(ii) Possible objects to be revitalized are presented as engineering and architectural complexes of closed mines, factories and plants, as well as various man made landscapes.
(iii) There are no revitalized industrial objects in the city, so this niche is completely free.
(iv) In the city, there are very powerful and wealthy enterprises that can sponsor revitalization of certain industrial facilities, especially if these belong to their structures.
(v) The city authorities are interested in revitalizing both industrial and other purpose objects.

"W" – weaknesses

(i) Implementation of revitalization projects requires very significant financial allocations.
(ii) The management of powerful industrial enterprises do not consider it is expedient to invest in such projects.
(iii) Some promising objects are characterized by either an inconvenient remote location or, in particular like the Burshchytsky dump, they are located next to the solid domestic waste landfill.
(iv) The negative tourist image of the region.
(v) The negative environmental situation which affects adversely the desire to visit the city.
(vi) Lack of an established strategy for revitalization of abandoned industrial facilities.
(vii) Incompleteness, ambiguity and inconsistency of the current regulatory framework, which complicates the process of changing the ownership of certain land territories.
(viii) Lack of recreation culture among the local population.

"O" – opportunities

(i) Revitalized objects can become completely new attractions for the residents and visitors to the city.
(ii) Their creation can significantly intensify development of industrial tourism in Kryvyi Rih and, accordingly, increase tourist flows.

(iii) Revitalized objects can serve as a training ground for activation of small and medium businesses, as attracting visitors will contribute to additional opportunities for businesses to sell their own products.
(iv) Certain remoteness of revitalized objects from the populated part of the city will allow holding noisy events there (festivals, concerts, etc.).
(v) A high degree of attractiveness of these objects can raise investors' interest.
(vi) These projects envisage creation of completely new and creative locations, infrastructure facilities and attractions.
(vii) Eradication of the negative stereotype of Kryvyi Rih, which is figuratively called "Ukrainian Detroit".
(viii) Attraction of additional funds to the budget of the region; Creation of additional jobs.
(ix) Expansion of the network of tourist infrastructures; Increase in the volume of attraction of foreign investments.
(x) Preservation, development and popularization of industrial heritage monuments.

"T" – threats

(i) Since implementation of these projects is planned in several stages, there is a risk of not finalizing it, not advancing past initial stages.
(ii) The situation in the city and the country is not stable, so financial investments in creation of such large-scale projects bear significant risks associated with possible bankruptcy of executors and unprofitability of the leisure infrastructure today.
(iii) The situation with the owners of abandoned industrial facilities is not always transparent, which makes it impossible for third-party organizations to promote investments.
(iv) Restored mining equipment and available specific industrial orientation of attractions can cause injury if they are used improperly.
(v) According to the proposed projects, revitalization involves preservation of authentic industrial themes, life of local residents is oversaturated with this matter, so it may not find sufficient positive feedback and, accordingly, the demand for visiting the created facilities from local residents.

In order to identify how external factors will affect the process of revitalization and further operation of these objects, we have conducted a PEST analysis. According to its results, the following conclusions are highlighted.

In **the political aspect**, a special role is played by changes in power, in legislation, influence of power structures on industrial performance, etc. If we consider the direct influence on development of revitalization processes in the city, it should be noted that such organizations as Kryvyi Rih Foundation for the Future, Urban City, which develop various socially oriented projects, involve city activists in their development and help in implementation, are a positive factor. The opportunity for city residents to participate in open contests and competitions on the platform "Public Budget" to win funding for implementation of their projects creates favorable conditions for implementation of revitalization projects as well. In addition, some political candidates include revitalization projects in their election programs, which is also a favorable factor. Among the negative factors, one should note certain difficulties associated with obtaining ownership of or transferring the above-mentioned objects to the city fund in order to further conduct the processes of revitalization, renovation, reclamation, or complete reconstruction. In general, based on both the shortcomings and the advantages of political influence on this process, it should be noted that the political aspect can be considered favorable rather than unfavorable one.

In **the economic aspect**, it should first be noted that in the context of the global pandemic, any projects, especially related to the field of leisure and tourism, are in less demand. Funding is mostly aimed at development and maintenance of the medical sphere. That is why at present, the opening of new leisure facilities is not profitable, and their funding by the state and third-party investors is almost impossible due to current irrelevance of this area development. At the moment, external economic factors are unfavorable.

The analysis of **the social aspect** enables asserting that in general, residents of the city need new both cultural and leisure objects, which will lead to not only improvement of the city, but also new jobs, and small and medium businesses will have new opportunities to sell their own products. Unfortunately, this need is currently complicated by the pandemic situation in the world, permanent quarantine restrictions on leisure facilities functioning, and a decrease in the number of those wishing to visit crowded places. In addition, a significant proportion of the city's population are workers with not sufficiently established culture of leisure activities. Therefore, within the framework of the current epidemiological situation, the social aspect is rather unfavorable, but the end of the coronavirus epidemic could revive cultural life.

The analysis of **the technological aspect** enables stating that in general, the construction technologies available in the country and the possibility of installing certain infrastructure facilities are sufficient for implementing planned revitalization projects, since all projects have been planned within the framework of existing and real opportunities for attracting certain technologies. However, involvement of certain technologies will be regulated exclusively by the current budget allocations for revitalization of old industrial facilities. Therefore, this aspect should be determined as rather neutral.

Thus, analyzing the data of the two methods, it can be argued about the huge potential and opportunities of revitalization of the industrial heritage in Kryvyi Rih, but realization of this potential is restricted by a number of not quite favorable economic and social factors.

5. Conclusions

Revitalization of industrial facilities is now a trend in many leading countries. Ukraine has clearly focused on the European model of development and actively begun to implement the practice of giving "a second life" to both industrial facilities and urban complexes in general. Unfortunately, the most powerful industrial center of the country – Kryvyi Rih region – is not yet implementing such a positive practice, although it has a significant resource and potential for this.

Thus, the main tasks facing the city authorities in this context are:

- convincing the city community of the need and prospects for revitalization of industrial facilities, since the majority of residents have a low level of industrial culture and, accordingly, lack of awareness of this issue;
- involving leading industrial enterprises in cooperation and investment in industrial heritage objects, especially if these objects were operated by these enterprises or are in their zone of influence;
- encouraging investors from both Ukraine and abroad, in particular, by creating favorable tax conditions for investment and by submitting various proposals for various grant financing competitions;
- developing a step-by-step strategy for revitalization of Kryvyi Rih region industrial heritage, considering economic, social, cultural, tourist effects;
- combining efforts of small businesses engaged in tourism, organization of leisure and cultural events to develop a common algorithm of actions in the field of activating the cultural component and holding various events at those industrial heritage sites where it does not

require significant investments (the Burshchytskyi and the Petrovskyi dumps, damaged zones, remnants of the Chervonyi Bridge, flooded open pits, etc.);
- improving the city infrastructure.

Implementation of everything outlined will stimulate preservation and popularization of the industrial heritage, maintain authenticity of the urban cultural complex, form a culture of leisure activities among the population and a tolerant attitude to achievements of the industrial era of society development.

Emerged modern revitalized objects will become an additional tourist magnet and another important step to popularize industrial tourism, which the city is trying to intensively develop and which is identified as one of the priorities of its strategic development. All this, in turn, will contribute to stabilization of the socio-economic situation in the city and improvement of both its tourist and overall image.

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To cite this article: L V Kalashnikova *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012083

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012083 doi:10.1088/1755-1315/1049/1/012083

Evaluation of police activity as an indicator of public safety: the experience of empirical research in Ukraine

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Abstract. The ability of a society for sustainable development is determined by its ability to maintain and develop the parameters of life within the security corridor not least under the condition of continuous action of both internal and external factors. The connection between the activities of law enforcement agencies and the sustainability development of socio-territorial communities is obvious since the leading mission of the police is to prevent the constantly growing threats associated with various kinds of offenses. It is well known that the development of public opinion is an integral part of the rule of law and civil society. In the context of active reformation of law enforcement agencies, empirical sociological studies play the role of a measurer of efficiency, a barometer of public trust. The leading task of sociologists is to establish a two-way communication with the population whose security should be ensured by law enforcement officials. The article summarizes the experience of existing empirical sociological research of public opinion on the evaluation of the formation of a new methodology and methods of evaluating the effectiveness of the police. The authors of the article note that to date, considerable research experience has been accumulated, a base of empirical research has been formed to study the effectiveness of the national police, but there is still some methodological and methodological inconsistency. Researchers point to the appropriateness of using the in-depth interview method of the police officers themselves, conducting a focus group and expert evaluation.

1. Introduction

The ability of a society for sustainable development is determined by its ability to maintain and develop the parameters of life within the security corridor not least under the condition of continuous action of both internal and external factors. The connection between the activities of law enforcement agencies and the sustainability development of socio-territorial communities is obvious since the leading mission of the police is to prevent the constantly growing threats associated with various kinds of offenses. Accordingly, the possibility of increasing the efficiency of their activities using available methods and tools in particular public opinion will remove some of the obstacles to the country's sustainable development. That is why an important component of the analysis in this study is to determine the place and role of empirical sociological studies of public opinion regarding the assessment of the activities of law enforcement agencies as a leading indicator of the safety of life in society and a leading precondition for its sustainable development. Thus, the logical consistency of the implementation of research activities is based on determining the range of basic issues related to the need to involve the public in assessing the state of problems and prospects for reforming the national system of law enforcement agencies. There is also a need to substantiate possible ways to solve them, in particular, by defining the circle of the main informants and expanding the system of indicators for making indicative assessments within the framework of conducting mass public opinion polls.

Of course, in any country, region there are reasons for dissatisfaction with the activities of law enforcement agencies, which vary depending on the quality of the functioning of a given state social institution, as well as the state of legal awareness of representatives of the local community. The basic need for efficiently ensuring the safety of citizens' life, maintaining law and order in modern society is satisfied by the state, namely the institution of law enforcement agencies, in particular, the police. Of all the representatives of law enforcement agencies, the "closest" to ordinary citizens are the police officers with whom they most often come into contact. Therefore, oddly enough, most of them draw conclusions about the effectiveness of law enforcement agencies precisely taking into account their own experience of interacting with the police. In this sense, it is public opinion that influences the law enforcement system, first of all, by providing feedback. On the other hand, the persistent negative image of a police officer in the minds of most citizens, characterized by a certain set of moral and business characteristics, significantly complicates professional selection. After all, most worthy representatives of this profession refuse to work in the system, taking into account their own principles and ambitions. No less significant is the fact that the negative attitude and distrust of citizens towards representatives of the law enforcement system negatively affects the desire to cooperate with them, making it difficult to insure the protection of law and order, crime detection, and the like. Also, non-compliance with laws on the part of law enforcement officers themselves destroys the rule of law and the legal consciousness of citizens, thereby threatening public safety and law and order in general. It is well known that the development of public opinion is an integral part of the rule of law and civil society. In the context of active reformation of law enforcement agencies, empirical sociological studies play the role of a measurer of efficiency, a barometer of public trust. The leading task of sociologists is to establish a two-way communication with the population whose security should be ensured by law enforcement officials.

2. Materials and methods

This study involved the use of a mixed methodology, that is, a combination of general scientific and special methods, the choice of which was determined by the purpose and objectives of this scientific work. In particular, the work used the method of systematization, traditional and critical analysis to summarize the experience of conducting sociological studies of the effectiveness of the police. To identify the problems of methodology and methodology for evaluating the activities of the police through the study of public opinion, special sociological methods were used, namely the method of secondary analysis of the results of surveys conducted by the European Social Survey, the Institute of Sociology of the National Academy of Sciences of Ukraine, the Razumkov Center, the Sociological Group "Rating", TNS Ukraine, Kharkov Institute of Social Research and other research organizations in the period 1994-2021. The use of the scenario planning method made it possible to formulate practical recommendations for changing the strategy for conducting monitoring public opinion polls regarding the effectiveness of the police in the realities of Ukraine.

3. Stages of development of the methodology and methodology for studying the level of public confidence in the police

Studying the experience of monitoring public opinion on the evaluation of law enforcement agencies, a number of researchers (A. Bova [1], D. Kobzin, A. Chernousov, R. Sheiko, S. Shcherban [2,3], Y. Krapivin [4] and others) state that there are certain difficulties in forming a national system of evaluation. Basic works devoted to the study of the reliability and validity of methods for assessing public opinion regarding the effectiveness of police work and trust in it are practically absent in the sociological literature. Separate attempts in this direction were made by J. Engel [5], J. Jackson and J. Sunshine [6], E. Maguire and D. Johnson [7], B. Bradford [8], J. Zhao, C. Tsai, L. Ren and Y. Lai [9], S. Morgan, D. Murphy, B. Horwitz [10], C. Mills, A. Kwon, K. Brown [11], who tested European measures of trust in law enforcement, consulted with police stakeholders to identify and test factors that may affect their policing performance.

The norm enshrined in the law of Ukraine "On National Police" is rather declarative. At present, neither the state nor the society has the proper tools to evaluate the effectiveness of law enforcement agencies, and the police themselves do not understand exactly what should be changed to increase the level of public trust in them. In this sense, public does not control their activity.

A multidimensional approach to measuring police performance involves conducting public opinion polls using two types of questions for respondents: direct (about victim experience and real help from the police) and indirect (about trust in the police and satisfaction with their work in general). Accordingly, standardization, consistency and clarity of wording of the questions allow for comparative studies. The purpose of this article is to review and critically evaluate current survey methods used to measure policing performance in common law jurisdictions. In particular, the public opinion polls that were conducted in Ukraine and other countries are analyzed in order to develop practical recommendations for improving the quality of the methodology and methodology for conducting such monitoring polls.

The prerequisites for the formation of a methodology and methodology for assessing the effectiveness of police activities were laid down in the works of the American scientist A. Bellman, who developed a scale for rating police organizations in accordance with standards, a method of survey and measurement of citizens' assessment of police activities [12].

The first experiments with alternative methods of evaluating the police effectiveness were conducted by American sociologists in the 1960s. Thus, in 1966, the Center for Public Opinion Research at the University of Chicago, on behalf of the Presidential Commission on Law Enforcement and Management, conducted a survey of 10,000 families determining the level of their victimization [13]. Since 1972, the US Bureau of Legal Statistics has conducted national surveys of crime victims twice a year, with a representative sample of 49,000 families. Widespread use of opinion polls in the US and European countries dates back to the 1980s. It was determined by the sharp surge in crime and the need to counteract it by intensifying cooperation with the population [4].

One of the most famous studies of public attitudes towards the police is the work of S. Decker, who attempted to analyze the impact of individual and contextual variables (race, socio-economic status, place of residence of citizens, crime rate, etc.) on the attitude of the public towards the police and its employees [14].

In 1982, a Crime Prevention Unit was set up in the United Kingdom. It developed a number of projects, including the Neighborhood Observation Program (1983), the establishment of advisory committees (1984), the Safe Cities Volunteer Units (1986). Since 1982, there have been regular surveys of respondents (British Crime Survey) at the place of residence using a methodology that identifies the variety of crimes faced by people during the year, the level of community satisfaction with police work, the nature and extent of cooperation with local authorities, the number of antisocial manifestations, incidents of violence, road accidents, etc. [4].

In the 1990s, the innovative information system Compstat was introduced in New York. It regularly provides information on recorded crimes and offenses. Since 2016 Compstat 2.0 has been available to all police officers via smartphones. In parallel, the On-Line Complaint System operates to record complaints of victims. Alternative sources of information include results of surveys of the population, including police officers and persons who have directly contacted them [13].

In the late 1990s, a successful American experience of "community policing" was actively introduced in France, Sweden. In Germany, a police-private-partnership program has been operating as a corps of voluntary police assistants since 2000. According to the German authorities, the closer cooperation of the population with the police through the formation of voluntary units, the increased visible presence of law enforcement, the higher level of trust in them [13].

Since 1987, the United Nations Inter-regional Crime and Justice Research Institute (UNICJRI) has launched an international Crime Victims Survey in more than 80 countries around the world [12]. Since 1997 Ukraine has participated in it. A separate European Survey on Crime and Safety is being conducted in the European Union [15].

In Poland, by 2006, a similar, objective (quantitative-statistical) system of performance appraisal had been in operation. From 2007 the best practices of the United Kingdom, Norway, the Netherlands, France and Germany have begun to be implemented. In particular, external (public opinion polls in the areas served by territorial police units) and internal (clarifying police evaluations) sociological surveys are conducted [4].

According to A. Kiselev an integral part of implementing the doctrine "police in the service of a society" in the US and European countries was the audit of law enforcement agencies. It allowed to deploy a large-scale PR company aimed at increasing public confidence in the police [15]. This, in turn, according to S. Korablev, has led to the need to change the directions of vocational training in police academies. It happened since programs of social and psychological training of police officers for effective communication with different categories of the population actively introduced [16].

Governmental structures of the US and European countries sought to make the most effective transition from a repressive model of law enforcement to a socially oriented one to ensure public order, taking into account the peculiarities of historical experience and sociocultural differences. Such innovations have resulted in a change in the social status of police officers, an increase in the level of trust in them as an indicator of legal integration of citizens. It is expressed in the desire to comply with the law, to participate in law enforcement, freelance cooperation with police, creation of initiative groups, etc.

Mass studies on victimization in the USSR were not conducted. In the USSR during 1970-1990 only episodic, mostly closed sociological surveys were carried out. In 1990-1991 State Statistics Committee and Scientific Center of Management and Sociology, which operated at the Academy of the Ministry of Internal Affairs of the USSR conducted the first poll on the effectiveness of law-enforcement bodies. In Ukraine, there have been only a few attempts to carry out such research, mostly to determine the level of victimization of the society, trust in law enforcement agencies. They were implemented mainly within the framework of powerful international research projects.

Trends in the development of methodology and methods for assessing the effectiveness of police activities are determined by the intensification of research aimed at identifying the level of victimization of society, studying the problem of crime prevention, which are of immediate practical importance. Historically, the development of theoretical provisions provides for the allocation of three stages:

1) 1940-50s The first attempts of empirical sociological research of public opinion to assess the effectiveness of police activities, the study of the emergence of victimology as an independent

area of criminology;

2) 1960-70s systematization of empirical public opinion polls, victimological research, development of theoretical research and development of programs to provide assistance to victims of crime and compensation for harm caused to them;

3) 1980s to the present – active involvement of the public in the process of reforming the law enforcement system at all levels, institutionalization of public control over the activities of police officers, the stage of practical implementation of victimological research, institutionalization of the protection of victims interests, international cooperation in order to prevent the victimization of society.

4. Experience in conducting empirical research in Ukraine

Since 1994 the Institute of Sociology of NASU has conducted annual nationwide polls, some questions on the victimization of Ukrainian society, as well as the trust in law enforcement agencies. The results showed a low level of trust in law enforcement bodies. From 1994 to 2004, the respondents from the social groups that play a significant role in the life of Ukrainian society gave priority to the mafia and representatives of the criminal world. Crime ranked third after unemployment, rising prices and hunger in the rating of Ukrainians' fears. The level of trust (the total number of respondents who gave a positive answer ("I fully trust", "rather trust") to the question "Do you trust the police?") remained almost unchanged during 1994-2005, varying from 10,7% to 14,2%, compared to 7,0% in 2013 [17].

Within the framework of the common European monitoring project "European Social Survey" during 2005-2011 experts from the Institute of Sociology of NASU realized four waves of the nationwide poll. In the section entitled "Law, Morality, Religion" respondents were asked to express their opinion on trust in the country's judicial and legal system, assessing it as a 10-point system (respectively, 0 – "do not trust at all", 10 – "completely trust"). As a result, it was determined that the average score in Ukraine in 2005 was 3,91, in 2007 – 2,45, in 2009 – 1,91, in 2011 – 2,26. Similarly, the average indicator of trust in the police in 2005 was 3,30, in 2007 – 2,61, in 2009 – 2,27, in 2011 – 2,50. Almost one in five respondents (17,5%) in 2005, one in seven (13,8%) in 2011 were victims of robbery or physical abuse in the last 5 years. In the dark period of the day, 44,3% of the respondents felt danger in 2005, compared to 49,9% in 2011 [18].

Comparing the average indicators of trust in the police in different countries, presented in table 1 [18], let us designate that this indicator is the highest in Finland, Denmark and Norway, but the lowest in Russia and Ukraine.

Taking into account the numerical indicators of the existing level of victimization (see table 2 [18]), it cannot be argued that there is a functional inverse relationship between the level of trust in the police and the level of victimization, and then crime.

After all, a high level of victimization does not always correspond to a low level of trust in the police, or vice versa. In this sense, in order to determine the pattern, the level of trust in the police should be determined by posing this question to those respondents (victims) who had direct experience of communicating with them. Such a survey model will allow assessing the level of trust, using the thoughts of real informants, taking into account the level of their willingness to seek help again.

During 2000-2004, the Razumkov Center conducted a survey of public opinion on trust in law enforcement agencies, during which 2,000 respondents were interviewed in all regions of the country. This survey was carried out every two years. According to the results of the last research (April 2004), 14,2% of the respondents rated the activity of Ukrainian law enforcement officers as "very bad", 32,4% – "bad", 40,9% – "satisfactory", 7,9% – "good", 1,1% – "excellent". Among the reasons for dissatisfaction with the activities of law enforcement agencies, respondents indicated a low level of their morality and culture, merger of law

Table 1. The average indicator of public confidence in the police.

Country / Year	2005	2007	2009	2011
Austria	6.18	6.30	-	-
Belgium	5.78	5.94	5.96	6.01
Bulgaria	-	3.89	3.29	3.85
United Kingdom	6.12	6.00	6.24	6.24
Greece	6.03	-	4.88	4.63
Denmark	7.94	7.83	7.58	7.68
Estonia	5.69	5.54	6.05	6.17
Israel	-	-	4.76	4.80
Ireland	6.59	6.15	-6.51	
Spain	5.91	6.04	6.10	6.25
Cyprus	-	5.63	5.94	5.46
Latvia	-	4.20	4.61	-
Luxembourg	6.47	-	-	-
Netherlands	5.97	6.18	6.34	6.26
Germany	6.48	6.63	6.85	6.86
Norway	7.13	7.16	7.04	7.20
Poland	4.58	5.01	5.12	5.39
Russia	-	3.38	3.70	3.53
Romania	-	4.56	4.36	-
Slovakia	4.35	4.71	4.80	4.49
Slovenia	4.71	5.01	5.05	4.99
Turkey	-	-	6.51	-
Hungary	5.17	5.12	4.30	5.10
Ukraine	3.30	2.61	2.27	2.50
Finland	7.96	8.05	7.99	8.03
France	5.66	5.71	5.78	5.64
Croatia	-	-	4.37	4.40
Czech Republic	4.23	-	4.81	4.91
Switzerland	6.86	6.93	6.85	7.03
Sweden	6.49	6.54	6.55	6.98

enforcement agencies with criminal structures, low level of funding, insufficient level of vocational education, technical insecurity, commercialization of law enforcement structures, and lack of public control. Ukrainians considered corruption as the leading determinant of negative attitude towards law enforcement agencies [19].

The Razumkov Center carried out the project “Ukrainian Police through the Eyes of Citizens: Assessments of the State, Problems and Prospects for Reforms” during August 2012 – March 2015. The results determined a decrease in public confidence in the police from 30,2% to 24,6% of respondents. Citizens trusted more local law enforcement agencies with whom they are in direct contact. Regarding the forms of public participation, it should be noted that 23,4% of the respondents are not ready to assist the police in any circumstances. It shows again low efficiency of law enforcement activities. Over the past year, 20,0% of the respondents had direct contact with law enforcement officials. An indirect criterion of law enforcement effectiveness is people’ fear for their own life. Thus, 41,8% of respondents feel threatened to become a victim of

Table 2. Distribution of positive answers of respondents to the question "Have you or your family members been victims of robbery or physical violence in the last 5 years?", % of the total respondents.

Country / Year	2005	2007	2009	2011
Austria	10.9	9.3	-	-
Belgium	26.9	25.0	24.1	21.7
Bulgaria	-	21.7	15.2	15.8
United Kingdom	25.7	24.1	26.4	20.3
Greece	18.9	-	16.3	19.9
Denmark	26.8	24.9	22.8	24.0
Estonia	26.1	24.8	25.1	22.5
Israel	-	-	14.0	10.0
Ireland	24.7	-	-	-
Spain	26.5	20.1	21.0	23.4
Cyprus	-	6.4	5.5	11.2
Latvia	-	12.1	18.6	-
Luxembourg	24.9	-	-	-
Netherlands	18.9	18.4	20.2	18.0
Germany	10.8	9.6	9.2	9.5
Norway	24.8	22.0	20.2	18.6
Poland	21.3	17.9	14.1	10.6
Russia	-	21.8	15.7	14.4
Romania	-	15.2	10.9	-
Slovakia	14.9	14.6	9.6	11.9
Slovenia	11.8	13.5	11.4	9.2
Turkey	-	-	7.1	-
Hungary	20.2	14.4	11.8	13.8
Ukraine	17.5	14.0	14.3	13.8
Finland	32.1	29.0	27.4	27.1
France	27.4	26.1	25.9	21.6
Croatia	-	-	5.9	4.6
Czech Republic	18.9	-	11.7	11.5
Switzerland	18.0	18.2	15.9	16.1
Sweden	27.0	24.7	24.2	25.3

an insult in a public place, 37,6% fear road accidents, 36,9% – fraud, 32,9% – robbery, 32,0% – physical violence. In parallel with the mentioned research, expert evaluation and interrogation of law enforcement officers were carried out. Significantly alarming is the fact that 28,0% of the polled police officers have acknowledged the existence of corruption in law enforcement agencies. They also note that the reason for the low level of their activity efficiency is the lack of adequate material and technical support, overtime employment, low salary. While identifying priority forms of public control, 54,6% of polled law enforcement officers and 72% of experts preferred public opinion polls [20].

In December 2011, the Sociological group "Rating" conducted a nationwide survey on trust in law enforcement agencies, internal security issues, and public preparedness to cooperate with police. The data obtained indicate a low level of trust in all law enforcement agencies by

Ukrainians. Responding to the question “To what extent do you think such law enforcement and judicial authorities in Ukraine deserve credibility ...?”, more than a third (33,9%) of the respondents said that none of these institutions is credible. Ukrainian population trust more the local police than the national one. The confidence indicator in the East and South of the country is significantly lower than in the West and in the Center. It is significantly higher in the village than in the city. Among the problems which obstruct the police to perform their functions effectively, the respondents noted the corruption in law enforcement agencies, mistrust of the population, low level of morality of police officers, dependence on high-ranking officials and politicians, etc. Concerning forms of public participation, only 14,0% of the respondents said they would assist police officers in all circumstances. While the vast majority (54,0%) are prepared to take active action only in the absence of a threat to their own lives or their relatives’ interests, which is again a consequence of distrust of law enforcement officers [21].

From January 2016 to September 2019, the Sociological group “Rating” with the support of the Center for Analysis and Sociological Research at the International Republican Institute conducted five waves of a nationwide municipal survey in 24 regional centres of Ukraine. Among a number of measured indicators were determined indicators of a sense of security in the city, approval of the activities of law enforcement agencies. On average 21.5% feel at risk after dark in the area of residence. According to evaluative judgments of Ukrainians, the five most dangerous regional centers of Ukraine include Kherson, Kropyvnytskyi, Zaporizhzhia, Poltava, Kyiv. The whole Western region of the country is relatively safe. Regarding police activity, the average index of its approval ranged from 1,7 to 1,0 (where 0 is “completely disapprove”, 3 is “completely approve”). This indicator is the highest for residents of Mariupol, the lowest – for residents of Odesa and Kyiv. An almost similar situation is observed with regard to the evaluation of the activities of courts, prosecutors, security services of Ukraine [22].

In 2012, the Kharkiv Institute for Social Research with the financial support of the International Renaissance Foundation conducted a nationwide survey of 15,000 people over the age of 16. The data obtained showed that only a quarter of respondents (25,2%) considered police activity effective. The level of fear of being a victim of a crime is quite high and is characteristic of more than two-thirds (64,6%) of Ukrainians. Only 6,0% of the respondents experienced similar situations last year. Not all respondents contact law enforcement agencies as needed, as 72,7% of them do not believe in police effectiveness [23].

Talking about domestic experience of studying trust in law enforcement agencies and a sense of personal security, it would be advisable to analyze existing regional surveys in addition to these national studies.

According to D. Kobzin, the first experience of introducing regional public surveys on the effectiveness of police activity was dated 2003. The staff of the National University of Internal Affairs conducted interviews with the population of two district departments of Kharkiv region [24].

In 2010, the first comprehensive regional survey was conducted in Kharkiv on law enforcement issues using a structured interview method at the place of residence (2,000 respondents were interviewed) and a focus group with police officers, law enforcement agencies and local media. The data obtained allowed us to conclude on the level of personal safety of the locals (35,0% of the respondents are afraid of becoming a victim of crime at their place of residence). The most dangerous places in Kharkiv are public transport and large crowds. The majority (68,0%) of those who were victims of crime (6.0%) and sought help from law enforcement agencies are satisfied with their activities. Among the leading deficiencies in the work of the police, 45,6% of the respondents identified their corruption. Nearly one-third (27,3%) of Kharkiv respondents are ready to assist the police in any situation [24].

During 2013-2017 in Kharkiv and Kharkiv region, with two-year intervals, three waves of public opinion polling were conducted by the specialists of the research laboratory on crime counteraction at Kharkiv National University of Internal Affairs together with the Main Directorate of the National Police in Kharkiv region with the financial support of the European Union Advisory Mission. The results assessed the subjective perception of the crime rate in the region. In particular, these indicators in 2013 reached high and average levels of 8,2% and 45,9% of the respondents respectively, while in 2017 there was a significant deterioration of the situation – 19,0% and 55,6%. Almost two-thirds of the respondents felt anxiety and fear about it. The average score for evaluating the effectiveness of local police in 2013 was 0,07 in the city and 0,17 in the oblast (from –1 – "very bad", +1 – "excellent"), in 2017 – 0,22 and 0.23. Instead, the index of confidence in local police in 2013 was 0,17 in the city and 0,28 in the region (from –1 to "completely distrust", +1 to "completely trust"), in 2017 – 0,30 and 0,29, respectively. In 2013, 11,4% had direct contacts with police (appealed for help during the last year) and 44.3% of whom were satisfied with their work; in 2017 – 22,1%, and 46,3% of whom consider this experience a positive one [25].

In September 2016 and January-March 2017, TNS Ukraine conducted two waves of research in 12 cities of Ukraine as part of a pilot project on cooperation between people and police (Kramatorsk, Sloviansk, Mariupol, Sievierodonetsk, Rubizhne, Lysychansk, Kropyvnytskyi, Vinnytsia, Chernihiv, Ivano-Frankivsk, Uzhhorod, Mukachevo) [26]. During 2016, experts from the Expert Center for Human Rights, with the support of the International Renaissance Foundation's Human Rights and Justice Program, conducted a sociological survey on security and community-based policing in Bar, Vinnytsia [27, 28]. In 2017, the Chernihiv Civic Committee for the Protection of Human Rights, with the support of the International Renaissance Foundation, conducted a public opinion poll "Safe Chernihiv". The list of social indicators measured during the survey: the level of satisfaction with the local police, the level of credibility in local police activity, changes in police activity over the past year, community readiness to assist the police, etc. [29].

As we can see, the analyzed data testify to the persistent negative attitude of the public towards the police officers. The reason is that problems are constantly identified, discussed, but not solved. The problems are corruption, abuse of power, use of authority for personal purposes, low level of communication culture, immorality, lack of a proper level of vocational education, aggressive behavior towards citizens, etc.

Determining the current problems of evaluating the effectiveness of law enforcement agencies, as a result of the planned system of crime detection in the Soviet system, there is still a "chase" to positive indicators today Therefore, even in the face of a worsening crime situation, law enforcement officers report a relatively stable percentage of case investigations, and consequently, corruption, abuse of authority and other illegal actions among police officers who are "programmed" to succeed in crime fighting. Overt fears to get negative public opinion led to the fact that the Ministry of Internal Affairs of Ukraine tried to assess their activity by conducting research by specialists of public relations departments who lacked the proper methodology. While most opinion polls conducted by international or national research agencies contain questions about crime rates, citizens' concern to become a victim of crime. These are some of the leading indicators of law enforcement activity. Unfortunately, during the introduction of the experience of such surveys, the Ministry of Internal Affairs of Ukraine ignored the data obtained and the most important aspects of their effectiveness – independence and objectivity.

The situation was changed with the departmental reform which involves the introduction of public control, in particular by means of conducting opinion national and regional polls by independent sociological services. Namely, in order to determine the level of trust, a mechanism was developed, approved by the Resolution of the Cabinet of Ministers of Ukraine of February 7, 2018 No. 58 "On approval of the Procedure for assessing the level of public confidence in the National Police". Regarding the analysis of the results of recent research in this area, they are quite contradictory, primarily given the method of assessing the level of confidence used.

During November-December 2018, a nationwide public opinion poll "Assessment of National Police Activities" was conducted. 19,5 thousand respondents participated in it. According to the survey, it was determined that Ukrainians are most afraid of becoming victim of road accidents (71,9%), theft (62,2%), robbery (57,3%), and physical violence (55,8%). 33,7% and 29,5% of respondents respectively consider the work of local and national police as generally satisfactory. The lowest scores were given to the effectiveness of police activity in Kyiv, Kherson and Dnipropetrovsk regions. Over the past year, 14.3% of informants had experience of direct communication with the police. 40,4% of respondents trust the modern national police, 11,9% trust prosecutors, 10,3% – judicial authorities, and 18,1% – Security Service of Ukraine. 36,3% of the respondents expressed their willingness to assist police officers in any situation. Among the main disadvantages in the work of the police, respondents identified the lack of professionalism, corruption, inaction, unwillingness to protect ordinary people. 10,2% of Ukrainians became the direct victims of crime last year. Among reasons for not reporting crimes to the police was distrust [3]. The study conducted is more informative than past experience. In particular, some indicators were studied for the first time. Namely, it is a thorough analysis of work with victims of crime. The following information was determined: type of crime, the amount of material loss, reasons for not reporting to the police, methods of a message, assessment of the speed of the statement acceptance, the quality of informing the victim about the progress of the investigation, etc.

Table 3. Distribution of respondents' answers to the question "How much do you trust the police?", % of the total number of respondents.

Country/ Level of trust	Trust completely	Trust somewhat	Do not trust very much	Do not trust at all
Greece	20.0	51.1	22.7	6.2
Germany	24.2	62.6	11.6	1.7
Russia	12.1	39.6	30.2	8.1
Romania	14.4	34.4	32.6	18.6
Turkey	38.4	45.9	11.6	4.2
Ukraine	4.2	34.7	37.6	23.6

According to the World Values Survey 2017-2020 (see table 3, 4 [30]), despite the active reforms of the law enforcement system in Ukraine, which have been implemented over the past 5 years, the situation has hardly changed. Only 36.9% of Ukrainian respondents trust the police, this indicator is the lowest in comparison with other countries, despite the fact that the number of respondents who feel safe is significantly greater and is 76,7%. Consequently, the question arises about the content of the term "safety" among representatives of different countries, as well as the correspondence of the subjective assessment of the level of life safety to its real objective meaning. Equally important is the place and role of the police in its fencing, taking into account the value judgments of the respondents themselves.

For the first time after the signing of the Resolution of the Cabinet of Ministers of Ukraine dated February 7, 2018 No. 58, Forservice UA Sales LLC, which won the tender announced by the National Police of Ukraine, conducted a nationwide public opinion poll in November 2020 (N = 15000 Ukrainian over 18 years old, all regions of Ukraine are covered, with the exception of the temporarily occupied territories) [31]. The first question that arises relates to the competence of the specialists who were involved in this study. After all, this organization does not have an

Table 4. Distribution of respondents' answers to the question "Could you tell me how secure do you feel these days?", % of the total number of respondents.

Country/Level of security	Very secure	Quite secure	Not very secure	Not at all secure
Greece	14.1	44.3	28.2	13.5
Germany	27.5	58.7	13.0	0.7
Russia	12.1	54.3	30.0	3.7
Romania	36.2	50.3	11.0	2.4
Turkey	8.5	68.0	20.5	3.0
Ukraine	16.6	60.1	20.8	2.5

official website or a page on social networks, where one could get acquainted with the statutory documents, organizational structure, the main results of earlier studies. In academic circles, no information has been found about this research agency either.

The methodology for assessing the level of trust in the police, which was used, also raises doubts, since it is not possible to assess the validity of the trust scale without presenting the research instruments. According to the results of the study, it was found that the level of trust in the national police is 40,8%. However, the researchers did not determine to what extent the interviewed Ukrainians trust the police? It was also noted that the highest is the level of trust in the police in the Zakarpattia, Kharkov, Nikolaev, Donetsk and Poltava regions. But the work of police officers in Zhytomyr, Odessa, Dnepropetrovsk and Zaporozhye regions was recognized as "ineffective". Kiev. But was the representativeness of the sample population of respondents ensured by regions, too?

Since only short press releases based on the results of the study were made public, and the promised detailed report was not presented on the official website of the National Police of Ukraine, it is incorrect to compare by any parameters of sociological measurement. And how all the procedural components were met, however, it is too early to talk about the effectiveness of such work. In May 2021, the Ilko Kucheriv Democratic Initiatives Foundation conducted a public opinion poll (N = 2020 people over 18 in all regions of Ukraine with the exception of the Autonomous Republic of Crimea and the occupied Donetsk and Luhansk regions). The analysis of the results obtained allowed us to conclude that the level of Ukrainian confidence in the police does not exceed 31.0%. The better the financial situation of the respondents, the higher the trust in law enforcement agencies. Assessing the state of security and public order, the most pessimistic about this are residents of cities with a population of one million and urban-type settlements, respondents from the southern regions of Ukraine. Also, respondents from the largest cities often complain about the deterioration of security and public order in their communities and near their homes. The situation has changed somewhat under quarantine conditions. In particular, the respondents noted an increase in the crime rate [32].

5. Conclusions and discussion

Systematization and comprehensive analysis of published studies, as well as methodological literature in the field of studying the effectiveness of police work using surveys, led to the conclusion that, considerable research experience has been accumulated, a base of empirical research to study the effectiveness of national police activity has been formed but still remains some methodological inconsistency. Most of the questions are of a direct nature, so the possibility of avoiding socially unacceptable questions for the respondents is not excluded. In addition, the study of problems is superficial. Most of the polls only state dissatisfaction with the police, but it does not identify the causes and factors that lead to such a situation in society. Therefore, it can not be used to develop and implement specific management decisions.

An analysis of the available scientific research has led to the conclusion that the study of value judgments of citizens about the activities of the police and the assessment of the trust of its employees are extremely complex theoretical models that take into account various combinations of variables. Now in foreign studies, attention is focused on such social characteristics as place of residence and income level, age, gender, race, income level, education, etc. There is still no consensus as to which combinations of variables explain the greatest deviations. But in domestic empirical sociological studies, only the causal relationship between indicators of trust in the activities of police officers and the place of residence, gender and age of respondents is analyzed rather narrowly.

It should also be noted that the formation of a subjective attitude towards the police is an extremely complex process, determined, first of all, by the experience of direct communication and the peculiarities of the conceptualization of police activities in general.

Most of the analyzed studies measure five main groups of social indicators:

1) security of life (subjective perception of crime rate, its dynamics; anxiety level, including fear of becoming a victim of crime, etc.);

2) evaluation of law enforcement agencies effectiveness (subjective perception of the success of specific tasks assigned to them, approval of work);

3) trust in law enforcement agencies;

4) interaction with police officers;

5) problems of law enforcement at the community level.

The above list is necessary but not sufficient. When evaluating the performance of the police, it is necessary to take into account both direct and indirect indicators. Direct measures of police performance can be compared with official statistics on crime rates, number of arrests and fines, clearance rates, and response times to support calls. At the same time, some indirect indicators of the work of the police should include not only surveys, but also direct observation of social behavior, situational reactions of respondents, which the researcher can record during the survey.

Indirect questions provide a generalized assessment of the performance of the police, allowing you to assess the overall level of satisfaction with the police, without highlighting specific information about what citizens like / dislike about police services. Through these questions, it is impossible to identify what exactly the respondents are dissatisfied with. Other methodological problems are associated with non-standard, inconsistent wording of questions and categories of answers, which makes it impossible to conduct comparative studies. No less important is the problem of categorizing the concepts of "trust" and "satisfaction" used in various studies measuring public sentiment.

In Ukraine, only one national survey conducted by the Institute of Sociology of the National Academy of Sciences covers the period 1994-2021 and asks six questions about police work. This is the only source of indicators of the work of the public opinion police, which is comparable over time, in different regions of Ukraine. Most police services conduct their own annual or biennial opinion polls, which include many general and specific questions about policing. However, the questions, as a rule, are not standardized, inconsistent, with different categories of answers, which makes them incomparable both in time and in the context of different regions of the country. More research is needed to test the validity and reliability of the methods used to assess the effectiveness of police performance, or the creation of new standardized questions, in order to improve the measurement of public satisfaction with the services provided by the police in Ukraine. In the absence of credible, reliable and standardized metrics, police services and politicians will continue to ask different, sometimes vague questions that are not comparable. This inconsistent measurement can lead to misjudgment of the performance or policies and practices of policing across Ukraine. In our opinion, important indicators are:

expectations of the population regarding the work of police officers, the level of legal protection of police officers, access to sources of information about their activities, awareness of police departments work, evaluation of the effectiveness of appeals. Speaking about the possible objects of empirical sociological research, we point out the expediency of conducting surveys among both ordinary citizens and groups of individuals who had direct experience of communication with law enforcement representatives. It would be appropriate to use the in-depth interview method with police officers, focus group or expert evaluation. By the way, the experts involved in the study could be divided into dependent (internal, directly related to the work of the department) and independent (external, non-departmental), etc.

It is also important to recognize that the sociological data on police activities obtained during monitoring studies should be an informative basis for outlining the range of major problems and developing effective mechanisms to solve them. In this sense, the development of external relations system at law enforcement agencies should be aimed at optimizing the police with other institutions in order to achieve the sole purpose – ensure the safety of society.

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To cite this article: N O Andrusiak *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1049** 012084

Assessment of ecological and economic competitiveness of regions using factor analysis

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Abstract. The article examines the assessment of ecological and economic competitiveness of regions using factor analysis. Ecological and economic competitiveness of the territory is formed from groups of components, some of which will determine its basic potential, others - the potential of possible development trajectories. The ratio of these components is different for each region and in each period of time when competitiveness is determined. Ecological and economic competitiveness of the region is determined by the ratio of several areas that interact and interdependent: social, economic, environmental. It is proposed to introduce the amount of atmospheric rent into the indicators of assessing the competitiveness of regions. Atmospheric rent is a fiscal lever of influence and a stimulus for the formation of ecological and economic competitiveness of the region. The factor analysis confirmed that the value of atmospheric rent is a significant indicator that belongs to the first, most important group of indicators, and therefore should be taken into account when conducting environmental and economic assessment. To study the ecological and economic competitiveness, there were built two models and compared by the results modeling. The most accurate model turned out to be additive, which is explained by a more balanced consideration of the load of indicators and the share of explained variation of data by each of the factors. The assessment of ecological and economic competitiveness was carried out on the example of regions of Ukraine and the ranks of these regions were determined.

1. Introduction

The current stage of development of the regional economy both in the world and in Ukraine requires active research by scientists. This is primarily due to increased interregional, national and global competition. Recently, the vector of development of economic systems is focused on the environmental component. This contributes to the formation of a new type of regional competitiveness. The importance of the environmental component of competitiveness can be proven by the results of real environmental disasters, when the importance of all other major and related subsystems was eliminated. Ecological and economic competitiveness of regions is a consequence of sustainable development of the world economic system. Therefore, there is an urgent need to increase the economic and social efficiency of market transformation, taking into account changes in the level of development of innovation, production and economic potential of the regions and compliance with modern environmental and economic challenges. Thus, increasing the ecological and economic competitiveness of regions is of renewed importance, related to adjusting the priorities of regional economy management, supporting small and medium-sized businesses due to decentralization of the economy, and forming and developing a new market architecture that is informational and ecologically economic. It is important to recognize and take into account, along with the interests of business, environmental and economic interests of the population of the regions.

Ecological and economic directions of regional development are formed and concretized at the state level, substantiated in the legal framework, instructional documents, which regulate the purpose, objectives, principles and sequence of directions of greening economic processes and creating a system of environmental security. Thus, the Resolution of the International Environmental Forum "Environment for Ukraine" contains proposals for a policy of balanced environmental and economic development, which provides for strengthening the role of regions in its development and implementation [1]. Ensuring the environmental component of economic development is different in each state and corresponds to the strategy and scenarios of its development, which depends on the social, economic, demographic, environmental characteristics of development.

The formation of a new economic augmented reality in the socio-economic life at different levels of economic aggregation has an impact on the competitiveness of the regions, which accelerates the digitalization of the Ukrainian economy. According to Kraus, Kraus and Andrusiak [2], the transformation is carried out with the help of digital technologies, based on the introduction of innovative changes, such as BlockChain, FinTech, front office, back office, Middle office, omni-business. Due to the ever-growing interest of researchers in the sustainability of the regional economy, Martin and Sunley [3] reveal issues of regional economic sustainability. According to the study, Martinez and Poveda [

ΩΩimmediateínez2022] provide an assessment of the impact of environmental indicators on competitiveness. The authors use a stochastic approach, various environmental indicators and the Global Competitiveness Index of the World Economic Forum. The results of this study are of practical importance in the development of tools, where the main elements of sustainability will be environmental performance and competitiveness. Doyle and Perez-Alaniz [5] propose to adjust the global competitiveness index to sustainability. This approach will expand the possibilities of measuring international competitiveness. The updated indicator can be used to analyze the time series and identify the relationships between indicators (economic, social and environmental) and sustainable competitiveness. The book of Huggins et al. [6] highlights the importance of the concept of competitiveness and the growing role of the region as a key spatial unit. The authors study the results of the World Index of Regional Competitiveness. This illustrates the changes in the competitiveness of regions around the world. Rizzi, Graziano and Dallara [7, 8] analyze the complex concept of sustainable competitiveness. The authors emphasize the benefits of balancing economic, social and environmental factors. Karman, Miszczuk and Bronisz [9] consider the competitiveness of regions in the context of climate change using a comparative and logical analysis of the concept of regional competitiveness and heuristic conceptual methods. Dziembała [10] notes that the key issue today is to increase the competitiveness of the regions, emphasizes the prospect of sustainability. The article proposes reformatting the composition of factors and identifying priority, namely social and environmental factors. According to the results of the grant project, Kourilova et al. had the opportunity to assess the regional competitiveness of EU regions using the methodology of the Regional Competitiveness Index [11]. The authors have identified universal and specific factors of competitiveness, and the achievement of long-term sustainable competitiveness is possible under a combination of different factors. The method of analysis of the effect of separation is proposed by Anikina and Anikin [12]. The article presents the results of calculations of the level of "environmental and economic risk" of the regions, which is an indicator of competitiveness. Kharlamova and Vertelieva [13] use cluster analysis to study national competitiveness and identify specific structures. Möbius and Althammer [14] offer a new consolidated index of sustainable competitiveness for the studied regions in 28 European countries. The authors combine factor analysis with modeling of structural equations. This allowed us to obtain a statistically reliable index, which can be especially useful given a small sample of empirical data. The proposed index reveals the possibility of long-term sustainable competitiveness under favorable environmental, social and economic conditions.

The article proposes models of ecological and economic competitiveness, with the help of which the actual ecological and economic competitiveness of regions is assessed and their rating is obtained. Factor analysis was used to determine the most important indicators and their weight. It is proposed to introduce atmospheric rent into the indicators.

2. Materials and methods

Ecological and economic competitiveness of the territory is formed from groups of components, some of which will determine its basic potential, others the potential of possible development trajectories. The ratio of these components is different for each region and in each period of time when competitiveness is determined. We propose to identify the following groups of components of environmental and economic competitiveness of the region:

Group I – geographical features of the region (availability of natural resources, climatic features, relief);

Group II – assimilation potential (ability to compensate for the impact of the economic system on the environment);

Group III – capacity of the ecological system (consumption by the economic system of the region of primary natural resources without changing the quality of the ecological system);

Group IV – technological ability of the economic system to create and consume environmental alternatives, analogues of natural resources, secondary raw materials;

Group V – economic incentives for investment in environmental innovation.

The environmental component has an important and special impact on certain areas of economic activity. Developed industries need more resources, attract investments that help increase production, improve product quality, accelerate its implementation, and so on. Due to traditions, the presence of similar positive experience in previous investment processes, similar successful examples of investment, fast payback periods, etc. these industries "win the competition" for resources in many regions simultaneously. At the same time, environmental factors that have a decisive influence on the competitiveness of the region's economy are also duplicated in different areas. These features can be used in the study of environmental and economic competitiveness as a relatively stable component of the system.

Ecological and economic competitiveness of the region is determined by the ratio of several areas that interact and interdependent: social, economic, environmental.

We propose to introduce the indicator of atmospheric rent in the indicators of the ecological group. For the region, atmospheric rent is the price it has to pay to the state (an institution defined by law) for the use of atmospheric air for the production of annual GRP. The justification for the use of atmospheric rent for the regions is the statement:

(i) atmospheric rent of the region, as well as the state, is a stable indicator that is adjusted to the environmental and economic multiplier of the region. The multiplier involves changing the efficiency of production (introduction of environmental technologies), operation of environmental products and their disposal for the calendar year;

(ii) the amount of rent payment in the region is directly proportional to the social component and the cost of recreational activities. The social component, firstly, has a global vector, ie the expenditures of the region's population on health care, preventive measures related to polluted air, morbidity, etc. are focused on world averages; secondly, it reflects regional specifics and social costs overdue (for example, related to the disposal of environmental products and taking into account their service life);

(iii) atmospheric rent of the region is the same constant indicator as the atmospheric rent of the state, which is determined by the share of participation of each region in air pollution.

The indicator of atmospheric rent of the region is calculated by the formula:

$$AR_n = C_{Sn} - \left(C_{rrn} + \frac{Ef_{emn}}{E_{Pn}} \right), \tag{1}$$

where AR_n – atmospheric rent of the n-th region; C_{Sn} – social costs, which are the cost of the population for material objects in the region (prevention and prevention of degradation), the cost of the population to restore the recreational value of the region (reservoirs, forests, parks, etc.); E_{Pn} – emission of pollutants of the n-th region; Ef_{emn} – the effectiveness of environmental measures in the n-th region.

Factor analysis combines methods for estimating the dimension of a set of variables by studying the structure of correlation or covariance matrices. Factor analysis assumes that the correlations between a large numbers of variables under study are determined by the existence of variables that were not included in the observation and which are smaller in number.

Let $X_1, \ldots, X_n$ to be the results of observations. Linear model:

$$X_i = \sum_{j=1}^{k} a_{ij} f_j + b_i U_i + \epsilon_i, i = 1, \ldots, n, \tag{2}$$

where random variables f_i - general factors, random variables U_i – specific factors that do not correlate with f_i, ϵ_i – random deviations, a_{ij} – factor loads (loads of the i-th variable on the j-th factor), which are the general models of factor analysis. The values of a_{ij}, b_j, σ_i^2 – are unknown parameters to be estimated. Equation (2) includes a hypothesis about the covariance and variance of x_i, which can be tested [15].

Under the condition of a problem with one factor (k=1), it is sufficient to calculate the correlation between variables to unambiguously determine the load. When $k > 1$, it is impossible to unambiguously determine neither the factors nor the load, because the factors can be replaced by any orthogonal transformation with the corresponding load transformation. This quality is used to transform or rotate factors. Rotations are selected in such a way that the variables have the maximum possible load on one factor and zero or almost zero load on other factors.

Practical implementation of the factor model allows to adequately calculate the covariance structure between a relatively large numbers of observed variables due to fewer simple factors, which simplifies data analysis.

Assessment of the degree of applicability of factor analysis to a given sample can be performed using the criterion of adequacy of the Kaiser-Meyer-Olkin sample:

– ≥ 0.9 - unconditional adequacy;
– [0.8; 0.9) - high adequacy;
– [0.7; 0.8) - acceptable adequacy;
– [0.6; 0.7) - satisfactory adequacy;
– [0.5; 0.6) - low adequacy;
– < 0.5 - factor analysis cannot be applied to the sample.

It is logical to use the following sequence of actions for factor analysis [15, 16]:

1) calculation of the matrix of cross-correlations of indicators;
2) determining the feasibility of factor analysis using the Kaiser-Meyer-Olkin test;
3) determining the number of factors through the analysis of the eigenvalues of the matrix of cross-correlations;

4) factorization of the cross-correlation matrix;
5) rotation of the matrix of factors;
6) determination of the factor structure;
7) calculation of factor coefficients;
8) calculation of the index of ecological and economic competitiveness on the basis of calculated values (the last action is formulated for a specific task).

3. Research findings

The following initial facts were selected to study the ecological and economic competitiveness of the regions, taking into account the groups of indicators and coefficients that reflect the ecological, economic competitiveness, social (human factor) and the introduction of atmospheric rent:

x_1 – gross regional product (at actual prices), UAH million for 1 person;
x_2 – consumer price indices (December to December of the previous year), interest;
x_3 – the number of business entities, including financial institutions per 10,000 population;
x_4 – number of sole proprietors per 10,000 population;
x_5 – volume of sold products, UAH million per 10,000 population;
x_6 – retail trade turnover, UAH million per 10,000 population;
x_7 – commissioning of housing, thousand m^2 of total area per 10,000 population;
x_8 – freight turnover of motor transport, million tkm per 10,000 population;
x_9 – passenger turnover of all types of transport, million per 10,000 population;
x_{10} – density of paved public roads, km per 1000 km^2 of territory per 10,000 population;
x_{11} – volume of sold services in the field of telecommunications and postal services (in actual prices including VAT), UAH million per 10,000 population;
x_{12} – mobile subscribers, thousand subscribers per 10,000 population;
x_{13} – Internet subscribers, thousand per 10,000 population;
x_{14} – life expectancy, years;
x_{15} – employed population aged 15-70 years, thousand people per 10,000 population;
x_{16} – the number of students, students of vocational schools per 10,000 population;
x_{17} – number of students, students of higher education institutions per 10,000 population;
x_{18} – household income, UAH million;
x_{19} – the value of total expenditures of households on average per month per household, UAH;
x_{20} – number of doctors of all specialties per 1 person;
x_{21} – housing stock, thousand m^2 of total area per 1 person;
x_{22} – the number of detected crimes (cases) per 10,000 population;
x_{23} – number of tourists served by tour operators and travel agents (persons) per 1 person;
x_{24} – volume of discharge of polluted return waters into surface water bodies, million m^3 per 1 person;
x_{25} – volume of waste generation per km^2 tons;
x_{26} – volume of emissions of pollutants into the atmosphere from stationary sources of pollution, thousand tons;
x_{27} – volume of waste generation per person, kg;
x_{28} – total amount of waste accumulated during operation in waste disposal sites, thousand tons per 1 person;
x_{29} – the amount of capital investments in environmental protection, UAH million;
x_{30} – the amount of current expenditures on environmental protection, UAH million;
x_{31} – the amount of atmospheric rent, UAH million.

Among the selected indicators, the indicators $x_1 - x_{13}$ belong to the economic group of indicators, the indicators $x_{14} - x_{23}$ – to the social group of indicators, the indicators $x_{24} - x_{30}$ – to the environmental group. The atmospheric rent indicator introduced in this study x_{31} will be referred to the ecological group of indicators.

In order to ensure the accuracy of the analysis, the initial data for each indicator were pre-normalized by the formula:

$$y_{norm} = \frac{y - M(y)}{\sigma(y)}, \tag{3}$$

where $M(y)$ – the mathematical expectation determined for the current time series; $\sigma(y)$ – standard deviation.

During the following calculation of the assessment of environmental and economic competitiveness, the initial data were reduced to the interval [0;1] using the formula:

$$\hat{x} = \frac{x - min(x)}{max(x) - min(x)} \tag{4}$$

which is explained by the requirements of the resulting calculation models to the original data, in particular, the requirement of non-integrity, while the use of formula (3) leads to fluctuations in values around 0.

There were analyzed 465 values in total. Given the symmetry of the cross-correlation matrix and without taking into account the units on the main diagonal of the matrix, it had 289 positive elements out of 465 elements in total, which is satisfactory for the analysis.

The value of the Kaiser-Meier-Olkin test is 0.89, which indicates the high adequacy of the sample to factor analysis.

The number of factors was determined by the number of eigenvalues of the matrix of cross-correlations greater than 1, based on this it was concluded that there are 7 factors. Table 1 shows the first ten eigenvalues, sorted in descending order, together with the percentage of data variation due to the relevant factor. As can be seen from table 1, together the first 7 factors explain 86.5% of variations in all data, which is a high indicator.

Table 1. The first ten eigenvalues and the explanatory percentage of variation of the data, sorted in descending order.

№	Eigenvalue	The explanatory percentage of variation	Cumulative explanatory percentage of variation
1	10.507746	33.895955	33.895955
2	4.783858	15.431802	49.327757
3	3.771401	12.165810	61.493567
4	2.842798	9.170316	70.663883
5	2.215177	7.145732	77.809614
6	1.482508	4.782285	82.591900
7	1.212210	3.910354	86.502254
8	0.814161	2.626325	89.128579
9	0.656179	2.116708	91.245287
10	0.597984	1.928982	93.174268

After factorization of the cross-correlation matrix and rotation of the factorized matrix, only indicators with a load value greater than 0.70 were selected from the resulting matrix. The result of the calculations is presented in table 2.

Table 2. Classification of the studied indicators by factors.

Indicators	Factors					
	1	2	3	4	5	6	7
1						0.84	
2							
3							
4							
5	0.72						
6							
7				0.89			
8					0.83		
9		0.75					
10			0.75				
11							
12							
13		0.78					
14			0.82				
15							
16							
17							
18	0.73						
19							
20							
21							
22	0.75						
23			0.72				
24	0.9						
25	0.9						
26	0.81						
27					0.85		
28	0.92						
29				0.83			
30	0.82						
31	0.84						

Of the seven pre-determined factors, only 6 are applicable, as for the last, seventh, factor there are no indicators with a high value of load. In total, the factors include 19 indicators, which reduces the amount of data processed in the process of assessing environmental and economic competitiveness. Among the selected indicators, 7 belong to the economic group of indicators, 4 - to the group of social indicators, the remaining 8 - to the group of environmental indicators (ie all indicators of this group). The first factor, which covers 9 indicators at once, deserves attention:

1 from the group of economic indicators (volume of sold products);

2 from the group of social indicators (income, crime rate);

6 from the group of environmental indicators.

Given that the first factor explains almost 34% of the variation in the data, the indicators of this share have the most significant impact on the system as a whole, and therefore will be the most important indicators for assessing environmental and economic competitiveness. Note that the value of atmospheric rent belongs to the indicators of factor 1.

IOP Conf. Series: Earth and Environmental Science 1049 (2022) 012084 doi:10.1088/1755-1315/1049/1/012084

The conducted factor analysis allowed to identify the most important indicators and determine the weight of individual groups of indicators, which was taken into account for the development of models for refined assessment of environmental and economic competitiveness.

To assess the ecological and economic competitiveness, there were used two models, which differently take into account the obtained values of the load of factors and the percentage of variations explained by factors.

In the first model, calculations are performed according to the formulas:

$$F_i = \sqrt[N_i]{\prod_{k=1}^{N_i} \hat{x}_k^{f_{ik}}}, \tag{5}$$

$$I = \sqrt[N]{\prod_{i=1}^{N} F_i}, \tag{6}$$

where $\hat{x}_k$ – the value of the k-th indicator related to the corresponding factor; f_{ik} – load of the k-th indicator in the i-th factor; N_i – the number of indicators in the i-th factor; F_i – the value of the i-th factor; N – number of factors; I – the value of assessing environmental and economic competitiveness.

In the second model, calculations are performed according to the formulas:

$$F_i = \sum_{k=1}^{N_i} f_{ik} \cdot \hat{x}_k, \tag{7}$$

$$I = \sum_{k=1}^{N} p_k \cdot F_k, \tag{8}$$

where $\hat{x}_k$ – the value of the k-th indicator related to the corresponding factor; f_{ik} – load of the k-th indicator in the i-th factor; N_i – the number of indicators in the i-th factor; F_i – the value of the i-th factor; p_k – the proportion of the explained variation by the factor k; N – number of factors; I – the value of assessing environmental and economic competitiveness.

Model (7)-(8) is additive, which also takes into account the load of indicators and the share of data variation explained by factors. By its nature, the second model is more like an expert assessment of environmental and economic competitiveness.

Table 3 summarizes the values of environmental and economic competitiveness estimates obtained using the described models and the corresponding ranks of the regions.

Analysis of assessments of ecological and economic competitiveness of regions allows us to conclude that, first, the result is stable, because for 12 regions out of 22 ranks obtained by different models differ by no more than 3 points. Secondly, the comparison of the results of the built models with the average value of the competitiveness index shows greater similarity of the results of model (7)-(8) and is explained by the higher accuracy of the model by choosing the indicators that carry the greatest load.

4. Conclusion

According to the results of the study using factor analysis, 7 groups of indicators were identified that most significantly affect the assessment of environmental and economic competitiveness and are the basis for its assessment. The identified indicators can be decisive for the development of regional and state development strategy (environmental and economic component).

The authors propose an introduction to the indicators of assessing the competitiveness of the regions of the value of atmospheric rent. Atmospheric rent is a fiscal lever of influence and a

Table 3. Assessment of ecological and economic competitiveness of regions.

Region	Model (5)-(6)		Model (7)-(8)	
	Index value	Rank	Index value	Rank
Vinnytska	0.2715	8	0.7973	9
Volynska	0.2578	9	0.6220	14
Dnipropetrovska	0.3738	1	2.6053	1
Zhytomyrska	0.2165	18	0.5507	17
Zakarpatska	0.2395	11	0.4451	21
Zaporizka	0.2155	19	1.3613	2
Ivano-Frankivska	0.2968	4	0.7745	10
Kyivska	0.3503	3	1.2052	3
Kirovohradska	0.2232	15	0.6116	15
Lvivska	0.2728	7	1.1348	4
Mykolaivska	0.1953	21	0.8300	8
Odeska	0.3702	2	1.0975	5
Poltavska	0.2538	10	0.9754	7
Rivnenska	0.2780	5	0.5350	18
Sumska	0.2169	17	0.7035	11
Ternopilska	0.2095	20	0.5101	19
Kharkivska	0.2393	12	0.9816	6
Khersonska	0.1688	22	0.4315	22
Khmelnytska	0.2777	6	0.5929	16
Cherkaska	0.2282	13	0.6965	12
Chernivetska	0.2248	14	0.4753	20
Chernihivska	0.2198	16	0.6313	13

stimulus for the formation of ecological and economic competitiveness of the region. The factor analysis confirmed that the value of atmospheric rent is a significant indicator that belongs to the first, most important group of indicators, and therefore should be taken into account when conducting environmental and economic assessment.

To study the ecological and economic competitiveness, two models were built and the results of modeling were compared. The most accurate model turned out to be additive, which is explained by a more balanced consideration of the load of indicators and the share of explained variation of data by each of the factors. The assessment of ecological and economic competitiveness was carried out on the example of regions of Ukraine and the ranks of these regions were determined.

The proposed methodology can be used to assess the environmental and economic competitiveness of regions for any country in the world.

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