Managing the Change:
Tasks of Post-Mining in Ukraine

Forschungszentrum Nachbergbau (FZN)

Technische Hochschule Georg Agricola University

A Joint German-Ukrainian Collection of Scientific Papers
devoted to the issue of Post-Mining in Ukraine,
including the actual war districts: hazards an perspectives

In cooperation:

The Technische Hochschule Georg Agricola University,
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The State Ecological Academy of Postgraduate Education and Management,
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The Dnipro University of Technology, Dnipro, Ukraine

The Ivan Franko National University of Lviv,
Department of Constructive Geography and Cartography

The Institute of telecommunications and global information space, Kyiv, Ukraine

The Department of automatization and computer systems
at the National University of Nutritive Technologies

*Despite the war in Ukraine, the closure of illiquid coal mines is an urgent task,
and inappropriate approaches to this issue will have the negative consequences
that could last for decades.*

Imprint

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Environmental impact of the unplanned closure of coal mines. Coal mine in Luhansk Oblast, Ukraine, flooding of the coal mine in course of the war actions. ©THGA/Natalia Lubenska

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Table of Content

Foreword

Germany is a post-mining country and thus an international pioneer in terms of structural change, risk management and land recycling. Mining leaves marks behind – and we have the necessary expertise to deal with this legacy responsibly. Since 2010, with the support of the RAG Foundation, the THGA has been building the first scientific post-mining center in Germany.

Unlike any other facility in the world, the Research Center of Post-Mining attends to the issues that emerge as mining activity ceases. It has considerable expertise and covers almost all areas of the post-mining phase – from sustainable water management in former mining regions to geomonitoring, the area of materials science and socio-economic issues.

Our expertise is in demand worldwide, and we are connected by long-term cooperation and friendship with colleagues from universities in Ukraine. Therefore, we are very proud that together with our Ukrainian colleagues we can publish this volume "Managing the Change: Tasks of Post-Mining in Ukraine".

It is a central concern of the THGA to advance the topic of sustainability and to make a significant contribution to a sustainable future, especially when peace has returned to Ukraine. The 17 Sustainable Development Goals (SDGs) of the United Nations underline how complex the topic is. Sustainability in the sense of the SDGs comprises three pillars: the economic, the social and the ecological pillar. Sustainability therefore involves much more than just the ecological aspects. We want to contribute to creating a world worth living in for future generations: "Engineering for a better world".

The scientific cooperation between our colleagues from Ukraine and Research Center of Post-Mining is one component for achieving these goals. Let us hope that peace will return to Europe soon and that our research collaboration will get stronger each passing day. We will support you in these difficult times.

Warmest regards,

Prof. Susanne Lengyel

President of the Technische Hochschule Georg Agricola, University

Editorial of the Research Center of Post-Mining

Given the generally recognized climate policy, the rejection of coal-fired power plants and the closure of mines is an objective reality for the whole world. In Germany, this process started in the 1960s. Initially, the closure of the mines was due to purely economic reasons. With the increase in the depth of mining, it became more expensive to produce coal, maintain the infrastructure of the road gates; The mines caused losses and the energy crisis in the 1950s only exacerbated the situation. Subsequently, negative repercussions for the environment were brought more and more into focus. After all, burning coal pollutes the atmosphere and, among other things, causes global warming and climate change. However, the closure of mines without a program of social support for the population of these areas and without envisioned alternatives, has negative consequences. In 2018, the last hard coal mine was closed in Germany. This was preceded by an extensive coal industry transformation program that offered alternatives to the people working in the sector and the region. Therefore, the experience of Germany in the field of post-mining is fundamental to many countries worldwide that still have to manage their post-mining transitions.

Post-mining excellence requires a high motivation as well as a high level of abilities and skills. Because of that, the TH Georg Agricola University (THGA) offers a master degree course in „Geo-Engineering and Post-Mining“ and founded the Research Center of Post-Mining – Located in the Metropole Ruhr – Germany's biggest metropolitan and post-mining area – the Research Center of Post-Mining develops innovative solutions which can serve as a role model for the implementation of post-mining all around the world. It conducts interdisciplinary investigations into the best ways to organize the complex tasks surrounding the closure of mines and their subsequent use – all with a particular focus on the aspect of future potential. We feel committed to share our knowledge with others.

The Ukrainian government has declared its readiness for a complete rejection of coal combustion by 2050, which was set out in the Green Transition 2050 concept presented in January 2020. It focuses on a common vector of movement together with the European Union, which officially proclaimed the adherence to the European Green Deal to overcome the global climate crisis.

On behalf of Ukraine's Ministry of Energy, the State Enterprise "OK Ukrvuglerestrukturisatia", the authority responsible for the closure of coal mines, concluded the letter of intent with the THGA in Bochum on September 9th, 2021. The framework of the project provides for scientific exchange on the topic of post-mining challenges in the Ukraine, especially in the Donbass coal basin. The Environmental Academy of Post-Graduate Education and Management (Ministry of Environment of Ukraine) was appointed as the main representative from the Ukrainian side. After that, other leading mining universities and other expert organizations of Ukraine joined the consortium.

The topics the expert group considered:

- Procedures of mine closures with an emphasis on technical, social, economic and environmental aspects;
- On-site and satellite monitoring;
- Conservation of industrial heritage;
- Training of post-mining engineers, etc.

The aggression by the Russian Federation in February 2022 has thrown all plans into disarray. In connection with the war, there are new challenges that the Ukrainian society has to face. At the same time, the inappropriate closure of coal mines can cause ecological threats which will not be eliminated in decades. We thank our colleagues from Ukraine: the State Ecological Academy of Postgraduate Education and Management, Kyiv, Ukraine; National Technical University of Ukraine "Ihor Sikorskyi Kyiv Polytechnic Institute", Kyiv, Ukraine; Dnipro University of Technology, Dnipro, Ukraine; Ivan Franko National University of Lviv, Department of Constructive Geography and Cartography; Institute of telecommunications and global information space, Kyiv, Ukraine; Department of automatization and computer systems at the National University of Nutritive Technologies – who were able to finish the preparation of this scientific work despite the difficult situation.

We kindly thank the team of the Research Center of Post-Mining for their contribution, and special thanks to Prof. Goerke-Mallet and Natalia Lubenska who initiated this cooperation.

With kind regards,

Prof. Dr. rer. nat. Christian Melchers

Vice-President for the Research Center Post-Mining
Technische Hochschule Georg Agricola, University

Editorial of the State Ecological Academy of Postgraduate Education and Management

The State Environmental Academy of Postgraduate Education and Management (DEA) is the leading organization of the Ministry of Environmental Protection and Natural Resources of Ukraine for scientific, practical and methodical work on environmental protection, rational use of natural resources, ensuring environmental safety, conducting environmental expertise, implementing environmental management mechanisms, in particular, environmental audit, standardization, certification and metrology in the field of environmental protection, preparation of scientific ecological expert assessments of the state of objects of increased ecological danger. The Academy coordinates the development and implementation of new instructional-methodical and recommendation documents regarding the specified areas of activity.

Today's ecological challenges, society's responsibility to preserve the environment for current and future generations, the processes of European integration determine the need to ensure ecological balance and reasonableness of management decisions affecting the environment. Without taking into account the ecological component, it is impossible to solve the economic and social problems facing society at the local, national and global levels. A low level of environmental knowledge leads to violations of environmental legislation and is the cause of management inaction and inadequate response of the population.

Taking into account the fact that Ukraine has made a choice in favor of the European path also in matters of ecology, within the framework of the tasks set before the DEA by the Ministry of Environmental Protection, we were glad to lead the work of Ukrainian universities in the framework of cooperation together with colleagues from the Technische Hochschule Georg Agricola University regarding the preparation of this band of scientific articles devoted to the restructuring of the coal industry of Ukraine.

It should be noted that the experience of Germany and the Technische Hochschule Georg Agricola University regarding the environmental-friendly closure of coal mines is unique on the international level.

We hope that in the future, also with the support of international partners, we will be able to introduce a system of education for future post-mining engineers in Ukraine, as well as to establish, following the example of the Technische Hochschule Georg Agricola University the similar center for post-mining, which will be able not only to spread advanced know-how in the field of restructuring and rehabilitation of former mining facilities, but also to control the effectiveness of the implementation of this process.

We sincerely thank our colleagues from the Technische Hochschule Georg Agricola University and we hope for continued cooperation.

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Assessment of the consequences of closing mines taking into account the world and domestic trends

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G. Simanovich[3]

About 7.8 billion tons of coal is mined annually in the world, and the trends in this production are relatively contradictory: on the one hand, there is a trend of stable growth in coal production, on the other hand, there is the same steady process of closing mines, especially in European countries.

To complete the disclosure of contradictions in Ukrainian coal mining, let's turn to the socio economic issues of the state of the industry.

In the spring of 2020, the Ministry of Energy reported that they would not close unprofitable mines for the time being, and this decision could be continued in 2021. Then they will decide on the possible sale of some state-owned mines.

The other side of power generation is due to alternative energy sources, which are developing rapidly, but traditional coal mining still remains relevant throughout the world.

When closing coal mining enterprises, one has to face a number of problems – it is necessary to solve emerging social, environmental and economic problems, as well as technical and technological issues of safe reduction and complete cessation of coal mine activity.

Closing a mine is a lengthy process that requires an assessment of all the associated risks. All risks are interconnected and therefore an integrated approach is needed to minimize them. First, it is required to determine which activities lead to risks. Secondly, it is necessary to develop actions that prevent or minimize their occurrence.

The problems that arise during the closure of coal mines are that the risks of adverse consequences, namely environmental, social, land, legislative, financial and technical, are significantly

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increased. It is generally recognized that a structured consideration of the risks associated with mine closures should be part of mine design and planning.

An integrated approach to the closure of coal mines provides one of the important measures for the extraction of metal structures from the remaining mine workings: the disposal of scrap metal and the reuse of significant volumes of accumulated raw materials fall under the concept of resource saving and environmental protection. However, the exploitation of many mine workings has been stopped for a long period of time, the examination of their condition (where it is still possible) is carried out extremely rarely and is associated with a considerable danger of such work. Therefore, forecasting the state of workings on the basis of existing regulatory and technical documentation and studies of geomechanical processes is of particular relevance.

The results of the analysis of existing ideas, problems and methods for their solution during the closure of coal mines in the process of a general decrease in coal consumption, primarily in Europe, have identified a number of main areas, among which three factors (geomechanical, technological and hydrogeological) should be considered, limiting the negative impact of which will allow successfully implement environmental, economic and social tasks in the coal regions of Ukraine.

Thus, the task is to minimize the risks of closing coal mines in Ukraine by geomechanical, technological and hydrogeological factors based on the established patterns of manifestations of rock pressure, the process of mine water desalination and hydraulic regimes of water inflows.

The Mine Life Cycle and the United Nations 2030 Agenda – A Sustainability Analysis

Prof. Dr. P. Goerke-Mallet[1], Prof. Dr. C. Melchers[1]

Agenda 2030 and the sustainable development goals have continued the process of giving equal consideration to social, ecological and economic aspects in the planning and implementation of projects of all kinds. The dynamics associated with the increasing world population, globalization and the fight against the climate crisis have taken on an essential role. This brings to bear developments and instruments that cannot be ignored by the raw materials industry, as they are associated with considerable opportunities and risks. In fact, the provision of geo-resources requires an adjustment of operational activities and communication adapted to these new conditions. This paper identifies the fields of action for sustainable mining processes in the mine life cycle and addresses the consequences of the circular economy and the recently passed supply chain law on mining. The narrative for mining that can be derived from this can demonstrate its contribution to the implementation of the 17 Sustainable Development Goals (SDG). In the authors' view, these goals can indeed only be realized with mining. However, the extractive sector must actively demonstrate that it is part of the solution. This requires transparent and comprehensive opportunity-risk management, a process based on adapted monitoring data and the involvement of all affected parties and stakeholders. Future mining projects will be significantly influenced by the positioning of the parties involved with regard to transparency, commitment, participation and communication.

Introduction

The 2030 Agenda was adopted by the 193 member states of the United Nations (UN) in 2015 with the aim of initiating fundamental changes for sustainable developments worldwide [1]. At the time, Germany's Environment Minister Barbara Hendricks described the agenda as historic, setting in motion a systematic transformation. Against the backdrop of climate change, the agenda is

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about combating poverty, global environmental protection, better social standards and climate- and environmentally compatible economic activity.

The World Commission on Environment and Development, also known as Brundtland Commission [2], fundamentally defined sustainable development in 1987. Quote: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs and choose their own lifestyles". The further prehistory of the 2030 Agenda includes the Rio Conference in 1992 and the Agenda 21 adopted there, as well as the Millennium Summit in 2000, where the eight Millennium Development Goals (MDGs) for 2015 were adopted [3]. Among other goals, the MDGs aim to improve upon poverty reduction, education, health, ecology and partnerships. These goals are also addressed by the 2030 Agenda and adapted to the globally changing framework conditions.

During the preparation phase of the UN Summit in New York in 2015, a document titled "Trans forming our world: the 2030 Agenda for Sustainable Development" was drafted [1]). The pre-amble defines the thematic areas of the Agenda under five headings – the 5 Ps: People – Planet – Prosperity – Peace – Partnership. This clarifies the goal of the Agenda: Pursue sustainable development within the context of peace and partnerships, whilst balancing economic, ecological and social goals.

It is immediately apparent that the five key messages address essential elements of the mine life cycle. The deposit at the center of the mining process is part of our planet. Its use is by people for people and, in this respect, is aimed at mutual well-being. The (at least) temporary interventions of mining in the environment and the burdens for the people affected can only be kept on an orderly course through partnerships and peace. In the broadest sense, this aspect is also strikingly expressed by the well-known phrase "mining is not one man's business."

This view is supported by the results of the survey of major international mining companies published by the management consultancy Ernst & Young (EY) [4]. According to the survey, the loss of the license to operate has been regarded as the greatest entrepreneurial risk in the last few years. For companies, the license to operate mines has both a legal and a social component. Without the consent of stakeholders – meaning all stakeholders and those affected – it is practically impossible to operate mines. In [5], Parra, Lewis and Ali highlight the importance of mining within primary production and lament that the benefits of mining are often hidden from the end consumer.

In fact, Georg Agricola had already dealt with the social license to operate in his fundamental opus of mining and metallurgy "De re metallica libri" [6]. In particular, in the first book, entitled "Arguments for and against this art" he deals with the arguments of the public critical of mining. His analysis of mining-induced damage to the environment and the benefits that mining activities bring to society can be understood as a risk management approach. As a polymath, he has observed, interpreted, and communicated mining, its characteristics, and its impacts. The Research Center of

Post-Mining (FZN) at Technische Hochschule Georg Agricola University (THGA) in Bochum/Germany is committed to the tradition of the university's namesake [7]. This applies in particular to the holistic view of mining and its life cycle, which is reflected in the four main research areas of the FZN (Figure 1).

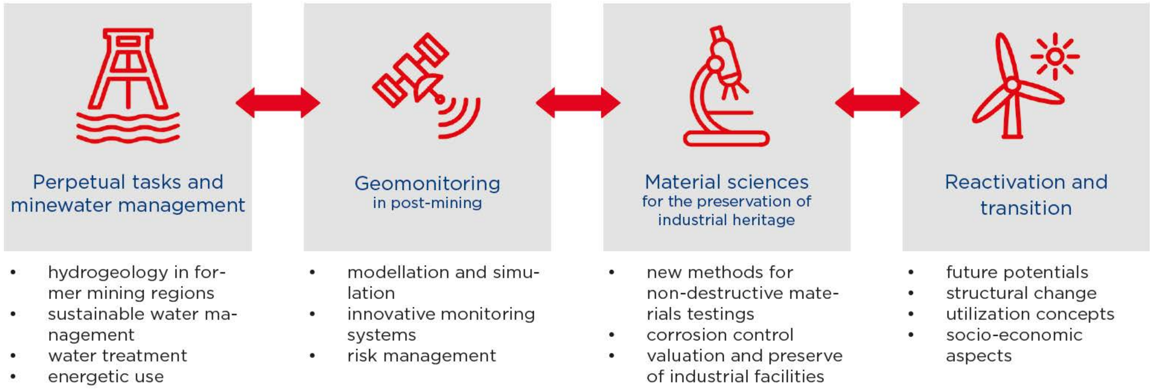

Fig. 1. Focal points of research at the FZN. Source: FZN

World population growth is expected to increase demand in georesources, and the resource mix will change as a result of technological progress and social processes. In order to enable transparent supply chains and achieve circular value creation, a broad social discussion about the necessity and meaningfulness of mining projects is required. The goal must be to create transparency for the entire mine life cycle and its relevant processes and to create an understanding within the context of comprehensive communication with all relevant stakeholders. At this point, the question arises as to the connection between the use of deposits (georesources) and the concept of sustainability as well as sustainable practice.

Meeting the raw material and energy requirements of the population, manufacturing and industry is not possible without mining and the power industry. This is associated with influences on the environment of the mines and the production facilities that cannot always be limited in space and time. This raises the question whether mining can actually be developed, managed and terminated sustainably. In view of the fundamental definition of the term sustainability, this must probably be answered in the negative. However, the question formulated above has prompted the authors to find answers and develop arguments. Even with a broad implementation of circular economic processes, mining-derived raw materials to national economies will remain necessary. In this respect, the mining industry must actively engage in the discussion on sustainability. Indeed, the mining sector is intensely involved in the quest to implement the 2030 Agenda. It must be an active participfiant in the transformation process in order to continuously demonstrate its future viability. This position is also supported by the call for increased transparency in supply chains.

The 2030 Agenda and the 17 Sustainable Development Goals (SDGs)

The 5 Ps become more concrete through the 17 Sustainable Development Goals (SDGs) [8, 9]. In the figures 2 and 3, the 17 goals are assigned to the 5 Ps and shown in full. The content of the 17 SDGs is further described by 169 targets.

Fig. 2. The 5 Ps and the 17 Sustainable Development Goals (SDGs). Source: FZN

Addressing mining through the 17 SDGs

In dealing with georesources, the research work of the FZN is increasingly focused on aligning mining processes with sustainability goals on the basis of substantial scientific findings, such as remains from past extraction of georesources as well as current or planned projects for their use. The German Sustainability Strategy has adopted the 17 global SDGs [8]. The core messages, the 5 Ps, are directly related to mine life cycles and to economic issues related to the management of georesources:

- Planet: Georesources are part of our planet. Their sustainable use must be in harmony with limiting climate change. As essential parts of the natural basis of life, georesources must be used carefully with a view to future generations.
- People and Prosperity: Available sustainable georesources need to contribute to creating orderly living conditions for people, reduce global inequality and shape globalization.

- Peace and Partnership: The georesource economy can only be organized sustainably on the basis of global solidarity and appropriate partnerships. Only in this way human rights and peaceful coexistence can be guaranteed.

Fig. 3. The 17 Sustainable Development Goals (8).

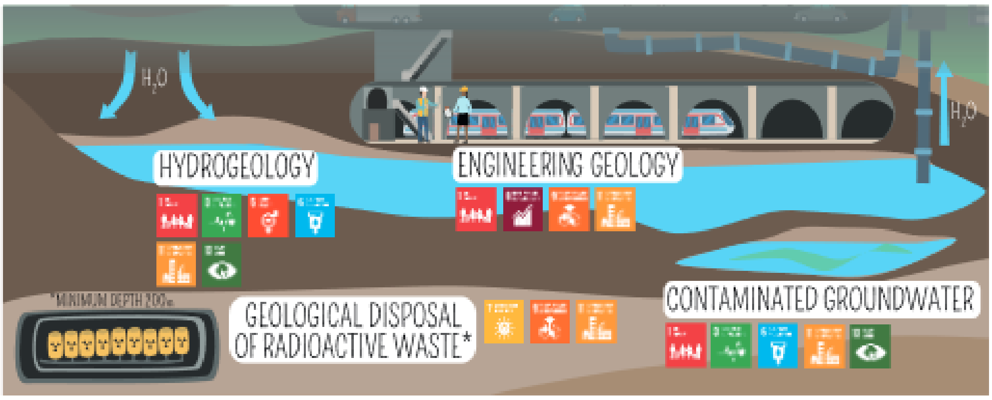

Fig. 4. Geosciences for the future (excerpt) after (10).

Against this background, it is evident that mining processes and the sustainable use of geo-resources directly addresses all 17 SDGs. To this end, the individual SDGs are linked to corresponding statements. The 169 sub-goals are also included in this analysis. In a poster of the Geological Society entitled “Geosciences for the future”, the SDGs are clearly assigned to individual disciplines and challenges [10]. Figure 4 gives an impression of the information content of the poster.

Linking the 17 SDGs with aspects of the mine life cycle leads to the following discussion points:

SDG 1 No poverty

Provide access to georesources; ensure land and natural resource ownership; organize participation in the economic process; improve the quality of the environment through revitalization; involve stakeholders and local structures in the economic processes of georesource extraction and use; create skilled jobs with good earning potential; reduce public vulnerability to disasters.

SDG 2 Zero hunger

Revitalize former mining areas in a timely manner and make them available for food production; reliably provide fertilizer and water; develop social and economic perspectives for those affected by mining activities; preserve ecosystems.

SDG 3 Good health and well-being

Improve occupational safety in the extraction and processing of georesources; minimize/ prevent pollution of the environment; promote the reuse of mining sites; preserve the quality of life of those affected; minimize mining risks; stakeholder participation; create economic prosperity through the mining sector; improve management of health risks; observe the transparency of supply chains.

SDG 4 Quality education

Provide education opportunities for students; create awareness of sustainable processes; expand existing global networks; enter into global research collaborations; participate in the development of global standards (ISO), intensify communication; provide special vocational training, e. g. mine rescue; upgrade skills through education and training of professionals at home and abroad; build know-how for participation in the change process among affected people; qualify for decent employment and decent work; value cultural aspects.

SDG 5 Gender equity

Create transparency and acceptance regarding the role of women in the georesource sector; prepare them for leadership roles; strengthen the position of women in decision-making processes; prevent discrimination; improve right of access to economic resources.

SDG 6 Clean water and sanitation

Follow groundwater and drinking water protection guidelines; manage water as a resource; use geospatial information and environmental and geomonitoring data; deal with mine/ groundwater issues; clean groundwater and mine water purification; pollutant analysis and treatment issues; build infrastructure for supply and disposal; increase water use efficiency; protect ecosystems.

SDG 7 Affordable and clean energy

Utilize geothermal energy and hydrogen; reactivate areas for the production of renewable energy; use energy potentials from the production chain of raw materials (mine water and heat, methane, etc.); minimize environmental impact from energy production; secure access to energy services; support local community energy supply; advance the coupling of the electricity, heat generation and mobility sectors.

SDG 8 Decent work and economic growth

Decouple economic growth and environmental impact; create transparent supply chains; end forced and child labor; create processes for sustainable use of georesources; optimize processes in extractive industries; improve job prospects; involve affected people in change processes; improve participation; strengthen labor rights.

SDG 9 Industry, innovation and infrastructure

Invest in science, research and research collaboration; observe reactivation and transition; shape structural transformation; establish innovative post-mining investigation methods; promote growth of start-ups (products, services, etc.); promote qualified laboratories; improve infrastructure reliability; promote local technology development and value creation; minimize CO_2 and CH_4 emissions; promote climate-neutral processes.

SDG 10 Reduce inequalities

Improve market access for products from countries in the global south; create transparencyin the context of research collaborations and knowledge transfer; promote social and economic inclusion; improve participation in decision-making in global institutions; create jobs for local people; ensure decent pay and social protection.

SDG 11 Sustainable cities and communities

Create measures for reactivation and transition; conduct environmental- and geomonitoring; optimize management of water resources; monitor microclimate; sustainable georesource management and use; promote circular economy; improve groundwater protection; reduce environmental pollution; minimize ground movements; avoid and regulate mining damage in an orderly manner; make mining legacies reusable in a timely manner; minimize risks to surface safety; create new perspectives in the post-mining phase.

SDG 12 Sustainable consumption and production

Create transparency in supply chains; improve communication; highlight importance of mining raw materials within the circular economy; optimize re-use of tailings and dump materials; plan and organize post-mining phase; organize sustainable management and use of georesources; handle waste materials in an environmentally sound manner; keep social and environmental risks low; plan operating facilities and take into account extreme weather events; carry out raw material processing close to the extraction site; optimize logistics chains; optimize extraction, production and processing from a sustainability perspective; reduce footprint; pursue urban mining; manage decarbonization.

SDG 13 Climate action

Conduct environmental- and geomonitoring; prevent CH_4 leakage through active use for power and heat generation; mitigate extreme weather events through use of mining infrastructure; avoid land degradation; undertake reforestation; keep CO_2 sequestration and underground storage in view; generate CO_2 reduction; initiate processes for climate-neutral resource extraction.

SDG 14 Life below water

Reduce discharge of polluted mine water into receiving waters; provide water treatment measures; sustainable extraction of georesources in the marine environment; conduct environmental- and geomonitoring; protect ecosystems; plan use of submarine deposits (marine mining) with environmental costs in mind; keep an eye on the post-mining phase.

SDG 15 Life on land

Plan reactivation of mining areas with high standards and implement in a timely manner; consider subsequent use of infrastructure; organize stakeholder participation; improve understanding of ecosystems; optimize water management in mining, e. g., in polder areas; counteract soil degradation; preserve biodiversity; reforestation; develop final disposal of highly radioactive waste in a transparent manner.

SDG 16 Peace, justice and strong institutions

Create transparency regarding the provision and use of georesources; strengthen participation; promote skills development; end human exploitation; strengthen communication; promote rule of law; counter corruption; provide access to raw materials and resources.

SDG 17 Partnerships for the goals

Enter into research collaborations; form networks; intensify communication; organize knowledge transfer; improve collaboration in science, innovation and technology development; promote skills development; increase market access; design partnership-based business models; develop quality criteria for organizing partnerships and establish measurable criteria; intensify participation.

The analysis shows a considerable range of options for action regard the opportunities and risks as well as the challenges of the mining life cycle. To develop a narrative for mining, the three fundamental aspects of a sustainable process – ecological, social and economical – will need to be considered. The following section provides a summary of the main points.

Ecology

During the entire life cycle of a mine, i. e. from exploration through the production phase to closure and reclamation, a variety of impacts on soil, water and air can be observed. Methane, a greenhouse gas found in coal and lignite, oil and natural gas, is released. Dumps and industrial tailings ponds take up land and can lead to substance inputs into groundwater and surface water. Surface facilities cause soil sealing. The extraction of georesources in the subsurface or on the surface also interferes with the natural groundwater balance or can lead to permanent alteration of water bodies. These impacts do not end with the cessation of mining, but also influence the postmining phase to a considerable extent. Among other things, this raises the question of how sustainable processes can be organized in the course of the remediation and restructuring of mining facilities when perpetual tasks are at issue. In this context, the resource water is of particular importance.

An adapted monitoring program in connection with risk management permanently improves the understanding of processes taking place. This also increases the certainty of forecasts and develops knowledge essential for binding, reliable and trustworthy communication with stakeholders, including those affected [11].

Social

Sustainable use of georesources is an important prerequisite for the acceptance of future resource extraction, also in Germany. Transparent communication of the ecological, social and economic impacts, as well as broad public approval, are key prerequisites for the social license to operate, i.e. social acceptance. This also applies to the post-mining phase, since successful structural change is an essential ingredient for acceptance of measures.

Mining processes often exhibit enormous spatiotemporal dynamics that can only be communicated to the public through a holistic approach. In other words, communication must find comprehensible, clear and credible arguments for all aspects of the mine life cycle. This also includes a very early look at issues of transition and reactivation of areas used for mining. Successful structural change can only be achieved with the involvement of all stakeholders and the assessment of the socio-ecological and socio-economic framework conditions.

Economics

The authors are aware of the complexity of mining processes. Central aspects are the location-dependency of deposit sites and the question of legal availability. Forecasts document mining risk regarding the nature and creditworthiness of the deposit and the long-term nature of the life cycle with low certainty. Reference should also be made here to the ultimately almost non-existent flexibility of primary production industry branches. These remarks could be continued at will. It should be noted that the above-mentioned risks need to be adequately hedged. Sociopolitical debates need to discuss whether such risks only apply to economic dimensions or whether there are other incentives to take up mining activities in the future. Does the attempt to locally overcome the Saint Florian principle (nimby-attitude) with regard to raw material projects relevant to society as a whole seem too ambitious? A debate about the necessary preconditions shall be supported by this paper.

Beyond the consideration of the three central aspects, it should be noted that mining processes can only be designed sustainably if the responsible individuals are qualified and educated. In this respect, the proven system of close links between research and teaching must be continued. This also applies to the permanent exchange between practice and science on the basis of existing national and international platforms. These include professional organizations as well as specialist committees and standardization institutions.

As part of the transformation, science is tasked with helping further develop knowledge of the public and to shape the narratives for mining companies. This includes taking up on-the-ground projects and presenting their significance in the context of society as a whole. In the anthology edited by Parra, Lewis and Ali [5], an evidence-based analysis of the linkages between mining and the SDGs is pursued. Through the supporting and inhibiting factors discussed in 17 individual chapters, it aims to advance the general discourse and defuse polarizing positions between policymakers and industry.

From the point of view of corporate practice, one might conclude that the sustainability paradigm has not yet been a great success. This view is the basis of the analysis by Blühdorn et al. [12], in which a team of authors takes a critical look at the status of the transformation process. They criticize the fact that sustainability policy is not empirically concerned with conditions and changes in the environment, but more with the concerns and fears of social actors. The word “hope narrative” is used to express skepticism about its broad effectiveness of transformation. In the opinion of the authors of this paper, this assessment falls short with regard to the use of georesources. The intersection of “sustainability,” “increasing transparency in supply chains,” and the “circular economy” creates considerable opportunities for the raw materials sector that should not remain unexamined.

Supply chain transparency

The Supply Chain Act (Gesetz über die unternehmerischen Sorgfaltspflichten zur Vermeidung von Menschenrechtsverletzungen in Lieferketten – Lieferkettensorgfaltspflichtengesetz – LkSG) – was published on 16th July 2021 [13] and will enter into on 1st January 2023. The aim of the law is to improve the protection of human rights in global supply chains, including the prohibition of child and forced labor [14]. The act also specifies the due diligence obligations of companies in Germany. These relate to the entire supply chain, i. e. from raw material to the final product. In this context, the requirements placed on companies are graded in terms of their ability to exert influence.

The adoption of the Supply Chain Act brings about a paradigm shift [15]. This is aligned with the demand of NGOs to reform Germany’s raw materials strategy and policy. It is lamented that raw material extraction far too often creates problems that cannot be solved by those affected alone. In this respect, raw material wealth can become a curse. In fact, there are numerous indications that human rights are violated and environmental damage is caused in the raw materials sector [16]. These undesirable developments must be countered by greater diligence and transparency along the supply chains. By moving away from voluntary corporate social responsibility and toward binding requirements, due diligence and environmental obligations are being established and regulations enforced. These efforts are supported at the EU level by the Conflict Minerals Regulation, which came into force on 1st January 2021. Importers of tin, tantalum, tungsten and gold are now subject to specific due diligence and verification obligations along the supply chain [17]. Reference should also be made here to the European Green Deal, which aims to promote resource-efficient measures and improve the participation of the population and regions [18].

The initiated processes should have an influence on society's overall perception of the global availability of raw materials. In fact, the general public hardly engages with its own consumption behavior and with questions about the origin of the raw materials in the products it consumes. As in other sectors of primary production, there is considerable alienation of the public regarding the context in which raw materials are extracted and processed. In the discussion about the energy and mobility turnaround, this attitude is particularly evident. Thus, a broad discussion about the availability of the required raw materials has hardly taken place so far. In this context, reference should be made to the work of the German Mining Network, which consists of eight competence centers for mining and raw materials at foreign chambers of commerce in important raw material nations [19], supported by the Federal Ministry for Economic Affairs and Climate Protection (BMWi). Among other institutions, the THGA is a member of this network.

Creating transparency should be combined with improved communication efforts. In this way, a better public understanding can be generated for national and global challenges facing the extractive industries. The Extractive Industries Transparency Initiative (EITI) is a transparency initiative currently supported by 56 countries [20]. Its objectives are to provide data for processes along the entire value chain of raw materials, to shape the dialogue on the use of revenues from the extractive sector and to contribute to better governance. By transposing the international standards into the national framework, the German government, together with experts from industry and associations, among others, already set the course in 2015 for improving transparency in the domestic mining sector as well [21]. In its current contribution on the topic of "raw materials", the BMWi explicitly highlights the advantages of domestic extraction of raw materials. It is more ecological, safer (occupational health and safety) and more participatory (local jobs) [22]. The declared aim of the German government is to bring national mining in line with the 17 SDGs and to align the entire raw materials sector with the circular economy [23]. This position is supported by a discussion paper from the raw materials specialist group of Scientists for Future [24]. It proposes strengthening domestic mining with regard to critical raw materials and addresses responsible mining and the promotion of the circular economy.

Circular Economy

The concept of the circular economy is based on closed cycles in the development, production, use and disposal of products [25]. The entire life cycle of a product, its value creation process and its benefits for consumers are considered. In contrast to the current linear economic model, economic growth in a circular economy is ideally not based on the use of primary raw materials, but still creates room for innovation and economic development. Such an economic system can also be considered sustainable in light of the 17 SDGs. The process of circular value creation and its elements is illustrated by Figure 5.

The importance of the circular concept for mining and the raw materials economy is obvious. However, it is important to note that primary raw materials are also needed within this economic model. The proportion of raw materials produced by mining is likely to vary greatly from product to product. In this respect, the comprehensive description of different life cycle stages of individual products is indispensable. At this point, a variation of the well-known saying, “If you can’t grow it or reuse it, you have to mine it,” fits.

A look at the arguments of the skeptics of the concept of circular value creation reveals several points [27]. The example of the raw material sand shows that, among other things, the final product concrete is essentially dependent on a “fresh” aggregate. Also, applicable technical and safety regulations are hardly adapted to the more extensive use of recycled materials whose quality properties are uncertified. A look at the raw material deposit of e-waste shows that concentrations of certain elements are significantly greater in natural deposits. The environmental compatibility argument of the process is often assumed to be inherent in the system, but lacks concrete proof. With regard to Germany as a major exporting nation, it should be noted that the raw materials present in exported goods have left the closed loop and are no longer available to balance circular value creation.

This is also where the question of the so-called rebound effect comes into play. According to this effect, a reduction in manufacturing costs of a product – which would ultimately have to result from circularity – increases consumption. It is therefore also interesting to better understand the wishes and reactions of consumers. There is a risk that the technical view of circular value creation is misaligned with consumer preferences [27].

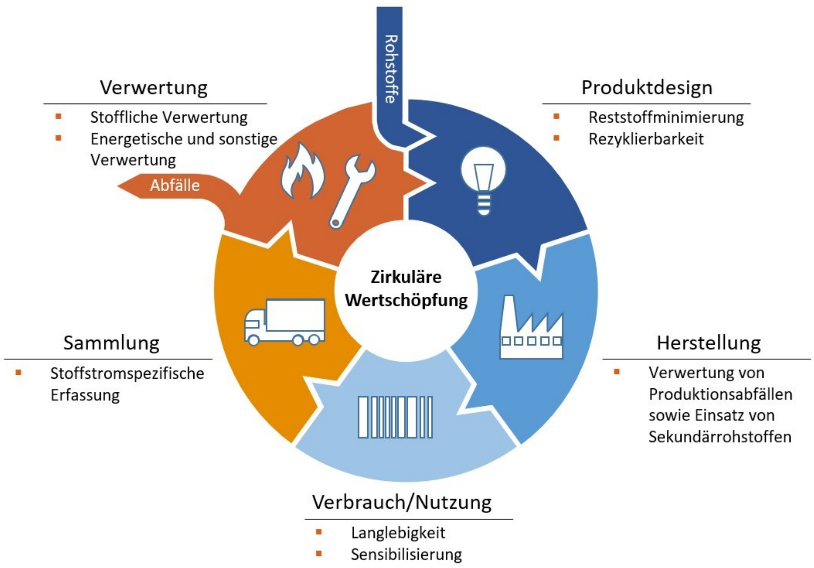

Fig. 5. Circular Economy (26).

The strategy of circular value creation must be seen as a consistent response to the new sustainability paradigm. The transformation process associated with this is particularly challenging due to the holistic nature of the circular economy. Thus, fact-based thinking in terms of opportunities and risks, constant observation of the processes taking place, and the creation of transparency through communication with all stakeholders is also crucial for this concept.

Conclusions

A world population of almost 8 bn people and their right to decent living conditions pose enormous challenges for the use of georesources. Dealing with climate change, the energy and mobility transition as well as the digitalization will change the composition and scope of the raw materials mix. The provision of these resources must be guided by the Sustainable Development Goals formulated in the UN Agenda 2030. Otherwise, the alienation of consumers from mining as an essential element of primary production that exists today would be further reinforced. The associated loss of the social license to operate must be effectively countered under all circumstances in the interests of the financing and feasibility of mining projects.

The key for the extractive industry is to actively address the implementation of the 17 SDGs, which cover many aspects of mining. The opportunity-risk potential of mining projects must be managed over the entire life cycle, accompanied by appropriate geomonitoring programs and made transparent through binding communication with stakeholders.

Sustainability is also a key part of supply chain transparency for a wide variety of raw materials and products, as well as in the design of processes for circular value creation. Companies and institutions involved in the provision of georesources will have to become involved in these developments. This requires a narrative for mining that convincingly expresses its active efforts toward sustainability, transparency and communication. In the future, corporate responsibility will include a broader group of stakeholders in addition to shareholders. Mining could thus assume the role of a provider of raw materials that the world can count on to tackle global challenges.

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Mine Water Rebound Processes in Europe

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Abstract

During past decades, mining ceased in many European hard coal mining disctricts. In most cases, the process of decommissioning is due to the phase out of governmental subsidies. With the mine closure and the cessation of pumping, mine water rebound processes were initiated. For a better understanding of this complex process, experiences regarding the rebound processes gained in whole Europe have been collected and reviewed in a three year study by the Research Institute of Post-Mining at the TH Georg Agricola in Bochum/Germany.

Introduction

In 2010 the European Union (EU) decided, to phase out subsidies for the hard coal mining industry by the end of 2018 (Council Decision 2010/787/EU). Corresponding to this decision, the last German hard coal mines Ibbenbueren, North-Rhine Westphalia, Tecklenburger Land, and Prosper Haniel in the Ruhr District area were closed in August and December 2018, respectively. Several other coal mining regions of the EU have already been closed several years ago: The United Kingdom closed down its last colliery in 2015 (Kellingley), France closed its Lorraine coalfield in 2004 and Spain closed its last subsidized collieries in Asturias at the end of 2018 (Figure 1). The termination of mining activities means, that there is no operational need to dewater the mine workings anymore. Hence, the era of post-mining takes over at this point. A key issue is how to deal with the mine water in the long term. The complete and abrupt cessation of pumping and dismantling of pumping stations can lead to an uncontrollable rise of mine water in the mine, with possible impacts to the environment, whereas a perpetual pumping is likely to be economically unfeasible. Pros and cons of a complete mine water rebound are still being discussed by different stakeholders.

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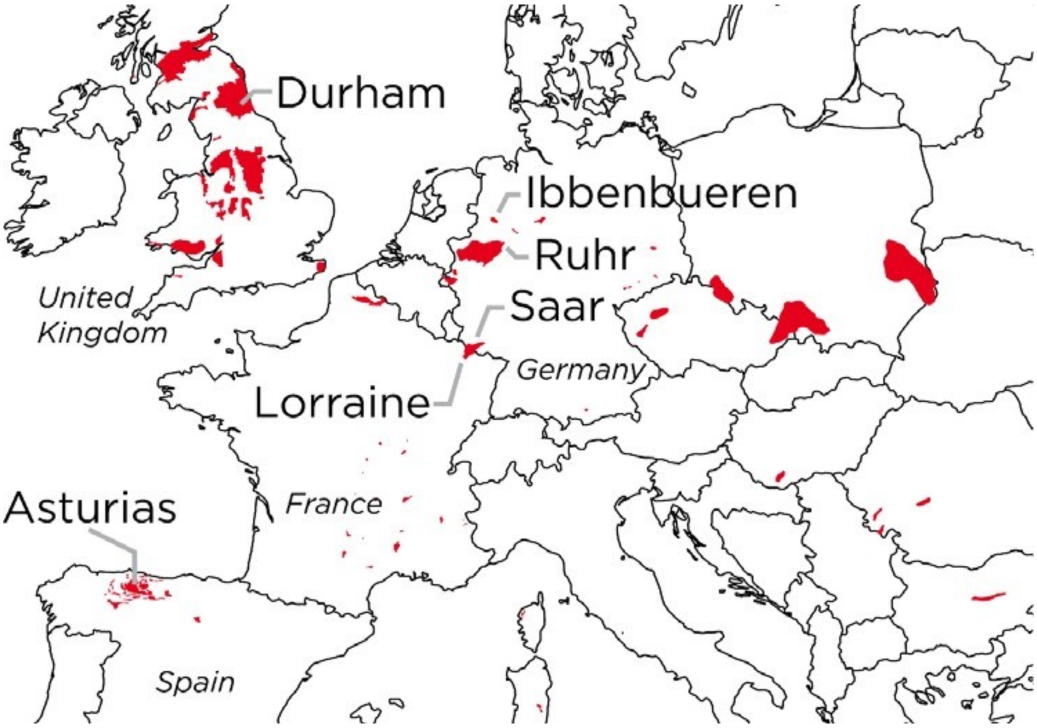

Fig. 1. Coalfields and hard coal mining districts of Europe.

The inevitable end of the German hard coal mining sets the background for the foundation of the Research Institute of Post-Mining, which is embedded in the TH Georg Agricola in Bochum (Germany). The institute deals with the manifold challenges the era of post-mining implies for the natural and anthropogenic environment. For this purpose different research projects were funded, from the mapping of hundreds of old shafts, the development of underground probes for insitu collection of mine water data, application of satellite data for sophisticated monitoring systems up to the social aspects of the transition process of coal mine regions (“structural change”). In this paper the results of the research project “Evaluation of mine water rebound processes in Germany at the Ruhr area, the Saar region and Ibbenbueren and adjacent European hard coal mining districts” are being presented. It has been focused on the findings, which were collected by reviewing the documented experiences in the United Kingdom, France and Spain, especially with respect to their long-term mine water management strategies [1-3].

Legal background

The responsibility for the legacies of the mining is handled differently in every country. In Germany the last operational mining company is legally bound, which means for the hard coal sector that the RAG (Ruhrkohle AG) was held responsible for financing all occurring aspects induced by mining within the post-mining period, which are summarized in the term “eternal tasks”. The RAG-Foundation was established in 2007 by the RAG for this purpose. If there is no legal successor of a closed mining company, the state is in financial charge.

In the United Kingdom, ample structural changes occurred in the hard coal mining sector since World War II. In 1947, the whole industry was nationalized under the name “National Coal Board”, which was renamed to “British Coal” in 1987. In 1994 British Coal ended in the framework of the “Coal Industry Act 1994”. The administrative tasks were transferred to the newly established Coal Authority, whereas the operational business was merged with RJB mining in 1999 to form the UK Coal corporation. As mining companies, that closed before 1999, have not been responsible for their mining legacies [4] and as the hard coal mining sector was nationalized for decades, the public authority is in financial charge for most of the post-mining challenges. Although it was not originally her duty, the Coal Authority took over the responsibility of the eternal tasks.

Mine water strategies in Germany

In Germany, there is a lively discussion about mine water management in the hard coal sector. There is the threat, that mine water might contaminate some drinking water reservoirs, if the mine water level rises in an uncontrolled fashion. As the moneyed RAG-foundation took over responsibility for the completion of the post-mining tasks including the management of the mine water there is the de-mand that the mine water should be infinitely pumped. This led to a debate about the question, to what extent the mine water level could rise to avoid any contamination of the drinking water hori-zons. In the Ruhr area, the RAG-foundation favors a mine water table, that is situated 150 m below the base of the Haltern Sands, the major drinking water aquifer in the region [5]. Between the mine water and the aquifers, there is a natural geological barrier, i.e. an aquitard: The “Emscher Mergel” is a sedimentary succession of marls, which can be up to 800m thick in the basin centre. From a geolog-ical and scientific point of view, the petrophysical properties of this barrier needs to be evaluated to estimate a risk for the drinking water reserves.

Experiences in Europe: United Kingdom, France and Spain

Following the recent discussions about the appropriate and long term sustainable level of the mine water in the Ruhr and Saar regions, the Research Institute of Post-Mining at the TG Georg Agricola initiated a project, which aims to analyze the influencing parameters of the mine water rebound and to collect the experiences, which have been made so far in other countries in Europe dealing with the same problems. In this paper, the international experiences of the long-term strategies dealing with the mine water rebound shall be emphasized.

United Kingdom

In the United Kingdom, there was the only in Europe documented case of the infiltration of mine water into an aquifer [6-8]. The Durham hard coal mining region is situated at the northeast coast of England and comprises the so called Magnesian Limestone Aquifer. The area is crossed by a large sealing fault (“Butterknowle fault”), which subdivides this region roughly into two smaller, hydrogeologically isolated coalfields. The last mine in the southern field, which is called the “South

Butterknowle" area, was closed at the end of the 1960`s/ beginning of the 1970`s. In this time, there were several investigations about the mine water rebound including pumping tests, which should exhibit the influence of the pumping rate to the mine water chemistry [9]. Although it was known, that the comparably small barrier between the deposit and the aquifer was disturbed by mining influence, the dewatering systems were switched off in the middle of the 1970`s and the mine water was able to rise in a uncontrollable manner. Shortly after the final cessation of pumping the mine water level began to rise up to the overburden. As the recharge zone of the mine water is situated in the western part of the coalfield, where the coal seams crop out at the surface at a height of about +125 m ASL, the mine water was able to built up a hydraulic head that is remarkably higher than the surface of the ground water levels at +90 m ASL. Consequently the mine water was able to infiltrate the aquifer. This was recognized by a sudden increase of the sulphate concentration within the ground water, from originally 30-40 mg/L to 200 mg/L in 1978 and more than 600 mg/L in the 1990`s [7]. Despite this increase in sulphate concentration, the expectable increase of the total iron concentration did not appear. The reason was that the limestone bearing strata in the aquifer increased the alkalinity of the infiltrating mine water, raised the pH and thus was leading to a precipitation of iron oxides inside the fractures of the limestone [6]. Until today the sulphate concentration of the ground water increases and the contaminant plume is expected to reach the nearby drinking water wells between 2019 and 2024 [7].

The northern bordering part of the Durham coalfield is known as the "East of Wear" area. The last mine in this part closed in the middle of the 1990`s. Following the west to east dipping of the coal seams, the mining activity was expanded offshore. Learning from the events in the South Butterknowle area, the danger of a disturbance of the Magnesian Limestone Aquifer was well known. So the mine water rebound was monitored carefully and the time, the mine water would be able to interfere with the aquifer, was anticipated [10]. For a control of the mine water level, appropriate water management systems were put in place and reinitialized before the mine water was able to infiltrate the aquifer. This way, the hydraulic head of the mine water is equilibrated some meters below the ground water level, avoiding a mixture of both waters. Until today, there is no contamination of the aquifer documented.

France

A similar approach to the East of Wear concept of managing the mine water rebound was applied in France. The last producing mining district in France was Lorraine region. It is situated in the eastern part of France and bordering to the Saar mining district in Germany. It stopped production in 2004, when the mine La Houve, operated by Charbonnages de France (CdF), was abandoned.

Sandstones of the Triassic form an aquifer of regional importance in this area for potable and industrial water abstraction. This aquifer is separated from the deposit by marly sediments at the top of the Carboniferous. This marl is recognized as a hydrological barrier which lost its function due to mining induced alteration. With this hydraulic connectivity the ground water was able to enter the mine during operations and active water management, resulting in a lowering of the ground water table. When the pumping ceased in 2006 [12-13], the mine water level began to rise. A monitoring program for measuring the mine water level was implemented. When the mine water approached the overburden, the same approach as in the East of Wear mining district in the United Kingdom was used: the pumping was started again in order to keep a head difference of 5 to 10m between the mine water and ground water level [14]. This does not mean that the mine water level was held strictly below the base of the ground water. Instead, the hydraulic head of the mine water was located within the water saturated zone of the ground water. An infiltration was prevented just by keeping a small head difference between these waters, in order to force the ground water to discharge into the mine water, but not vice versa. Despite that, the ground water level also rose according to the decline of the discharge into the mine water, leading to a rise of the water table.

Comparable to the case in the United Kingdom, there is no evidence of a contamination of the ground water by mine water following this "head" approach.

Spain

In Spain the biggest and most important hard coal mining district was the Asturian coalfield [15-16]. Asturias is an autonomous community in the north-west of Spain, situated directly at the Atlantic coast. Compared to Germany, the subsidized hard coal mining similarly came to an end in 2018, after several years of decline in production.

From a geological point of view this deposit is very different from most industrial important hard coal deposits in Germany, United Kingdom and France. The seams dip very steep, sometimes even vertical, which prevented a highly effective and automatized mining process [17-18]. The coal seams crop out at the surface. Hence, there is no overburden providing significant aquifers. The potable water is provided by a dam, that is located several tens of kilometers southeast of Oviedo, the capital of Asturias.

A single mine water rebound in the Asturian coalfield was described in the literature for the Barredo and Figaredo mines [15]. In Figaredo the mining activity as well as all pumping stopped in 2007, in Barredo (Figure 2) several years earlier. Both mines were hydraulically connected, so that the trend of both water levels are nearly the same. The mine water levels began to rise immediately and were monitored. Within less than one year the mine water levels in both shafts rose from -150 m ASL to +140 m ASL, which means a comparably fast rise during the mine water rebound. Nowadays the water level is equilibrated at approx. +150 m ASL and the pumped water is discharged into the nearby river Turon.

Fig. 2. The Barredo shaft in Mieres (Asturias, Spain).

Different ways of using the mine water as a resource have been studied for more than 10 years [15-16, 19]. Due to the lack of natural aquifers in this area, it was investigated whether the old mine workings could serve as an artificial drinking water resource. With an estimated volume of some Million cubic meters and with respect to the average longterm rainfall data, it was estimated that this reservoir could deliver potable water for 60,000 people [15]. Secondly, it was studied, how the mine water could be used as a geothermal energy resource to provide heat to buildings. The studies found out, that the mine water in the Barredo and Figaredo mines could deliver a thermal energy of up to 28.6 GWh per year, acting positively on the greenhouse gas balance in comparison to fossil energy use. This is why two of the biggest geothermal systems in Europe were installed in two buildings near the old Barredo shaft [20]. One new building of a research center from the Spanish coal company Hunosa near the Mieres Campus of the University of Oviedo is equipped with 2 x 362 kW heat pumps using the geothermal energy of the mine water. Another system with heating power of 3.5 MW is installed in a nearby hospital.

Conclusion

Mining is one of the key industries that form the base of civilization, providing employment for several generations of people. When mining ceases, subsequently the era of post-mining starts. At this point it is the duty of society, to manage the legacies of mining in a sustainable ecological and effective way. One of the key aspects in relation to the environment is the appropriate mine water management. The mine water rebound is the natural process that emerges when mining ends and there is no need to dewater the deposit anymore.

The experiences made in the United Kingdom and France with the strategy of protecting overlying aquifers by keeping the hydraulic head of the mine water slightly below the ground water potentiometric surface has indicated to be a feasible strategy to avoid contaminations. In both countries, no interference of the aquifer by the mine water is documented so far. In a case of stopping or failure of the pumping installments and a consequent rise of the mine water, a mixing of the ground water and mine water is possible. So appropriate back-up solutions, i.e. backup pumping systems, should be provided at any time.

On the other hand the Spanish experiences demonstrate, that mine water should not only be seen as a threat, but also as an opportunity for beneficial use. The concept of using the old mine workings as an artificial drinking water reservoir might be an interesting option for regions that suffer from droughts. The most popular use of mine water is probably to generate heat or electricity for people as a renewable energy source. With sufficient infrastructure in place and enough regional consumers it offers a promising source of renewable energy with a high opportunity to reduce greenhouse gas emissions. This resource can be regarded as a feasible alternative to oil and gas in the light of global warming aspects.

Acknowledgement

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Post-mining Challenges and Knowledge Transfer for the Ukrainian coal industry

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Abstract

The Ukraine has started to restructure its coal mining activities. The country will probably face similar challenges and obstacles that German hard coal mining had experienced. The restructuring of old mine sites to new economic hubs requires governance practices and efficient management processes. Best practice, lessons learned, training and re-skilling approaches of the young generation from the coal mining region Ruhr area are described and how they can be transferred to the Ukraine.

Situation in the Ukraine

The coal mining industry in the Ukraine is facing similar challenges than other European coal producing countries. According to Euracoal's country report, coal production has dropped by 7.7 % from 31 Mio t of coal to 28 Mio t. from 2019 to 2020. At the end of 2020, 71,000 people were employed in underground hard coal mines, a decline of 1 % [1]. Private mining companies produced in 2020 90 % of the total production. Between 2013 until 2020 coal production has dropped by 66 %. The Ukrainian government subsidized the coal industry with around 3 bn UAH in 2020 [2]. Around 70 cities with 1 Mio people are relying on the coal mining industry [3].

Although hard coal mining is still the major energy source; it has now currently reached the final phase of its mining life cycle (figure 1). The life cycle model is based on the market development phases after Heuss and combines an in-depth consideration of market cycles and their ideal life stages with expected entrepreneurial characteristics [4]. Kretschmann has transferred this life cycle model to the mining sector [5]. He pointed out that on the one hand, the mining segment may only have a small number of product groups and, on the other hand, the sales market must be

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clearly defined, which is largely the case for coal production. The decline goes hand in hand with mine closure and abandonment [6].

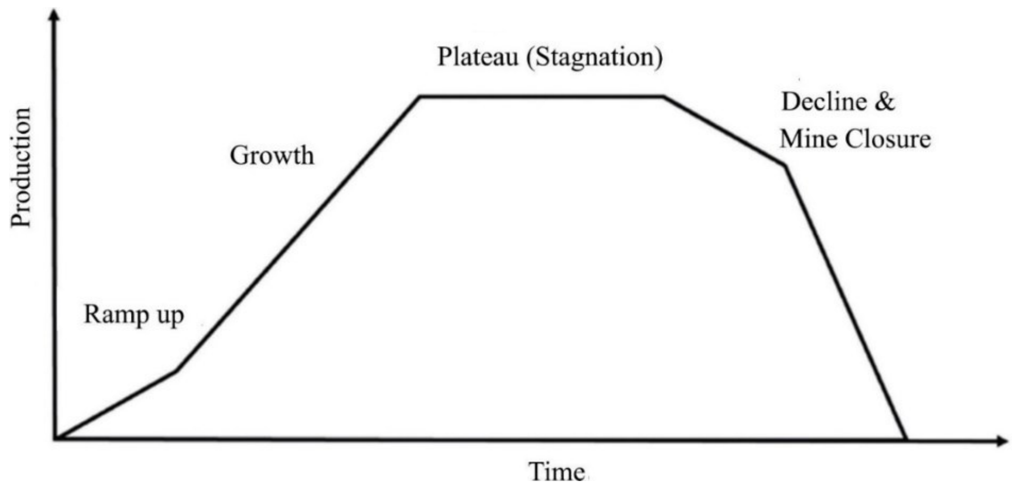

Fig. 1. The life cycle model for mining [6].

Applied to Ukraine, one can conclude that Ukraine has reached the final phase of the life cycle in its mining industry. According to the Ministry of Energy and Coal Industry of Ukraine, since 2004, 68 state-owned mining companies have been liquidated in Ukraine, 19 state-owned mines have started the process of closure or are in preparation for closure as of 2018 [7]. With declining mining production and resulting mine closures, post-mining challenges arise. These challenges comprises effects of mine water rebound processes on the surface and infrastructure, on methane degassing and other environmental aspects but also on the re-utilisation of former mine sites, establishment of new businesses and reskilling of workers in the transition process.

The Ukraine joined the European Coal Regions in Transition Platform. Last December a platform initiative for the Western Balkans and Ukraine was initiated. The politicians expect that the platform would provide support in developing and implementing programs and projects to overcome the above mentioned challenges. The government should adopt and implement a comprehensive coal restructuring program in line with EU state aids. The plan should also address the social, environmental and economic consequences of coal mine closures.

Against this background, the government set up a coordination centre to accompany the transition process and elaborated a just transition concept for the coal regions. This concept is intended to be used as a basis to develop a 2030 State Just-Transition Programme for Coal Regions.

In August 2020, Ukraine and Germany signed a partnership on energy sphere. Working groups have been set up and will focus on five topics:

- Technical support
- Strategic and legislative framework
- Strengthened civil society

- Technical and environmental aspects of mine closure
- Pilot projects, financial mechanism

These working groups can built upon the experience and knowledge that Germany has gained in the on-going transformation of the German lignite mines and in the transition of the coal mining sector at the Ruhr and Saar. In particular, the Ruhr area has managed this transition process in an effective way. The policies and management practices implemented here can serve as guidance for other regions. Because the transition process takes many years, even decades, the management of this process and the proper implementation of the projects is crucial for a fair transition.

Coal brownfield agreement of the Ruhr area

The Ruhr area is home to more than 5 Mio inhabitants on an area of 4000 km². The functional requirements of the former coal mining and steel making activities shaped the structure of the cities. The transformation process already started in the late 50ies of the last millennium with first coal mine closures. In peak time, the coal mining companies in this area employed more than 500.000 people in numerous coal mines. Due to the substitution of coal by other fossil fuels like oil and gas and nuclear power, the number of mines decreased with an accompanying reduction of mine workers. For example until 1963 already, 33 coal mines were closed with an annual total output of 10 Mio t.

Start of the transformation process

In 2008, the German government decided to phase out hard coal mining by 2018. This decision enabled the coal mining regions in Germany, the Saar and the Ruhr area to prepare the post coal mining time within this period of 10 years. In the metropolitan Ruhr area, the challenge was and still exists to successful transform the former mining region. So the cities and districts in the Ruhr area concluded jointly to cooperate and to initiate an intercommunal decision matching and dialogue process.

The first step in this transformation process was the development of a strategic perspective for the region for the next decade. Based on the previous urban development policies, the so called “concept Ruhr” took up the future challenges and turned into operation in regional development concepts and master plans. These concepts and plans were also the base for applying and receiving EU regional development funding. One important topic of the “concept Ruhr” was the “site precaution” in the frame of the coal reduction because the effects of mine closures were clarified at an early stage and prevented potential drastic regional disruptions. Besides actual mine closures, long-term future closures were considered. In total, 15 mine sites in the region were included in the “concept Ruhr” and this perspective were the big chance for this ten years lasting anticipation process.

The second step in this transformation process was the position paper “Change as a chance” in autumn 2008. The aim of this paper was to assess the joint implementation of the medium and longterm concepts because of the coal decision. It tackled more than 40 cities and communities in the Ruhr area. The position paper described the framework conditions in the region and stated fundamentals for joint actions. In addition, spheres of activity for a coordinated strategy of all actors and precise local and regional projects were determined.

Areas should first be safeguarded and afterwards been developed in a sustainable way. The focus was on coordinated research and technology valorisation. New utilisation and development was the base to focus on major mining areas and resulted in the coal brownfield agreement. The regional association Ruhr RVR (consisting of Ruhr cities), the Ministry of Economics NRW and the coal mining company RAG and its subsidiary RAG Montan Immobilien (the Real Estate company) finally undersigned in 2014 this document.

Coal brownfield agreement

This agreement was the start of a new cooperation process. From 2009 to 2014, the parties negotiated the priority development areas. Criteria such as long-lasting reuse, urbanistic priority, industrial location and employment effects, stabilisation of social structures and limitation of land consumption were guiding. The final selection of 20 mine sites and the agreement upon common objectives, which should be achieved in shared responsibility of the partners, was the foundation for the coal brownfield agreement.

For the management of the entire process the parties have established a steering committee and an inter-communal platform. The steering committee consists of representatives of the municipalities, of the director of the regional association Ruhr, of the Ministry of Economics of North Rhine-Westphalia, of the respective functional departments of the Ministries and of the District Councils and of the board of directors of the coal mining company and is steering the entire process on decision level. In annual meetings, the parties are discussing questions related to funding, project development and financing, but also local characteristics. The steering committee assesses the progress reports and compares the outcomes with the annual land use evaluations.

By establishing the coal brownfield agreement and based on the long-lasting trustful informal collaboration the municipalities in the Ruhr area obtained a formal framework. Within this structure, the cities and districts are working together in close relationship with the common objective to realise successful the transition of former mine sites on local level.

The regional association Ruhr is coordinating the collaboration and is offering exchange platforms for the town councils. The inter-communal design matching strengthens the position of the councils as a whole towards the other parties. It also allows to transfer knowledge between the local project responsibilities and to increase competences on land development. The inter communal knowledge transfer helps to identify challenges, which are specific for the transformation of mine sites and require special solutions. Because the municipalities are the numerical largest party in this process, they use the exchange for harmonisation of overarching questions in the sense of a regional consensus. The exchange also allows show promptly obstacles and progress. In that way, the parties can analyse difficulties, align measures and develop solutions.

Effect and benefits of the coal brownfield agreement

The selection of 20 hard coal mine sites for an accelerated development laid the main foundation for this form of cooperation. and provided the new frame for the collaboration of the partners.

The contents and the structure of the agreements have a direct and indirect impact on the spheres of activities:

- Surface area with the issue of realisation of successful land usages
- Financial dimension with the issue of financing models and access to funding grants
- Time dimension with the issue of coordinated and integrated developments as well as acceleration of the processes
- Organisation with the issue of a reliable and target-oriented collaboration of the partners

All partners state that the coal brownfield agreement provides a frame for short information and decision processes as well as for a quick exchange and knowledge transfer. The aim of an integrated successful land development is supported by interdepartmental coordination and funding priorities of the State of North Rhine-Westphalia. Crucial is bundling of the activities in a leading department (in this case the Ministry of Economics) including the interdepartmental coordination as well as the expansion of utilisation options from pure economic ones to integrated land development.

The specific structures and instruments of the coal brownfield agreement enable an acceleration of the processes and decisions. The annual progress reports demonstrate evolution and obstacles in a transparent manner and are the base for a common evaluation. Action requirements are getting obvious in time and essential decisions can be prepared.

The responsibility for the development actions of each site remains with the proprietary and with the city respectively. On local level, particular structures are created for example cooperation agreement or the establishment of project companies. Local experiences are shared for mutual benefit in two-sided discussions as well as in intercommunal meetings. The project manager and the sites are benefitting from this knowledge transfer.

On each site, collaboration and design-matching processes are initiated, which are not self-evident. One example is the forward-looking design matching process between the mine owner and the respective city regarding the future use of the brownfield in the framework of the mine closure plan.

Compared to other land development projects, the proprietary can be more involved in project financing due to waiving distribution of profits and rolling financing. The intercommunal adoption of usage and development foci as well as market accesses led to common actions rather than concurrent ones. The exchange on topics and problems resulted in a common understanding and benefits for the parties because solutions are presented in time and can be discussed amongst the partners. At the same time, the regular exchange and the evaluation avoids process-inhibited activities. Since the signature of the agreement, the government of North Rhine-Westphalia supports the decision by implementing funding priorities. The local projects benefit from focussing and bundling of the grants for the prioritized projects. The open-minds of the Ministry of Economics for integrated or neutral use approaches of the land development and the inter-departmental coordination allows even integrated financing. The government can tackle upcoming problems and urgent challenges with a high degree of solution.

Lessons learned

In conclusion, it can be said that the coal brownfield agreement is a well-established and reliable form of collaboration between partners with a special focus on financial and human resources for the transformation of mine sites. Regular land evaluation leads to transparent development processes; outcomes and challenges are obvious at an early stage and can be addressed appropriately.

With this site-overarching approach, single areas have received a higher attention. The coal brownfield agreement has raised the importance of the sites in the view of the project participants without losing the overall focus. Coordinated objectives and planning avoids regional concurrence and fosters interdisciplinary acting.

Therefore, the coal brownfield agreement is an interesting model for the transformation of mine and industrial sites. As a regional instrument and considering social, environmental and economic objectives, it can provide valuable advice for a transition of a region in Germany, Europe and in the Ukraine. The coal phase out in many of these regions and the post-mining period will now start. In North Rhine-Westphalia and in particular in the Ruhr area this transition process is still ongoing.

The experience can act as an impulse and create new actions in North Rhine-Westphalia as well as in the Ukraine. Prerequisites are:

- Faith in the partners based on long-lasting collaboration
- Common concern regarding the challenges and understanding of the opportunities to develop together a strong position for a successful transformation
- Chance to use the phase out time period for forward-looking actions
- Preparedness for inter-communal design-matching and decision process to acquire financial grants from EU funds and international institutions.

The availability of engineers and other experts with the necessary qualifications will become indispensable in the future. In order to deal with all these different aspects, mine closure and postmining challenges require new skills and education such as training programs or Master Courses for post-mining.

Education and training of post-mining experts

The countries where mining was terminated and mines were closed like in Germany have experienced problems such as increasing underground water level, instability of surface etc. and with possibilitiesof their re-usage also. However, they cannot apply their experiences in practise anymore, because theirmines were closed, filled up and redeveloped. On the other hand, there are countries where underground hard coal mining will be terminated within next years and where the experiences could be practically applied. It is very important to prepare experts and engineers for planning of mine closure and their usage in time before mines will be closed and redeveloped. In connection with the gradual mining phase-out, it is also important to update the study curricula at universities and colleges for mining programmes in order to prepare experts in mining as well as experts able to maximize the potential of abandoned mines. Taking into consideration the specificities of different regions, it is important to search for new ways to exploit the potential of old and recently terminated mine workingsor future cessation. It is therefore necessary to liaise experts from regions with rich experience and from countries that are beginning to face the challenge. Thanks to the creation of new university courses, the knowledge and experience will be shared with mining and engineering students.

With the decision of the German government in 2007 to phase out the underground coal mining activities in Germany, the Technische Hochschule Georg Agricola University (THGA) decided as the first of its kind worldwide to focus on mine closure and post-mining. Safeguarding and rehabilitation measures are needed to manage the risks at former mine sites. The development of follow-up uses opens up sustainable future prospects for the affected regions. Since 2012, the university is offering a Master degree program called "Geoengineering and Post-Mining" which deals with all aspects of mine closure and post-mining on surface and underground. Aim of this part time program is to educate the students in all (hydro-) geological, (geo-) technical, legal, socio-economic, planning and management aspects of mine closure and post-mining. Currently, roundabout 90 students are enrolled in this Master course. More than 20 students have graduated in the last years. As a rule, geotechnical engineers, geoscientists, but also geographers, geologists as well as civil engineers and recently more and more students from abroad study at the THGA. These have often studied Geotechnics, Geosciences or Drilling-Reservoir Engineering and want to deepen their knowledge of post-mining in the Master degree program. The special feature of the Master's program is its practical part within a lot of practice-oriented teaching content with examples and excursions. The lecturers use their good business contacts for extraordinary field trips. Students have the choice between traditional full-time study and part-time study, in which courses and lectures take place in the evenings and on weekends. This makes it possible to combine job, family and studies in a flexible way. In addition, it enriches the courses by allowing students to bring in topics and fields of work from their everyday professional lives and mirror them from a scientific perspective.

In particular, the career prospects for graduates are excellent. From construction site manager to managing director, in industry or departments. Graduates of the Master's program are needed and hired across the world. A later cooperative doctoral study is also possible. This enables to pursue anacademic career and to accompany the development of post-mining from a scientific perspective. Inpost-mining research, numerous innovative methods and procedures are currently being developed andimplemented in order to process the post-mining system with the latest scientific findings in the future.In addition, THGA is engaged in the new Erasmus+ project "Creation of a new online study course Use of Abandoned Mines". The partner universities from Germany, Spain, Czech Republic and Poland will develop e-learning courses and perform summer schools and other activities. For instance, the course will focus on environmental impacts of mining including hazardous gases from abandoned shafts, abandoned mine methane, reclamation of post-mined landscapes, legal aspects of mine closure and re-utilisation of abandoned mines, general geomechanical aspects of abandoned underground mines or re-usage of abandoned mines for geothermal purposes, thermal energy storage systems or for electric energy storage.

International cooperation enables knowledge transfer and exchange of good practice – the most effective tools for enhancement of skills and professional knowledge of people because new challenges arise from mine closure and the handling of post-mining legacies, which requires innovative solutions from research and development.

The Research Center of Post-Mining

The Research Center of Post-Mining at the Technische Hochschule Georg Agricola University (THGA) in Bochum, Germany, is also focused on finding efficient and a high degree of sustainable solutions around the subject of mining, especially hard coal mining. Therefore, it provides a team of experts in different fields of research, who are analysing the existing problems left behind due to the hard coal mining. In particular, when it comes to long-term sustainability and measures, as well as solutions, research and development are required constantly. After the decision to phase out from the hard coal in Germany, the Research Center was established in 2015 at the THGA. The varieties of different research disciplines allows a wide range of knowledge to be covered. Furthermore, although the units are differentiated in foci, the work there is done interdisciplinary to ensure efficiency. In total, the Research Center offers four different research areas: the first area focuses on perpetual ecological tasks, which mostly consists of the mine water management. The second area is about geomonitoring and mine surveying, while the third unit deals with material science and the preservation of industrial heritage. Lastly, the fourth unit deals with the reactiva tion and transition (e.g. of former mining sites, sustainable re-use etc.) (figure 2). science and the preservation of industrial heritage.

Lastly, the fourth unit deals with the reactivation and transition (e.g. of former mining sites, sustainable re-use etc.) (figure 2).

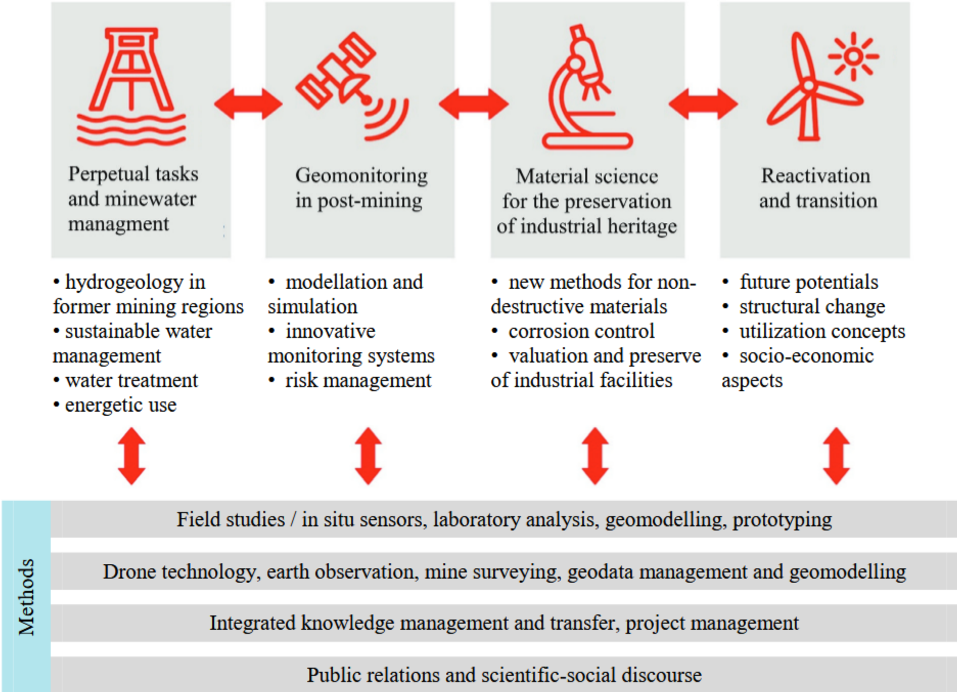

Fig. 2. Research areas at the Research Center of Post-Mining at the THGA in Bochum, Germany (Research Center of Post-Mining).

In more detail, the processes in mine water rises, which the first unit is dedicated to, werespecifically analysed for the Saarland, Ibbenbüren, Ruhr area and other hard coal mining area in Germany, but also for other European countries. Scientists developed worldwide the first monitoring system for mine water rebound processes and implemented in an underground mine. The monitoring system was adopted to the particular conditions in an underground mine (figure 3).

Fig. 3. Underground monitoring system for mine water rebound at the former coal mine Auguste Victoria (courtesy of RAG, Marin Schnieder, Martin Justa).

While the geomonitoring is, among other disciplines, more about technical sets in using the life cycle of a mining site to evaluate the situation. Furthermore, the so-called “Digital Twin concept” is used, where industrial processes can be entirely digitally recorded – starting with an idea, over an implementation, maintenance to monitoring and dismantling. After this work is done, it is possible to make a twin out of it, a locations digital image utilising pictures from drones (figure 4).

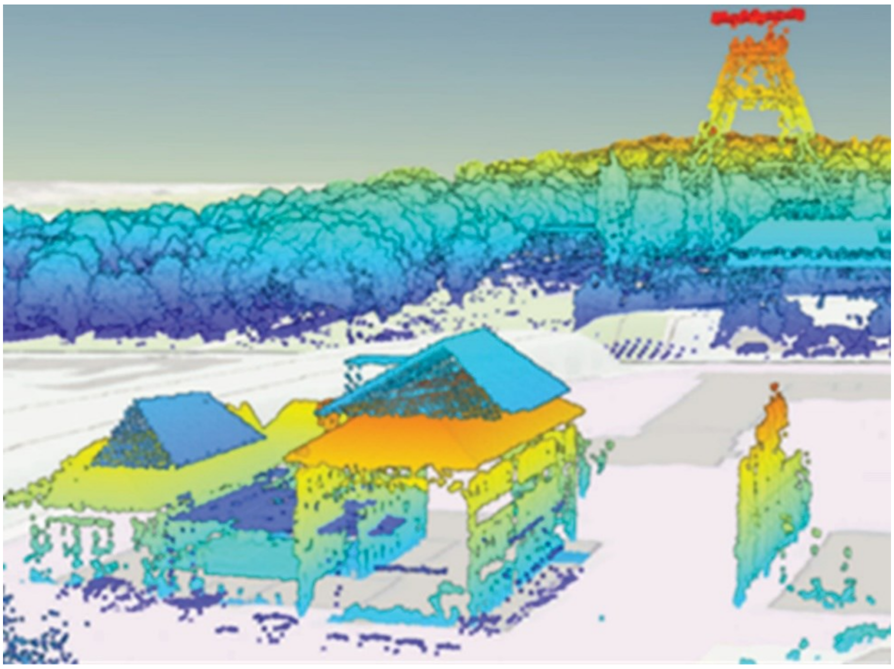

Fig. 4. Example for the application of analysis data as a texture to a 3D model (here: a laser point cloud from publicly accessible Reference data) by Benjamin Haske, Research Center of Post-Mining.

The scientists in the research area “Material Science” are developing new technologies to conserve the cultural heritage of mining. For instance, drones are used to identify corrosion in the steel structureof head frames of former shafts. Researchers in the fourth area “Reactivation and transition” are developing new business models for the re-utilisation of former sites like in the EU RFCS project POTENTIALS.

Research projects and technologies help to progress in dealing with post-mining tasks and to work on preserving potential of former mining areas. In the same instant, costs and risks need to be identified while solutions are worked on. This is why the Research Center of Post-Mining is intervened with the holistic view on the mine life cycle [6]. In achieving this goal of a sustainable future without hard coal, not only in Germany, but internationally and in this example for the Ukraine, the Center is working together with a big network of different companies and researches from Germany and globally. The above-mentioned actors in this sector, namely e.g. the RVR or the RAG, are also part of the network of the Center to ensure a better future potential for all people that are left with the consequences due to hard coal mining.

Given the width of the interdisciplinary tasks involved, appropriate solutions and recommendationsare required. The many years of comprehensive specialized knowledge and experience in Germany, especially the Research Center of Post-Mining can be deployed as a role model for a sustainable postmining development.

Conclusions

In Germany, there is a saying: ”Mining is not a one man’s job“. This is also true for the closure of coal mines and the management of transition processes. It requires international exchange and collaboration, willingness to learn from each other, educate the post-mining generation for these challenges, transfer knowledge and experiences and adopt it to the local conditions. Acknowledging this, the authors describe a method how to manage the transition process. They also address the task to educate the next generation of mining engineers, who have to solve the legacies of mining. The described approaches could be a blueprint for the Ukrainian coal transition.

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Tasks for restructuring the coal industry in Ukraine in the context of the European experience

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Abstract

Ukraine has decided on a policy of "green" energy transition until 2050. This implies the development of alternative energy sources, the gradual decarbonization of the energy sector and the phase-out of the coal industry. The liquidation of coal mines is associated with the solution of a whole range of problems, from purely technical ones, such as the management of mine waters, and the solution of social and economic problems associated with the transformation of entire coal regions.

The article provides an overview of the situation with mine closures in Europe and concludes that not only in Ukraine, but also in other countries, the adaptation of energy policy in accordance with the decision to close mines is most often delayed, which can lead to an imbalance in energy security, economic instability and social tension. The article provides a detailed analysis of the World Bank report "Coal Mine Closing: A Just Transition for All" (2018) with step-by-step instructions for the systematic implementation of the coal industry restructuring program at the government level.

As a successful example, the experience of Germany in closing mines is considered as the most optimal for Ukraine. Although the coal industry of Ukraine and Germany has much in common, and the Ruhr coal basin can be compared in many ways with the Donetsk coal basin, the situation with the closure of mines is exacerbated in Ukraine by the difficult situation in the Eastern Donbass. Here the issue of restructuring is most acute.

Employment of miners and related professions in single-industry towns of controlled coal regions, infrastructure and environmental issues are the basis for the future prosperity of the region. And, unfortunately, without the full support of the international community,

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Ukraine is not able to resolve this issue on its own. Therefore, the experience of international colleagues, not only Germany, in solving the problems of restructuring the coal industry is invaluable for Ukraine.

The coal industry in the EU countries is at the stage of "transition", that is, at the stage of gradual abandonment of coal mining.

First of all, this is dictated by the EU's course to reach a carbon-free economy by 2050, which means a gradual abandonment of coal generation and a transition to renewable energy sources. And also in accordance with EU Directive No. 787 in 2010 on the need to close unprofitable mines before January 1, 2019 [1].

The current situation with underground coal mining in Europe

Over the past half century, large-scale changes in the coal industry have taken place throughout Europe, and most recently in the United States and China, have left nearly 4 million miners out of work. The main drivers of these changes are the mechanization of mining operations, government policies and competition from other fuels in the electricity markets. Economies in Asia, Eastern Europe and Africa are currently facing the same drivers of change, with significant job losses already occurring in China and the same is likely to happen in Asian countries.

The Euracoal report for 2019 [2] states, given climate trends in connection with greenhouse gas emissions, a reorientation of coal supplies from west to east and a trend towards a gradual reduction in coal production.

In 2015, there were 128 coal mines operating in 12 EU Member States with a total annual production capacity of 498 million tons. Poland had the largest number of coal mines (35), followed by Spain (26), Germany and Bulgaria (12 each). Germany was the largest producer (184 Mt), followed by Poland (135 Mt), Greece and the Czech Republic (46 Mt each).

The comparison of Fig. 1 and Fig. 2.

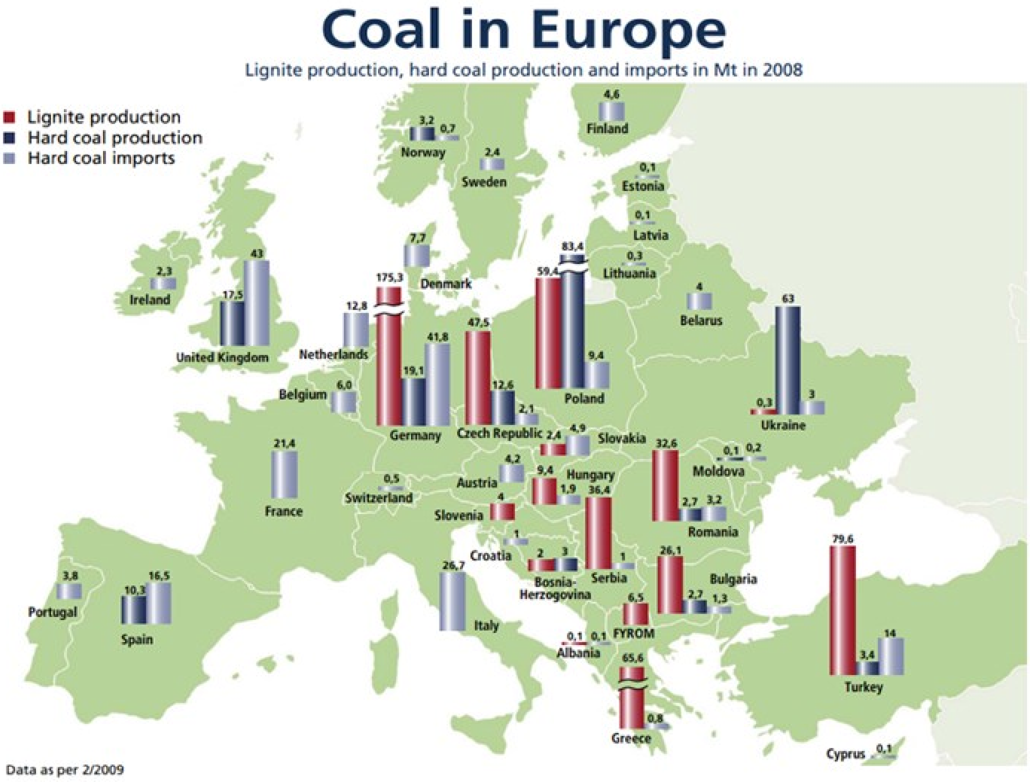

Fig. 1. Extraction of hard and brown coal in 2008 in Europe (according to Euracoal)

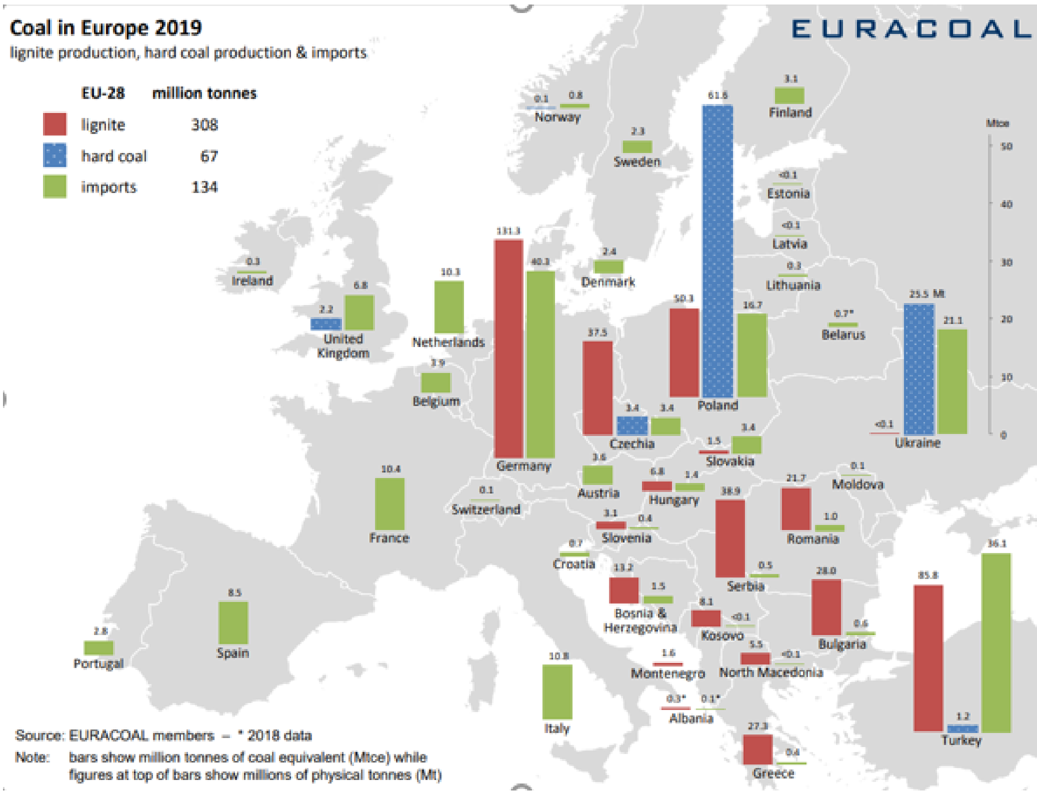

Fig. 2. Hard and brown coal mining in 2019 in Europe (according to Euracoal)

How the coal industry was curtailed in European countries [3].

In Austria, with the growth of trade and the trend towards increased use of oil and fossil gas, underground coal mines became less competitive and were closed as early as the 1960s.

Belgium's national coal production peaked at 30 million tons in 1952 and maintained that level until the late 1950s. As the mines in Walloon and Limburg closed, production gradually declined: the Eisden mine in 1987 and Belgium's last mine at Heusden-Zolder in 1992.

Underground coal mining in France ended in April 2004 with the closure of the last active La Houve mine in the Lorraine region. The state-owned coal company Charbonnages de France went out of business at the end of 2007.

On January 8, 2019, the Italian government submitted its draft Integrated National Energy and Climate Plan (PNIEC) to the European Commission. It places great emphasis on accelerating decarbonization policies and promoting renewable energy as part of the overall economic transformation. For coal, the plan confirms what was proposed in the 2013 National Energy Strategy, i.e. the closure of all Italian coal-fired power plants by 2025.

Coal mining in the Netherlands ended in 1974 when the private coal mines Oranje-Nassau I and Julia closed. The Emma Mine, the last state mine, was closed in 1973.

However, mining at Svea Nord and preparatory work at the new mine at Lunckefjell were suspended by the Norwegian government in January 2015 as low coal prices led to a difficult economic situation.

The last Germunde coal mine in the Castelo de Paiva region (Portugal) was closed back in 1994. In November 2017, the Portuguese government announced its intention to decommission all coal-fired power plants by 2030.

The closure of mines is associated with the solution of many important economic, environmental and social problems. And if some countries, like Germany, approached this process in advance, then, for example, Spain faced the need to close 26 mines in a short time. The government of Ukraine will have to deal with the same problems.

The closure of mines often leads to mass protests and strikes. So it was in Ukraine, Russia, Poland, Great Britain, Germany, in all countries where a decision was made at the government level to close coal mines. This is a complex process, the consequences of which, in terms of social long-term impact, are not yet well understood.

Researchers at the University of Queensland in Australia, Nicholas Banton and Sarah Holcomb, analyzed the social aspects of mine closures [4]. At the same time, they highlight some topics that are not yet sufficiently studied and the solution of which will allow the world to avoid the mistakes of the past. First of all, they focus on the need to intensify the international exchange of experience, since no one really knows the whole complex of factors in the closure of mines and the scale of their influence. The authors state the need to compare the regulations of different countries, the need to involve all involved persons both at the national and regional levels, and the need for a more thorough study of the relationship between the closing process and subsequent post-mining processes.

Mine closure lessons

The November 2018 World Bank report "Coal Mine Closures: A Just Transition for All" [5] summarizes the lessons learned from the experience of mine closures in the Russian Federation, Ukraine, Poland and Romania from 1994 to 2012, supplementing data on the impact of coal mine closures. mines in the UK, the Netherlands, the US and China show that job losses occur not only as production declines, but even as production increases. The mitigation of social conflicts and economic distress is of great concern as the global coal industry enters a new era of contraction. The purpose of this report is to share with governments the lessons learned from coal mine closures. Indeed, the full set of issues related to the closure of coal mines is varied, and to date, several positive examples from practice can be used. The complexity of technical issues and proprietary interests, along with the many potential risks that may arise, will require a combination of time-tested and new approaches. In this white paper, World Bank experts have attempted to draw lessons from the past that can help policy makers be more successful in closing mines in the future.

In general, the World Bank draws 9 conclusions that it recommends that the governments of countries involved in mine closures use.

1. The state should give clear requirements and recommendations for the closure of mines. All specialized institutions and organizations should participate in determining the state policy in matters of mine restructuring.
2. The allocation of large amounts of money to solve technical problems with the closure and sanitation of production sites, as well as to pay monetary compensation to miners who have lost their jobs.
3. Cooperation with regional administrations and trade unions.
4. Planning for the transformation period for mine closures should start as early as possible.
5. The state should provide a social base for the employment of miners in the format of a national strategy. For example, in Germany, 50 years have passed from planning to closing the last mine in December 2018 [6].It is necessary to develop a system of temporary benefits, compensations, social insurance against unemployment, early retirement opportunities for miners who have lost their jobs.
6. It is necessary to develop mechanisms for the employment of miners who have lost their jobs, which will subsequently relieve the burden on social funds. Miners have not only knowledge in the field of mining, they are excellent electricians, mechanics, fitters, etc. In

Germany, there is an excellent experience of combining mining teams into service enterprises that carried out work for other enterprises on an outsourcing basis.

7. The issues of rehabilitation of industrial sites should be taken into account at the stage of mine planning. This includes an assessment of the possible negative impact on the environment, issues of long-term monitoring, pumping and purification of mine water, etc.
8. Financial mechanisms should be defined that would cover the costs of liquidating mines, since often an enterprise is not able to solve this problem on its own, and in the event of an enterprise's bankruptcy, this completely becomes the responsibility of the state.

The indicated conclusions or lessons are also applicable in the realities of Ukraine, however, do not forget that in addition to the above issues, there are also national and local problems related to the fact that some coal enterprises of the Donetsk coal basin are divided as a result of hostilities in the Donbass. At the moment, uncontrolled flooding of mines occurs in the territory of Donetsk and Luhansk regions, that with the closure of coal mines monotowns and organizations from areas related to the coal industry, as well as social institutions that were often on the balance sheet of coal enterprises or supported by them, these are, first of all, kindergardens, schools, medical institutions. Plus, this also includes issues of coal-fired power plants and private households at the expense of coal.

The most acute environmental problems in the Eastern Donbass are caused by the restructuring of the coal industry. The massive closure of coal mines has led to an aggravation of environmental and social problems in the region [7].

Considering the above, we can say that Ukraine is already late in developing a strategy in advance, when this process needs to be planned for 20-30 years. And taking into account the difficult economic and social situation in the region, aggravated by military operations, it is necessary to approach the issue of restructuring the coal industry even more carefully. During the transformation period, it is necessary not only to employ citizens who have been left without work as a result of such a transformation, but also to completely reorient the coal region, ensure the reliability of energy supply from other alternative sources of electricity, including hydrogen energy, and create all the necessary infrastructure for this.

It is encouraging that Ukraine, in matters of mine closure, is guided by the German approach, which is the most systematic and consistent in Europe. So, in a conversation between Prime Minister of Ukraine Denys Shmyhal and Bundeschancellor Angela Merkel in April 2020, the German government assured representatives of Ukraine that it would support Ukraine's pilot project to transform coal regions.

Energy Strategy of Ukraine

The main document defining the energy policy of Ukraine is the Decree of the Cabinet of Ministers of Ukraine dated August 18, 2017 No. 605-r “On Approval of the Energy Strategy of Ukraine for the period up to 2035 “Safety, energy efficiency, competitiveness” [8]. This document canceled the previous Energy Strategy of Ukraine until 2030. The new Strategy provides for reforming the energy sector until 2025, integration with the European energy market, maximum diversification of primary energy supplies, more than halving energy intensity and increasing energy efficiency, increasing the share of renewable energy sources from 4% in 2015 to 25% in 2035. In matters of energy regulation, the basic rules of the EU countries are taken as a basis.

The energy strategy of Ukraine will be implemented in three stages:

1. The first stage (2018-2020) is aimed at creating competitive energy markets and reducing state interference in their work.
2. The second phase (2021-25) focuses on the development of the energy infrastructure and its integration with the European system, as well as attracting the necessary investments in the energy sector.
3. The third stage (2026-2035) concerns sustainable development: meeting commitments to reduce greenhouse gas (GHG) emissions; renewable energy sources; and ensuring energy independence.

Given that Ukraine, when developing an energy strategy, relies on climate and energy strategies common in the EU, the decision to close unprofitable mines by 2035 becomes absolutely logical. In addition, the Ukrainian government has declared a phase-out of coal-fired generation by 2050 [9]. Ukraine ratified the Paris Agreement in 2016 and announced the transition to a climate neutral economy by 2070.

Conclusions

Ukraine has embarked on the path of energy transformation of the transition to a carbon-free economy. This decision will certainly lead to the need to abandon the coal industry. The liquidation of coal mines must necessarily provide for the solution of environmental, economic and social problems. It is absolutely correct that the transformational process of closing mines in Germany is chosen as a reference model. The German government succeeded in the course of a planned transformation not only to eliminate the accumulated environmental damage, the legacy of the former GDR, but also to turn the former coal region of North Rhine-Westphalia into an information and research hub and an environmentally attractive region, where the annual European Flower Show takes place on the site of former industrial facilities. [10].

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Analytical modeling of mine water rebound: Three case studies in closed hard-coal mines in Germany

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Abstract

Purpose. In this paper we present and validate an analytical model of water inflow and rising level in a flooded mine and examine the model robustness and sensitivity to variations of input data considering the examples of three closed hard-coal mines in Germany.

Methods. We used the analytical solution to a boundary value problem of radial ground water flow to the shaft, treated as a big well, and water balance relations for the series of successive stationary positions of a depression cone to simulate a mine water rebound in the mine taking into account vertical distribution of hydraulic conductivity, residual volume of underground workings, and natural pores.

Findings. The modeling demonstrated very good agreement with the measured data for all the studied mines. The maximum relative deviation for the mine water level during the measurement period did not exceed 2.1%; the deviation for the inflow rate to a mine before its flooding did not exceed 0.8%. Sensitivity analysis revealed the higher significance of the residual working volume and hydraulic conductivity for mine water rebound in the case of thick overburden and the growing significance of the infiltration rate and the flooded area size in the case of lower overburden thickness.

Originality. The developed analytical model allows realistic prediction of transient mine water rebound and inflow into a mine with layered heterogeneity of rocks, irregular form of the drained area, and with the inflow/outflow to a neighboring mine and the volume

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of voids as a distributed parameter without gridding the flow domain performed in numerical models.

Practical implications. The study demonstrated the advantages of analytical modeling as a tool for preliminary evaluation and prediction of flooding indicators and parameters of mined out disturbed rocks. In case of uncertain input data, modeling can be considered as an attractive alternative to usually applied numerical methods of modeling ground and mine water flow.

Introduction

Extensive closure of hard-coal mines became a common trend in European countries with developed coal-mining industry in the last decades [1-3]. For example, Belgium closed its hard-coal mines in 1992; France did it by 2005, and the United Kingdom by 2016. The last two active hard-coal mines in Germany, Prosper-Haniel (Ruhr area) and Ibbenbüren (Tecklenburg region), have been closed in December 2018. In 1996 to 2013, 37 hard-coal mines were closed in Ukraine; according to long-term plans of the government, 29 mines should be closed in the country by 2050.

Closure of the hard-coal mines made topical assessing the consequences of extensive and large-scale flooding [4] and sustainable resource utilization in post-mining period [5, 6]. This requires reliable prediction of mine water rebound, understanding the driven forces and key factors of this process, evaluation and refining flow parameters of disturbed rocks, which is of growing significance for water management in post-mining areas.

Most frequently mine water rebounds and inflows to the mines are simulated by numerical methods including finite-difference models [7-10] finite elements [11, 12] and volume balance models (like the box model 0), which require, as a rule, many geological data for large mined out areas with quite heterogeneous rocks. In practice, studying the process of flooding the mines often runs across the scarcity and uncertainty of available data, which creates some difficulties to the application of widely used numerical models that need detailed parameter distributions on fine grids. At the same time, many data on spatial distributions of underground workings, especially those old and abandoned, are often either unavailable or uncertain.

Under these limitations numerical models may lose their advantages in comparison to other more simple methods based on fundamental equations of water balance and seepage theory including analytical methods for modeling ground water flow [14, 15]. Moreover, in many studies, especially for preliminary assessments, a detailed account for geometry of underground voids is unnecessary except some specific cases like inter-mine hydraulic connections or drainage through underground galleries. But even this case can be simulated by analytical methods [15, 16].

In this paper we present an updated analytical model of inflow and rising mine water level in a mine being flooded that has been presented firstly in [15] and updated in [17]. The aim of this study is to demonstrate the possibilities of analytical modeling to evaluate and predict flooding indicators and parameters of mined out rocks. To perform a comprehensive study we examined the model robustness and sensitivity to key parameter variations on the examples of three flooded mines in Germany.

Methods

Below we describe an analytical model to analyze flooding a mine applicable under the following assumptions.

1. Generally we simulate an isolated mine; however, hydraulic connections to neighboring mines can be taken into account as additional terms in the water balance equation.
2. The draining effect of a mine is simulated by a single well located in a geometrical center of the flow domain of circular form. Thereby we simulate radially symmetrical ground water flow to the shaft.
3. Underground workings within the mine are interconnected, so if the mine water level rises at a rate up to a few m/d, horizontal disturbances of flow propagate much faster than vertical ones; hence, the mine water level rises simultaneously in all workings.
4. Rocks within the drained area have layered heterogeneity because of geological settings and mining operations.
5. The residual volume of voids created by mining operations is uniformly distributed over each horizontal section within the mine.
6. The ground water level on the outer boundary of the flow domain remains stable during flooding the mine.

Under these assumptions we can simulate radial ground water flow to the shaft with the time-dependent water level at the inner boundary (Figure 1). The outer and inner boundaries of the flow domain in a planar view are replaced with two circles shown by dashed lines in Figure 2.

To keep the maximum conformity between the real flow domain and the radial flow domain in the model we assume their areas are equal, with the shaft located in the geometrical center of the real domain. This can be acceptable under the assumption nr. 3 on interconnectivity of all underground workings even if there are irregularities of their locations. The evaluation of how shaft location influence the mine water rebound needs a special numerical study.

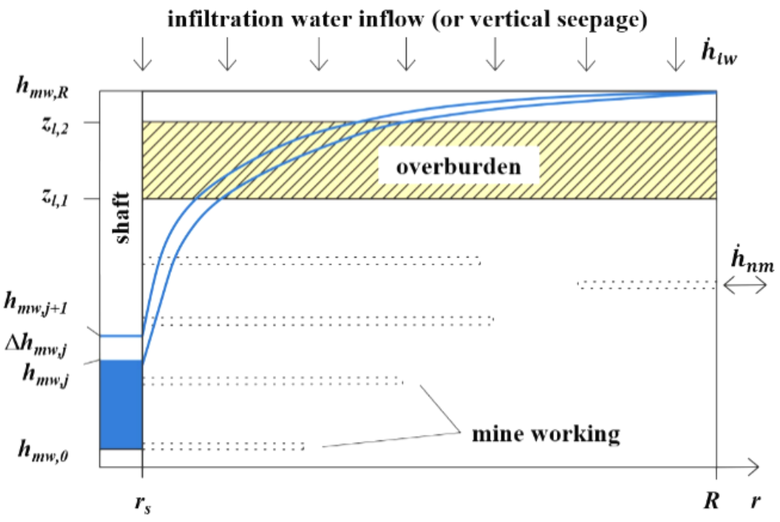


Fig. 1. Vertical cross-section of the flow domain

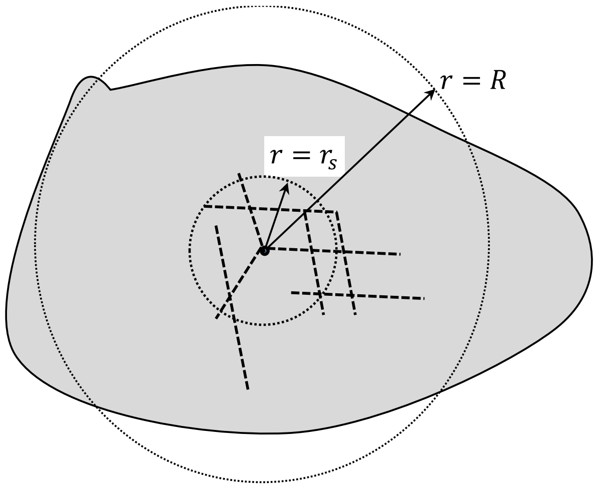


Fig. 2. Approximation of flow domain boundaries. Bold lines are real boundaries, a point is a shaft, dot lines are the circle approximation of outer and inner boundaries, and dash lines are the contours of underground workings

Ground water flow in a mine being flooded can be governed by the equation of radial flow to a single well, with the radial coordinate r in the range $r_s \leq r \leq R$

$$\frac{\partial(n_e \cdot h_{gw})}{\partial t} = \frac{1}{r} \cdot \frac{\partial}{\partial r} \cdot \left(k_f \cdot h_{gw} \cdot r \cdot \frac{\partial h_{gw}}{\partial r}\right) + \dot{h}_{iw} + \dot{h}_{nm} \tag{1}$$

where

n_e – total effective porosity of rocks, dimensionless;

$n_e = n_{e,n} + n_{e,a}$;

$n_{e,n}$ – natural floodable porosity, dimensionless;

$n_{e,a}$ – porosity of anthropogenic origin emerged as a result of mining operations, dimensionless;

h_{gw} – ground water level, m SL;

k_f the hydraulic conductivity of rocks, m/d,

r the radial coordinate, m;

t – time, d;

$\dot{h}_{iw}$ – specific inflow rate of infiltration water to the flooded area, m/d;

$\dot{h}_{nm}$ – specific outflow rate (related to the flooded area) to neighbouring mines through connective galleries, m/d.

The ground water level h_{gw} at the inner boundary $r = r_s$ changes in time simultaneously with the water level in the shaft and connected underground workings h_{mw}:

$$h_{gw}(r_s, t) = h_{mw}(t). \tag{2}$$

The hydraulic radius r_s of the shaft can be evaluated as

$$r_s = \sqrt{\frac{A_{rw,av}}{\pi}}, \tag{3}$$

where:

$A_{rw,av}$ – average value of $A_{rw}(z)$ which is the horizontal area of the residual volume all underground workings at the elevation *z,* m^2; it is calculated as

$$A_{rw}(z) = \frac{V_{rw,12}}{(z_{l,2} - z_{l,1})}, \tag{4}$$

where:

$V_{rw,12}(z)$ – volume of all underground workings in the layer limited by two horizontal sections $z = z_{l,1}$ and $z = z_{l,2}$ ($z_{l,1} \le z \le z_{l,2}$), m^3.

The ground water head h_{gw} on the outer boundary $r = R$ remains constant till the mine water level will completely rebound

$$h_{gw}(R, t) = h_{gw,R}. \tag{5}$$

The radius R of the flow domain is evaluated similar to Eq. 3

$$R = \sqrt{A_{wca}/\pi}, \tag{6}$$

where:

A_{wca} – surface of the water catchment area drained by the mine, m^2.

At first approximation this area can be represented as the combination of areas each drained by one of mining zones located at different depths, with each zone having its individual area of influence. As a rule, the lowest mining zone has the largest area of drainage influence. Within each zone we can discriminate two subzones; the first one envelops the outer horizontal contour of underground workings (A_e), the second one is the ring-like area of drainage influence around the first zone (A_d). Under this considerations the water catchment area of the mine can be evaluated as follows

$$A_{wca} = A_e + A_d, \quad (7)$$

where:

A_e – area enclosing the horizontal projections of all underground excavations, m^2;

A_d – ring-like area drained by all underground workings, m^2.

Converting the actual water catchment area to its circular equivalent of the same area (Figure 3), taking into account Eq. 7 and overlapping the different projections of mining zones located at different depths we can suggest

$$R_e \leq R \leq R_e + R_d,$$

where:

R_e – radius of a circle with the area equal to A_e, m;

R_d – distance of drainage influence created by underground workings concentrated in the circle of the radius R_e, m.

Following Eq. 6 and the assumption on circular form we can evaluate R_e as

$$R_e = \sqrt{\frac{A_e}{\pi}}.$$

The distance of drainage influence R_d can be evaluated for each mining zone individually. However, regarding to uncertainties of the data on locations of underground workings and hydraulic connections, the optimal approach to evaluate R_d is to calculate the draining influence for the whole mine.

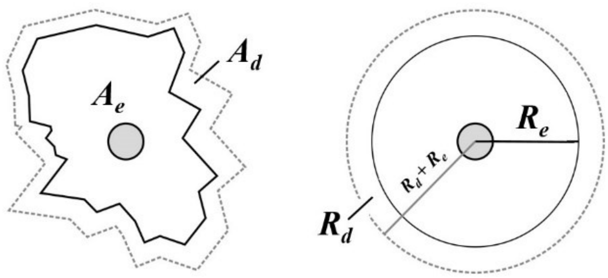


Fig. 3. Conversion of the real area of drainage influence (left) into the model-confirming shape (right)

The well-known formulae of W. Sichardt and I. Kusakin [14] valid for a single well in homogenous aquifer hardly can be applied in case of mined out rocks. In contrast, the formulae proposed by Ye. Kerkis [18, 19] based on empirical data on mine drainage took into account the specifics of mined out rocks and are valid for late stages of mine drainage, which is in good agreement with the conditions of mines before their flooding. Regarding to overlapping of drainage influence zones the expected value of the radius *R* can be calculated as

$$R_e = \sqrt{R_e + \frac{R_d}{2}}, \tag{8}$$

where R_d is calculated by the formulae in [19] and refined in modeling of mine water rebound.

The term $\dot{h}_{nm}$ in Eq. 1 can be calculated as

$$\dot{h}_{nm} = \frac{\dot{V}_{nm}}{A_{wca}}, \tag{9}$$

where:

$\dot{V}_{nm}$– outflow rate to neighboring mines through connective galleries, m^3/d.

The boundary value problem defined by Eqs. 1, 2, and 5 is non-linear because rock transmissivity $T = k_f \cdot h_{th,gw}$ depends on the groundwater-filled thickness $h_{th,gw}$. Besides, the mine water level $h_{mw}(t)$ in Eq. 2 depends on the inflows governed by ground water head gradient. For these reasons Eq. 1 cannot be solved in an integral form, therefore we divide the total period of flooding t_f on a number *N* of equal time steps of duration Δt, so

$$\Delta t = \frac{t_f}{N}, t_j = j\Delta t, j = 0, \dots, N, \tag{10}$$

and the mine water level before flooding $h_{mw}(0) = h_{mw,0}$.

Instead of solving the non-steady flow problem defined by Eqs. 1, 2, and 5 we solve a series of *N* successive steady-state flow problems that differ each from other by the mine water level at the inner boundary $r = r_s$. For each *j*-th steady-state flow problem we calculate the water balance defined by the equation

$$\dot{V}_{in,j} - \dot{V}_{nm,j} = \frac{\Delta V_{\Sigma,j}}{\Delta t}, \tag{11}$$

where:

$\dot{V}_{in,j} = \dot{V}_{gw,j} + \dot{V}_{iw,j}$, m^3/d;

$\dot{V}_{gw,j}$ – the ground water inflow rate, m^3/d;

$\dot{V}_{iw,j}$ – infiltration water inflow rate (or vertical seepage rate), m^3/d;

$\dot{V}_{nm,j}$ – outflow rate to the neighboring mine(s); all are calculated for *j*-th time interval, m^3/d;

$\Delta V_{\Sigma,j}$ – change of water volume in the flow domain during the period Δt, m^3.

Ground water inflow rate to the mine is calculated based on Dupuit-Thiem formula for radial free surface flow [14].

$$\dot{V}_{gw,j} = \pi \cdot \overline{k}_{f,j} \cdot \frac{h_{gw,R}^2 - h_{mw,j}^2}{ln\left(\frac{R}{r_s}\right)}, \quad (12)$$

where:

$\overline{k}_{f,j}$ – average hydraulic conductivity of rocks within the minimum and maximum water levels during the time interval from t_j to t_{j+1}, m/d; $\overline{k}_{f,j}$ can be evaluated by the formula

$$\overline{k}_{f,j} = \frac{1}{h_{gw,R} - h_{mw,j}} \int_{h_{mw,j}}^{h_{gw,R}} k_f(z) dz \quad (13)$$

Eq. 13 enables taking into account layered heterogeneity of rocks due to geological settings and mining operations. Because of the raising mine water level the hydraulic conductivity $\overline{k}_{f,j}$ changes in time. The average natural porosity is calculated by analogy to Eq. 13.

Infiltration rate (or vertical seepage rate) can be calculated depending on the mine water level position over the bottom of the low-permeable layer $z_{l,1}$

$$\dot{V}_{iw,j} = \begin{cases} k_{f,b} \cdot \pi \cdot R^2, h_{mw} \leq z_{l,1}, \\ \dot{h}_{iw}, h_{mw} \geq z_{l,1}, \end{cases} \quad (14)$$

where:

$k_{f,b}$ – hydraulic conductivity of a low-permeable layer of the overburden, m/d.

Eq. 14 means that the hydraulic conductivity of low-permeable layer controls the infiltration rate to underground workings until the mine water level is lower than the layer bottom. In practice $k_{f,b}$ and $\dot{h}_{iw}$ are quite often evaluated based on the water balance before flooding.

The outflow rate to neighboring mines $\dot{V}_{nm,j}$ is calculated for each case individually. In case if the hydraulic parameters of a connective inter-mine gallery are available, the method proposed and tested in [15] can be applied. If two mines, one is being flooded, the other is drained, are contacted through low-permeable barrier, the inflow rate to the drained mine can be calculated as shown below in the next section on the example of the colliery Königsborn.

The volume of water that flows in the mine $\Delta V_{\Sigma,j}$ during the time interval Δt is distributed between residual man-made voids including underground workings of the volume $\Delta V_{rw,j}$ and floodable natural pores of the volume $\Delta n_{e,n,j}$

$$\Delta V_{\Sigma,j} = \Delta V_{rw,j} + \Delta n_{e,n,j}. \quad (15)$$

Assuming the interconnectivity of all underground workings the volume $\Delta V_{rw,j}$ under relatively slow mine water rebound (i.e. small $\Delta h_{mw,j}$ during Δt) can be calculated as

$$\Delta V_{rw,j} = A_{rw,j} \cdot \Delta h_{mw,j}, \tag{16}$$

where:

$\Delta h_{mw,j}$ – increment of the mine water level during the time interval Δt, m.

The volume $\Delta n_{e,n,j}$ is the volume of rocks limited by two curves in Figure 1 that are the surfaces of ground water head within the depression cone at the beginning and the end of the time interval Δt multiplied by natural floodable porosity $n_{e,n}$. The value $\Delta V_{e,n,j}$ is calculated based on the ground water head for free surface flow at the discharge defined by Eq. 10.

Using Eqs. 15 and 16 we can rewrite Eq. 11

$$\Delta V_{\Sigma,j} = A_{rw,j} \cdot \Delta h_{mw,j} + \dot{V}_{nm,j} \cdot \Delta t + \Delta V_{e,n,j}, \tag{17}$$

and calculate the rise of the mine water level during the time interval Δt as follows

$$\Delta h_{mw,j} = \frac{\Delta V_{\Sigma,j} - \dot{V}_{nm,j} \cdot \Delta t - \Delta V_{e,n,j}}{A_{rw,j}}. \tag{18}$$

Because of non-linearity of Eq. 18 ($\Delta V_{e,n,j}$depends on the mine water level increment $\Delta h_{mw,j}$) we solve it numerically using an iterative procedure.

The mine water level at the moment t_{j+1} is calculated by adding $\Delta h_{mw,j}$ to the mine water level at t_j

$$h_{mw,j+1} = h_{mw,j} + \Delta h_{mw,j}. \tag{19}$$

Eqs. 11–19 define the time-dependent cycle; after its completion we obtain the mine water level and water balance components for all moments t_j during the flooding period.

To validate the model we have first to minimize the deviation $\Delta\dot{V}_{iw}$ between the calculated and measured initial inflow rate to the mine, which allows balancing inflows of ground water and infiltration water before flooding. Then we have to minimize the deviation Δh_{mw} between the calculated and measured mine water level for the period $[0, t_f]$

$$\Delta h_{mw} = \sqrt{\frac{1}{t_f}\int_0^{t_f}\left[h_{mw,c}(\tau) - h_{mw,m}(\tau)\right]^2 d\tau}, \tag{20}$$

where:

$h_{mw,c}$ and $h_{mw,m}$ – measured and calculated mine water level, respectively, m SL.

The deviation in Eq. 20 is the function depending on model parameters; those minimizing Δh_{mw} can be interpreted as optimal model parameters for the measured mine water rebound. Regarding to low accuracy of geological data the task has to be evaluation of not only the optimal values of parameters but also their plausible intervals and model sensitivity to parameters variation.

The model sensitivity can be evaluated as the change of Δh_{mw} caused by parameter variations. To evaluate the model sensitivity we used the relative deviation $\Delta h_{mw,r}$ (Eq. 20)

$$\Delta h_{mw,r} = \frac{\Delta h_{mw}}{h_{mw,dif}} \cdot 100\%, \quad (21)$$

where:

Δh_{mw} – the deviation calculated by Eq. 20, m;

$h_{mw,dif} = h_{mw,max} - h_{mw,min}$, $h_{mw,dif}$ – difference between the highest $h_{mw,max}$ and lowest $h_{mw,min}$ water levels during mine water rebound, m.

In this paper we examine the influence of four parameters on model sensitivity that are the radius of the flooded area *R*, the specific inflow rate of infiltration water to the flooded area $\dot{h}_{iw}$, the volume of residual underground workings V_{rw}, and hydraulic conductivity k_f; the last two parameters depend on the vertical coordinate *z.* Model validation and parameter identification are performed in the following steps:

1. evaluation of the guessed parameters (R,$\dot{h}_{iw}$) for which the calculated initial inflow rate is the closest to the initial measured inflow rate,
2. variation of the distributions of underground workings and hydraulic conductivity of rocks within estimated intervals in order to achieve the best coincidence with the measured mine water level,
3. analysis of model sensitivity to parameter variations.

The algorithm has been implemented and tested by D.V. Rudakov in the Turbo-Pascal programming environment.

Results and discussion

The analytical model was used for modeling of mine water rebounds in three selected German mines (Figure 4, Table 1) [20]. The collieries Westfalen (in Ahlen [North Rhine-Westphalia]) and Königsborn (in Unna [North Rhine-Westphalia]) are located in the south-east of the former Ruhr hard-coal mining area. The colliery Ibbenbüren is located in the Tecklenburg region (North Rhine-Westphalia). These three collieries have been closed and flooded for many years ago. They differ in their thickness of the overburden strata that consist of the less permeable strata of the Emscher formation (claystone) and the fissured and water-bearing strata of the Upper Cretaceous (marl limestone). Vertical distribution of the residual volume of under-ground workings for the studies mines is shown in Figure 5.

Fig. 4. Location map of studied mines in Germany (Red squares: I: colliery Ibbenbüren. K: colliery Königsborn. W: colliery Westfalen. Numbers: last active hard-coal mines. 1 – colliery Prosper-Haniel. 2 – colliery Ibbenbüren) [21]

Table 1. Basic data on flooding the selected mines

Colliery	Westfalen	Königsborn	Ibbenbüren
Day when flooding began	04.09.2000	15.09.1996	01.01.1980
Measured mine water level, m SL	-1 178	-894	-496
Measured inflow rate into the mine, m^3/d	3 600	4 608	21 744
Day of last available measurement	28.11.2016*	30.11.2016*	28.12.1982
Measured mine water level in the shaft, m SL	-431	301	66
Area occupied by the mine, km^2	140	16	37
Residual volume created by mining, m^3	$1.02{\cdot}10^7$	$1.01{\cdot}10^7$	$5.54{\cdot}10^6$

* flooding is still continuing

The colliery Westfalen has the biggest thickness of overburden rocks that varies between 795m and 889m. The thickness of the less permeable strata of the Emscher formation is between 475m and 600m.

Compared to the colliery Westfalen the colliery Königsborn has a lower overburden thickness. It varies between 180m and 300m. The average layer thickness of the fissured marl limestones is about 130m.

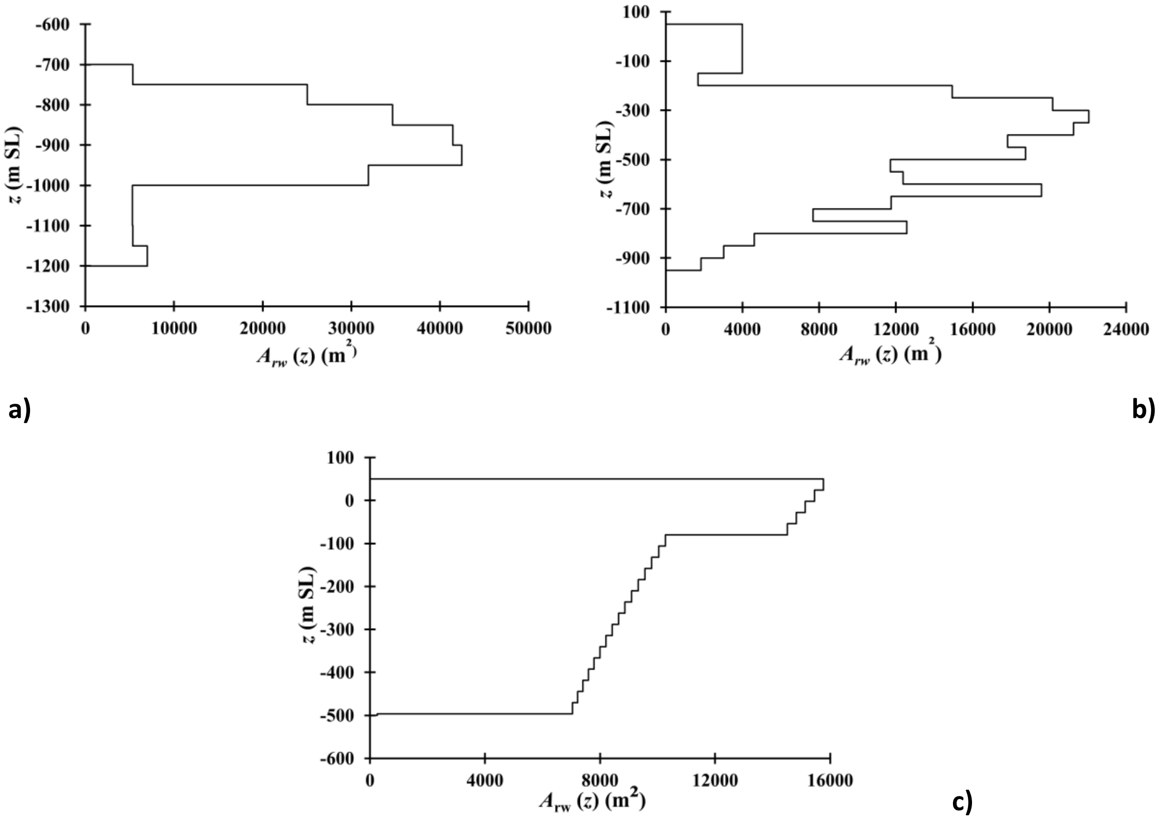


Fig. 5. Vertical distribution of the residual volume of underground workings expressed as the surface of a horizontal cross-section of the mine workings $A_{rw}(z)$: a) colliery Westfalen, b) colliery Königsborn, and 3) colliery Ibbenbüren (Westfeld)

Due to close location of the shaft to low-permeable barrier to the neighboring colliery Heinrich Robert/Ost the area of colliery Königsborn is approximated as the half-circle. In calculations we took into account that the hydraulic conductivity of the Turonium + Cenomanium aquifer (Upper Cretaceous) is three orders higher than the hydraulic conductivity of the intact Carboniferous rocks.

Outflow rate to the neighboring mine at the mine water level $h_{mw,Kb}$ in the colliery Königsborn below the bottom of the Turonium + Cenomanium aquifer at $z_{T+C,1}$= -217.8m (position "1" in Figure 6) is calculated assuming unconfined ground water flow through a vertical wall of the length 4km with the hydraulic conductivity of intact Carboniferous rocks of 10^{-5}m/d and the mine water level in the colliery Heinrich Robert/Ost maintained at -900m SL

$$\dot{V}_{nm,1} = k_{f,b} \cdot \frac{h_{mw,Kb}^2 - h_{mw,HRO}^2}{2l_b} \cdot l_{nm}, \tag{22}$$

where:

$h_{mw,Kb}$ and $h_{mw,HRO}$ – mine water level in the collieries Königsborn and Heinrich Robert/Ost, m SL;

l_b – thickness of the low-permeable barrier between the mines, m;

l_{nm} – horizontal length of this barrier with the neighboring mine, m;

$k_{f,b}$ – its hydraulic conductivity, m/d.

For the mine water level over the bottom of the Turonium + Cenomanium aquifer ($h_{mw,Kb} \geq z_{T+C,1}$) and below than its top ($h_{mw,Kb} \leq z_{T+C,2}$) at position "2" in Figure 6 the additional outflow rate from the colliery Königsborn can be calculated as

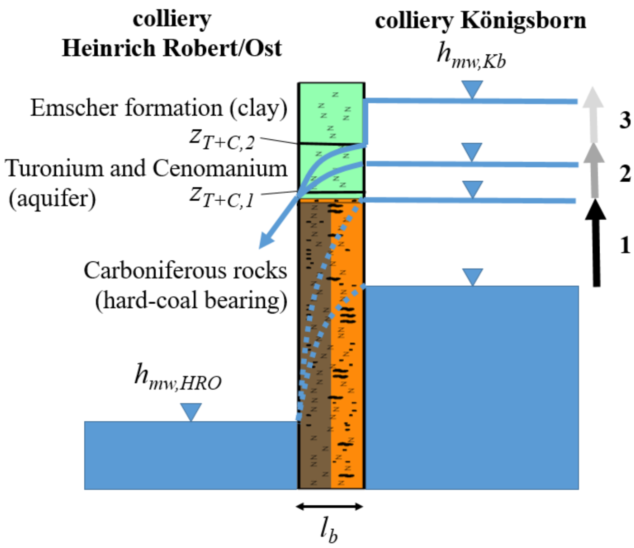


Fig. 6. Sketch to calculate water flow through the low-permeable barrier between two mines. 1, 2, 3 are the water levels in the flooded mine and ground water heads in the low-permeable barrier. Notations see in text

$$\dot{V}_{nm,2} = \dot{V}_{nm,1} + k_{f,T+C} \cdot \frac{h^2_{mw,Kb} - z^2_{T+C,1}}{2 l_b} \cdot l_{nm}, \quad (23)$$

where

$k_{f,T+C}$ – hydraulic conductivity of the Turonium + Cenomanium aquifer, m/d;

For the mine water level higher than the top of the Turonium + Cenomanium aquifer $z_{T+C,2}$ ($h_{mw,Kb} \geq z_{T+C,2}$) the additional outflow rate from the colliery Königsborn is calculated as confined flow (position "3" in Figure 6) by Eq. 22 replacing its second term in the right hand side with

$$k_{f,T+C} \cdot \frac{h_{mw,Kb} - z_{T+C,1}}{2} \cdot \frac{z_{T+C,2} - z_{T+C,1}}{l_b} l_{nm}.$$

The colliery Ibbenbüren is divided into a western and eastern mining field. While the mining field "Westfeld" was flooded in the 1970s, hard-coal mining was carried out in the mining field "Ostfeld" until 2018. The hard-coal deposit of the colliery Ibbenbüren (in the following, only the mining field "Westfeld" is considered) emerges morphologically from the surrounding area as a horst structure of the Carboniferous strata. Therefore, the hard coal-bearing strata are not covered by any overburden and crops out at the surface. Due to the missing of an overburden, the rainwater enters the mine directly.

Using the available data on geology, hydrogeology, and mining we evaluated the optimal model parameters (Table 2) that minimize the deviation Δh_{mw} between measured and calculated mine water level in Eq. 20.

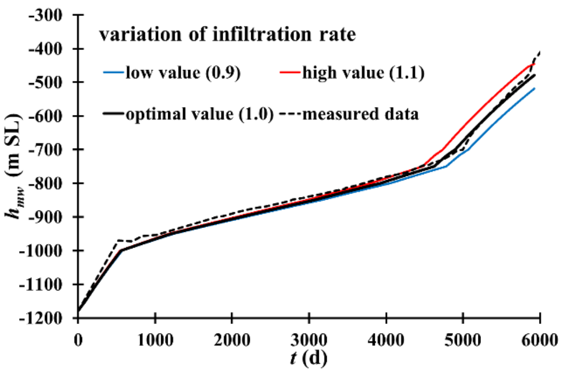
Table 2. Parameters evaluated by inverse modeling

colliery	Westfalen	Königsborn	Ibbenbüren
R, m	5 700	3 000	2 800
$V_{rw}{}^{*}$, m^3	$1.02{\cdot}10^{7}$	$1.01{\cdot}10^{7}$	$5.5{\cdot}10^{6}$
$\dot{h}_{iw}$, m/d	$8.0{\cdot}10^{-6}$	$1.39{\cdot}10^{-4}$	$6.35{\cdot}10^{-4}$
$k_{f,av}{}^{**}$, m/s	$4.65{\cdot}10^{-8}$	$8.32{\cdot}10^{-8}$	$1.29{\cdot}10^{-9}$

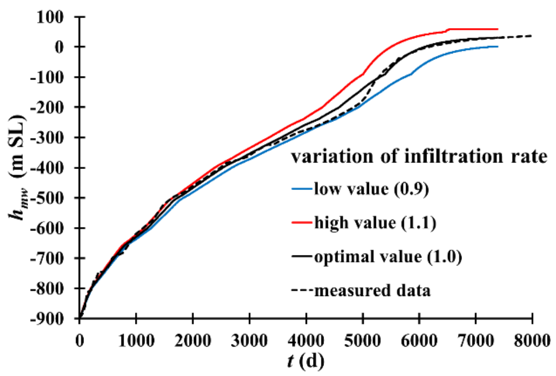
* total value distributed over the flooded thickness of rocks;

** average value distributed over the flooded thickness of rocks.

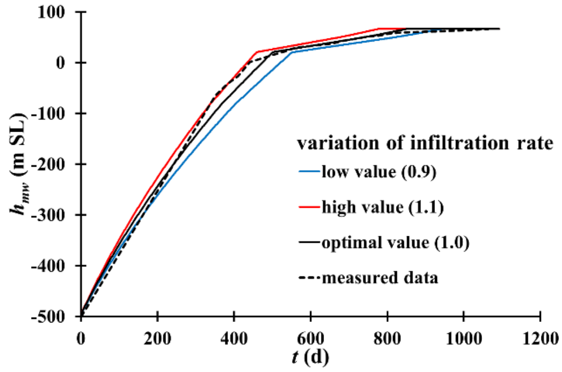
The calculations demonstrated very good agreement with the measured data for all mines (Figure 7, Table 3). The maximum relative deviation for the mine water level during the measurement period did not exceed 2.1%; the deviation for the inflow rate to a mine before its flooding did not exceed 0.8%.



a)



b)



c)

Fig. 7. Mine water level h_{mw} versus time t in the collieries Westfalen(a), Königsborn (b), Ibbenbüren (c) at the parameters from Table 3 and different infiltration rates: 1,0ε (black line), 0,9ε (blue line), 1,1ε (red line); black dots show the measured mine water level

Changing of the infiltration rate $\dot{h}_{iw}$ up to ±10% does not deviate significantly the calculated values from those measured during the most part of flooding interval; changing of other parameters has similar effect. The results of sensitivity analysis (Figure 8) confirmed that the parameters in Table 3 are optimal for Eq. 20 because they minimize the deviation Δh_{mw} whereas changing all four varied parameters increase Δh_{mw}.

Table 3. Minimum relative deviations between measured and calculated data, %

colliery	Westfalen	Königsborn	Ibbenbüren
mine water level	2.1	1.2	1.0
initial inflow rate	0.8	0.1	0.1

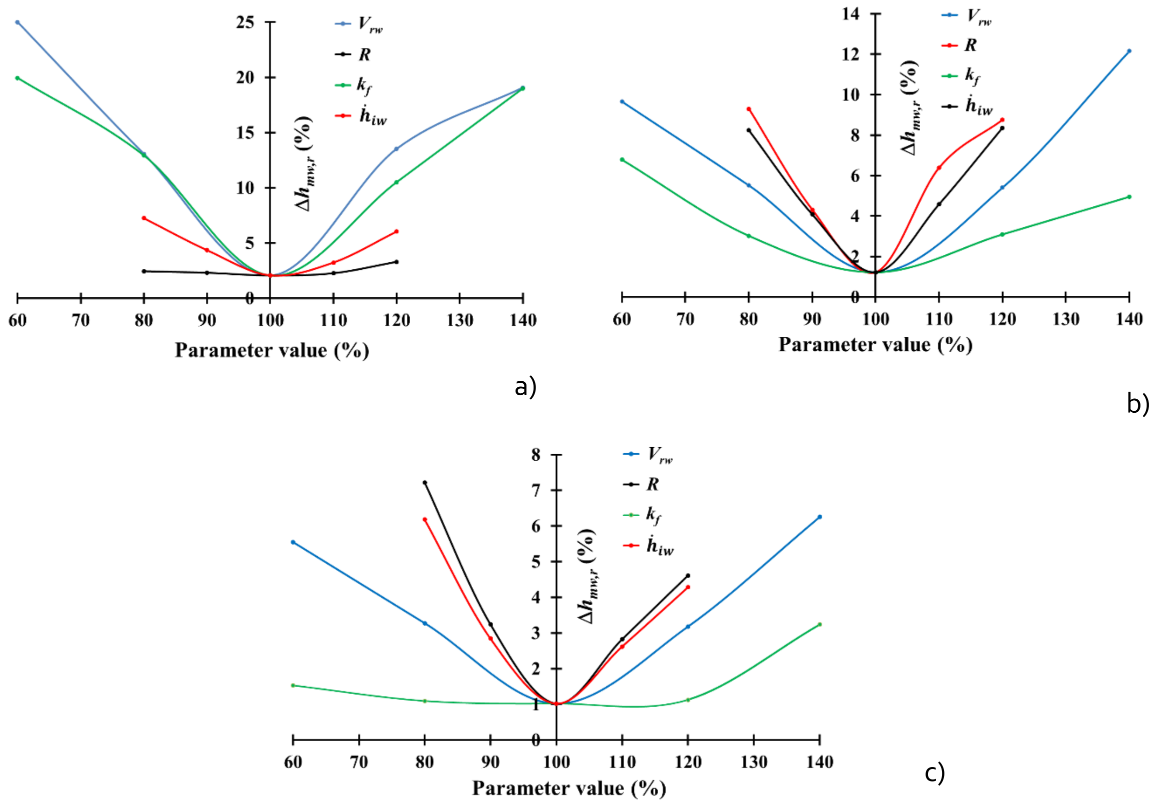


Fig. 8. Relative deviation $\Delta h_{mw,r}$ between calculated and measured mine water level (Eq. 21) versus change of input parameters for the collieries Westfalen (a), Königsborn(b), Ibbenbüren (c)

For the colliery Westfalen with higher thickness of overburden the most influential parameters in terms of model sensitivity were found the residual volume of underground workings V_{rw} and hydraulic permeability of rocks k_f, which means domination of the factors of deep water inflow. In contrast, for the collieries Königsborn and Ibbenbüren with lower and insignificant thickness of overburden the most influential parameters are the flooded area radius R and the infiltration rate

$\dot{h}_{iw}$; this is fully in line with growing significance of parameters that characterize vertical recharge of the flooded area.

Conclusions

The mathematical model based on analytical relations of ground water flow theory and adapted to the availability of critical hydrogeological and mining parameters has been developed to simulate flooding the underground workings. The model has been tested for the examples of three closed hard-coal mines in Germany selected as case studies.

We used the analytical solution describing radial ground water flow to the shaft and water balance relations for the series of successive stationary depression cones. It takes into account layered heterogeneity of hydraulic conductivity, porosity, vertical distribution of underground workings, irregular form of the drained area, the inflow/outflow to neighboring mines without gridding the flow domain as it is performed in numerical models.

The modeling demonstrated very good agreement with the measured data for all studied mines. The maximum relative deviation for mine water level during the measurement period did not exceed 2.1% and the deviation for the inflow rate before flooding did not exceed 0.8%. Sensitivity analysis revealed the higher role of the residual working volume and hydraulic conductivity for mine water rebound in case of thick overburden above underground workings like colliery Westfalen. Along with this, lowering thickness of overburden increases the influence the infiltration rate and the flooded area size in terms of model sensitivity for collieries Königsborn and Ibbenbüren.

The study demonstrated the advantages of analytical modeling as a tool for preliminary evaluation and prediction of flooding indicators and parameters of mined out disturbed rocks. In case of uncertain input data it can be considered as an attractive alternative to usually applied numerical methods of modeling ground and mine water flow.

Acknowledgements

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The Application of freely available Remote Sensing Data in Risk Management Systems for abandoned Mines and Post-mining

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Prof. Dr. Tobias Rudolph[1] and
Prof. Dr. P. Goerke-Mallet[1]

Freely available remote sensing data hold real potential for the geomonitoring and risk management systems that are required for abandoned mines and post-mining. Various remote sensing systems were therefore analysed, compared and assessed in terms of their suitability for geomonitoring tasks.

Introduction

Mining activities over numerous years have had a lasting impact on many regions in Germany and elsewhere in the wider world. In Germany the centuries-old coal mining industry has left behind clear traces, especially in the Ruhr, Saar and Aachen areas. Abandoned elements of the mining industry in the southern part of the Ruhr basin, for example, have been a focal point for risk management actions as here the coal was frequently worked at fairly shallow depths and without today's high standards when it comes to safety and documentation. These legacy elements, including countless mine shafts and shallow workings and many kilometres of tunnels and adits, have as a result created a real risk potential for people and surface structures alike. A comprehensive risk management system, based on a meaningful geomonitoring concept, therefore has to be developed in order to address these challenges [1]. The application of the remote sensing and photogrammetric survey methods available today has proved very promising when it comes to meeting the necessary requirements for such a geomonitoring regime in terms of spatial and temporal coverage. The freely available data from various European and American satellite missions, along with data provided by the EU's INSPIRE initiative (Infrastructure for Spatial Information in the European

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Community), also have significant potential to offer. Work is now under way to investigate how this body of data can be applied and used for risk management activities associated with abandoned mines and post-mining and this article seeks to sum up these investigations and their findings.

Purpose and Methodology

A Master's thesis entitled 'The application of freely available remote sensing data to issues associated with risk management in the field of abandoned mines and post-mining', which was submitted for the degree course on geo-engineering and post-mining at Technische Hochschule Georg Agricola University in Bochum, has provided an analysis of the remote sensing methods and systems currently available and has compared the different types of mining-related features at risk while also assessing the benefits and usefulness of this technology [2].

The findings are based on the methodology presented in Fig. 1. The first step comprised the recording and analysis of currently available remote sensing systems and risk-prone features, the aim being to link these together via an assignment matrix. By this means it was possible to identify how effective individual systems were at monitoring some of these mining-related elements. The advantages and drawbacks of suitable systems were then weighed against each other and checks were made to establish whether the generated data could basically be incorporated into a risk management system before the actual application was tested for real.

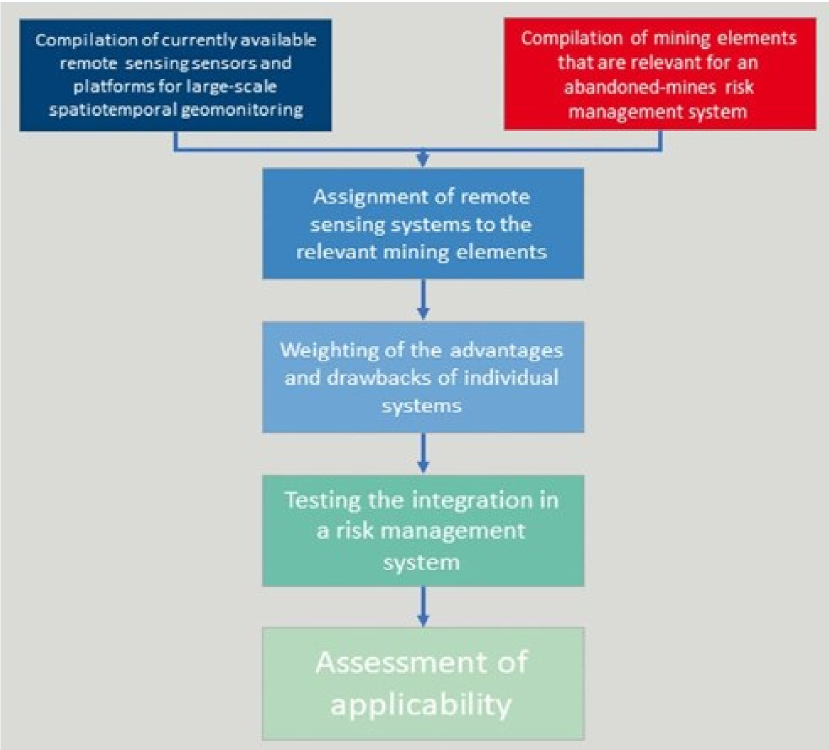


Fig. 1. Methodology

Remote Sensing Systems and Mining Features selected for the Survey

The selection of remote sensing systems and mining features used in the survey was based on current research findings. The investigation covered both active sensors (e. g. radar) and passive sensors (e. g. multispectral cameras) operating on different types of platform [3]. Here the focus was mainly on satellite remote sensing technology (Table 1), as compared with other aerial and ground-based systems this offers certain benefits as far as large-scale geomonitoring is concerned on account of its large capture range, short measurement intervals and free availability over large areas. According to the configuration of the satellite the ground resolution of the target zone will depend on various factors, such as recording method and swath width (swath = strip of land covered by the survey) (Fig. 2).

Table 1: Current and imminent Earth observation satellites

Name	Sensor	Ground resolution [m]	Availability	Comment
EnMAP	Hyperspectral	30	from 2022 [4]	
Landsat 8	Multispectral	15 - 100	since 2013	
Landsat 9	Multispectral	15 - 100	from 2021 [5] [1)]	
Pléiades	Multispectral	0.5 - 2	since 2012	tandem
Pléiades Neo	Multispectral	0.3	since 2021	
RADARSAT 2	C-Band SAR	1 - 100	since 2007	
Sentinel 1	C-Band SAR	5 × 5 - 20 × 40	since 2014	2 (+2 planned) satellites
Sentinel 2	Multispectral	10 - 60	since 2017	2 satellites
Sentinel 5P	Multispectral	7000 × 3500	since 2017	forerunner mission
SPOT 6/7	Multispectral	1.5 - 6	since 1999	tandem
TanDEM X	X-Band SAR	0.25 - 40	since 2007	tandem with TerraSAR X
Terra	Multispectral	15 - 90	since 1999	
TerraSAR X	Band SAR	0.25 - 40	since 2007	tandem with TanDEM X
WorldView [1)]	Multispectral	0.31 - 3.72	since 2014	

[1)] not yet in orbit at the time of writing

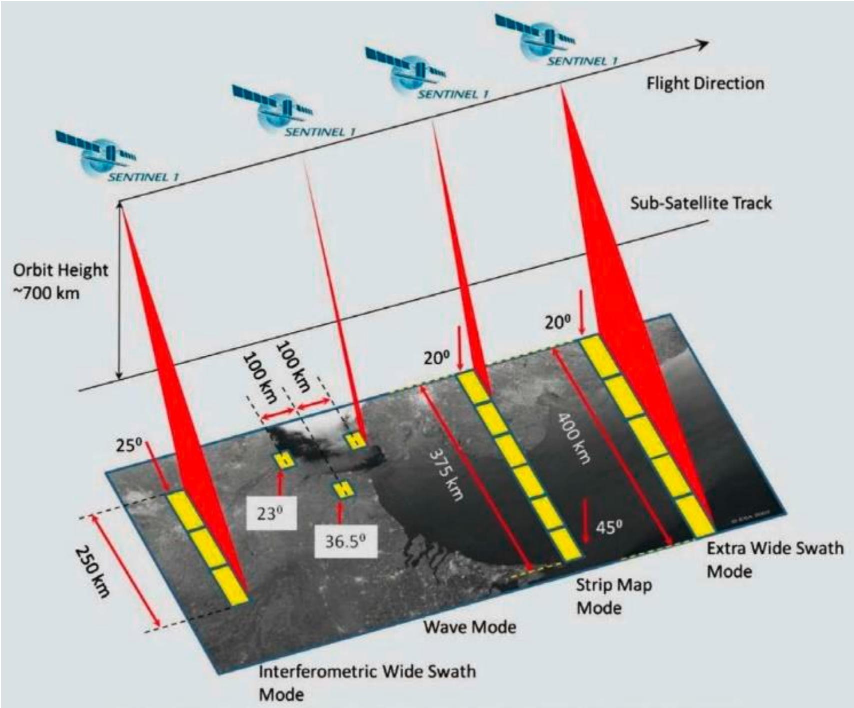


Fig. 2. Schematic representation of different recording methods and swath widths in satellite remote sensing using Sentinel 1 as an example [6]

Because of the comparatively low ground resolution of individual satellite sensors the comparative survey also included, for reference purposes, two commercially available survey drones (UAS - unmanned aerial systems) and the digital orthophotos (DOP) supplied by the Land Survey Offices (in this case the North Rhine-Westphalia LSO) that are freely available in Germany (Table 2). Data from airborne laser scanning missions were not used. The freely available point clouds provided by the state of North Rhine-Westphalia, for example, are generated in a five-year cycle and have a positional accuracy of 30 cm and a height accuracy of 15 cm [7], this making them unsuitable for high-precision, spatiotemporal monitoring.

Table 2. Terrestrial systems for reference purposes

Name	Sensor	Ground resolution [m]	Availability	Comment
Digital Orthophotos NRW	Multispectral	0.1	since 2016[1)]	processed
DJI Phantom 4 RTK	RGB	0.03[2)]	since 2018	
DJI Phantom 4 Multispectral	Multispectral	0.053	since 2019	

1) current ground resolution 10 cm

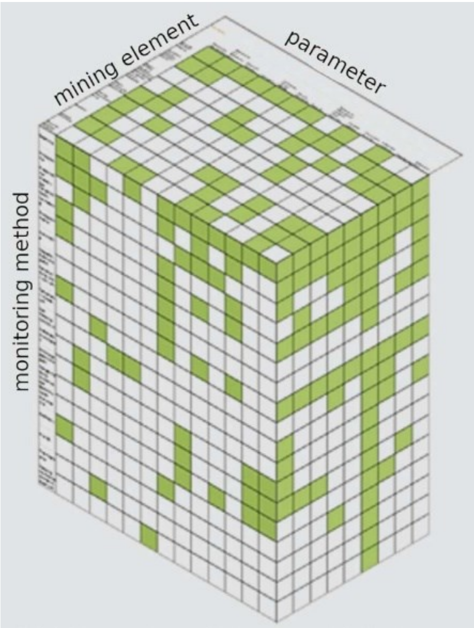
2) at altitude of 100 m

When exploring active and former coal mining sites different published works have taken various (abandoned) mining features for application in the relevant risk management systems [1, 8, 9, 10]. There is not as yet a single uniform system for carrying out this work. Features present in the Ruhr coalfield area were therefore selected for the survey described here [11]:

- Shallow mine workings
- Mine shafts and surface openings
- Subsidence troughs and uplifts
- Discontinuities
- Mine gas emissions at ground surface
- Ground-water and surface-water drainage
- Mine water
- Recycling of mining spoil material
- Site remediation at former mine workings

Assessment Matrix

Several processing steps then followed in which the available remote sensing data were logged, analysed and evaluated for usability within the risk management systems being developed for abandoned mines and post-mining. Here the methodology was based on the principle of the 3D monitoring cube for abandoned mines that shows the relationships between the monitoring process, the mining elements and the various parameters (Fig. 3).



green = correlation, white = no correlation

Fig. 3. Sample presentation of the 3D monitoring cube for abandoned mines [8]

The geomonitoring techniques were first contrasted with the examined remote sensing systems in order to determine how effective the sensors were for measuring various monitoring parameters (e.g. soil water content). Investigations were then conducted to ascertain how suitable the remote measurement of these parameters was for monitoring the mining element in question. Both these investigations used a suitability scale ranging from 0 to 2, where 0 meant 'no suitability', 1 'limited suitability' and 2 'good suitability'.

The mining elements were then assigned directly to the remote sensing systems using an assessment matrix. In order to examine the suitability of a particular remote sensing system for monitoring a certain mining element the corresponding values of the first two tables were offset against one another and an overall value was produced by means of multiplication. A specimen calculation for checking the usability of data from the Terra system for monitoring shallow mine workings is shown in Fig. 4.

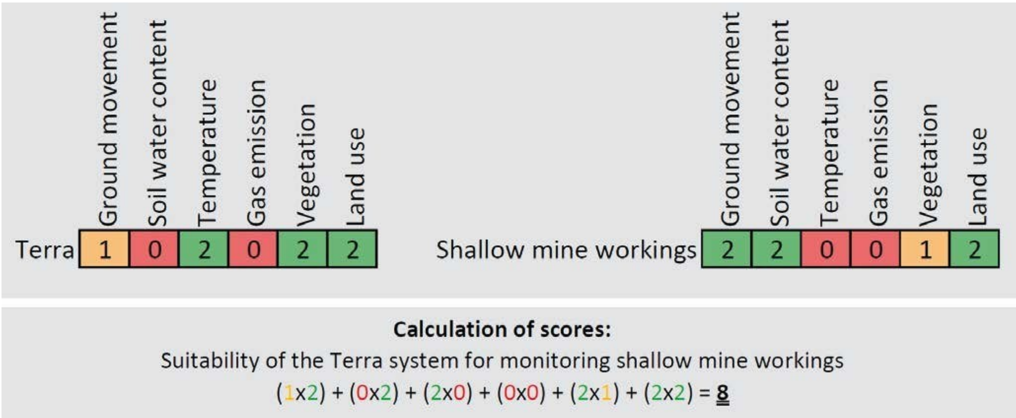


Fig. 4. Case example for calculating the suitability of a remote sensing system for monitoring a mining element

Results

The usability of the parameters for monitoring the mining elements was based on three gradings denoting the suitability of the measurement or observation in question. The findings are displayed in colour in Fig. 4 where 'good suitability' is represented by value 2 (green), 'limited suitability' by the value 1 (yellow) and 'no suitability' by the value 0 (red).

The measurement of vertical and horizontal ground movements, soil water content and actual land use, for example, is a very effective way of monitoring shallow mine workings (value 2). Measuring vegetation parameters is of limited suitability (value 1) as measurable plant damage can occur after a long delay, may not in fact happen at all or may be due to other biogenic or anthropogenic factors. Moreover, such damage is often just the secondary effect of other factors, such as soil water content. Measurements of soil temperature and gas emissions have to date proved unsuitable for the monitoring of this mining element. The evaluation of the remote sensing systems included in the investigations was based on researched performance data for the sensor technology, such as the type, ground resolution and swath width of the sensor unit, the measurement interval and the available products (classification based on NASA Data Processing Levels [12]). Following the initial literature review it was decided not to continue with the investigation of the Pléiades, Pléiades

Neo, RADARSAT-2, SPOT 6/7 and WorldView-3 systems, which were originally included for reference purposes, as it was considered not economically viable to use commercial data in a long-term, large-scale monitoring operation.

	Shallow mine workings	Surface shafts and mine openings	Subsidence troughs and uplifts	Discontinuities	Mine gas emissions	Ground water and surface water	Mine water	Spoil tips	Site remediation
EnMAP	14	12	10	12	6	12	4	8	10
Landsat 8/9	6	6	6	6	6	8	4	8	6
Sentinel-1	12	10	8	10	4	10	4	8	9
Sentinel-2	6	6	6	6	6	8	0	4	6
Sentinel-5P	0	1	0	0	2	1	2	1	1
TanDEM-X	13	11	9	11	5	10	4	6	8
Terra	8	8	8	8	6	8	6	10	7
DOP	6	6	6	6	6	8	0	4	6
Phantom 4 RTK	7	7	7	7	5	6	2	4	5
Phantom 4 Multispectral	8	8	8	8	6	8	2	6	7

Fig. 5. Assignment of remote sensing data to mining elements

As the last step in the analysis process the remote sensing systems were assigned to the mining elements and a value was attributed that signified their suitability for monitoring the element in question. The values range from 0 to 14 (of a theoretically possible 24), as the remote sensing data from one system can be used to monitor several parameters. The results of the analysis are presented in Fig. 5, where the colour scale is graded accordingly.

The system that immediately stands out from the others is the EnMap program, which is not yet fully active. This is the only system to be equipped with a hyper- spectral sensor, which means that it can measure various vegetation, soil and water parameters that can provide important information for the monitoring of legacy elements of the mining industry. It was also found that because of the very low resolution involved the data from Sentinel 5P were unable to contribute in any significant way to the monitoring of the mining elements. Every system included in the survey has problems when it comes to monitoring mine drainage operations as these processes essentially take place far below the observable ground level.

Evaluation

The interpretation of the findings highlighted clear differences between satellite-supported radar and multi-spectral sensors and the data recorded by aircraft and UAS flights in terms of their spatiotemporal coverage and resolution. Satellites have clear advantages when it comes to providing large-scale and fully updated data. With a view to integration in a risk management system all the satellite data meet the requirements for updating, resolution, accuracy, coverage and consistency while the reference systems failed to make the grade due to their long measurement intervals, high measurement outlay and low spatial coverage. However, with their several times higher resolution capacity the latter systems can be used to locally supplement or verify the measurement results from the satellite-borne sensing systems.

Whereas optical sensors are particularly well suited to analysing vegetation and land use, active sensors – which use radar interferometry – are able to detect with great precision the distances between the satellite and the surface of the Earth, in other words they can measure ground movements. Depending on the wave lengths used it is also possible to measure, either directly or indirectly, other parameters such as soil water content. Ground temperatures can only be measured by means of the ASTER sensor system that is fitted to the Terra and Landsat satellites, while it is practically impossible to use the investigated data to detect gas emissions. Even though the Sentinel 5P system can detect single gases, its low resolution capacity is of limited use when it comes to the quantities generated in the form of local mine-gas emissions.

After all the different analysis steps had been completed it was found that the satellite missions by En-MAP, Landsat, Sentinel 1, Sentinel 2 and Terra were highly suitable for monitoring individual mining elements over longer periods of time.

Only by combining all the relevant data together, however, will it be possible to establish a comprehensive risk management regime for the abandoned mines and post-mining sector, as the weaknesses of one system can be offset by the strengths of the others. Here the required technology combination will have to be individually matched to the respective requirements and circumstances of the monitoring zone. An imaginary scenario for two such deployments is shown in Fig. 6.

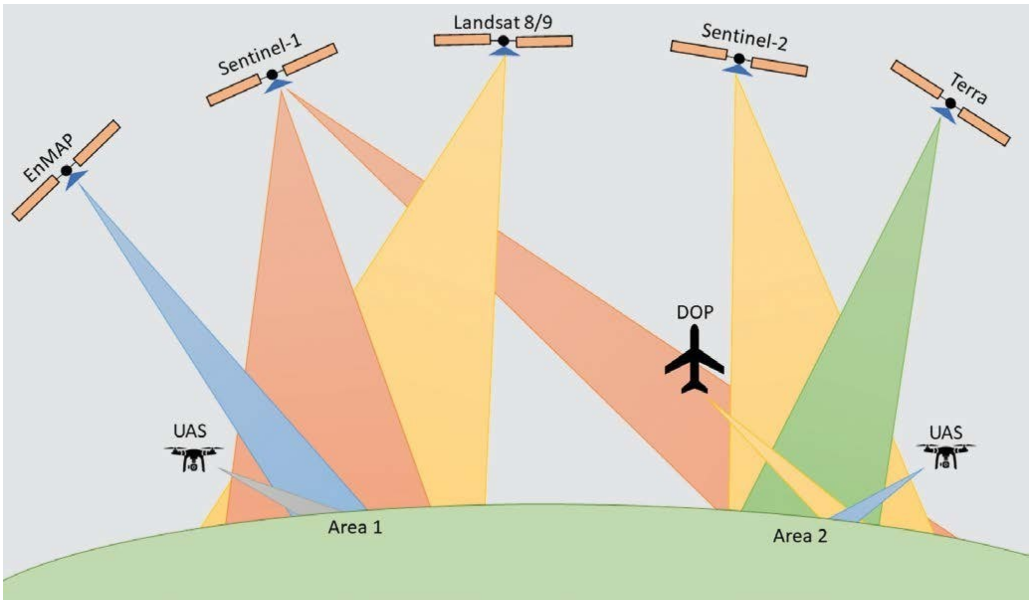


Fig. 6. Application of freely available remote sensing data, digital orthophotos (DOPs) and detailed UAS flights for the geomonitoring of target survey areas

In any case the remote sensing data presented here are but one aspect of a comprehensive risk management regime for the abandoned mines and post-mining sector, for they must also crucially be referenced and validated by means of suitable in-situ measurements. It is also vital to draw on historic data, local experience and expert knowledge as a basis for the risk assessment process.

Conclusions and Outlook

Any risk management system for the abandoned mines and post-mining sector will, because of the extent and complexity of the area being monitored, necessarily impose high demands on a spatio-temporal geomonitoring application. It is clear that today's satellite-borne remote sensing technology, with its hyperspectral, multispectral and radar sensors, is particularly well suited for the large-scale monitoring of abandoned mining and post-mining structures, whereas individual drone flights and orthophotographic images for land surveying purposes, which have a high resolution capacity, can provide detailed information on more confined areas. In order to set up a comprehensive geomonitoring regime it is therefore essential to employ a combination of different remote sensing systems so as to counterbalance the weaknesses of individual sensors and platforms with the strengths of others. The data obtained also have to be verified by local information and interpreted using expert know-how. As part of the future research effort in this topic area the data obtained from the featured systems will have to be examined and coordinated in greater detail and preparations drawn up for their application in a dedicated risk management system.

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Hyperspectral Sensing to Boost AMD Monitoring in Post-Mining Scenery

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The evolving hyperspectral sensors have become a big ally for a large range of applications in remote sensing for the monitoring of a variety of earth ecosystems and processes (natural and anthropogenic). The processes occurring within the mining life cycle are not an exception. Hyperspectral sensors have been widely used in a large number of applications ranging from exploration, operation and post-mining. In this work, the authors explore particularly the use of hyperspectral methods to contribute to the monitoring of one of the most important environmental phenomena that many mining operations might face: acid mine drainage (AMD). Failure of accurately monitoring and remediation of such complex, leads to long-term impacts on ecosystems and human health, in addition to significant financial consequences and reputational damage to operators. Hyperspectral imagery represents one solution to enhance the quality of classical geochemical analyses in post mining-related contaminated scenarios, which can increase the overall accuracy of the monitoring, allowing frequent and multi-temporal observations to detect risk areas and take fast corrective actions.

Environmental monitoring of AMD

Acid mine drainage (AMD) is an environmental phenomenon that can occur either by the natural exposition of sulfate metals to weathering conditions or as a consequence of certain mining activities. Lottermoser [1] defines AMD as a process whereby low pH mine water is formed from the oxidation of sulfide minerals. These acidic and metal-enriched waters can negatively affect the natural ecosystem’s quality and aquatic life. Mainly impacted areas are rivers, lakes, estuaries, and coastal waters. Its advancement can take years or decades and can continue spatially increasing for centuries [1]. Therefore, such an environmental problem needs to be carefully monitored and ideally remediated.

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Several efforts have been applied in order to monitor the spatial distribution of contamination by AMD, commonly involving systematic sampling and laboratory analysis of stream sediment followed by interpolation of the results in assembled distribution maps [2, 3] however, such approaches can be time consuming, costly, and with limited spatial coverage. The environmental monitoring of such complex and diverse adverse effects on earth ecosystems requires frequent and multi-temporal observations. Active control can serve as an effective method for successful conservation or rehabilitation of natural systems. In this sense, remote sensing tools have been widely used in many environmental investigations since the technique enables the use of digital imaging sensors to reveal key information from a distance, typically from satellite or aircraft [4]. Thus, traditional monitoring studies based only on certain ground-sampling locations can be expanded to large areas from derived aerial-image products. In general, optical spectral analysis refers to the measurement of matter-light interactions as a function of their energy. More specifically, this comprehends any radiation that is emitted, reflected or transmitted from the investigated target [5]. The development of new generations of sensors made it possible to examine processes on earth, beyond the visible spectrum of the human eye. Commonly, these devices can acquire data in different wavelength ranges – from the ultraviolet to the far-infrared spectrum of electromagnetic radiation – and have evolved from spectral over multispectral to hyperspectral sensors for different kinds of earth's surface investigations.

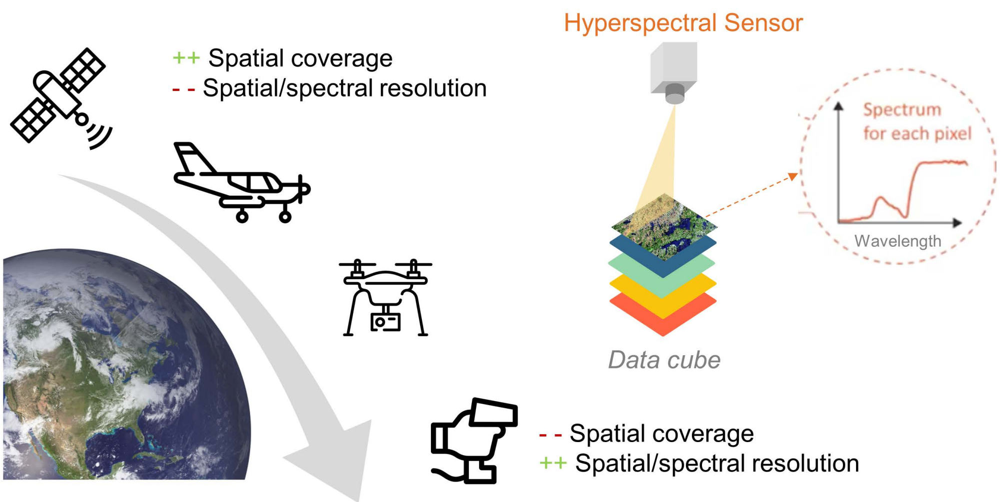

Fig. 1. Downscaling (multi-scale) scheme for hyperspectral sensing from high spatial cover age of satellite based sensors to high spectral resolution of drone-borne/terrestrial sensors and hyperspectral data cube scanning general concept. Source: THGA

The trend toward progress for higher spectral resolution (hyperspectral remote sensing) has grown in the last decades. While the majority of space-borne sensors traditionally used for geologic remote sensing like ASTER or Landsat contains information in only a few wavelengths or bands, hyperspectral sensors are able to provide a continuous spectrum for each pixel of the dataset [6]. Currently, hyperspectral sensors are employed in a wide range of spatial dimensions (scales) according to the platform used for data acquisition, e. g., satellite, airborne, up to lab- scale sensing for detailed-mineralogical analyses (Figure 1). The emergent use of unmanned aerial systems (UAS), like multi-copters, and new generation lightweight hyperspectral sensors have become a tool to collect data at a higher spatial resolution than some of their aircraft and satellite counterparts, resulting in greater precision (higher spatial resolution of a scene and enabling the investigation of up to a few centimeters sized pixels) [7]. In this article, some studies will be reviewed that have took advantage of hyperspectral imaging to monitor AMD occurrence, mineralogy and related geochemistry.

From spectral to hyperspectral sensors

The main purpose of hyperspectral remote sensing – also known as imaging spectrometry or imaging spectroscopy – is to measure quantitatively the components of the Earth System from calibrated (radiance, reflectance or emissivity) spectra acquired as images in many, narrow and contiguous spectral bands [6]. Hyperspectral sensors can capture data from the visible through the near-infrared wavelength ranges over a determined terrestrial surface of the earth. Collected data results in a three-dimensional data-cube composed of a set of pixels represented as vectors, containing the measurement corresponding to a specific wave-length [8]. This provides the opportunity to query a plottable spectral signature for each spatial position on a surface. The accompanying amount of information results in much larger data sizes compared to polychromatic or multispectral imagery [9].

The vector size is equal to the number of bands or spectral channels. In opposition to multispectral data, which usually acquire up to tens of bands, hyperspectral data channels are able to collect several hundreds of contiguous bands along the spectral axis [6].

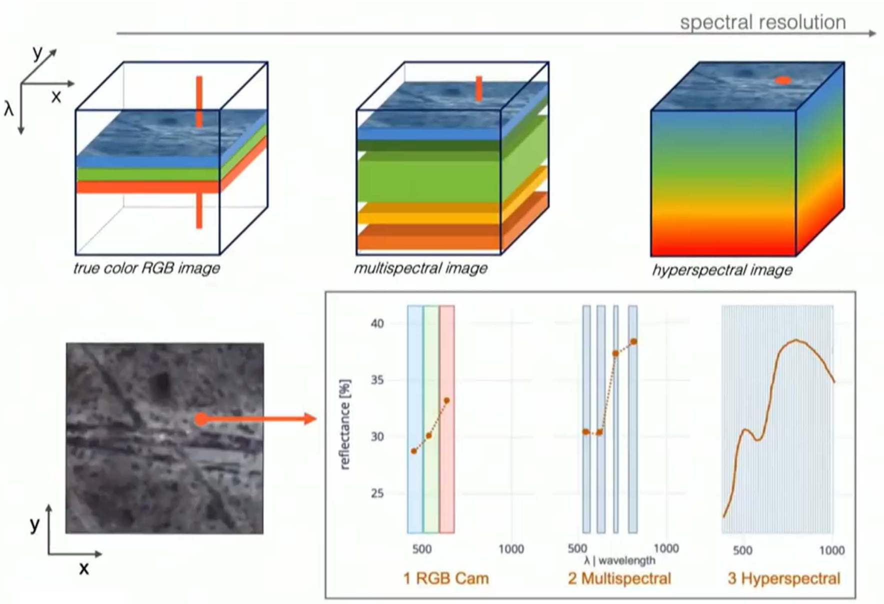

Fig. 2. Schematic examples on different levels of dimensionality of spectral data with x, y, λ being x and y the spatial and λ the spectral (modified from [9]).

Regardless the scale of acquisition, hyperspectral sensors bring higher spectral resolution, in comparison to multispectral sensors, offering higher accuracy to detect targets and characterize earth surface processes. In Figure 2, is possible to distinguish the differences between a common Red Green Blue (RGB) composite, a multispectral dataset and the hyperspectral. The visualization format of any spectral dataset is similar, regardless the covered wavelength range, scanned specimen or area, and the spectral process underlying. A spectral imaging dataset is composed by three dimensions with at least one, even indistinct, value defining the measured signal intensity along at least two spatial and one spectral axis [9].

Multi-scale approach in post-mining applications

Mining wastes are quite heterogeneous compared with other industry sectors due to their quantity, mineralogical formation, and their properties. It varies depending on the mineral preparation and enrichment process applied. Waste in mines is usually stored in dumpsite and slurry ponds, while it is stored in some mineral sites in the form of post-leaching ore piles. As introduced early AMD can occur in these waste sites and if superficially dumped, when iron sulfide in coal mines or sulfur in base metal mines, can undergo into oxidation conditions [10]. With the removal of ore from the ground exposure of sulfides to water and oxygen in air takes place, in turn, the oxidation processes of pyrite FeS2 associated with iron, coal, and sulfur deposits can produce an acidic environment [1]. Particularly, the visible to shortwave infrared electromagnetic range has been widely used to monitor AMD mineralogy at mining surroundings since iron and also REE present strong and narrow absorption features in the visible to near infrared (VNIR). Mine waste dumps, pit-lakes, stockpiles and tailings generally contain high dissolved iron and sulfate content normally associated with this kind of metalliferous drainage, which makes possible to provide qualitative and (semi-) quantitative information on the composition, characteristics and spatial distribution of AMD processes.

The characteristics of drainage waters may present high concentrations of metals and ions such as iron, manganese, aluminum, and sulfate. Elements like zinc, cobalt, lead, chro-mium and copper are commonly found in trace concentrations [11]. These elements react with the surrounding environment, and in conjunction with other abundant ions, lead to the precipitation of a broad list of secondary minerals, which are not exclusive to mine tailings and AMD waters, having also been found in high saline environments regardless of pH values [12].

Satellite-airplane scale

Several studies have shown the benefits of remote sensing data for many environmental monitoring purposes. In relation to AMD, some studies have demonstrated the feasibility to use field and imaging spectroscopy for the detection of minerals containing metals as contamination proxies in mining areas [2, 13]. Another attempt to map iron-bearing minerals with satellite data was performed by Swayze et al. [14] including validation studies with XRD and field spectroscopy. Montero et al. studied the characteristics of waste rock associated with acid drainage for protecting water reservoirs [15], while Sares et al. focused on indirect pH estimations of an AMD-stream by identifying iron-bearing minerals precipitated on the stream bed [16].

Most recently, hyperspectral sensors have been used in the study of mine tailings using airborne platforms [17, 18]. These studies focused on the responsible minerals of acid formation in tailings and the distribution of the secondary minerals, e. g., jarosite, ferrihydrite, goethite/hematite, as indicators of the degree of environmental pollution using reflectance spectroscopy [19]. Quick mineral diagnosis of short-lived thin-crusts concentrating metals by means of high spectral resolution imagery has been gathered in a spectral library for AMD minerals by Crowley et al. [20].

Over river sediments and vegetation, visible-near-infrared spectroscopy has been researched by Clevers und Kooistra [21]. Each mineral provides a unique spectral signature that allows distinguishing between them. In this sense, Figure 3 shows reflectance for four of the main distinctive iron-secondary minerals related to AMD production (goethite, jarosite, hematite, and schwertmannite).

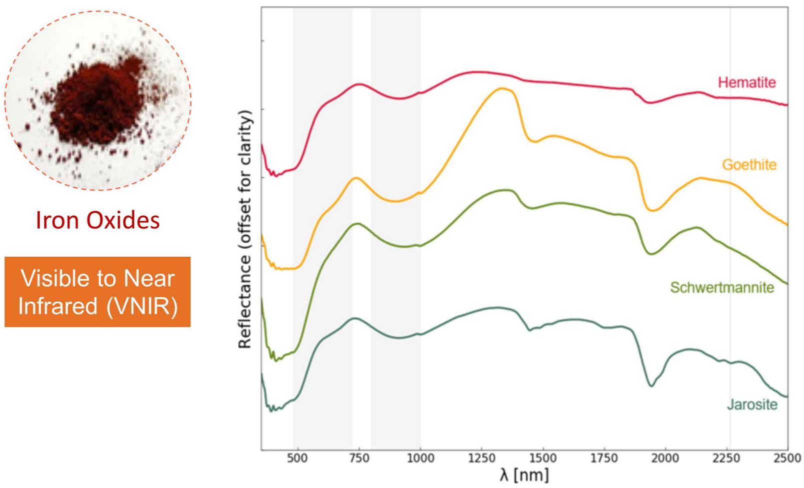

Fig. 3. Spectral curves for the main secondary iron-minerals typically of AMD (hematite, goethite, jarosite and schwertmannite), indicating prominent absorption features of each, using the spectral library of Crowley et al. (20).

Spectral curves reveals distinctive absorption features depths of each iron mineral. Two regions are gray-shaded in Figure 3 to analyze the shapes and wavelength positions of each mineral in the charge transfer (ligand to metal charge transfer) transition and those triggered by the crystal field effects (transitions of electrons from lower to higher energy states) [22]. Hematite characteristically has a narrower absorption at wavelengths surrounding 880 nm, while goethite has a broader feature with wavelengths around 920 nm or greater [22]. This feature associated with crystal field absorption around 900 nm is also found in the jarosite and schwertmannite spectral curves. However, the charge transfer shoulders around 650 nm, associated with the charge transfer of change to $Fe3+$ and change to $Fe2+$ [23] allow further distinction for schwertmannite which has no known inflection point at 650 nm and spectral peak location at 738 nm [20].

The peak location at 720 nm and a small distinctive absorption feature at 2.264 nm confirms spectral identification for jarosite. Several minerals have been collected in so called spectral libraries for validation purposes by the USGS spectral library [24] and Crowley Library for AMD mine als [20].

Large mining operation vicinities have been monitored by means of remote sensing imagery. Davies and Calvin have studied the Leviathan lake from mine tailings [25] and the spectral behavior of surface waters [26], while Swayze et al. studied the Venir pile in California/USA [14]. The Iberian Pyrite Belt (IPB) in south-ern Spain has been also a target area for many remote sensing and compositional studies related to AMD chemistry [27, 28]. The Sokolov mining district of the Czech Republic AMD phenomenon has been generally studied by Murad and Rojík [12] and by means of airborne hyperspectral data by Kopačková and Hladíková [29] for determining water surface parameters in water.

Unmanned Aerial Systems (UAS) scale

The emergent use of unmanned aerial systems (UAS), like multicopters coupled with lightweight hyperspectral sensors has be come a tool to collect data at a higher spatial resolution than most of aircraft and satellite counterparts, resulting in greater precision (higher spatial resolution of a scene enabling the investigation of down to a few centimeters pixel size) [7]. Most recently Jackisch et al. [30] implemented the use of UAS-hyperspectral imaging for high-resolution, multi-temporal mapping of proxy minerals for AMD in the Sokolov lignite region, Czech Republic, while Flores et al. [31] has focused mapping not only mineralogy but also hydro geochemical properties to assess the extent of AMD in Odiel and Tintillo waters, in the Iberian Pyrite Belt in southern Spain. In this study, several techniques have been combined to produce high resolution maps (Figure 4), a machine learning approach using regression has been used to fuse geochemical data from validation points at the field with the hyperspectral dataset. Also a 2.5 photogrammetric model was constructed using Structure-from-motion (SfM) Stereophotogrammetry to compute a digital surface model (DSM).

Laboratory Scale

In addition to the airborne monitoring approach, hyperspectral sensors have been widely used on multiple laboratory scale applications for mineralogical characterization and AMD prediction. The so called geoenvironmental risks, has been used to evaluate the potential for AMD formation based on core logging, static chemical testing, bulk- and hyperspectral mineralogical techniques [32].

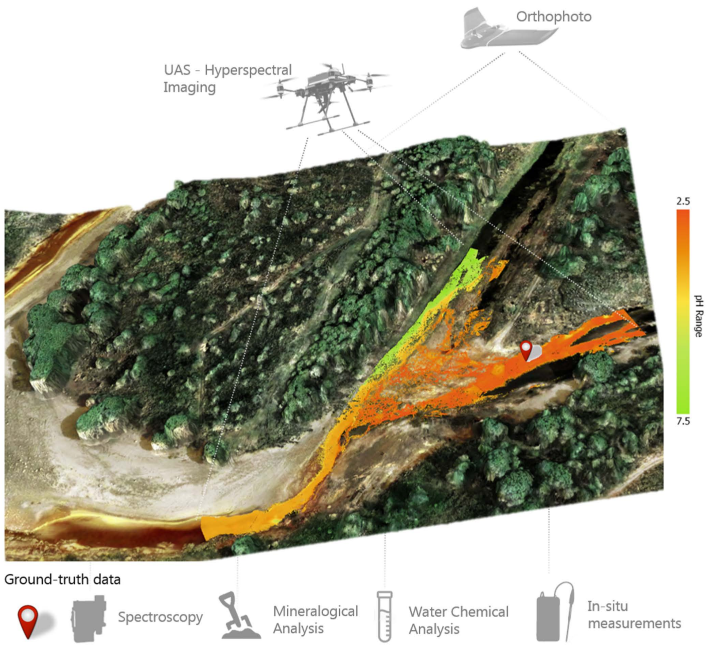

Fig. 4. 2.5D surface model representation of the AMD affected waters in southern Spain. Base layer are the combination of the orthophoto on top of the DSM and the produced regression-pH map for the river flow path (not drawn to scale). Modified from [31].

Fig. 5. Experimental set-up for hyperspectral scanning of Schleenhain and Peres samples in TRIM4Post-Mining EU Project. Source: THGA

As means of identifying AMD drivers of acidification in Schleenhain dump, the visible-near infrared (VNIR) and short wave infrared (SWIR) regions have been investigated by the TRIM4Post-Mining – a Horizon 2020 project funded by the Research Fund for Coal and Steel – for the detection of secondary iron oxides, hydroxides and sulfates in lignite waste dump material. For this purpose, two hyperspectral sensors (FX10 and FX17; from manufacturer Specim, Spectral Imaging Ltd.) has been used to acquire part of the VNIR and SWIR on the available samples.

No sample preparation is needed for the hyperspectral scanning. A portion of each sample was set on a white paper-sheet directly under the camera. The holder where the sample lay, moves in a horizontal direction and the line scan camera captures the hyperspectral image similar to a conveyor belt. This is achieved with the rail-like construction shown in Figure 5 together with a controllable motor. The stage moves directionally depending on the position with adjustable speed to the right or to the left depending on the position.

In general all hyperspectral surveys, should be accompanied by validation campaigns, in where point spectral measurements have to be done in discrete and strategic spots of the investigated area, as well as the incorporation of further geochemical/geophysical datasets to support the spectral method. Figure 6 shows a classification map created over scanned samples for validation from AMD affected site in the Sokolov lignite region [30]. Accurate compositional information of the mine waste materials is fundamental to understand the reaction schemes associated to AMD production and needed for geochemical modelling. Either by identifying primary sulfides prone to AMD or detecting secondary-iron sub products after weathering effects needs to be analyzed in or- der to locate risk areas, and provide adequate mitigation or prevention routines, prior to select the best post-mining plan.

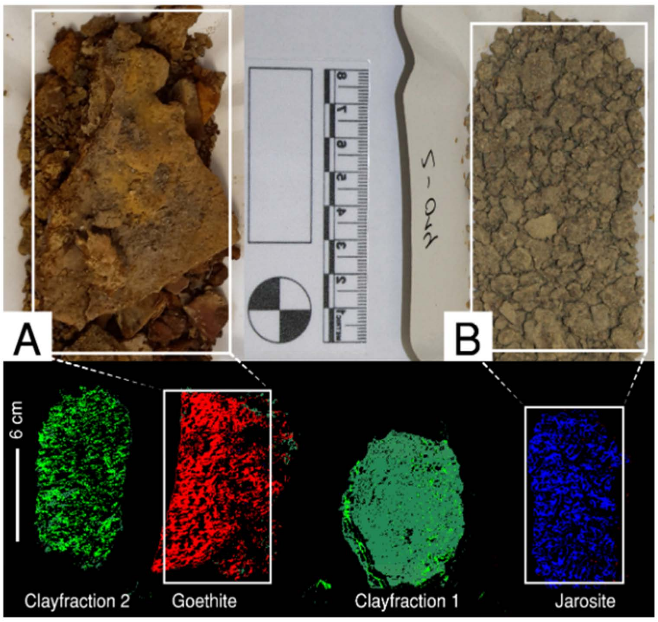

Fig. 6. Spectral mapping using supervised classification from Litov AMD in the Sokolov lignite region. Modified from [30].

Conclusions

Together with the high demand for raw materials in post-industrial societies comes the waste generation and all the task concerning their efficient management and risk assessments. In this sense, accurate and constant monitoring on terrain or vegetation cover of spoil banks is often required for two different reasons in post-mining management:

1. to monitor and prevent adverse effect of hazards; and
2. to assess restoration success.

Hyperspectral data brings several advantages as a complement to traditional environmental monitoring studies. The development towards lighter and smaller sensors, allows easier incorporation of hyperspectral technology into different stages of mine waste management. It could be used, rather during active mining to identify potential lithologies hosting minerals prone to AMD and forecast adverse effects, or in post-mining scenarios to target affected areas and continuous monitor restored areas. Traditional monitoring of soils and water quality is mainly based on the chemical analysis of samples routinely collected over the year and on the physical parameters of the groundwater measured by instruments located in the flow path. These tasks can be expensive, time-consuming and controlled by access limitations to the areas. In general, UAS mapping compared to ground surveying represents a reduction in the time employed on acquiring data. Furthermore, UAS allow reaching locations that may be difficult to access, are under protected status or that involve personal security risks for terrestrial-sampling. Regardless the scale, hyperspectral sensors allow repeatability and recurrent data-acquisition. Therefore, multi-temporal analysis is feasible and may allow constant monitoring of sensible ecosystems. Although many instr ments with higher spectral resolution and wider wavelength range have been developed. This equipment is too heavy, fragile, and costly to be mounted on UAS. Several efforts have been made on satellite development to increase their spatial resolution by enhancing band acquisition efficiency and making data available in open-source systems.

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Geomonitoring as an instrument to accompany structural changes in post-mining areas

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Introduction

In times of global energy crises and advancing climate change, the development of the energy industry as well as the further development of industrial branches cannot stand still. Rather, it is also necessary for the success of a green turnaround to view the major topic of 'mining' from as many different perspectives as possible and, where possible, to make it more sustainable. After all, mining does not only imply the traditional resources that are often associated with it, such as hard coal or lignite. For decades, these have contributed to a simple and secure energy supply and today, in regions or countries where coal mining is no longer actively practiced, they are an integral part of industrial culture. However, mining is also needed to cope with the energy transition with the help of renewable energy alternatives such as wind or solar power plants.

In order to produce the individual components of such alternatives, permanent magnets are needed for solar panels or wind turbines, for example (Carrara et. al 2020). These can primarily only be produced with the help of rare earths. These, in turn, are classically mined and then further processed by chemical processing to rare earth elements, which can then be used again (Navarro/Zhao 2014). Here, too, not only exhaust gases are produced that are released into the air and pollute the environment, but also wastewater and a general work process in countries such as China, where occupational health and safety and environmental protection often do not meet German or European standards (Peréz/Pitron 2020). Furthermore, some countries, such as Germany, have already phased out hard coal in 2018, while other countries are already well ahead of this goal or others are even further away from it (cf. RVR 2022).

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This means that many areas have to be optimized at the same time. On the one hand, where mining is actively practiced, it must meet modern environmental standards as far as possible, and everything that can be done to avoid pollution to the detriment of the environment must be avoided. The same applies to compliance with the highest standards of occupational safety for the employees involved. On the other hand, there are the regions or countries that have arrived in the post-mining era and are therefore no longer actively mining coal. Here, comprehensive monitoring is necessary to collect the legacy of mining with all its possible consequences: From soil subsidence, to unused waste rock piles, to mine water management as well as existing damage to vegetation and a possible development of new, and re-use concepts for former mining regions. Accordingly, a four-pronged approach is required, which was established at the Research Center of Post-Mining at the THGA University (Bochum in the Ruhr Area, Germany). Within four research areas holistic conceptualizations for an adequate and sustainable handling are developed. Essential for this is the understanding of how the life cycle of a mine is composed and that the end of the mine must be considered even before the start and use of such a mine in order to ensure a sensible subsequent use and to minimize possible consequential damage to the environment and the people living there (cf. FZN 2022a).

In addition to the technical requirements for efficient mine water management and dewatering, e.g., to keep mine water away from groundwater and drinking water or to analyze the vegetation and condition of the ground and workings through geomonitoring with various drones and satellite technologies, there is also a clear social aspect (Goerke-Mallet, Melchers & Kretschmann 2020). On the one hand, a combined use of drone technology and material science can contribute to the preservation and conservation of industrial heritage. By examining the condition of industrial equipment or headframes using thermal infrared and multispectral analysis, damage can be detected quickly and efficiently, and the costs and resources for necessary repairs and restorations can be better calculated in the long term (FZN 2022b). On the other hand, mine closures always have a crucial aspect: people lose their jobs. It is often not possible to offer suitable alternatives to those affected. Either they are already too old for possible retraining and are sent into early retirement, or there is a general lack of alternatives. For example, in the former mining regions of the Ruhr area in Germany, there is still an above-average unemployment rate compared to other regions, which is directly related to the closures. This shows that the development of entire regions suffers from such effects in the longer term and that the political framework and support for such profound structural change in highly industrialized regions must be designed differently. In addition to the necessary developments of possible after-uses of mines to conserve resources and sensible urban planning to satisfy citizens and revitalize tourism and culture, mental health is also appealed to here (van de Loo/Tiganj 2021).

Those directly and indirectly affected by job losses due to mine closures, i.e., the employees and their immediate families, sometimes suffer enormously from the effects. Either they cannot find a new job or they have clearly identified with their previous vocation. Scientific studies show the dangers to mental health of long-term unemployment. The longer unemployment lasts, the more those affected no longer feel like a full member of society. This can lead to feelings of exclusion and even depression. However, it can also manifest itself in the form of addictions, by resorting to narcotics, to name just one example (Fink, Titelbach & Mürzl 2018).

Therefore, a holistic approach from the technical side as well as from the economic, political and social side is necessary to successfully shape structural change in the long term and to further establish post-mining as a necessary instrument in this context. Due to operators responsibility in Germany a company is not allowed to close a mine without further caretaking on environmental aspects. This gives companies somewhat a social license to operate (RAG-Stiftung 2016). As a result, all post-mining areas has to be environmentally monitored. This shows the right approach to take responsibility, but it also needs the support of further scientific research in such new fields.

The authors of this article are therefore representing the research branches of "Reactivation and Transition" as well as "Geomonitoring in old and post-mining areas" of the Research Center of Post-Mining at Technische Hochschule Georg Agricola University (THGA). The article tries to combine both aspect, the social aspects, as well the technical aspects in the form of geomonitoring aspects are. A process understanding of the anthropogenic massively changed environment, which still underlies post-mining developments, can help to ensure better living conditions. Thus, Geomonitoring as a part of operator responsibility is a precondition to reduce impact on prosperity.

Global Climate- and Energy crisis

As noted at the beginning of this article, the advancing climate change is globally undeniable. If further measures are not taken as quickly as possible, such as an energy turnaround towards green and clean energy, life on earth will become very unpleasant in the foreseeable future. By missing the 1.5 degree target, as it was agreed upon after the Paris Agreement on sustainable development until 2030 in the context of the World Climate Conference on 12.12.2015 with 195 countries, consequences for the environment, animals and humans are imminent (BMZ 2022). This issue is not a new one, which is why the integration of renewable energies has already increased rapidly in recent years and research into further clean technologies is not standing still (Enerdata 2022). However, with the dawn of 2022, this is no longer the only problem that will have a global impact. The year 2022 also heralded an energy crisis of global proportions when Russia unexpectedly declared war on Ukraine overnight (24.02.22) (bpb 2022). The months of war since then have shown how dependent many countries are on other countries for their energy supply, such as Germany on Russia's gas supplies. Dependencies that have been known for a long time, but no need for action was seen here to create more independence (iwd 2022). This now leads to rapidly increasing energy and heating costs as well as the urge to decouple and find solutions to be able to return to a normal state. To this end, for example, the focus is on the further expansion of renewable energies. But here, too, the dependencies for Germany are very clear. China has the world's largest reserves of rare earths, which are urgently needed for the production of these energy alternatives or for electric cars, for example (Statista 2022). Here, too, dependence on imports is high and plays a major role in determining the further strategic and energy industry orientation and implementation. Nevertheless, the goals of phasing out lignite should be adhered to, as it has been recognized that this can no longer be the right path in the long term. Climate change is not halting its progress because of other possible circumstances, but the need for action remains, if not increases (IEA 2022).

However, this also implies an increased demand for rare earths and other materials needed to manufacture the solar panels or wind turbines: concrete, plastic, steel, aluminum, glass, chromium, nickel, copper, iron etc. (structural materials) and especially terbium, neodyium, praseodymium and dysprosium (rare earths). The extent to which demand for these materials to be prioritized for import will grow can be estimated using a 3-way scenario analysis. If the factors around the material intensity as well as the lifetime of a power plant and the respective market share for sub-technologies are taken into account, 3 different scenarios can be classified. These range from a minimum to a maximum demand estimate. Taking into account the materials mentioned, a minimum 2-fold up to a 15-fold material increase can be calculated for the production of wind turbines alone (cf. development of wind power in Figure 1). In order to establish a comprehensive integration taking into account further generation alternatives, it is quickly clear what quantities of material are being talked about (Carrara et. al 2020). This enormous hurdle must not be ignored. Furthermore, the recycling of used materials, such as rare earth products, is still in its infancy and needs much more research and new approaches. Otherwise, after an average service life of 20 years, a wind turbine will merely end up in another landfill site created for this purpose, because appropriate recycling is only partially possible or would be too costly to separate the materials still to be recycled from the rest (U.S. Department of Energy 2017; Umweltbundesamt 2020; c&en's 2022).

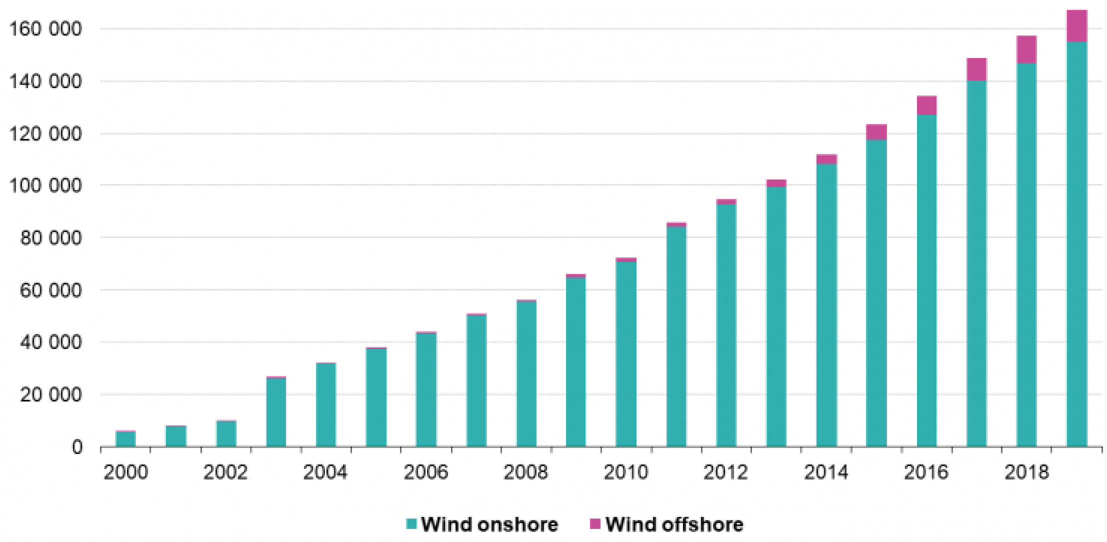

Fig. 1. Development of electricity production capacities for wind (onshore and offshore) from 2000-2019 in the EU (Eurostat 2022).

These moves towards green energy and away from coal, while meeting the goal of becoming carbon neutral by 2050, further imply that many countries are still looking forward to phasing out coal in the future. The sole integration of renewable energies will not be sufficient for this and many countries therefore want to leave coal behind altogether. Nevertheless, looking back at the facts earlier in this article, there are more hurdles to consider besides the growing demand in materials for a transition, such as the social acceptability of the coal phase-out.

Necessity and social impact of mine closure

As emphasized at the beginning, more importance should be given to the social aspect of transition through restructuring within an intensive industry. In the end, everything stands and falls with the people involved, and this does not only mean the involved institutions and executing actors themselves, such as the operator of a mine, but also the workers who keep that plant alive. Dealing with the people is essential and, just like an area-wide closure and the loss of simple energy supply security, has a lasting effect on civil society, such as the people who live and work in this society.

If the consideration as a reference example lies only on a worker himself, who now loses his job due to the closure of a plant, several side effects occur here directly, which go beyond the pure job loss: Financial security on the part of the worker himself is possibly endangered by this and/or externally supported security through provision by the state, for example, is not possible; henceforth and indefinitely no more taxes are paid in, the same applies to the pension, whereby other people can also be affected by a lack of tax money and this also has an impact on the local location; depending on the number of unemployed affected, possible sums are added up here and the rising unemployment rate can also be reflected in the social mood of the respective society (Deutsche Rentenversicherung 2021; Tiganj 2022). Such effects can have a negative impact on the further development of the region and, depending on the approach to solving the problem, can also have a far-reaching impact. Even if precautions are taken and, as in the case of Germany, early retirement was possible in the Ruhr region, this does not mean that this alone is sufficient to pick up the former workers psychologically (Kritzinger 2009). There is a need for alternatives for those who, for example, do not yet see themselves in retirement, but still have the need to actively participate in society's working life. This can sometimes be promoted if, in addition to funds set up for this purpose to provide financial security, retraining measures are also paid for or, in the case of the integration of new industrial operations into existing former plants, the possibility exists of taking over former personnel and training them accordingly. This can also give rise to spin-offs, which can lead to new concepts and implementations as a result of the research carried out, for example, in the area of post-mining, which in turn can provide new impetus for employment (van de Loo & Tiganj 2021).

Therefore, regional development is a very broad keyword that carries a lot of responsibility. After all, people and the environment can benefit from appropriate concepts for subsequent use by using resources, requiring workers, promoting sustainability and also advancing technology and digitization. A large number of aspects can be combined here, which together have a significant impact on the prosperity of a region. That is why it is so essential to further develop these topics primarily through a research perspective and to deal with as many aspects as possible. In addition to the social factors already mentioned, the “how?” is a crucial question. How are locations analyzed and monitored? What must be considered and what can be considered that benefits research and ultimately regional development in the course of structural change-related transition? Within the Research Center of Post-Mining, this is likewise the field of Geomonitoring.

Geo- and environmental Monitoring of post-mining areas

Geomonitoring is a holistic approach of the environmental understanding in the view of the scientists at the Research Center. It covers several levels of data collection and analysis. Fig. 2 describes the standard procedure: The conditions on a specific site are recorded and evaluated with high-precision“in situ sensors” like weather, levels, soil moisture, and etc. pp. Such sensors – supported by in situ and laboratory analysis e.g. of soil, plants and geology - form the basis for a process understanding as they describe the local situation in detail. They are able to measure aspects in a high timely frequency. As a limitation can be found that the sensors and analysis are reporting data only for a decided position and are not representing larger areas. Therefore, with a first, still local level, of extrapolation to a smaller area, an understanding of indicators, such as vegetation or water, is built up that adapt the found process understanding on an area basis. Here, for example, sensor-equipped flying robots (drones, Unmanned Aerial Vehicles - UAVs) are used for data collection. If there is the need to get information of entire regions, satellites come more into focus. At the Research Center, the freely available data from the European Copernicus satellite system are used. Some satellites like Sentinel 2 are carrying sensors that are partly comparable to those available at the UAV level. If the transfer from the in situ level to the drone level is working, the scientists are able to do the next step: transferring the understanding from the drone level to the satellite level. It is possible to adapt procedures and verify results using drones as ground truthing instruments.

If this multi-level approach is successful, the procedure can be applied in reverse. On the basis of the hereby generated understanding of satellite data means, satellites data can then be used to describe conditions on the ground in large areas and deliver, thus, in situ information without in situ sensors.

The data fusion is crucial. Using several software tools, mainly belonging to the GIS universe, data integration can be imagined as filling a data cube with different sub cubes, called “data tensor”. That is done because scientists are facing the classical big data ”4 V problem”. Data available today come from a wide variety of sources (variety), vary in accuracy and describe very different spatial units (veracity). However, there are increasingly large amounts of data (volume) that are supplied and processed at different speeds (velocity). In addition, data analysis in Geomonitoring are facing a special spatio-temporal problem: In situ data are measuring on exact one geographical position in a high timely frequency and very exact only one aspect or value. For example: Soil moisture with a value every hour - Radar satellites can measure soil moisture using radar reflectance as well. But they passing an area, e.g. every six days and covering large areas with a foot print of 10 m by 10 m. Drones then having a spatial resolution of some centimeters, using possibly water indices to collect information on soil moisture and flying only on demand. The colored cubes in Fig. 2 describe this wide variety of data sources. The binding element after integrating them into the data tensor is the spatio-temporal characteristics that is also part of the data science approaches.

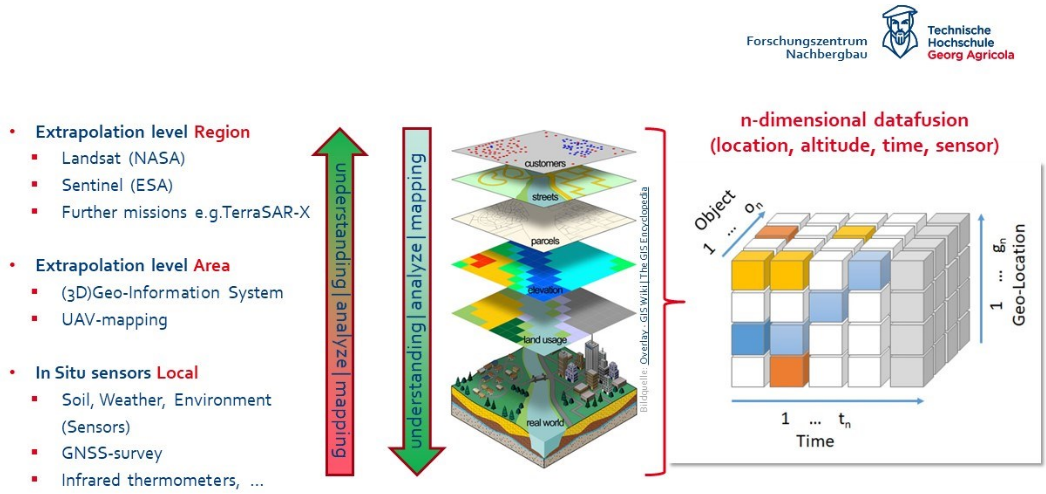

Fig. 2. Development of a process understanding from the data fusion of several data levels: in situ, area and region. The sensor fusion takes place in the data tensor, consisting of different input data in different temporal and spatial resolutions (different in color) (Bernsdorf, B. & Khaing Zin Phyu 2023).

To analyze data the entire toolbox of data science can be applied. The sub cubes can possibly underlie analysis of many mathematical and statistical aspects:

- reflection characteristics (satellite radar data),
- plant health and vitality (satellite and drone multispectral data),
- thermal anomalies (drone thermal infrared data),
- water indices (drone and satellite data),
- resampling (UAV to satellite data),
- anomaly detection (in situ data),
- outlier and cluster analysis (mainly in situ but also other sensors),
- change detection (drone and satellite data),
- Regression and correlation analysis (e.g. drone vs. interpolation of field measurements).

In some cases photogrammetric calculations and corrections have to be performed before data can be compared. For example, at the Research Center of Post-Mining different UAVs are at duty with different positional and spatial accuracy. Especially the different optical characteristics of the sensors make it difficult to compare data spatially. To ensure good results it is necessary to find ways to spatially reference pixel of different datasets to each other (sub-pixel matching), especially in change detection approaches this is crucial.

Geo- and ecosystem monitoring in post-mining areas

Project example C_2M_2

Climate Change – Management and Monitoring (acronym: C_2M_2) is intended to discover how climate change effects rebuilding strategies after mine closure. Within a science cooperation with the waterbody Emschergenossenschaft the Research Center worked on the correlation of the local level (in situ components) and the first areal approach (drone level). This should be a base for understanding the regional level (multispectral and radar satellite), which was worked on by a partner.

The overall question was whether the effort to rebuild a river close to nature is worth the investment if climate change – droughts and floodings - will hinder the healthy natural development of a river ecosystem (Middeldorf, 1904, Held 2007, Zepp 2017). The object to look on in detail was the river Emscher and its tributaries, especially the brook Boye. The basic idea in the project was to understand the correlation of water delivery from the catchment area to the receiving Emscher with criteria which can be observed using satellites. Beside the river Ruhr and the river Lippe, which was in former industrial times the fresh water sources, Emscher was rebuild to the central waste water channel of the Ruhr area. All its tributary was rebuild to typical V-shape as open channels to transport wastewater. The Emscher and its tributaries vanished as a "river" from the consciousness of the local population (Figure 3).

Fig. 3. The typical hazard sign in the Emscher catchment shows the public view on the rivers (Picture: Bernsdorf).

One - if not - that biggest hydraulic engineering project over the last years with a billion Euro effort was to rebuild the Emscher and the entire catchment as far as possible close to nature. The entire project was finished in 2022. However, while still working, Germany was hit by some years of abnormal doughtiness and high temperatures (2018, 2019, 2022) enclosing a year with a heavy rain disaster (2021). In 2019, with the background of a second drought year, the question arose whether the catchment, respectively the tributaries, can deliver enough water for a healthy close to nature development. The project C2M2 was set up. During the project work the heavy rain disaster "cleaned" the river beds due to flooding. This washed away not only the sensors, but also the delicately developing flora and fauna.

The scientific approach was to install different types of in situ sensors in the working area. The preassumption was the following correlation:

1. Soil type and grain size affects the water delivery to receiving water bodies and ground water.
2. This is because the pore volume is related to grain size which is the water reservoir for plants and can be measured as soil moisture.
3. Filling and emptying of this reservoir is related to rain and (soil) temperature.
4. Plant health relates to an optimal water supply given as field capacity. Reaching the withering point effects plant health as well as overwatering.
5. Plant health can be observed by multispectral drones mapping vegetation indices.

Thus, vegetation indices such as NDVI and others can be used as integrative reference to observe soil moisture and drought. If this first step of sensor fusion will work, it can be used as ground trothing for the satellite level. Thinking backwards: The in situ process understanding is the precondition to interpret and analyze multispectral satellite images in terms of drought by using vegetation indices.

To answer questions, in the C2M2 project frame soils sensors were installed (moisture and temperature), soil samples were taken (field and laboratory) and monthly drone flights applied (in RGB, thermal and multispectral). Especially "cheap" solutions for an area wide approach were in the focus of this scientific questions. Therefore, in addition to high end sensor solutions the project used sensors from different fields, especially moisture and temperature sensors from the food and greenhouse branch. In terms of drones custom market products were involved.

As one of several results, the project could find out that cheap soil moisture sensors have their problems in terms of giving correct measurement values. But applying classical descriptive statistics the sensors can be used, e.g. for describing annual cycles. Figure 4 and 5 show a comparison between TEROS and TELID soil moisture sensors. While the high end TEROS sensors show exact values the cheap TELID sensors have problems with that. But applying some simple statistical methods, TELID sensors are able to show the annual circle very close to the TEROS data. Therefore, for a more condense measurement network such sensors can be implemented and “anchored” in the data series of high-end sensors.

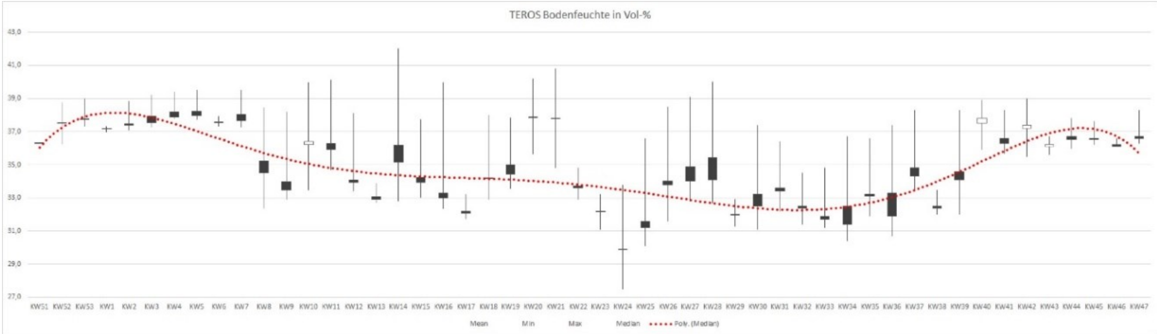

Fig. 4. Boxplot of data from a professional TEROS sensor station represents calendar weeks and thus the annual soil moisture circle. The red line shows a polynomial fit of the 6th degree (Bernsdorf et al. 2022).

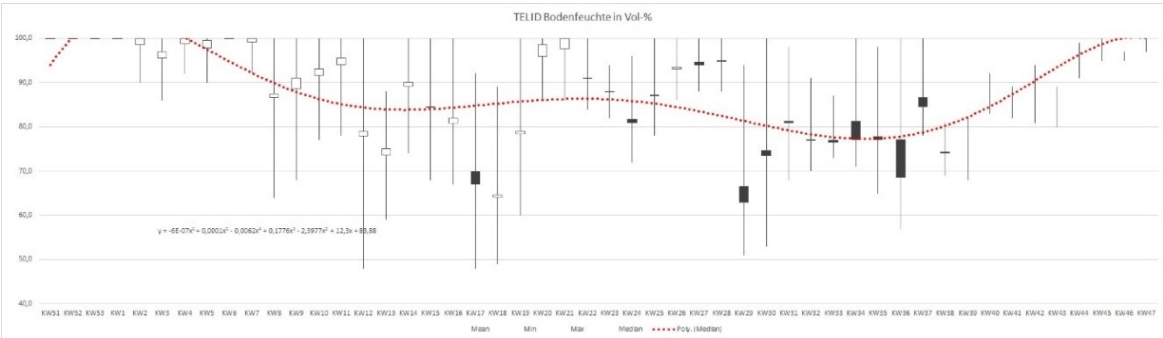

Fig. 5. Same location measured with a capacitive TELID moisture sensor from the greenhouse branch. The Box-plot represents calendar weeks as well. The red line shows a polynomial fit of the 6th degree (Bernsdorf et al 2022).

This finding was assumed for drone data as well. The scientists were investigating the value of low cost drones for nowadays in delivering high-resolution cameras. In terms of looking for plant health, several multispectral cameras like a DJI multispectral camera and a MicaSense RedEdge were used. But, looking on it realistically such sensors are not available in the broad. Therefore, over the year the scientists of the Research Center generated a time series with RGB drone ortho-photos on a monthly base. The first advantage is a monthly view on the working areas, which shows the vegetation development. This can be compared with a “normal” phenological cycle. In addition, simple vegetation indices can be applied on such datasets as well. The so-called “Green – NDVI” is not using the near infrared channel, but the red and green bands of the RGB camera instead (Pawlik et al. 2022). Figure 6 shows the application of a consumer market drone (DJI Mavic Air 2) with the classical 12 MP-RGB sensor. The Figure further shows the standard phenological development in the working area which can be compared to drought situations.

As another result the fusion of the ideas behind the approaches was to combine on a scientific base. Based on classical soil science knowledge about soil water, the project brought the grain size analysis and the soil moisture measurements together. This was done by a transposition of a classical soil moisture / matrix potential diagram from Scheffer/Schachtschabel (2010, p. 228). Figure 7 shows for the project frame in 2021 that water was not a limit in the working area. Therefore, vegetation developed itself like in any normal phenological cycle. The relation to the drone and satellite level could not be shown in the project frame.

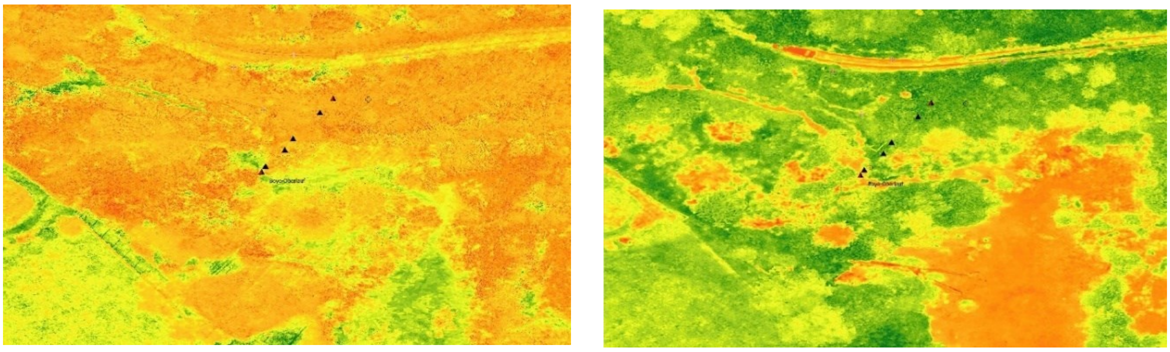

Fig. 6. "Green NDVI" derived from a RGB sensor of a DJI Mavic Air drone from February (left) and May 2021 (right). Red values indicate not yet developed vegetation, water areas and artificial landscape elements, green values healthy vegetation. The usual phenological development between the two months in the images can be seen (Bernsdorf et al 2022).

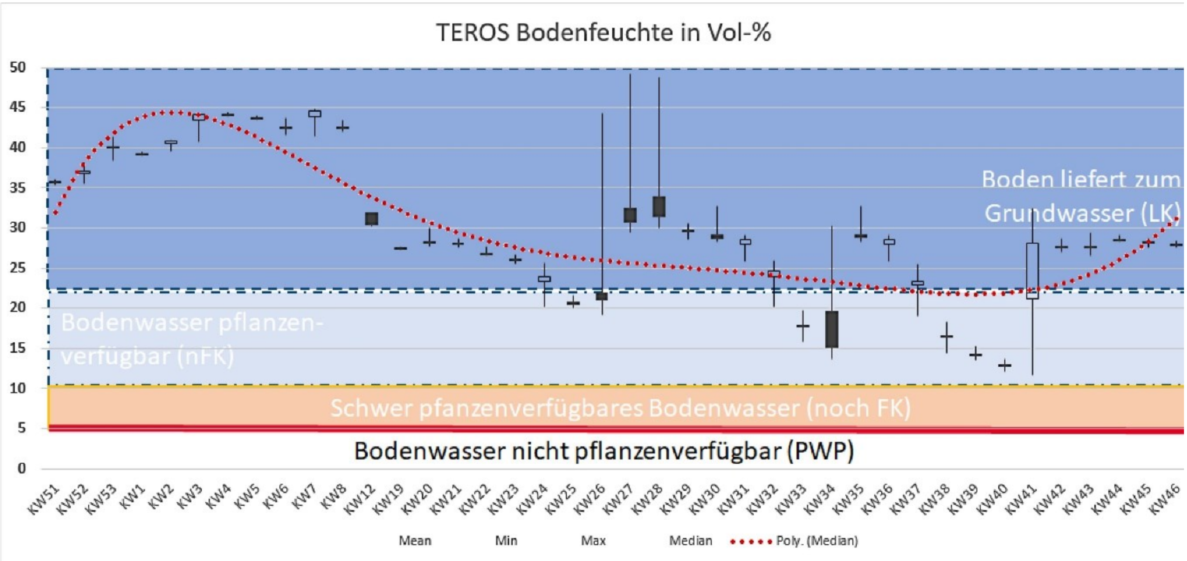

Fig. 7. Overlay of the soil moisture measurement data at Boye headwaters with the soil-physical characteristic values of the pF curve (Bernsdorf et al 2022).

Project example MuSE

Extraction of raw materials goes hand in hand with a more or less massive change in the landscape and natural conditions. The extraction of resources necessary for everyday life affects almost all aspects of the natural balance: water, soil, flora and fauna. From a geoscientific and geoecological point of view, this particularly affects the so-called polders in the Ruhr area; areas that have experienced considerable subsidence due to coal mining and now have to be continuously drained.

In the project "MuSE - Multisensory Geomonitoring for the Optimization of Post-mining Dewatering", concepts are to be developed for such areas according to which dewatering can possibly be optimized. The process understanding is close to that which was worked on in the C2M2 project described above. Furthermore, the aim of the MuSE project is to develop ideas for using the polder water sensibly in agriculture and forestry during periods of drought, for example, or perhaps even to be able to use the polder as a buffer reservoir during heavy rainfall events in order to prevent expected damage (Yin et al. 2022).

The entire report (available only in German language) can be found at Bernsdorf et al (2022) and as a StoryMap can be found under the following link for further reading:

https://storymaps.arcgis.com/stories/bee1d89ff0644d1592a3fbe6fff2d286.

In order to build up the process understanding the geoscientists are proceeding again in three stages shown in Figure 2: In addition to the classic geoscientific approaches on geology, soil, vegetation and weather parameters (in situ component), assessments based on satellite data (Sentinel 1 and 2) will ultimately allow for an area-wide statement. For a better interpretation of these data, high-resolution multispectral drones are used to map possible water and vegetation indices. To condense in situ measurement stations, a mobile GIS approach was developed which will be shown in this article as an example for the project work.

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The approach seamlessly follows the results from the C_2M_2 project. As mentioned above, there is a relation between plant health and soil moisture (Figure 7). However, a problem is the very high resolution of the drone data. At a flight altitude of 120 meters, five to six centimeters can be achieved. To put it more lightly: The multispectral drone data show plant health of every leave and blade of grass. The in situ measurements only can describe a few locations. In the MuSE project, there aresensors installed along of transects from the lowest subsidence points to the edge of subsidence. In total there ar sonsors at 14 locations installed (Figure 8).

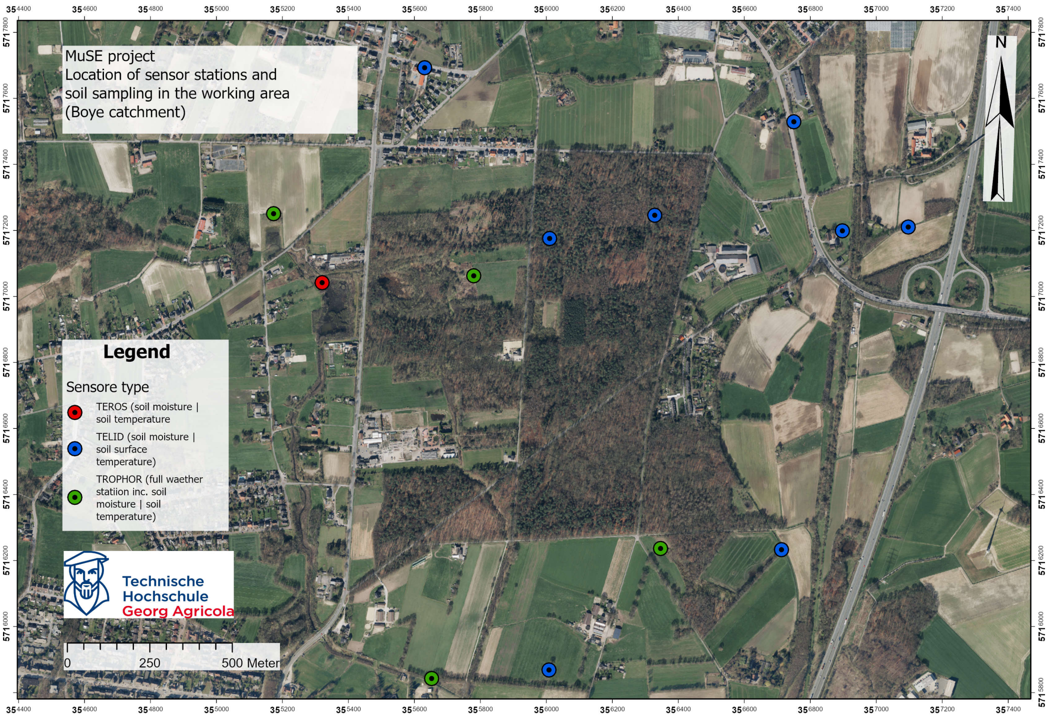

Fig. 8. Position of MuSE soil- and weather sensors.

Before installing the sensors in the field, some plausibility tests in defined environments were performed (Bernsdorf & Khaing Zin Phyu 2023). In general, the range of measured values between the individual sensors is astonishing due to the small size of the test fields. In contrast, the literature shows that soil moisture measurements in small areas can deviate quite considerably from each other. There are many reasons for this. Due to their design, the sensors require positive contact with the substrate. If the substrate is in natural storage and not homogenized, skeletal particles of the soil, creep of animals, variability of grain sizes or concretions of calcium, iron or manganese can influence the measurements considerably (Lehmann 1995, Rajkai & Rydén 1992, Scheffer/ Schachtschabel 2018). This explains small-scale differences and has to be addressed within the project frame. Therefore, a mapping method, which comes closer to the multispectral images, was developed. The concept was a dense sampling of some test fields. Soil moisture and soil surface temperature should be registered in a sampling task to be interpolated afterwards. This interpolation should be compared with indices like NDVI and others.

However, before sample points can be visited in the field, it must be ensured that the points are suitable for an interpolation. Certain geostatistical methods require that a data set does not contain systematic errors. Common sampling schemes that focus on determining “typical” or “average” expression are problematic. Such sampling, known as “purposive sampling”, has a specific intention, depends on the judgement of the processor and is subjectively influenced (Webster & Oliver 1990). This leads to the fact that specific sites being over or under sampled. For soil sampling in particular, convenience plays a role. Is the site easily or poorly accessible? Is it located on a pasture with grazing bulls? Is it located in a patch of forest that is difficult to access? Experience has shown that there are good reasons for landscape structures, which may well be soil-based (Crepin & Johnson 1993). As a consequence, sampling points are very often too far apart, have favored high quality soil, etc., which has an impact on the description of natural variability while interpolating such data (Laurini & Thompson 1996, p. 262).

The sampling plan used in the MuSE frame is based in its origins on the method known as Stratified Systematic Unaligned Sampling (SSUS), described as early as 1977 by Dixon & Leach (1977). Later Webster & Oliver (1990) added information to the method. Sampling in a regular grid is combined with systematic unalignment, which ensures that mappers do not pick sample sites according to their preferences. In ArcGIS, what is used in the project frame, this method is integrated as "Stratified Random Sampling". Here, a regular grid (fishnet) is first laid over the working area, after which the points are randomly distributed within the grid cells (ESRI [2] w.y.). Figure 9 shows the result of such a process. The red dots are the SSUS calculated sampling points. They were transferred to a mobile GIS for visiting them in the field. The blue dots describe the sampling points which were found by the mappers. Finding the exact position depends on GNSS signals. That is why not every computer calculated position could be exactly found in the field. Nevertheless, one can see that the samples are in most cases hit the specification. The interpolation than was performed with a kriging algorithm using a Gauss semiovariogram (Bernsdorf et al. 2023).

After interpolation, the data can be correlated to the vegetation indices. The NDVI (Rouse et al 1973) is a standard index to be shown in this publication. In the project frame others were used as well (e.g. GNDVI after Gittelson et al. 1996).The results are shown in Figure 10 for the correlation between NDVI and soil moisture and Figure 11 for the correlation between NDVI and soil surface temperature. Both works as expected: The positive correlation between NDVI and soil moisture shows that vegetation health is good when soil moisture is high. In terms of temperature at the soil surface it is just the opposite: Vegetation health performs better, when temperatures are low.

However, doing such research one has to address "older wisdom". In this case two old "Laws of Geography" has to be addressed for interpreting results in the correct way. The first "Law of Geography" comes from Tobler (1970). Correspondingly, the law says that what is located closer together is more similar than what is further apart (Tobler 1970). But he did not address the scale of this view. As an example, the air temperature at a given Moment in Bochum (Ruhr area, Germany) is more similar to the air temperature in Essen than in Krywyj Rih (Ukraine). But looking at certain aspects like soil moisture the scale has to be kept in mind. Because local aspects, e.g. grain size or soil type, will have effects on that.

Therefore, one has to apply the second "Law of Geography" after Goodchild cited in Shekhar & Zhang (2004). Accordingly, global geographic models can be inconsistent with local models. The authors point to the fact that classical GIS products can only insufficiently deal with complex, nonlinear structures. That is the reason, why possible relationships must be analyzed locally in certain scales. The approach to distinguish between "local" and "global" models is described by Shekhar & Zhang (2004). If one looks at a point cloud globally and puts a regression over it, a completely different statement might result than if looked at the local groups. In the example of Figure 12, a regression with a positive slope results in the global model, and one with a negative slope in each of the two local models.

Transferred to the MuSE project, this can be a hurdle in transferring the local finding with a high-resolution drone to the satellite level which will cover larger areas on a coarse resolution of about 10 m x 10 m. The reason is simple. Land cover reacts very different on drought. For example, a forest with deep-rooted trees are not dependent on short time variation in rain and soil moisture. Agricultural crops and grassland or pasture usually reacts much faster for the plants that are routing in the upper 10 cm of the soil.

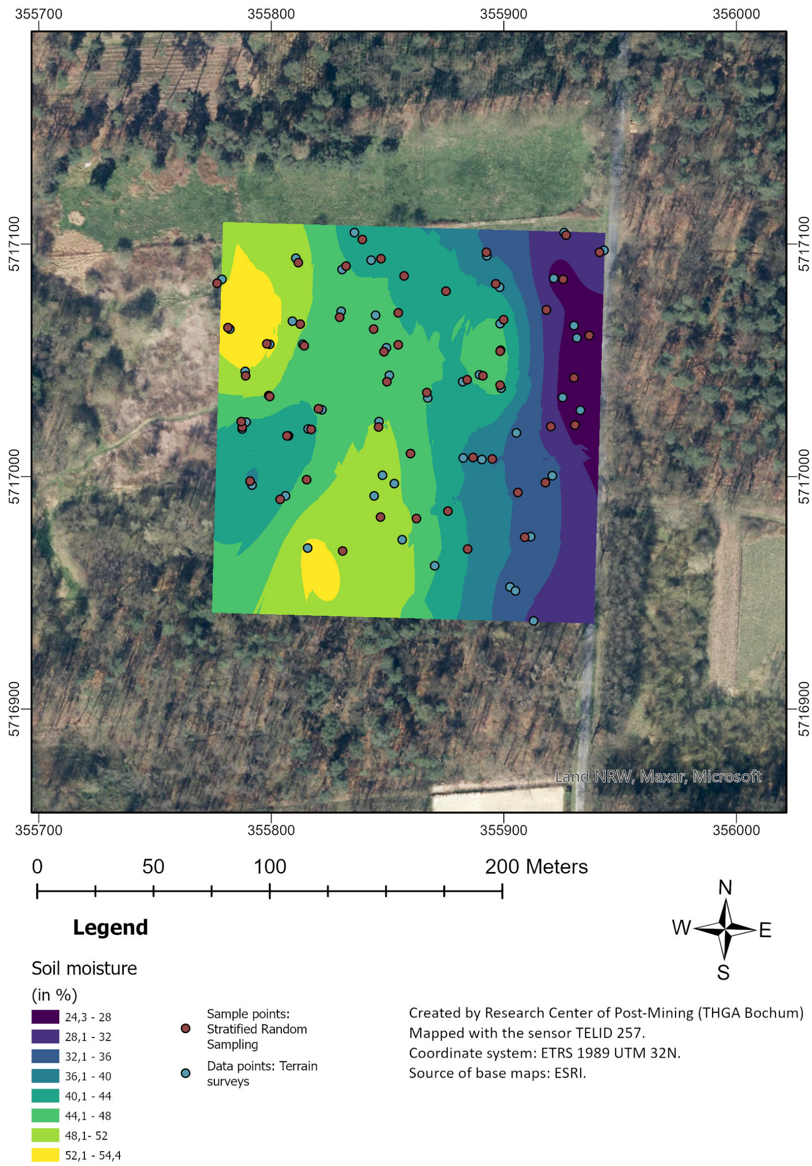

Fig. 9. Interpolation result using the SSUS-Method. For further description see text (Graphic: Marcin Pawlik, Bernsdorf et al. 2023).

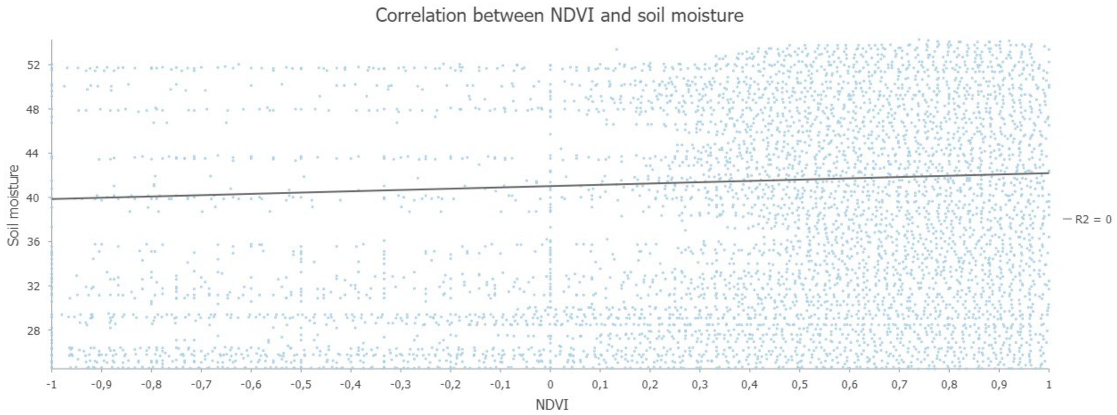

Fig. 10. Correlation between soil moisture and plant health (Measured as NDVI) (Graphic: Marcin Pawlik; Bernsdorf et al 2023).

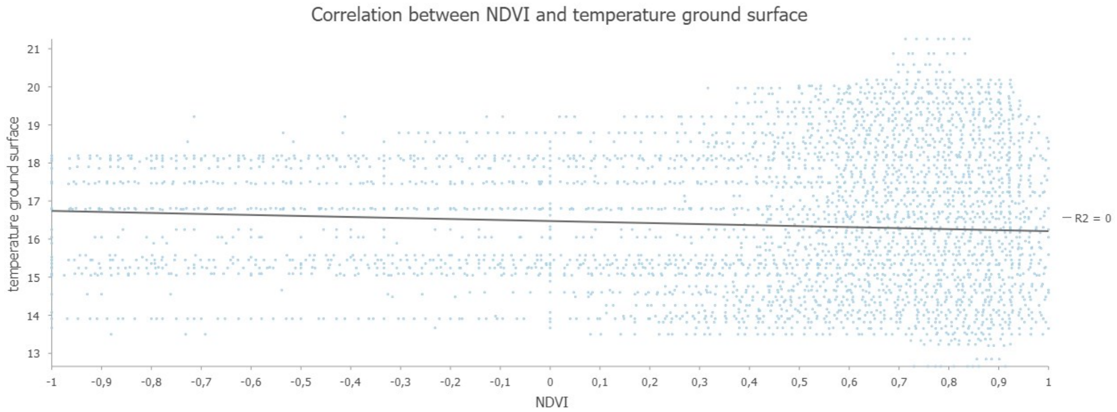

Fig. 11. Correlation between soil surface temperature and plant health (Measured as NDVI) (Graphic: Marcin Pawlik; Bernsdorf et al 2023).

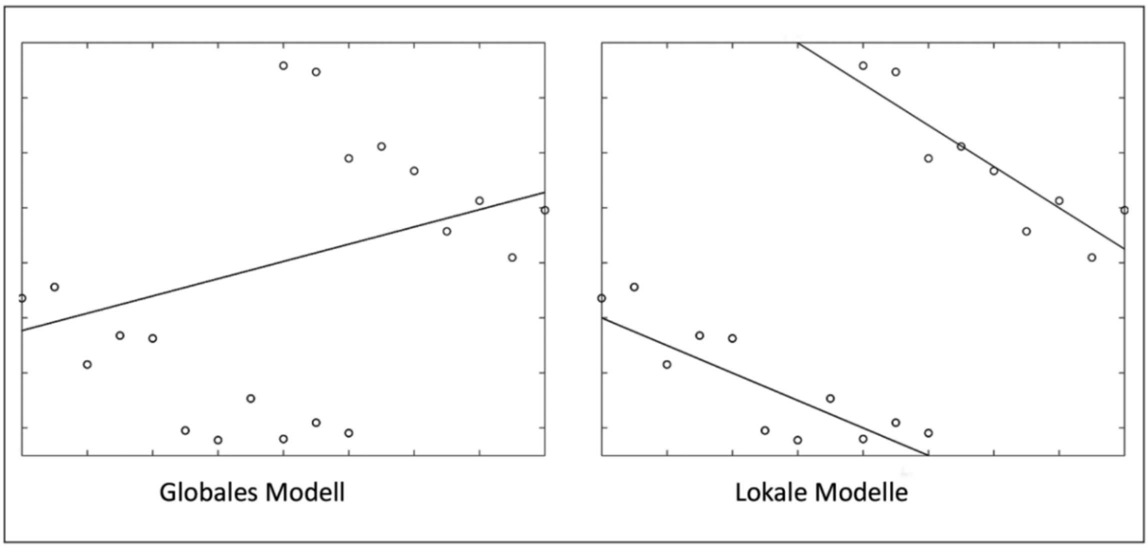

Fig. 12. The relation between “global” (left) and “local” (right) models (Shekhar & Zhang 2004).

Infrastructure monitoring in post-mining areas

Project example MUM InduKult

The project „Monitoring | Umwelteinflüsse | Modellbildung auf und von Objekten der Industriekultur im Ruhrgebiet“ (acronym: MUM | InduKult in English: Monitoring I Environmental influences | Modeling on and from objects of industrial culture in the Ruhr area) aims to assess the building fabric of identity-forming objects and monuments of industrial heritage in the Ruhr region and comparable regions. The Idea is to use modern methods of environmental monitoring and geomonitoring, in particular with the use of copter-based sensors (drones), to detect material damage to objects of industrial heritage and to make them assessable by material scientists. The project is a feasibility study, which, if successful, can lead to a simplification of a structural assessment and should provide reproducible results. This is particularly necessary with regard to climate change, which is the cause of increased material stress, so that classic assessment methods are hardly feasible in terms of time. Prolonged periods of heat, drought and heavy rain/storm events stress the objects of interest to such an extent that temporal repetition frequencies have to be increased. RGB, thermal and multispectral sensors should provide an improvement in the assessment method here (FZN 2022b).

A second aspect is the fact that industrial culture is changing and a temporal distancing of young people from the topics of mining, especially when it comes to coal or related traditional resources, is taking place, as relatives no longer work in these industries. Furthermore, the younger generations are actively living with the first real consequences due to climate change and are therefore interested in counteracting factors, such as heavy industry, which is contributing to the change in the first place (BMUV 2021). It is important to show and explain the basic understandings of why these resources still play an important role for the further development of renewable energies with the help of rare earths or still using coal or similar traditional resources to provide the standards of everyday life for everyone (Drebenstedt 2021).

In addition, the involvement of young people shall achieve an understanding for the preservation of the monuments in the form of industrial culture and further regional development in civil societies, which are heavily identifying with industry for many decades.

The approach is to find damages or hints of material changes, which can cause damages. If this is possible using standard Geomonitoring methods like integrating drones with several sensors, a frequent look based on a regular time schedule will be possible. It will also be more cost efficient than integrating industrial climbers or lift trucks with working platforms to do a close inspection. This can be added into the process when possible damages are found.

Here, a report from the ongoing project as a “work in progress” can be made. First ideas involved several types of sensors, such as RGB (classical pictures and the base for a 3D model), thermal images and multispectral approaches. Figures 13 and 14 visualize this fact. In Figure 13, the detection of different types of damages are evident, like rust and flaking paint which are detectable in different wave lengths.

Fig. 13. Different views using RGB or thermal images. Different types of damages can be seen in each spectral band.

The same is applicable while using multispectral images, what is shown in Figure 14. Using RGB the shaft head seem to be intact. But using multispectral images mosses and lichens can be seen. This vegetation needs moisture for living. Moisture again will damage steel.

Fig. 14. Like in Fig. 18 multispectral images can detect plant cover like mosses and lichens.

But not only the raw data, the view on the pictures are of interest – even they already give first hints on possible damages. Here, special analysis tools from classical geomonitoring can be applied to detect possible damages. In Figure 15, a classical vegetation index (NDVI) was calculated for the roof of a Hoesch steel house, which is a listed building. Areas were plants are growing can be found easily and for them to flower well, water is needed. Still, water on the roof of a steel house is causing damages very soon.

Fig. 15. Applying analysis tools on multispectral images "plant health" gives hints for available water as a base for plant growth.

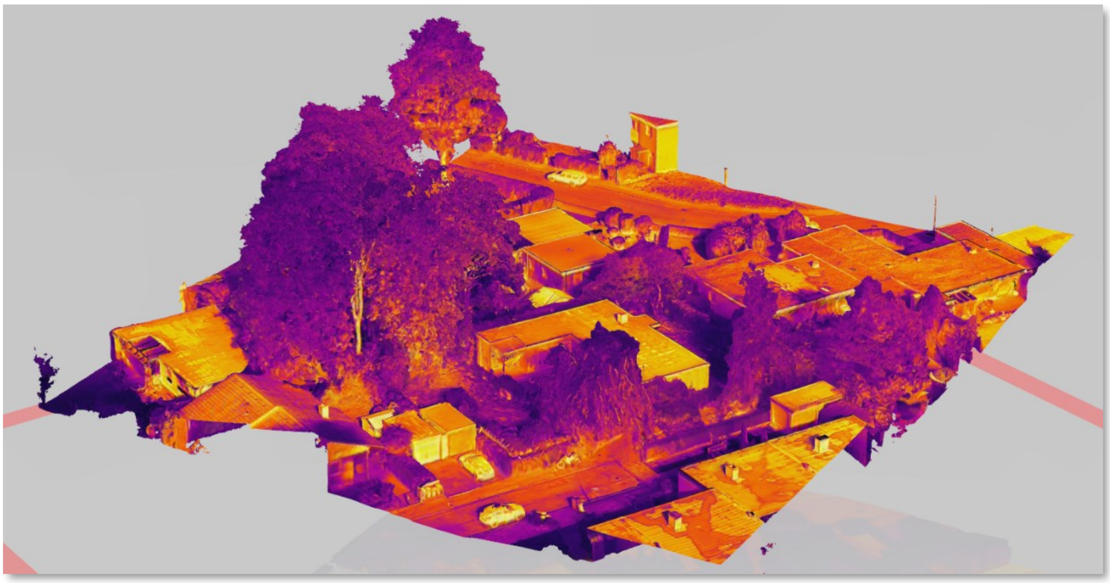

Fig. 16. 3D model based on an RGB orthophoto which "wears" a thermal image cover. Hoesch teel house, Dortmund (Drone flight Bodo Bernsdorf, modelling Benjamin Haske, FZN Bochum).

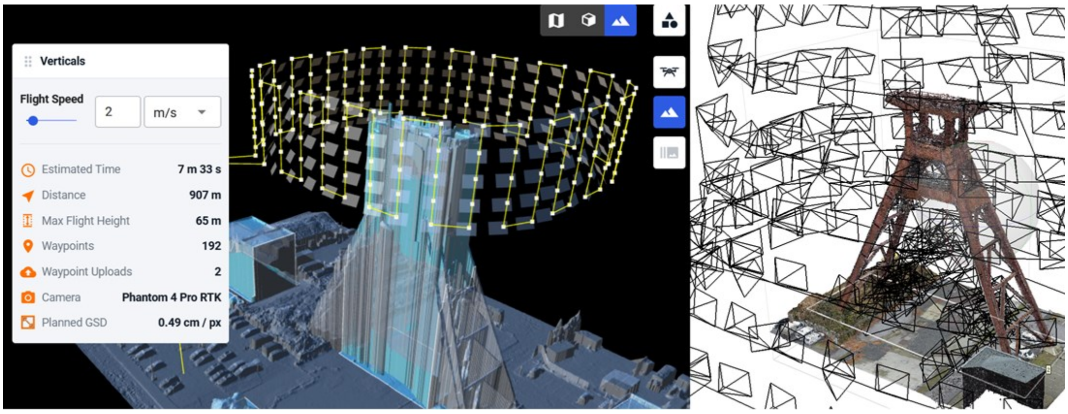

Fig. 17. Creation of high precision flight plans to perform the monitoring approach.

For doing samplings of such buildings, the platform used are drones again. Within the project frame, high precision flight plans are developed to 1.) perform a high precision sampling for finding damages and generating 3D-Models and 2.) to create a base for a repetitive monitoring. Using this flight plans, the exact same flight route can be applied on a frequent base e.g. every year (Fig. 17).

Case study: KaMonSys

In the research project KaMonSys (German abbreviation, translated as "Monitoring system for cavern storage safety using satellite and UAV data"), for over two years safety solutions for critical infrastructures have been developed in an interdisciplinary approach. Taking large scale underground storage facilities (USF) as an example, multisensory approaches have been developed to monitor the caverns, pipelines, facilities and their surroundings using satellite, UAV and in-situ data and to detect potential leakages, methane emissions, ground movements and vegetation health

(Haske et al 2022; FZN 2022c). The large-volume storage facilities for natural gas, oil, helium and (in the future) hydrogen, are located at a depth of over 1,000 m in former salt caverns, that were leached into the several hundred meter thick rock salt deposit under northern Germany (Figure 18) (Reitze et al 2014). The caverns are sealed by hundreds of meters of salt and rock and are geologically stable, while the wells, pipelines, and surface facilities used for injection and withdrawal, however, can be potential emitters of environmentally harmful liquids and gases and therefore require extensive monitoring. This protects not only the people living above the caverns, but also the intensively farmed areas and ecologically valuable protected areas such as the Amtsvenn and Huendfeler Moor. The monitoring is further complicated by the fact that agriculture and the moors themselves are also potential emitters of biogenic methane and can trigger ground movements through drying out and rewetting (Rudolph et al. 2022).

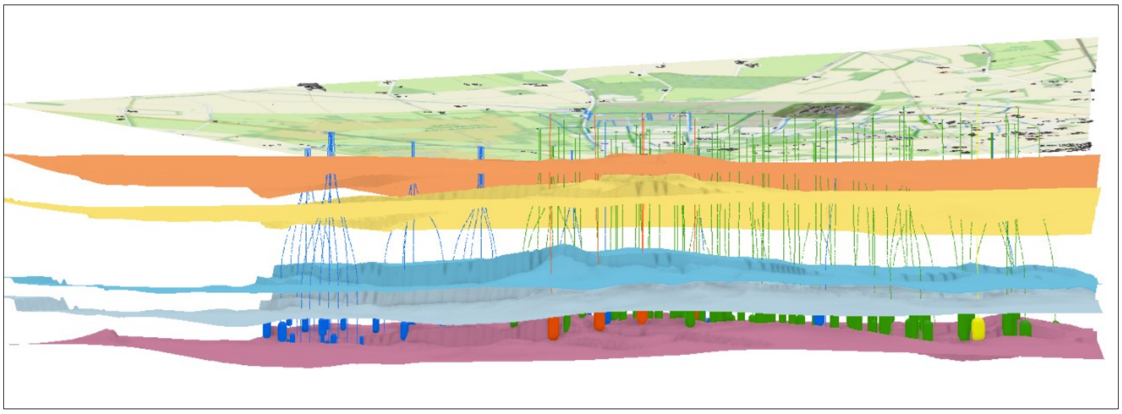

Fig. 18. Reused salt caverns for the storage of gaseous and liquid energy sources in northern Germany. Layers: Orange = Upper Bunter sandstone, Yellow = Dethfurt sandstone, Dark blue = Zechstein, Light blue = Werra rock salt, Purple = Lower Werra anhydrite. Caverns & Boreholes: Red = oil, Green = natural gas, Yellow = Red = oil, Green = natural gas, Yellow = helium, Blue = brine (Haske et al 2022).

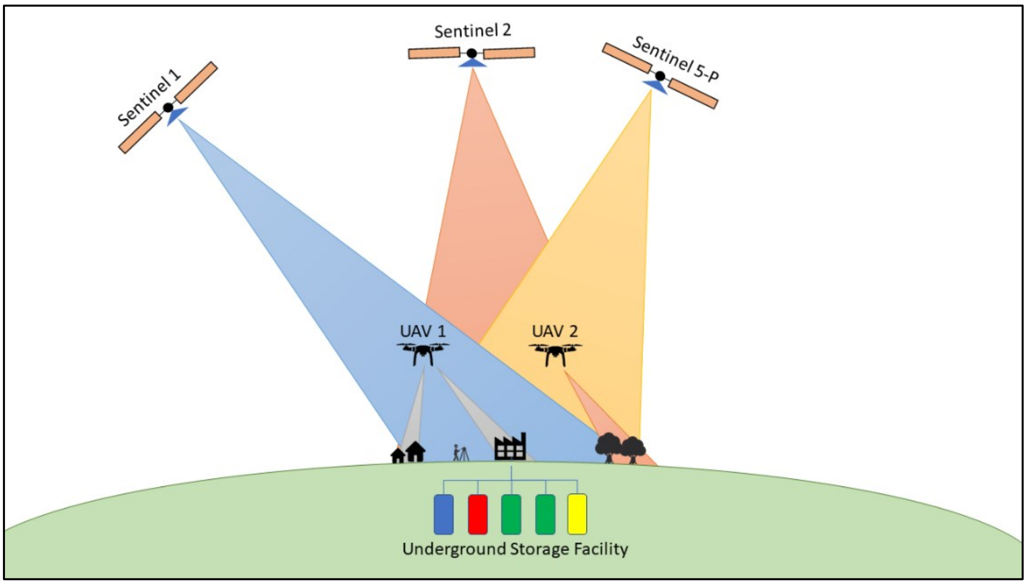

Fig. 19. Multi-layered, spatio-temporal geomonitoring of an underground storage facility developed in project KaMonSys (Haske et al. 2022).

Together with project and associated partners (EFTAS Fernerkundung Technologietransfer GmbH; Uniper Energy Storage GmbH; Salzgewinnungsgesellschaft Westfalen mbH; Gas- und Wärme-Institut Essen e.V.), the Research Center of Post-Mining has developed a multi-stage monitoring system in this project funded by the German Federal Ministry of Education and Research (SIFO 2022). The stages consist of large-scale monitoring using public satellite data from the European Copernicus program (Sentinel-1, Sentinel-2, and Sentinel-5P), self-performed multisensorale UAV flights, in-situ measurements, and a 3D geoinformation system (GIS) that brings all these data together (Figure 19) (Copernicus2022). This allows the strengths of the respective temporal, spatial and radiometric resolutions to be optimally exploited and their weaknesses to be compensated for.

The work of the project was divided into various task packages and milestones, which are not discussed in detail in this article (Rudolph et al. 2021). However, the steps for developing a large-scale environmental monitoring concept proved to be practicable and could already be used in adapted form in similar projects:

1. Data collection and development of an understanding of the geological, topographical and biogenic conditions at both surface and underground; Integration of the data into a 3D GIS (Figure 19)
2. Extension of the 3D GIS with anthropogenic structures (buildings, technical facilities, pipeline routes, boreholes, caverns)
3. Extension of the 3D GIS with processed UAV and in-situ measurements (e.g. surface classifications, temperature base data, identification of potential risk sources, wind edges, explosion protection zones)
4. Development of highly accurate 3D flight plans based on the acquired data, taking into account potential gas emitters and risk-based no-fly zones
5. Fusion of the 3D GIS with the evaluated satellite data
6. Development of workflows for a multi-level risk management from large-scale to point monitoring (satellite - UAV - in-situ)
7. Development of a Web-GIS as demonstrator for the data presentation and processing of the workflows

The result is an interactive, multitemporal GIS, in which free data sources (especially in the context of the INSPIRE directive), data of the project partners as well as own surveys, flights and analyses were merged (Figure 20).

One of the main aspects of the project that will be exemplified here, is the continuous vegetation analysis using multispectral Sentinel-2 imagery (Mader et al. 2021). Here, an algorithm was developed to quickly detect local, unseasonal vegetation degradation in spatial proximity with facilities and pipelines, as these could be related to undetected leaks (publication in progress). If such a suspected area is detected via a specific change detection algorithm between two Sentinel-2 images, a UAV will ascend and verify the suspicion. The UAV has a much better spatial resolution (10 m to 5 - 10 cm), so that the high temporal resolution images of the satellite are “sharpened” by it. The link between the high temporal and the high spatial resolution of the two platforms is the radiometric resolution, in which the channels of visible light as well as the near-infrared and red-edge range overlap (Figure 21).

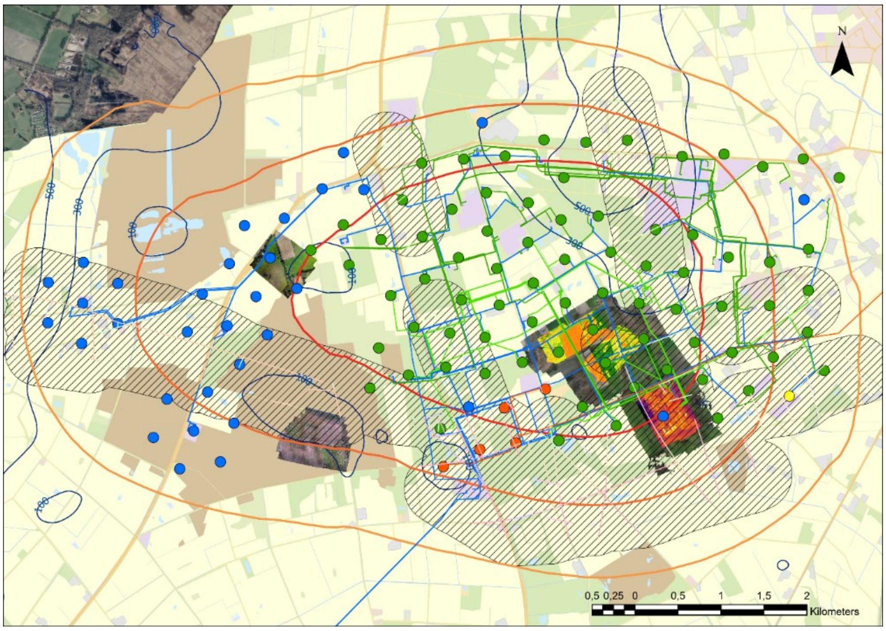

Fig. 20. The interactive GIS in the KaMonSys project. As an example, layers with information on pipelines, boreholes, caverns, land use, groundwater distances, ground subsidence, and geological faults are shown together with analyses of multispectral UAV flights (RGB, thermal infrared, NDVI).

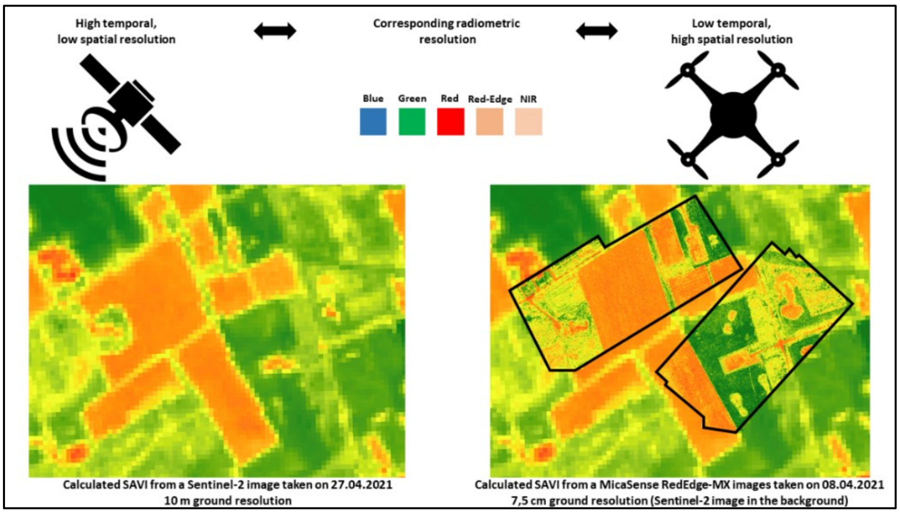

Fig. 21. Comparison between the spatial, temporal and spectral resolution of the Sentinel-2 satellite and a UAV-based MicaSense RedEdge-MX camera.

The monitoring approach was verified based on known pipeline processing facility and storage leaks in the past (e.g. cavern storage Epe oil spill, April 2014 (WDR 2017); Druzhba-Pipeline Poland leakage, October 2022 (PERN 2022)).

Conclusion and outlook

This article has provided a wealth of diverse information. Although mainly the two research areas reactivation and transition as well as geomonitoring with their respective different foci were presented (out of the four research areas that the Research Center provides), it has nevertheless become clear that a combination of the different research perspectives takes place here and is also necessary in order to design holistic solution approaches. It is not possible to depict the full range of all sub-areas without going beyond the scope. Many competencies and a wide variety of niche research are served, which together form a foundation. The aspects shown here in the article are only an excerpt. Therefore, by including social, political and economic framework conditions within the reactivation and transition, the influences on people and the environment are identified here. In this way, laws and strategic orientations can be aligned more successfully and specifically in the long term. The employment effects in the area of industry and its restructuring processes, particularly related to mining and its legacies, are analyzed and possible impulses are created on this basis. On the other hand, new concepts for the subsequent use of former mining regions can be developed more efficiently, which should enrich and absorb the affected regions and the people living in them. The counterpart to this is offered by the different approaches of geomonitoring. The presentation of a selection of currently active projects shows the abundance of possibilities and the wide range of points where to start. With its various approaches and analysis using different technologies, from drones and various sensors (RGB, thermal infrared and multispectral) to satellites to soil moisture sensors, indices and data processing, as well as data collection - this area offers the indispensable basis for the realization and exploration of possibilities for concept implementation. Here it is decisively determined what makes more precise monitoring necessary in order to secure former sites and to keep damage to the environment and people as low as possible. However, this is also a major driver of innovation, which offers the opportunity to close existing research gaps with new findings and to create new alternatives for post-mining.

The projects presented here already give an idea that further important findings will be available when the project is completed. They, in turn, form the starting point for further dedicated research in these fields and will also enable further active participation in promoting regional and national development in the future. But the transfer of knowledge does not stop here, it begins. Many of the projects are already being carried out in cooperation with national, but also with European partners. The aim behind this is always to learn from experiences together and to optimize one’s own development through the exchange of knowledge with other countries. In the future, other countries can benefit from Germany’s mistakes and the positive aspects of the hard coal phase-out and use this knowledge to strategically adapt their planning in advance and to carry out a socially more acceptable structural change.

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Assessment of ecological hazards in Donbas impacted by the armed conflict in Eastern Ukraine (natural and anthropogenic conditions affecting water supply in Donbas)

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Since Soviet times, Donbas has been a region of heavy industry with the highest levels of anthropogenic impacts on the environment. Such impacts include emissions of hazardous substances into the atmosphere, discharge of untreated wastewater into natural water bodies, and waste disposal. This was associated both with the local industry – notably coalmining, production of chemicals, coal metallurgy and machine-building.

For 200 years, people have been intensively extracting coal in Donbas in a relatively small territory of 15,000 square kilometers. Some 20 billion tons of rock were removed from the Earth's interior during this period, including 15 billion tons of coal. In an area of 8,000 square kilometers, the surface of the Earth has subsided on average by 1.5-2 meters; 600 cubic kilometers of the rock massif have suffered from deformation.

The anthropogenic hazard level in Donbas is primarily caused by the presence of potentially hazardous facilities in the territory. In 2009, operating in Donetsk oblast alone, there were 157 coal mines, 108 hydraulic engineering facilities, 537 petrol stations and 12 open-pit (or opencast) mines. There were also 11 railway stations, 115 bridges and crossovers, 1 tunnel for land transportation, and 13 major pipelines and branch pipes. In Luhansk oblast, there were 69 coal mines, 66 hydraulic engineering facilities, 247 petrol stations, 3 open-pit mines, 2 railway stations, 13 bridges, 5 major pipelines and branch pipes, and 4 oil deposits.

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At the beginning of 2013, in Donetsk oblast, there were 3,020 potentially hazardous facilities. This is approximately 13% of the total number in Ukraine, or 114 facilities per 1,000 square kilometers of land. Of the potentially hazardous facilities in Donetsk oblast:

- 1,443 were explosive
- 17 were radiation-hazardous
- 522 were flammable
- 111 were hydro-dynamically hazardous
- 22 were bio-hazardous
- 17 were assigned the first degree of chemical hazard
- 63 were assigned the second degree of chemical hazard
- 91 were assigned the third degree of chemical hazard
- 69 were assigned the fourth degree of chemical hazard.

In Luhansk oblast in 2013, there were 1,220 potentially hazardous facilities (5% of the total number in Ukraine, or 46 facilities per 1,000 square kilometers of land). Of these:

- 717 were explosive
- 7 were radiation-hazardous
- 798 were flammable
- 65 were hydro-dynamically hazardous
- 12 were bio-hazardous
- 6 were assigned the first degree of chemical hazard
- 29 were assigned the second degree of chemical hazard
- 43 were assigned the third degree of chemical hazard
- 6 were assigned the fourth degree of chemical hazard.

Conditions affecting water supply in Donbas

The literature surveyed provides a detailed description of the hydro- geological conditions of the Donbas region. Therefore, the literature and publications have been used to profile the territory in which this assessment of reserve sources of domestic water supply has been conducted. In this section, we cover only the singularities of the basin's geological structure and hydro-geological conditions which are connected with a dominant influence of coalmining and other economic activities, as well as the armed conflict, upon the environment.

Natural factors

There are two key singularities of natural conditions in the territory of Donbas:

1. **The structural geology** creates a variety of forms and sizes of folded basin structures. In terms of form, these are both synclinal (dipping) and anticlinal (rising) structures of folded rock layers. These range from linear to batchy folds with rock bedding ranging from horizontal to vertical. Coal mines occur in areas of particular landforms, and water catchment areas form over minefields, which creates a geologically non-homogenous environment. A non-homogenous environment is an upper layer of the lithosphere (rigid outermost shell of the earth's surface) which presents a mixed structure of rocks.
2. **The geology (structures and positions of rocks) affects water supplies in terms of quantity, volume and quality of** underground aquifers and surface water sources. The area of underground fresh and low-salt water depends on the position of different geological layers and the interstratifications of more and less permeable rock. (The recent flooding of unprofitable mines has reduced the number of areas containing fresh water.)

Human factors

There are three particular anthropogenic conditions in Donbas affecting water quality:

1. **Extensive coalmining**: there is an extremely elaborate system of mine workings at broad-ranging depths, with a large number of closed-down and flooded mines. There is considerable horizontal expansion of the field of operations and a long duration of mine exploitation.
2. **Unstable groundwater movement** within operating and closed mines. There are regional 'cones of depression' (areas of lowered groundwater levels) spreading far beyond minefields, as well as local cones of depression migrating along breakage faces. Recharge is increasing through the infiltration of atmospheric precipitation falling over the minefields due to the growth of jointing after the collapse of roofs over worn-out treatment facilities. There is also a rise in rock permeability where roofs have collapsed over mine workings, plus absorption and penetration of surface water into mine workings where solid rock massif under streams and water ponds has been disturbed.
3. **Land subsidence and compaction**. Troughs of land have subsided over minefields, to a depth of 3-4 metres in some cases, where waterlogged areas and wetlands have developed. After collapse of mine workings, rock compaction can occur, plus dehydration compression of soil. There is intensive industrial and urban pressure on most coalmining complexes, with additional anthropogenic recharge of groundwater.

Resources of surface water in Donbas

Mining operations over more than two centuries in Donbas have extremely adversely affected the quality of surface water and the mode of surface streams. The overall resource of surface water in Donbas is formed by the basins of the Dniper, the Siverskyi Donets and small rivers of Pryazovia (Figure 1).

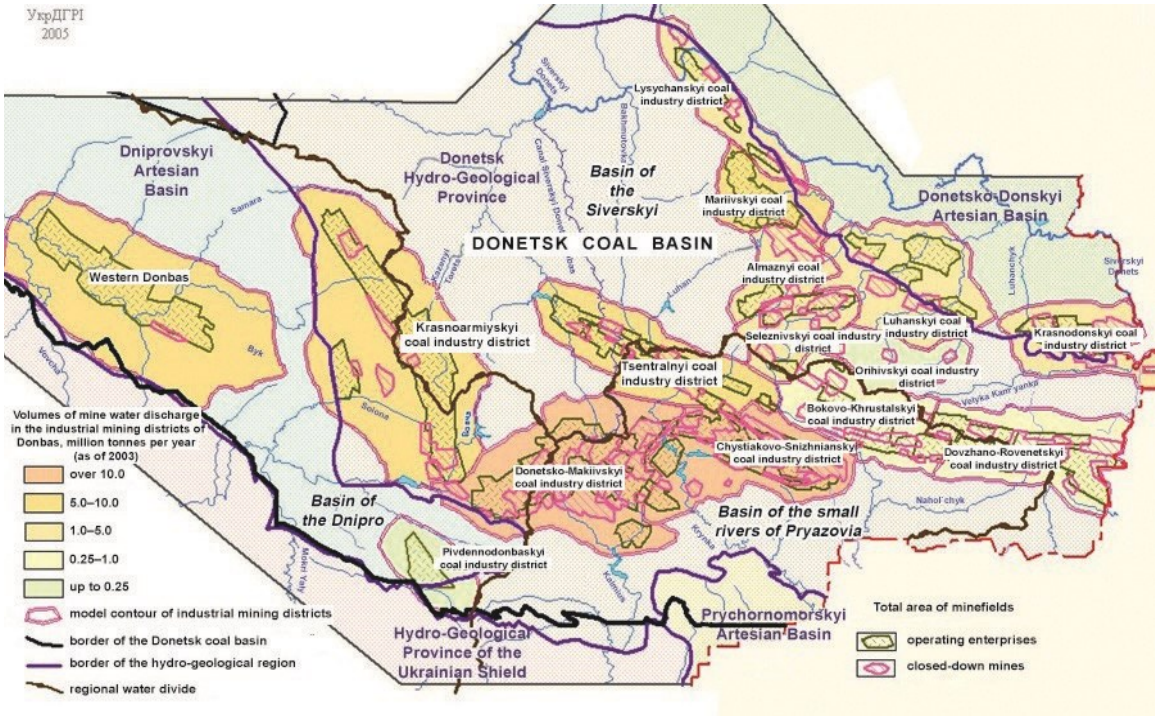

Fig. 1. Map of Donbas river basins: surface water resources and mine-water discharge

In natural conditions, the rivers of Donbas are primarily fed from atmospheric precipitation and especially the spring melting of snow, which delivers 40-80% of their runoff. Feeding from groundwater is significant only within the confines of the Donetsk Range where, due to down-cutting, river valleys drain aquifers in mineral coal deposits and covering deposits.

Mine drainage water (mine water) plays a significant role in the recharge of river runoff. The total discharge of mine water into surface streams in 1995 was approximately 25m^3 per second [1]. Now, according to the authors' estimates, it amounts to 24.2m^3 per second or 87,000m^3 per hour (Table 1). Industrial facilities in Donbas discharge approximately 70m^3 per second (252m^3 per hour). For domestic and industrial use, approximately 39m^3 per second (140,000m^3 per hour) of water are taken from the rivers according to the available data [2].

Measuring the impact of coalmining on the formation of ecological and resource-related parameters of the surface runoff was based on comparing natural indicators of the river mode in an undisturbed state and under the influence of human activities. However, the following circumstances complicated the task:

Table 1. Scale of coalmining operations by Donbas river basins, 2012/13

Donbas river basins of the 1st order		Minefield impact areas, thousand km^2	Mine-water discharge volume (for 2012), thousand m^3/hour	Coal extraction (for 2013), million tonnes/year	Total number of mines with water pumping: operating / closed	Mine-water discharge rate, m^3/hour per km^2
Basin of the Dnipro-Samara		1.59	14.70	18.17	31 / 4	0.8
Basin of the Siverskyi Donets		2.29	30.18	18.09	65 / 29	1.1
Small rivers of Pryazovia	The Kalmius	0.64	11.63	6.04	18 / 9	1.7
	The Mius	1.50	30.46	9.67	69 / 18	1.8
Total for Donbas		6.02	86.97	51.96	183 / 61	1.3

1. The development of coal deposits in Donbas, followed by the dewatering of solid rock massif and a large-scale discharge of mine drainage water into surface streams, began over 130 years ago. However, a systematic study of the hydrological regime of the rivers of Donbas started only in the second half of the 1940s, when significant human influence already existed – and no attempts were made to define and assess this.
2. Long-term systematic data concerning the quantity of mine water discharge in rivers are not available. The rivers of Donbas are characterised by an extremely broad range of river discharge values in different time periods. With such a range, a comparison is challenging since during flooding the impact of mine water discharge may be insignificant, while it may be a decisive factor in the dry- weather period. Therefore, for comparison, we can use only the river discharge calculated as an average over many years.
3. A natural broad range of the content of soluble salts is typical for the rivers of Donbas, particularly Pryazovia. Water salinity ranges from 0.2-0.3g/dm^3 at the time of seasonal flooding to 3.5-5.0g/dm^3 in the dry season. With mine-water salinity primarily at the level of 2.0-4.0g/dm^3, mine-water discharge into surface streams may have both a negative and a positive impact.

In Donbas, there is a large number of enterprises applying water-use technologies and having a substantial volume of discharge. In total, this is three times bigger than the volume of mine-water discharge: up to 70m^3 per second or 252,000m^3 per hour were discharged by urban industrial agglomerations recorded up until 2010.

To satisfy household needs, since 1958 the Siverskyi Donets- Donbas Canal has supplied water at the rate of up to 35m^3 per second. Since the beginning of the 1980s, the Dnipro- Donbas Canal has supplied up to 45m^3 per second. After such water use and irreversible technological losses, a significant portion of this water is discharged into rivers, thus entirely changing the river discharge.

Unfortunately, not all existing hydrological reference works take this into consideration [2, 3]. They reference only results of a study of multi-year materials without distinguishing the anthropogenic component.

The above-mentioned circumstances reduce the accuracy of the conducted assessments to some extent. However, even given their implications, in many cases the impact of coalmining enterprises upon surface-runoff formation is illustrative.

Resources of groundwater in Donbas

Regionally, there are complex and varied conditions for accumulating groundwater resources and determining its quality. The specific hydro-geological conditions of various zones of Donetsk and Luhansk oblasts arise from a complex interplay of geological factors. These include the composition of water- bearing rock (notably its solubility), physical-geographical factors (such as precipitation volumes, development of river networks and climate) and, in past decades, anthropogenic factors (such as drainage by mines, open-pit mines, water intake facilities and infiltration of anthropogenic contamination).

At the same time, there are distinct regional features in groundwater distribution, resources and quality. For instance, the zones of shallow and open coal seams ('Open Donbas' – the central and eastern parts of Donetsk oblast and the southwestern part of Luhansk oblast) are characterised by the development of porous cracks with an active water exchange in the water-bearing rock up to the depth of 100-200 metres. Northern regions of Donetsk and Luhansk oblasts have the hydro-geological structure of an artesian basin with a storey development of aquifers in soft sedimentary rock. Lower aquifers (the third and fourth, counting down from the surface) contain saline (salty) water, which accounts for a higher concentration of salts in mine water and its contaminating impact on rivers, springs, wells and the top groundwater layer.

Groundwater runs in all kinds of stratigraphic units of rock. The Dniprovskyi Artesian Basin and the Dniprovsko-Donetskyi Artesian Basin (along with the Donetsko-Donskyi Artesian Basin) are abundant with fresh groundwater originating in Meso-Cenozoic deposits. In the Donetsk hydro-geological folded province in the area of the Palaeozoic folded unit of metamorphosed sedimentary rock (from the Devonian period until the beginning of the Mesozoic age), groundwater reserves are confined to aquifer units of Jurassic, Triassic, Lower Permian and mineral coal deposits (see Figure 1, Table 2).

There are several key natural and anthropogenic factors in the formation of fresh groundwater resources within the Donbas groundwater basins. These factors also affect the interaction between groundwater and surface runoff. They include: specific features of the tectonic structure; relief fragmentation for active water-exchange zones with due account taken of water catchment areas and the boundaries of geological structures for slow water exchange zones; and the impact of mine drainage (water pumping) on the formation of cones of depression and discharges into the runoff of the Siverskyi Donets, the Luhan, the Kalmius and other rivers.

Table 2. Mining and population in hydro-geological areas, 1 January 2014

	Area, km^2			
Hydro-geological provinces, artesian basins	Region	Minefields	Towns, urban ettlements	Towns, urban ettlements over mines
Donetsk Folded Province	22,963	4,219	2,272	963.9
Dniprovskyi Artesian Basin	8,743	649	114.9	14.3
Dniprovsko-Donskyi Artesian Basin	311	–	–	–
Donetsko-Donskyi Artesian Basin	4,343	28	281.5	21.9
Hydro-Geological Province of the Ukrainian Shield	3,931	–	48.5	–
Prychornomorskyi Artesian Basin	789	–	12.2	–
Total	41,080	4,896	2,729	1,000.1

There are several key natural and anthropogenic factors in the formation of fresh groundwater resources within the Donbas groundwater basins. These factors also affect the interaction between groundwater and surface runoff. They include: specific features of the tectonic structure; relief fragmentation for active water-exchange zones with due account taken of water catchment areas and the boundaries of geological structures for slow water exchange zones; and the impact of mine drainage (water pumping) on the formation of cones of depression and discharges into the runoff of the Siverskyi Donets, the Luhan, the Kalmius and other rivers.

Prognosed resources[c] of drinking groundwater in Donetsk oblast total 2.4 million m^3 per day, including explored resources with approved reserves of 1.1 million m^3 per day (115 sites). Presently, the aggregate groundwater intake amounts to 0.34 million m^3 per day or 14% of the total quantity of inferred resources. In 2015, episodic contaminations by natural compounds were registered at 34 water intake facilities (an increase in dry residue, hardness, the content of sulphates, chlorides, iron, and manganese).

Luhansk oblast is mostly provided with inferred resources of fresh groundwater (4.8 million m^3 per day) and has a high level of exploration (98 sites with reserves of 1.9 million m^3 per day or 40%). In 2015, contamination was recorded at 12 water intake facilities (dry residue, hardness, the content of iron, manganese, nitrates, phenols, and ammonium). A lower level of contamination is attributed to a greater degree of protection by regional water-confining strata (poorly permeable layers).

In general, a majority of raions (districts) of Donetsk and Luhansk oblasts (provinces) have a substantial reserve of explored and prospective sites of drinking groundwater. It is reasonable to prepare such sites for exploitation as backup or basic water supply points for when there are disturbances in water supply by the Donbas Water Company from surface sources. Such surface sources are primarily unprotected from contamination due to adverse effects of military activity and the leakage of contaminated water from flooded mines. Sources of surface water are also unprotected from and the possible influx of contaminants from waterlogged and flooded landfill sites during spring flooding or times of increased precipitation, and from unauthorised discharges into domestic water reservoirs and other surface water bodies in the river basin of the Siverskyi Donets and its tributaries.

Current threats to domestic water supply

The current domestic water supply in Donbas and its development occur under special conditions due to the following factors related to technologies, resources and the environment.

1. Up to 80-90% of water in Donetsk oblast is supplied from unprotected surface runoff of the Siverskyi Donets through a hydraulic engineering complex of water reservoirs, canals and water pipes, which drastically diminishes sustainability and safety of domestic water supply systems.
2. The surface runoff of the Siverskyi Donets is characterised by significant seasonal fluctuations, with quality dependent on precipitation per year.
3. The water catchment area of the Siverskyi Donets in the Russian Federation, and in Kharkiv, Donetsk and Luhansk oblasts of Ukraine has a high level of plough disturbance (up to 65%) and contamination of water-collecting spots in the relief, great volumes of influx of industrial (mine) waste and a low degree of conservation of water protection zones.

In general, the domestic water supply in Donbas is seriously endangered by the armed conflict, which have caused destruction of water treatment facilities, hydraulic engineering structures and power supply systems. Dangerous repair and reconstruction works have led to deaths among professionals. This has required introducing restrictions on water supply, for the drinking water quality to cause minimum damage to the health of the local population and military personnel. At present, control of drinking water quality is primarily connected with Donbas Water Company's systems. Meanwhile, there are many scattered shaft wells, springs and local boreholes without a systematic water quality control. Their usage rate rises significantly when Donbas Water Company's facilities are damaged.

In addition to the direct effects of the ATO (anti-terrorist operation in the East of Ukraine), there is a growing threat of unauthorised discharges in surface runoff of the Siverskyi Donets basin. The assessment conducted for this study has demonstrated that enhancement of technological sustainability and ecological safety of domestic water supply in Donbas may be achieved through diversification of drinking water sources on the basis of the resources of explored groundwater intakes and individual boreholes. Groundwater sources of domestic water have a high degree of protection from contamination, stability of chemical composition and independence from annual precipitation.

There is a need for exploration of reserve water sources suitable for human consumption in these regions, as termination of centralised drinking water supply in the above-mentioned towns will result in a humanitarian crisis.

Concerning the enhancement of ecological resource-related safety of domestic water supply, a gradual increase in the number of operating boreholes could mitigate risks of water- ecological emergencies and reduce consequent social tensions. Findings of the HD mission's ecological survey of reserve water supply sources in Donetsk and Luhansk oblasts (carried out from 23 October to 4 November 2016) demonstrate that this gives room for manoeuvre for local administrations to ensure stable and ecologically safe operation of domestic water supply systems.

There are two broad implementation stages preliminarily identified in the diversification procedure for domestic water supply. The first stage entails a comprehensive ecological anthropogenic inspection of all available reserve sources of domestic water supply that are not part of the Donbas Water Company's complex. The second stage involves identification of locations for the first regular equipping of operating water boreholes and approval of operational regulations.

In general, increasing the use of contamination-protected groundwater will help to mitigate risks of ecological water emergencies affecting public health. The surface water resources of the Siverskyi Donets are now formed in the increasingly deteriorating ecological condition of the catchment area.

In this report, the authors talk about increasing the number of operating boreholes 'from the perspective of enhancing ecological resource-related safety of drinking water supply'. Some towns in Donetsk oblast in territory uncontrolled by the Government of Ukraine, such as Donetsk, Horlivka, Torez and Khartsyzk, as well as Pokrovsk, have no underground sources of drinking water supply. Presently, drinking water may be supplied to the population and the municipal infrastructure in these towns only from surface sources. There is a need for exploration of reserve water sources suitable for human consumption in these regions, as termination of centralised drinking water supply in the above-mentioned towns will result in a humanitarian crisis.

Furthermore, even the availability of centralised drinking water supply in towns of the oblast having their own groundwater sources will not resolve the problem since, in all large towns of the oblast, groundwater sources have played only an auxiliary role, complementing water from surface sources. The use of surface water sources to meet consumer needs is dangerous and alternative (underground) sources which are protected from contamination. Facilities with high epidemic risks (pre-school educational institutions and healthcare facilities, community dining facilities, and industrial facilities) will not be able to operate with a drastic decline in the volume of drinking water and should be the first to receive clear drinking water form alternative sources. Generally, clear water is delivered to the population by special-purpose vehicles, which have a limited volume capacity.

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Current threats to domestic water supply in Donbas region

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The current domestic water supply in Donbas and its development occur under special conditions due to the following factors related to technologies, resources and the environment.

1. Up to 80-90% of water in Donetsk oblast is supplied from unprotected surface runoff of the Siverskyi Donets through a hydraulic engineering complex of water reservoirs, canals and water pipes, which drastically diminishes sustainability and safety of domestic water supply systems.
2. The surface runoff of the Siverskyi Donets is characterised by significant seasonal fluctuations, with quality dependent on precipitation per year.
3. The water catchment area of the Siverskyi Donets in the Russian Federation, and in Kharkiv, Donetsk and Luhansk oblasts of Ukraine has a high level of plough disturbance (up to 65%) and contamination of water-collecting spots in the relief, great volumes of influx of industrial (mine) waste and a low degree of conservation of water protection zones.

In general, the domestic water supply in Donbas is seriously endangered by the armed conflict, which have caused destruction of water treatment facilities, hydraulic engineering structures and

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power supply systems. Dangerous repair and reconstruction works have led to deaths among professionals. This has required introducing restrictions on water supply, for the drinking water quality to cause minimum damage to the health of the local population and military personnel. At present, control of drinking water quality is primarily connected with Donbas Water Company's systems. Meanwhile, there are many scattered shaft wells, springs and local boreholes without a systematic water quality control. Their usage rate rises significantly when Donbas Water Company's facilities are damaged.

In addition to the direct effects of the ATO, there is a growing threat of unauthorised discharges in surface runoff of the Siverskyi Donets basin. The assessment conducted for this study has demonstrated that enhancement of technological sustainability and ecological safety of domestic water supply in Donbas may be achieved through diversification of drinking water sources on the basis of the resources of explored groundwater intakes and individual boreholes. Groundwater sources of domestic water have a high degree of protection from contamination, stability of chemical composition and independence from annual precipitation.

There is a need for exploration of reserve water sources suitable for human consumption in these regions, as termination of centralised drinking water supply in the above-mentioned towns will result in a humanitarian crisis.

Concerning the enhancement of ecological resource-related safety of domestic water supply, a gradual increase in the number of operating boreholes could mitigate risks of water-ecological emergencies and reduce consequent social tensions. Findings of the HD mission's ecological survey of reserve water supply sources in Donetsk and Luhansk oblasts (carried out from 23 October to 4 November 2016) demonstrate that this gives room for manoeuvre for local administrations to ensure stable and ecologically safe operation of domestic water supply systems.

There are two broad implementation stages preliminarily identified in the diversification procedure for domestic water supply. The first stage entails a comprehensive ecological anthropogenic inspection of all available reserve sources of domestic water supply that are not part of the Donbas Water Company's complex. The second stage involves identification of locations for the first regular equipping of operating water boreholes and approval of operational regulations.

In general, increasing the use of contamination-protected groundwater will help to mitigate risks of ecological water emergencies affecting public health. The surface water resources of the Siverskyi Donets are now formed in the increasingly deteriorating ecological condition of the catchment area.

In this report, the authors talk about increasing the number of operating boreholes 'from the perspective of enhancing ecological resource-related safety of drinking water supply'. Some towns in Donetsk oblast in territory uncontrolled by the Government of Ukraine, such as Donetsk, Horlivka, Torez and Khartsyzk, as well as Pokrovsk, have no underground sources of drinking water supply. Presently, drinking water may be supplied to the population and the municipal infrastructure in these towns only from surface sources. There is a need for exploration of reserve water sources suitable for human consumption in these regions, as termination of centralised drinking water supply in the above-mentioned towns will result in a humanitarian crisis.

Furthermore, even the availability of centralised drinking water supply in towns of the oblast having their own groundwater sources will not resolve the problem since, in all large towns of the oblast, groundwater sources have played only an auxiliary role, complementing water from surface sources. The use of surface water sources to meet consumer needs is dangerous and alternative (underground) sources which are protected from contamination. Facilities with high epidemic risks (preschool educational institutions and healthcare facilities, community dining facilities, and industrial facilities) will not be able to operate with a drastic decline in the volume of drinking water and should be the first to receive clear drinking water form alternative sources. Generally, clear water is delivered to the population by special-purpose vehicles, which have a limited volume capacity.

Coalmining impacts on the geological environment of Donbas

The geological environment in coalmining districts

Commercial development of mineral coal, occurring in the Donetsk basin for over 150 years, has resulted in the extraction of over 10 billion cubic metres of coal rock massif. This has been accompanied by regional disturbance of the geodynamic and hydrodynamic environment and ecological–geological conditions of the basin. Coalmining has been carried out at around 900 mines and 180 coal seams. In total, there are close to 2,250 extraction sites. Management of the roofs of worked-out coal seams by collapsing them entirely was applied practically universally. The volume of disturbed rock amounted to approximately 600km^3, or 14.3% of the total volume of rock massif within the confines of minefields.

Coal production reached its peak in the 1980s and 1990s when there were 254 mines operating in Donbas, extracting 180 million tonnes of coal per year (Figure 2). The impact of mining upon the geological environment was supplemented with those of production activities included in the mining complex. Specifically, there were 65 preparation plants, 9 coke plants, 17 chemical complexes and 9 metallurgical plants built and operated in Donbas.

As a result of largescale mining operations, the undermined areas make up approximately 8.2% and 7.8% of the territory of Luhansk and Donetsk oblasts, respectively as well as the mines, have undergone the greatest environmental changes. During field development, a large volume of rock undergoes mine dewatering – a process of pumping water from an underground part of a coalmine. A fall in the groundwater level within the technical boundaries of mines can reach 300–1,000 metres. Regional cones of depression' then emerge as a result of falling groundwater levels at the sites adjacent to mine boundaries, reaching up to 30-100 metres (Figures 2 and 3).

With the current annual volume of coal extraction at the level of approximately 50 million tonnes, up to 450 million cubic metres per year of contaminated saline water (rough estimates) is pumped out. This water primarily has high levels of salinity (2.0-4.0g/dm²). A decline in the volume of pumped-out water by nearly 300 million cubic metres per year brings about acceleration of mine flooding and an increase in the migration of contaminated saline mine water into aquifers and surface runoff into rivers, which are major sources of domestic water supply.

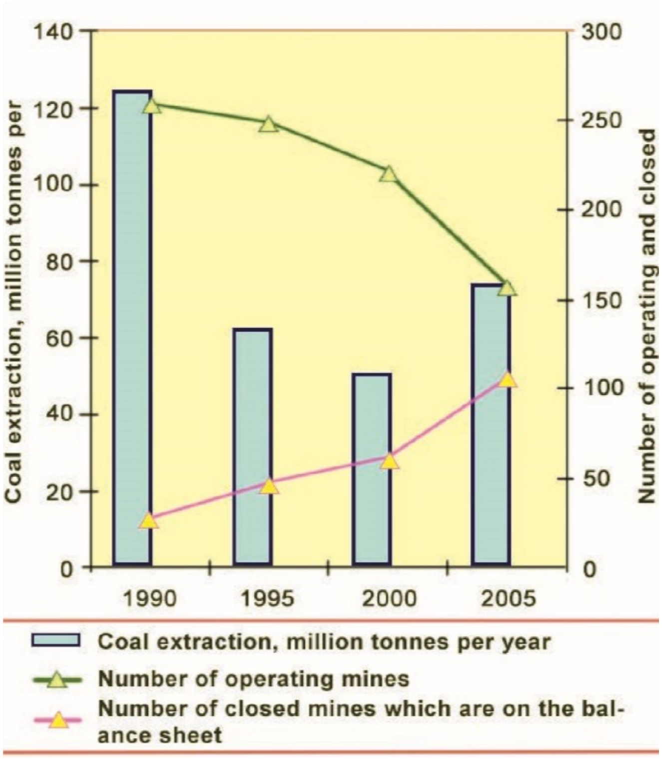

Fig. 2. Scale of coalmining operations in Donbas, 1990–2005

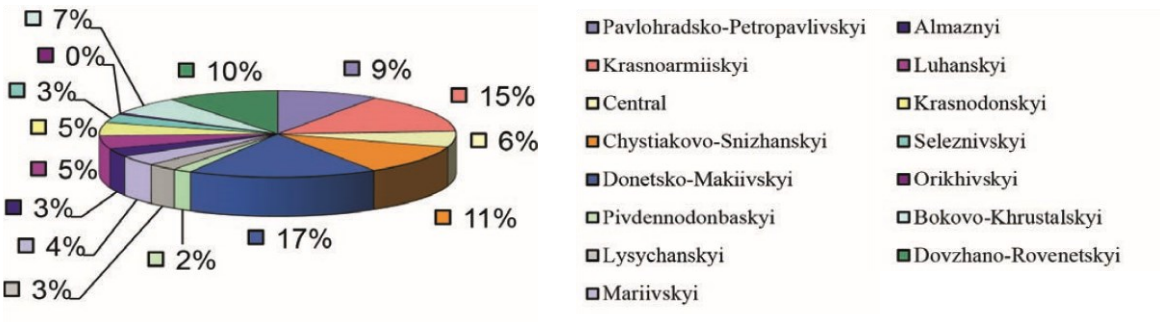

Fig. 3. Comparison of minefield areas by geological industrial districts of Donbas

The pressure from mining on the geological environment has formed in the Donetsko-Makiivskyi, Chystiakovo-Snizhnianskyi and Tsentralnyi geological industrial districts. There is less severe pressure on the Dovzhano-Rovenetskyi and Krasnoarmiiskyi geological industrial districts (Table 3).

The deepest mines are located in the Donetsko-Makiivskyi (1,420m), Chystiakovo-Snizhnianskyi (1,260-1,300m), Tsentralnyi and Dovzhano-Rovenetskyi (1,200m) geological industrial districts. The largest volume of disturbed rock is in the Bokovo-Khrustalnyi (102km^3) and Donetsk Makiivskyi (99km^3) districts.

Table 3. Areas affected by coal mines, by administrative units of Donbas

Number, in the Donbas Water system	Towns of oblast subordination, administrative raion within the boundaries of the coal-mining district	Area of the administrative unit (within the boundaries of the Donbas Water system), km²	Areas affected by coal mines		
			Total area of minefields, km²	Potentially waterlogged lands	Waterlogged land in towns and urban settlements, hectares
1	2	3	4	5	6
1. Donetsk oblast			2,664	65	5,369
1	Dobropollia, Bilozerske, Biletske	17.37	14.31	–	175
	Dzerzhynsk, Artemovo	14.39	13.87	–	–
	Dymytriv, town	18.91	18.61	–	–
	Oleksandrivskyi raion	1,005.04	64.59	–	175
	Dobropilskyi raion	940.07	189.60	–	–
	Kostiantynivskyi raion	1,340.83	65.38	–	–
	Krasnoarmiiskyi raion	1,463.19	434.64		570
	Mariinskyi raion	1,366.63	223.88	–	22
2	Horlivka, town	127.0	71.40	–	–
	Yenakiieve, Vuhlehirsk, Yunokomunarivsk, towns	39.57	13.56	–	27
	Avdiivka, town	11.33	2.24	65	–
	Yasynuvata, town	12.67	12.62	–	480
	Zhdanivka, town	3.87	2.30	–	–
	Kirovske, town	4.24	2.89	–	73
	Khartsyzk, Ilovaisk, Zuhres, towns	128.29	104.80	–	342
	Shakhtarsk, town	39.05	35.00	–	–
	Torez, town	49.65	46.70	–	–
	Snizhne, town	29.99	26.39	–	–
	Makiivka, town	75.21	75.21	–	–
3	Donetsk, Mospyne, towns	194.67	179.49		2,973
	Vuhledar, town	1.04	0.11	–	532
	Dokuchaivsk, town	9.80	–	–	–
	Artemivskyi raion	2,041.81	33.36	–	–
	Yasynuvatskyi raion	1,098.70	155.50	–	–
	Shakhtarskyi raion	2,234.38	889.81	–	–

	Volnovaskyi raion*	1,380.08	31.94	–	–
	Amvrosiiyevskyi raion	1,485.56	40.87	–	–

Table 3. Areas affected by coal mines, by administrative units of Donbas

Number, in the Donbas Water system	Towns of oblast subordination, administrative raion within the boundaries of the coalmining district	Area of the administrative unit (within the boundaries of the Donbas Water system), km^2	Areas affected by coal mines		
			Total area of minefields, km^2	Potentially waterlogged lands	Waterlogged land in towns and urban settlements, hectares
1	2	3	4	5	6
2. Luhansk oblast			2,189	10	7,222
4.	Rubizhne, town	16.90	–	–	–
	Severodonetsk, town	16.81	–	–	–
	Lysychansk, Novodruzhesk, Pryvillia, towns	54.99	23.75	–	255
	Pervomaisk, Zolote, Hirske, towns	45.89	37.90	–	2,581
	Kirovsk, town	5.14	0.02	–	3
	Stakhanov, Almazna, Teplohirsk, towns	69.32	53.44	10	8
	Luhansk, Oleksandrivsk, Shchastia, towns	119.33	4.57	–	4,115
	Brianka, town	38.82	29.46	–	–
	Alchevsk, town	21.75	0.73	–	46
	Krasnodon, Molodohvardiisk, Sukhodilsk, towns	27.47	23.72	–	40
	Krasnyi Luch, Vakhrusheve, Miusynsk, towns	68.49	50.56	–	155
	Antratsyt, town	24.01	9.23	–	–
	Rovenky, town	26.46	24.70	–	–
	Sverdlovsk, Chervonopartyzansk, towns	45.04	36.03	–	–
	Kremenskyi raion*	1,023.44	21.53	–	–
	Popasnianskyi raion	1,439.61	233.17	–	–
	Slavianoserbskyi raion*	1,087.16	100.59	–	–
	Stanychno-Luhanskyi raion*	578.37	3.67	–	–
5.	Perevalskyi raion	868.48	271.59	–	–

	Lutuhynskyi raion	1,069.91	194.63	–	19
	Krasnodonskyi raion	1,422.91	247.79	–	–
	Antratsytovskyi raion	1,823.89	512.19	–	–
	Sverdlovskyi raion	1,310.52	318.17	–	–

A critical aggravation of ecological conditions for the safety of human life and health and a decline in the reliability of domestic water supply systems are associated with the fact that 18% of mine-fields are located beneath built-up areas. In Donbas, 63 towns and 91 urban-type settlements, with a total area of 1,000 square kilometres, stand over minefields. On average, 25% of the area of the towns and 51% of the area of the other settlements are undermined. In certain locations, coal extraction operations in old mining areas are performed in the same territory simultaneously by several mines at different depths.

The runoff system of river basins and local groundwater basins undergoes comprehensive changes caused by a rise in the scattered runoff of contaminated water from mines that are being flooded. Determining the projected impact of coalmining enterprises on surface runoff, especially in the Siverskyi Donets basin, which will remain the key source of domestic water supply for a long time, is complicated. This is because of a decline in the level of regional ecological water monitoring, including the following factors.

1. There is a lack of multi-year systematic data concerning the amount of mining water discharged into rivers.
2. The rivers of Donbas demonstrate a substantial variability of river discharge in different seasons. This increases the relative share of mine water, industrial waste inflows and contamination levels of surface water, as a source of domestic water supply.
3. A natural broad range of the content of soluble salts is typical for Donbas, particularly for Pryazovia. Water salinity levels range from 0.2-0.3g/dm^3 during seasonal flooding to 3.5-5.0g/dm^3 in the dry season. With mine water salinity primarily at the level of 2-4g/dm^3, its discharge into surface water flows may have a predominantly negative impact, given the reduced surface runoff during dry- weather periods of summer–autumn and winter.
4. Even under the current conditions in Donbas, there are many enterprises applying water-use technologies and having significant volumes of discharges, which according to estimates may exceed the volumes of mine water discharge. This creates substantial risks of water-ecological emergencies.

Under the current water-use schemes, wastewater from mines, industrial plants and households is discharged into rivers, completely changing resource-related and hydro-chemical indicators of the river runoff. Unfortunately, due to the destruction of the surface- and ground-water monitoring system, the existing present-day hydrological data do not permit accurate calculations concerning the impact of these factors.

Potential radiation impact of burial of the Klivazh facility in Yunkom mine

Amid the closure of mines in Donbas, the ecological and geological environment responds with ‘auto-rehabilitation processes’. These have considerable effects on conditions affecting urban mining agglomerations. Key processes include a regional rise in groundwater levels within affected river basins. There is also an accelerated migration of anthropogenic contamination due to an intensified water exchange in the zones of aeration (also known as unsaturated zones or zones of suspended water). There is an expansion of waterlogged and flooded areas of geochemically contaminated sites, both under and above ground.

In addition to the above, in our opinion, additional rock subsidence during rock saturation with water and the development of new migration routes for explosive gases may to a great extent be qualified as auto rehabilitation processes. These are also occurring in connection with the closing of mines in coalmining districts of Donbas.

In 1979, an industrial underground nuclear explosion with a TNT energy equivalent yield of 200-300 tonnes (0.2-0.3kt) was produced at the Yunkom mine. This mine is in Yunokommunarovsk town, on the southeastern periphery of the Tsentralnyi coalmining district in Donetsk oblast. This happened for the first time in the world and in a densely populated and intensively exploited coal-mining district. The purpose of the underground nuclear explosion was to assess its effectiveness for reducing the frequency of sudden coal and gas outbursts in the process of coal bed workings. A code name for the section of the geological environment containing the chamber of the underground nuclear explosion and an adjacent jointing zone is the Klivazh facility (Figure 4).

In the opinions of the researchers of the present report, the planned closure of a group of hydraulically interconnected mines of the Tsentralnyi coalmining district, including the Yunkom mine, given insufficient physical and technological coherence of measures, creates a risk of practically uncontrolled flooding of the Klivazh facility. The consequences of this are difficult to predict precisely but may include the contamination of groundwater and the wider geological envi- ronment with anthropogenic radionuclides. This may lead to a risk from radiation to human health and life.

The Yunkom mine is a hydraulically interconnected area of the geological environments of the adjacent Chervonyi Zhovten and Poltavska mines. Groundwater contamination has been persistent here for the past 50 years, extending as mining operations have extended in depth and area. Key impacts include the enhanced infiltration of saline mine water, geochemical contamination of landscapes, and destruction of regional low-permeability layers. This has resulted in a practically complete replacement of fresh water (up to 1.0-1.5g/dm^3) and slightly saline water (1.5-3.0g/dm^3) with saline water containing concentrations of dissolved salts in the range of 3-5g/dm^3 in up to 70% of the research area.

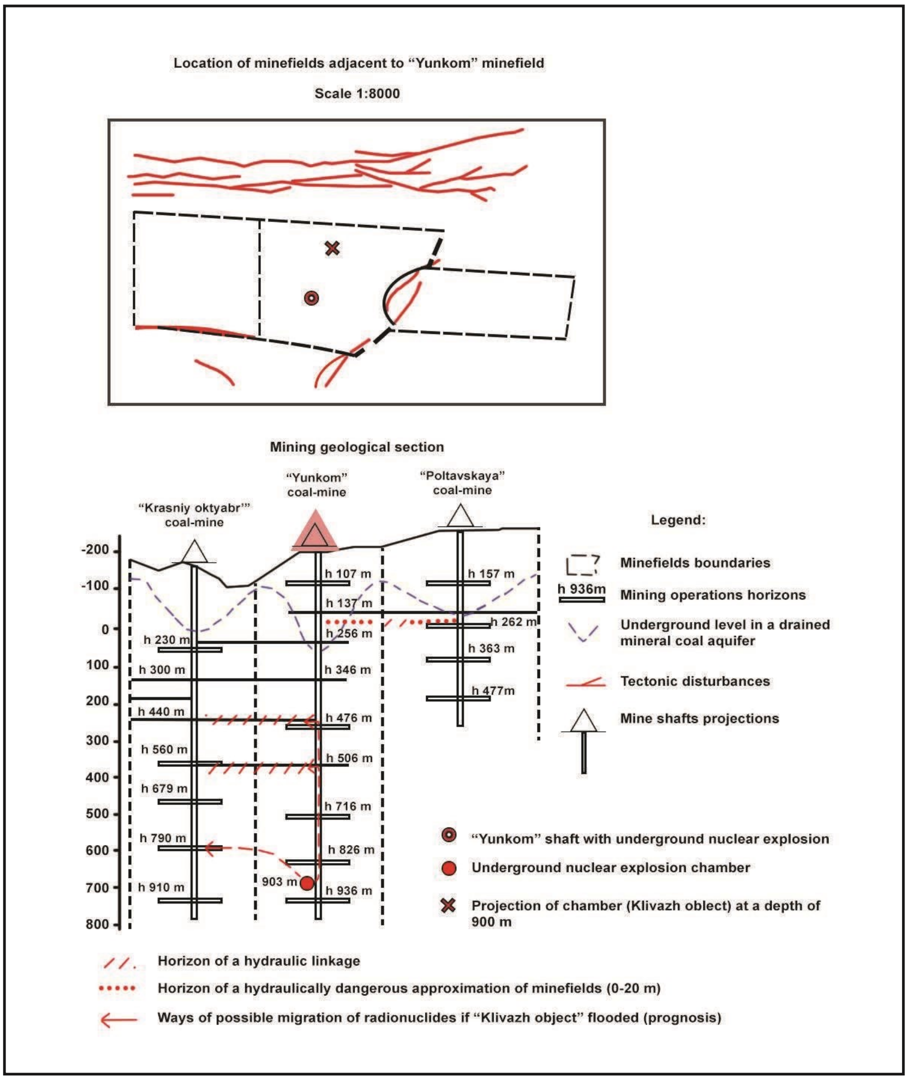

Fig. 4. The Yunkom mine area: adjacent minefields and a geological section

Various previous project studies demonstrate that accelerated groundwater contamination during the development of mining operations was caused by an increasing impact of the following factors:

- A rise in rock massif permeability due to the development of anthropogenic jointing in the areas where rock balance has been upset by mining operations.
- A rise in the infiltration of anthropogenic water and contamination caused by a more active interplay of surface and ground water, including due to the undermining of river beds.
- An increase in the area of landscapes contaminated through human activity, as well as in the number of filtering waste ponds with industrial and mine water.
- Development of poor drainage areas and non-contributing areas where land subsides over mine workings.

The vulnerability of groundwater has been assessed in quasi- stationary conditions when it is affected by mine water drainage, tectonic structures, a hydrographic network and a zone of aeration (groundwater depth levels). These assessments have demonstrated the prevalence of areas with a high level (60%) and an elevated level (30%) of proneness for aquifer contamination amid landscapes creation and changes induced by industrial activities.

Presently, in the area of declined groundwater levels of the Yunkom minefield within the confines of finished coal layers and the surrounding permeable sandstone, there is a possibility of an accelerated upward migration of saline mine water, including radionuclides of caesium-137 and strontium-90, during the flooding of mine workings. This may happen if there is a passive flooding and a partial decline in the level of hydro-isolation of the Klivazh facility while preliminary safeguarding measures to stabilise the adjacent rock massif are not implemented.

An analysis of the mining-geological conditions of the Chervonyi Zhovten and Poltavska mines, which are adjacent to the Yunkom mine, demonstrates that the presence of hydraulic linkages may be a contributing factor for the acceleration of upward and planned radionuclide migration processes. Key links are the horizons of 476m and 596m, and the hydraulically hazardous approaching of mine workings (the horizon of 262m of the Poltavska mine – the Yunkom).

The explosion chamber of the Klivazh facility is located in the central area of mining operations of the Yunkom mine, which is characterised by an utmost disturbance of coal- bearing rock massif and a significant depth of mine workings (up to 1km). Thus, if there is an accelerated hydro-geomechanical destruction of the Klivazh facility and the facility is upwardly flooded, there will be an increased risk of the manifestation of all groundwater vulnerability factors, as well as local contamination of surface watercourses (see Figures 1-3).

On the other hand, the explosion chamber of the Klivazh facility is located at a substantial depth (903m) and characterised by the local evolution of jointing and the absence of hydraulic linkages and hazardous geotechnical approximations with mine workings of the adjacent mines (the Chervonyi Zhovten mine and the Poltavska mine). There is also a slow rock deformation and low rates of the migration of water- soluble forms of radionuclide, namely caesium-137 and strontium-90, through a relatively solid layer of rock capable of absorption.

In addition, the flooding of a stabilised rock massif, provided there is a steady filtering saturation of the explosion chamber of the Klivazh facility with water, may lead to the establishment of a practically stagnant regime. This may result in decelerated sorption and migration processes in the enclosing rock.

Conclusion

(Preliminary ecological-geological assessment of the nuclear explosion chamber and the adjacent rock massif)

An ecological-geological singularity of the formation of the nuclear explosion’s affected area is the presence of an explosion chamber (a camouflet chamber), i.e. a chamber that has evolved without an explosion-driven outburst of rock. Field assessments have showed that vitreous sandstone melt may contain concentrations of up to 95% of radioactive explosion products (Semypalatynsk, Nova Zemlia, and other nuclear test sites).

Data obtained through probing boreholes and an inspection of the 936-metre horizon on 17 October 2001 indicate the following radio-ecological conditions in the explosion chamber of the Klivazh facility:

- Partial downward filtration of groundwater into mine workings at the horizon of 936m (33m below the explosion epicentre).
- Destructive deformations of the explosion chamber and water admission (according to the data obtained through a probing borehole, which opened the chamber in September 1991).
- A small horizontal radius of the explosion chamber – up to 5.0m (diameter up to 10.0m), with the formation of up to 100 tonnes (according to estimates) of a vitreous molten mass where 95% of radioactive explosion products are concentrated.
- Formation of an area of crushed (entirely ruined) rock, within the confines of which such rock is transformed into sand fractions and gravel fractions, with a radius of up to 8.0m from the explosion epicentre, i.e. with a stable area thickness of (8.0-5.0)≈3.0m.
- Development of a radial jointing area at a distance of up to 15m from the explosion epicentre or in the adjacent rock massif with a thickness of (15-8.0) ≈ 7.0m.

It is estimated that individual activated (formed) hidden fractures may appear at a distance of up to 20-25m from the explosion epicentre. Meanwhile, according to the data obtained through 23 probing boreholes, no radioactive melt residues have been detected in the radial jointing area.

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Substantiation of the mine working geomechanical state during the closure of coal mines in Ukraine in order to remove metal support

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Introduction

The analysis of literary sources and project materials for the closure of coal mines in Europe and Ukraine gives grounds for asserting that the main problems are the technical, environmental, legislative, and financial components of a single structure [1-3]. In this work, the problem of minimizing risks by the geomechanical factor is solved, namely, determining the patterns of development of rock pressure manifestations in underground mine workings, which are sequentially gobed.

The purpose of the conducted research is to fulfill the conditions of resource saving and material saving, primarily in metal supporting. Firstly, it is necessary to pay attention to the very contradictory trends of today in solving the issue of coal mining. On the one hand, there is a tendency to increase the volume of coal production, and on the other hand, especially in European countries, there is a steady process of mine closure [4, 5].

Nearly half of the coal is mined in China, where it is mostly consumed. With such volumes of mining, it is quite natural that China is the leader in the number of mines – more than 3 thousand. The characteristic of the main coal-producing countries is presented in Fig. 1.

When summarizing coal production in the above-mentioned and other countries, its dynamics until 2040 is predicted as positive and this trend is confirmed by the International Energy Agency assessment [6]:

- global coal production in 2040 will be 9.23 billion tons;
- the total share of China, India and Australia in the global coal production will be 64%;
- stable coal production growth is predicted in India – an average of +100 million tons every 5 years.

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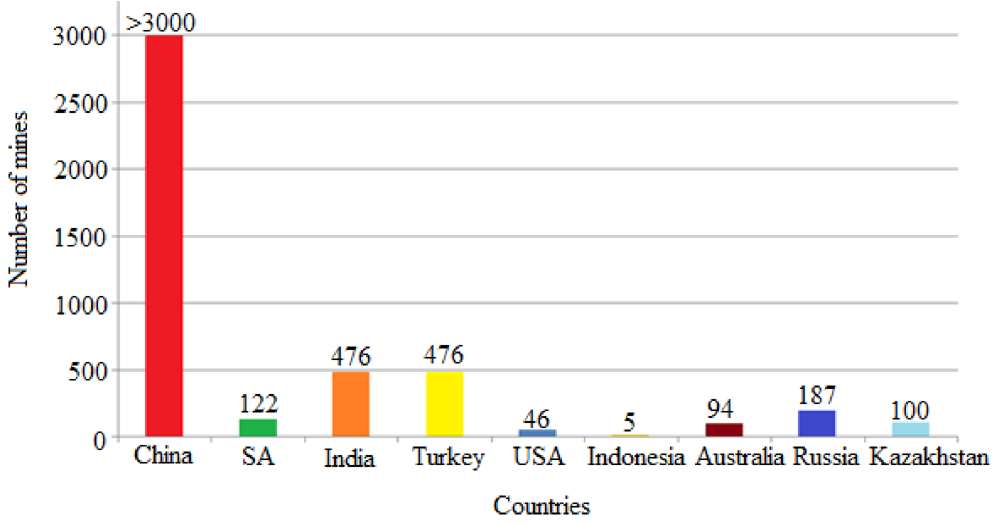

Fig. 1. Diagram of the number of mines in the main coal-producing countries

As for Ukraine, there are currently 146 mines operating in the country, of which 67 are in the uncontrolled territory, 33 are state-owned, and 46 are privately owned.

In terms of coal production volumes, after the occupation of a part of Donbas (where the majority of Ukrainian coal-mining enterprises are concentrated), they have been steadily declining. At the same time, the level of coal production by private mines is much higher.

The other side of power generation is conditioned by alternative energy sources, which are developing rapidly, but traditional coal mining still remains relevant throughout the world: while in Europe the coal industry is curtailing, for example, in China, coal deposits continue to be actively developed.

In Ukraine, there has been talk for decades about the coal industry decline and the need to close unprofitable mines, but, nevertheless, our state continues to be among the 15 countries where coal is mined.

Experience of mine closures in European countries and analysis of ways to eliminate negative consequences in Ukraine

When closing coal-mining enterprises, one has to face a number of problems – it is necessary to solve emerging social, ecological and economic problems, as well as technical and technological issues of safe reduction and complete cessation of coal mine activity. In this regard, the experience of closing coal mines and power plants in Germany and Poland is very useful.

Coal played a huge role in creating Germany's economic power. However, already from the end of the 1950s, German coal began to lose in price to imported coal, as well as to other carriers, which has led to the beginning of a crisis in the industry. From 1960 to 2000, the number of mines decreased from 146 to 12. In 2007, the Bundestag decided to withdraw from the spending industry to end in 2018.

Every unprofitable mine in Europe must stop mining from January 1, 2019 in conformity with the EU directive, according to which enterprises that do not make a profit are deprived of state funding. In Spain, for example, this has led to the closure of 26 coal mines. This deadline was set back in 2010, when the European Union began to take the initiative in the desire to get rid of dependence on coal. In Europe, they wanted to stop providing government funding to coal mines earlier, but industrial groups from Germany and Spain announced this possibility only until the end of 2018.

It should be noted that among the European coal states, Germany is by no means a pioneer in curtailing this traditional industry. For example, the last mine in Belgium was closed in 1992, in France – in 2004, and in Great Britain – in 2015. In Poland, the last coal mine is scheduled to close in 2049. In Ukraine, the processes of closing the mines began en masse in 1996, but there is no clear strategy in this regard. Excessive duration of liquidation works leads to unpredictable changes in the situation and the emergence of new circumstances. There have been a lot of debates on this topic recently, but few concrete actions.

When studying an integrated approach to minimizing risks during mine closure, we will study the geomechanical factor that forms the rock pressure manifestations in underground mine workings, as well as determines the activity and safety of their phased decommissioning.

The main tasks that need to be solved in assessing the impact of mine closures on surface objects and in developing measures to protect them are as follows [7]:

- determination of the zone boundaries of influence of mine workings and the prediction of the earth's surface deformations for the entire period of undermining the structure; determination of the zone boundaries of influence of residual deformations of the earth's surface and deformations from the activation of the displacement process above flooded mine workings, identification of possible watering zones and manifestations of concentrated deformations;
- classification of surface objects, assessment of their technical condition with the determination of the residual deformation resource based on the results of a visual survey and data from operating organizations;
- assessment of the impact of flooding, the earth's surface residual deformations and deformations from the displacement process activation above flooded mine workings on surface objects;
- development of a phased application of protection measures, taking into account the results of monitoring the deformations of the earth's surface, buildings and structures.

Approaches to assessing the expediency of phased gobing of mine workings at existing mines

An integrated approach to the closure of coal mines provides one of the important measures for the removal of metal structures from the rest of the mine workings: recycling of scrap metal and reuse of significant volumes of accumulated raw materials falls under the concept of resource saving and environmental protection.

Compliance with the norms and requirements of safety rules involves assessing the mine working state in terms of the possibility (or lack of it) of removing metal structures with the complete elimination of accidents and injuries to miners. The concept of "comprehensive substantiation" implies a prediction of rock pressure manifestations in the mine working for the period from the beginning of its driving to the moment of time using various methodologies both at the industry level (guiding normative documents [8, 9]), as well as predicting methods developed at the Department of Mining Engineering and Education of the Dnipro University of Technology [10, 11]. Consideration of the task set from different points of view will increase the reliability of the predictive assessment of the mine working state at a given point of time.

The main peculiarity of a reliable assessment of the mine working state is accountingt of its supporting period, during which development of displacements in the adjacent coal-bearing mass of different intensity occurs and the latter determines the technical decision on the necessity (or absence of such) to gob the mine working. From these positions, on the example of a specific mine working (its real state is known during surveys), the results of predicting the rock contour displacement have been compared using the methodologies indicated above.

On the basis of the example considered in the work [12] and the patterns obtained for the development of rock pressure manifestations in underground mine workings, it is necessary to develop a methodology for assessing their state at the present time.

Substantiation of principles for the expediency of gobing mine workings by a geomechanical factor

In the work [12], the expediency of applying the basic provisions of the methodology for assessing the mine working state and resolving the issue of its gobing is substantiated. Thus, it is planned to use the experimental method of instrumental mine observations on the development of mine working contour displacements and deformations of its support in combination with methods of correlation-dispersion analysis of the experimental data results [13-15].

The basic provisions of the methodology approach for predicting mine working contour displacements U are in determining the dependences between the parameter U relationship with the main geomechanical factors: H – depth of mine working placement; R – weight-average calculated compressive strength of lithotypes adjacent to the mine working. Other factors and parameters of mine working supporting (outside the impact zone of stope operations) are of minor importance and are taken into account by using the corresponding influence coefficients.

The approach developed to assessing the mine working state on the basis of its supporting period is designed to eliminate the disadvantages of the methodology [9], but with the preservation of the principle provisions regarding the main criterion for making a technical decision to gob the mine working – the contour displacement value for the entire period of its existence. The given task solution is based on the distinguishing of three groups of time dependences: $U^r(t)$ – displacement of the mine working roof rocks, $U^b(t)$ – its bottom heaving, $\mathrm{U^s(t)}$ – convergence of the mine working sides.

Mine working can lose its operational state for a number of reasons, the main of which are:

- the residual section S_{res} is less than the minimum permissible under the condition of supplying the required air volume;
- height h_{pas} and width B_{pas} of the people's passage zone do not meet the requirements of safety rules [16];
- distances and spacing δ during the transportation of goods and materials do not meet the requirements of safety rules [17];
- loss of stable form and destruction of the supporting structure elements.

In order to spread the recommendations on the assessment of the mine working state to a wide range of mining-geological conditions, the functions $\mathrm{U^r(t)}$, $\mathrm{U^b(t)}$ and $U^{res}(t)$ are determined depending on the main geomechanical factors: the depth $\mathrm{H}$of the mine working placement and the average calculated compressive strength$R$ of the adjacent coal-bearing mass. Solving the task set is complicated by the need for long-term instrumental observations of the rock pressure manifestations in a particular mine working, for which a new original methodology has been developed for constructing empirical dependences of the development of its contour displacements.

Principles of search and collection of information about the patterns of rock pressure manifestations during the mine working operation

The main task of the developed methodology is to increase the probability of predicting the development of the mine working contour displacements during the entire period of its supporting. The directions of its implementation are based on the elimination of identified disadvantages [9] with the simultaneous expansion of the field of application to coal-bearing regions with rocks of low and medium strength, which cover (under the current economic and political situation) almost all operational conditions of coal mines in Ukraine.

The work [12] presents an algorithm for studying and generalizing experimental data, which differs novelty and allows relatively short-term measurements of rock pressure manifestations in combination with information from mine surveying services to obtain an objective assessment of the mine working state during a long period of their supporting. First of all, some general positions in terms of initial conditions should be noted: the ranges of changes in the depth of mine workings location of H =200-1000m and the calculated compressive strength of the adjacent coal-bearing stratum of R =5-60 MPa are studied, covering almost the entire variation range of geomechanical factors. At the same time, the "extreme" limiting values of the criterion $\frac{H}{R}$ vary from 3.3 m/MPa to 200 m/MPa and are almost the same both for the Western Donbas and Krasnoarmiisk coal-bearing region; the most probable variation range of the criterion is $\frac{H}{R}$ =10-50 m/MPa.

Next, the first distinguished type of the adjacent coal-bearing stratum texture is studied – the immediate roof and the first layers of the main one are represented by argillites and siltstones with a total thickness of no more than 5-7m and a compressive strength in the sample of at least σ_{comp} ≥40-50 MPa; above it, there is a sandstone with a thickness of at least 3 – 0 m and a harness coefficient of at least f ≥6. Most of the lithotypes are in a naturally wet state with a low fracturing intensity; they are characterized by moderate rheological properties with damping creep.

In the absence of stope operations influence, overworking and undermining, mine workings basically retain their operational parameters in accordance with the requirements and norms [17]. Convergence of the roof and bottom $U^{r,b}$ ≤400-500 mm, convergence of the sides U^{res} ≤200-250 mm, section loss $\frac{\Delta S}{S_l}$ ≤20-25% (S_l – cross-sectional area of the mine working in the light before subsidence).

Such mining-geological conditions ensure a satisfactory operational state of the mine workings during the entire period of their supporting. The issue of gobing of mine workings is conditioned not by geomechanical factors, but by the technological-economic aspects of the mine operation.

The second structural type identified for the Krasnoarmiisk coal-bearing region is the immediate and main roof, at least 12-15m high, represented by low- and medium-strength argillites and siltstones (f =3-5), as well as fragile sandstone (f ≤6), characterized by a moisture-saturated state and intense fracturing. According to the normative methodology [8], the value of the average calculated compressive strength is R =5-10 MPa. When mine workings are placed at a depth of at least 200-250m, the index $\frac{H}{R}$ is 20-50m/ MPa and more with a corresponding intensification of rock pressure manifestations. However, lithotypes are characterized by creep damping with time.

The rock pressure manifestations for a given structural type and properties of the adjacent coal-bearing stratum are shown on the example of graphs of the convergence development in the roof and bottom $U^{r,b}(t)$, as well as the sides $U^{res}(t)$ of mine workings at two values of the geomechanical criterion $\frac{H}{R}$ (Fig. 2). All the graphs are quite similar and describe the process of damping creep deformations. Thus, at $\frac{H}{R}$ =40m/MPa, the convergence of the roof and the bottom practically stabilizes on the 138th day of supporting the mine working for $\left(t_{comp}^{r,b}\right)_1$ =138 days, while the convergence value has reached a value of $U_1^{r,b}$ =1370 mm and presents problems in ensuring the proper conditions for the mine working operation. The mine working arch is flattened with the occurrence of plastic deformations in the cap board, the yielding joists are partially destroyed, and the bottom heaving exceeds the permissible safe values during transport operation. The convergence of the mine working sides stabilizes at $\left(t_{comp}^{res}\right)_1$ =114 days, reaching a value of U_1^{res} = 430mm. This is more than double the permissible yielding property of traditional frame support structures, and their prop stays are exposed to plastic deformations with a partial loss of the load-bearing capacity of the frame as a whole. Permissible spacing and distances are not respected in accordance with the requirements of safety rules, and the mine workings themselves lose up to half of the cross-sectional area – problems arise with the supply of the required air volume.

Another pair of graphs (Fig. 2, line 2) characterizes more favorable conditions for supporting mine working by the geomechanical coefficient $\frac{H}{R}$ =20 м/МПа. Here, the rock pressure manifestations are less intense: the convergence of the roof and bottom stabilizes at the level of $U_2^{r,b}$ =615 mm at $\left(t_{comp}^{r,b}\right)_2$ =96 days, the convergence of the sides of U_2^{res} =190mm remains almost unchanged already at $\left(t_{comp}^{res}\right)_2$ ≥83 days. Despite the presence of local areas of plastic deformations, the frame support retains its stability, the loss of section does not exceed 25-28%, and the mine working as a whole ensures proper operational parameters.

Thus, the given example confirms the expediency of using a geomechanical criterion to display the mine working state: with its increase, the intensity of rock pressure manifestations increases, and the stabilization of contour displacements occurs much later.

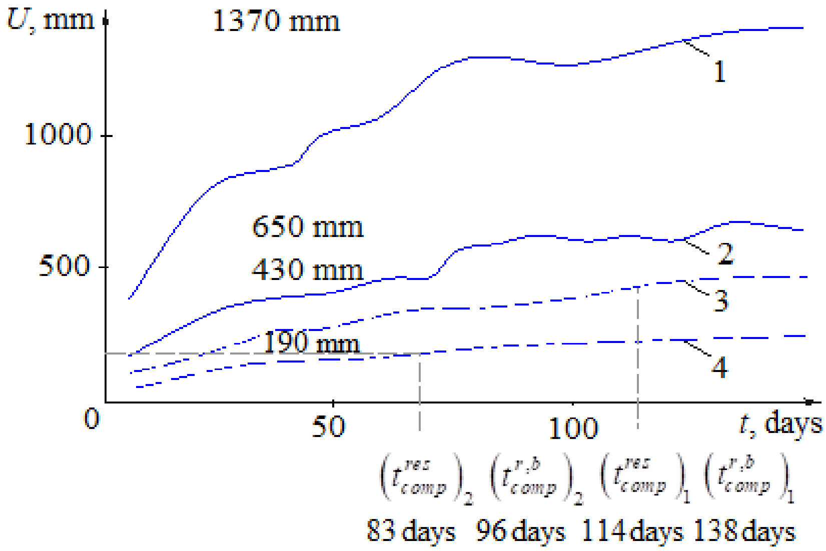

Fig. 2. Generalized dependences of the increase in displacements U of the mine working contour in time t of its supporting in the conditions of the Krasnoarmiisk coal-bearing region: 1 – $\frac{H}{R}$ =40 m/MPa; 2 – $\frac{H}{R}$ =20 m/MPa; — $U^{r,b}(t)$; - - - $U^{res}(t)$

The processing of the collected information by the methods of correlation-dispersion analysis allows for the second structural type and properties to obtain an equation for calculating the final displacements of the mine working contour $U_l^{r,b}$, U_l^{res} for a long period of their supporting

$$U_l^{r,b} = 8{,}45\left(\frac{H}{R}\right)^{1,4}, \text{mm}; \quad (1)$$

$$U_l^{res} = 3{,}1\left(\frac{H}{R}\right)^{1,35}, \text{ mm}. \quad (2)$$

In mine workings operated for a long period of time, the attenuation of their contour displacement rate is predominantly observed, mainly with the stabilization of the values $U^{r,b}(t)$ and $U^{res}(t)$. The time interval t_{st} from the moment of the mine working construction to the stabilization of its contour displacements also has a correlation with the geomechanical criterion $\frac{H}{R}$: the value t_{st} increases with the deterioration of mining-geological conditions, that is, with an increase in the ratio $\frac{H}{R}$. This pattern is quantitatively described by the dependences:

- for convergence of the roof and bottom of the mine workings

$$t_{st}^{r,b} = 236\left[1 - exp\left(-\frac{0{,}024H}{R}\right)\right], \text{day}; \quad (3)$$

- for convergence of the mine working sides

$$t_{st}^{res} = 187\left[1 - exp\left(-\frac{0{,}027H}{R}\right)\right], \text{day}. \quad (4)$$

In the mine workings of the Western Donbas mines, the collected amount of experimental data confirms the above patterns of increasing displacements of their contour, but only qualitatively, and in quantitative terms, a number of differences have been determined. The presence of functions $U^{r,b}(t)$ and $U^{res}(t)$ specifics is quite understandable, since the mining-geological conditions in the Western Donbas are characterized by the occurrence of less strong, more plastic, weakly metamorphosed lithotypes and a somewhat shallower mining depth, mainly up to 500-600 m. Even the strongest lithotypes – sandstone and coal – are characterized by a compressive strength in the sample, mainly σ_{comp} ≤40-50 MPa, and limestone has a slight distribution in the form of rather thin layers, usually less than 0.2-0.3 m thick. Taking into account the widely distributed weakening factors, moisture saturation and fracturing in the coal-bearing stratum, the real compressive strength of lithotypes drops sharply. To this should be added the clearly observed rheological properties of most rocks [18, 19], which together leads to a decrease in the calculated compressive strength of the adjacent coal-bearing stratum, mainly to R =5-20 MPa. Under such conditions, more intense rock pressure manifestations are quite expected.

Also, in the Western Donbas conditions, two forms of creep deformations are actively manifested, reflected in the patterns of displacement development in two forms: the first – with an increase in the duration of the mine working supporting, the displacement rate decreases to insignificant values and one can speak of some constancy of the values $U^{r,b}(t)$ and $U^{res}(t)$; this period is called the contour displacement stabilization time t_{st}, the second – as the time t increases, the rate decreases, but still remains a significant value for a long period of mine working supporting; this type of displacement development is determined by undamping creep of relatively weak rocks (mainly argillites) and is largely reflected in the methodology [9].

Thus, for the Western Donbas conditions, the main principle of dividing the patterns of displacement development is to take into account the rheological properties of the adjacent coal-bearing stratum lithotypes with a subordinate value of its texture: the predominant occurrence of more stable lithotypes of medium thickness and thick ones with a hardness coefficient of f =2-5 (in a moisture-saturated state, sandstones and coal seams are mainly exposed to moderate and intense fracturing, and argillites and siltstones are mainly in a naturally moist state with weak and moderate fracturing) contributes to the process of damping creep deformations and stabilization of contour displacements at some relatively constant level; the predominant occurrence of rather weak and moisture-saturated fractured argillites, as well as thin- and medium-layered siltstones provokes undamping creep deformations and constant increase in mine working contour displacements for a sufficiently long period of its supporting.

It should also be noted an important peculiarity of experimental measurements of the convergence $U^{r,b}(t)$ in the roof and bottom. It is well known that in the Western Donbas conditions, the value of the bottom heaving, as a rule, exceeds the lowering of the roof. In the conditions of undamping creep deformations, it is the bottom heaving that primarily disrupts the operational mine working state, which necessitates periodic ripping of the bottom rocks. Therefore, the measurements $U^{r,b}(t)$ after ripping do not correspond to the actual values of the convergence in the roof and bottom. This discrepancy is eliminated by simply summing the measurement values $U^{r,b}(t)$with the values of the preliminary bottom ripping; as a result, the sum found may exceed the passport height of the mine working under intense rock pressure manifestations, but this technique more likely reflects the conditions for supporting the mine working.

As an example of developing contour displacements with undamping creep deformations of lithotypes enclosing a mine working, Fig. 3 shows the graphs of dependences $U^{r,b}(t)$ and $U^{res}(t)$ for the same values of the geomechanical criterion$\frac{H}{R}$, which were obtained earlier in other mining-geological conditions.

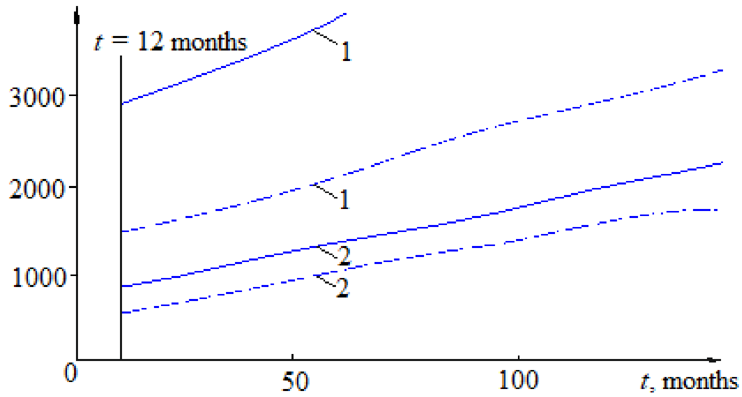

Fig. 3. Generalized dependences of growing displacements U of the mine working contour in time t of its supporting in the Western Donbas conditions with the undamping creep deformations of the lithotypes in the adjacent mass (the graphs are constructed taking into account periodic bottom ripping):
1 – H/R =40 m/MPa; 2 – H/R =20 m/MPa; — $U^{r,b}(t)$; - - - $U^{res}(t)$;

Thus, based on the generalization of the results of mine observations, taking into account normative documents, a methodology has been developed for obtaining an objective assessment of the state of mine workings over a long period of their supporting.

The methodology is an integral part of the comprehensive assessment program of the expediency of supporting mine workings for the future development of mining operations at a particular coal mining enterprise. It is designed to analyze the geomechanical situation by predicting the rock pressure manifestations in horizontal and inclined (gently sloping) mine workings, supported outside the influence zone of stope operations at depths of up to 1000 m in the conditions of the Krasnoarmiisk coal-bearing region and Western Donbas (Ukraine).

Conclusions

1. Based on the analysis of global and domestic trends, the patterns of coal mining with its contradictions, formulated at the present time in connection with the tendency of mine closure, have been determined.
2. The problems and consequences of the closure of coal mines are analyzed. Geomechanical requirements on the issue of liquidation of enterprises in the industry are formulated.
3. An analysis of the current normative methodologies and developments for predicting the parameters of rock pressure manifestations in mine workings supported outside the influence zone of stope operations in conditions of weakly metamorphosed rocks and close to them, makes it possible to substantiate the fundamental methodological provisions for the most reliable assessment of the state of mine workings, taking into account the long period of their operation.
4. The new methodology is based on generalizing the results of mine instrumental observations, taking into account the approaches of existing normative documents when separating the geomechanical situation according to two conditions: texture and strength properties of lithotypes in the adjacent coal-bearing stratum; peculiarities of manifestations of rheological processes of its displacement development into the cavity of mine working.
5. A family of generalizing graphical dependences of developing displacements in the mine working contour has been obtained, divided into four main groups according to the criteria of texture and strength properties of lithotypes in the adjacent mass, as well as the type of their rheological manifestations: damping and undamping creep deformations. For each group, using the methods of correlation-dispersion analysis, empirical formulas have been determined for calculating the convergence in the roof and bottom of mine workings, their sides, depending on the geomechanical criterion $\frac{H}{R}$ of supporting conditions and the duration t of this period.
6. The practical results of the conducted research is a new methodology for assessing the mine working state according to the patterns of predicting the displacement in its contour.

The revealed correlation ratios allow to promptly predict the residual mine working section at any time of its supporting, which forms the geomechanical component of the assessment of its operational state for making a decision on its gob or further supporting.

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Formation and Development of Post-Mining Geosystems in the Lviv-Volyn Coal Basin

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Abstract

The question of the emergence, formation and development of post-mining geosystems in the Lviv-Volyn coal basin is considered. The closure of unprofitable coal mines accelerated the emergence of new natural-anthropogenic geosystems on the territory of industrial sites and within mine fields. On the example of two model sites, the peculiarities of the functioning of post-mining geosystems, which were formed on the lithological basis of rock dumps and in areas of flooding and submergence of natural areas, were analyzed. Geo- information mapping and modeling of the environmental state of the research objects on a scale of 1:2000-1:5000 were carried out. Optimization measures were proposed to improve the environmental state of post-mining geosystems and rational use of natural resources.

Introduction

Extraction and purification of hard coal in the Lviv-Volyn basin leads to the development of dangerous endogenous and exogenous processes, which causes the transformation of landscapes and irreversible changes in the environment. The environmental condition of the geosystems of the basin is most significantly affected by the processes caused by the accumulation of mining waste in rock pits and dumps and the development of subsidence of the earth's surface, which leads to the formation of flooding and submergence zones. In the last 20-25 years, the ecological situation in the basin has changed significantly. This is due to the decrease in the volume of coal mining and the gradual closure of unprofitable mines. Today, 15 mines (68.2% of the total number) of 22 coal enterprises of the basin have been liquidated by means of flooding, and 2 more mines are prepared for closure. After the liquidation of coal mines, on their territory and within mine fields, the process of formation and development of post-mining geosystems began. The specifics of the formation of

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geosystems depend on the natural conditions of their placement and the technology of developing coal deposits.

Materials and methods

The results served as the scientific and methodological basis of the work own landscape and ecological studies, a description of the ecological situation of mining and post-mining geosystems of the Lviv-Volyn basin (Geoecology..., 2021; Ivanov, Kovalchuk, Tereshchuk, 2009; Rudko, Ivanov, Kovalchuk, 2019) and an analysis of the environmental problems of the functioning of various mining facilities (Ivanov, 2007, 2020; Strozik et al., 2016). Considerable attention has been paid to the functioning and development of post-mining geosystems in the areas of liquidated coal mines (Ivanov, Kovalchuk, Andreychuk et al., 2018; Ivanov, Kovalchuk, Tereshchuk, 2006) and optimization of the planning structure (Kovalchuk, Ivanov, Andreychuk, 2016; Ivanov, Kovalchuk, Tereshchuk, 2007a,b).

The conditions for the formation and restoration of the vegetation cover of coal rock dumps (Baranov, 2008; Bashutska, 2006; Kuzyarin, 2012) and the landscape and ecological basis of their reclamation were considered (Buchachska, 2002; Ivanov, Andreychuk, Knysh, 2018; Knysh, 2008; Popovych, 2014; Knysh, Karabyn, 2014; Popovich, 2016). Features of the spatial distribution and intensity of the development of the processes of subsidence of the earth’s surface, flooding and submergence have been traced (Ivanov, Kobelka, 2006; Ivanov, Kovalchuk, 2003; Karabyn, 2018; Kovalchuk, Ivanov, Lobanska, Tereschuk, 2012; Starodub et al., 2016).

The research used such methods as comparative-geographical, cartographic, geo-information modeling, landscape-dynamic, landscape-geochemical, etc. For geoecological mapping and modeling, plans of mining operations on a scale of 1 : 2000 - 1 : 5000 were used. With the help of topobases, digital models of the relief of the rock dump and morphometric models of the steepness and exposure of the slopes were built. To decipher the boundaries of plant communities, space images obtained from an available program were used Google Earth Pro. Space photographs cover the period from April 20, 2009 to March 29, 2014. The analysis of the content of chemical elements in the lithological deposits of the rock dump of the “Vizeyska” mine was carried out by the emission spectral method for 27 chemical elements (Toksiko- hygienicheskaya..., 1992) and the spectral semi-quantitative method for 10 chemical elements (Knysh, 2008; Knysh, Kharkevich, 2003).

Results and discussion

Closure of unprofitable coal mines of Lviv-Volyn region basin is aimed at solving environmental problems in the region. However, despite the apparent simplicity of the issue, the process of mine liquidation is very complicated. The closure of the basin’s mines predisposes to the activation of transformational processes, therefore, the projects for the liquidation of mining enterprises envisage environmental protection measures, which are often not carried out due to the lack of funding for reclamation. Due to the critical environmental condition of post-mining geosystems, the environmental monitoring system should be improved.

During the liquidation of mines, the land occupied by industrial sites, rock dumps and settling ponds is vacated and subject to reclamation with their further economic use. Mine liquidation projects (for example, Project..., 2001) envisage the filling of shafts and the installation of a fence around the concreted sites of the shafts, the destruction of buildings that do not have economic significance. After reclamation, these areas can be used for construction, vegetable gardens, and cattle grazing. Workshops of small enterprises have already appeared on the territory of many coal mines. Most of the reclaimed lands are in an unsatisfactory ecological condition: protective fences have been dismantled, industrial ground areas are neglected, overgrown with trees and shrubs, dug up and filled with industrial and household waste.

On the example of two model sites, we will consider the features of the formation and development of post-mining geosystems based on coal dumps and in areas of overflooding and flooding of natural areas.

Formation and development of post-mining geosystems on coal dumps

Near the coalmines of the Lviv-Volyn basin, there are rock dumps (complex systems of dumps), which mostly consist of two or three dumps. In most cases, the old dump has a conical shape, sometimes it has a truncated conical shape, and the new one has a flat shape. There are 52 rock dumps in the coal basin, of which 41 (78.8%) are inactive and post-mining geosystems are formed on them. The total area of rock dumps is 6.09 km^2, in which 96.2 million cubic meters of coal mining waste have been accumulated. The majority of the waste volume consists of sandstones, claystones, siltstones and carbonaceous shales, which belong tothe fourth class of danger. Along with this, the bedrock mass includes marl and chalk, which form the foundation of old dumps and in some places come to the surface. Chemical elements of the first class of danger include pyrites and sulfur, which account for about 1.8-2.0% of the volume of industrial waste (Rudko, Ivanov, Kovalchuk, 2019).

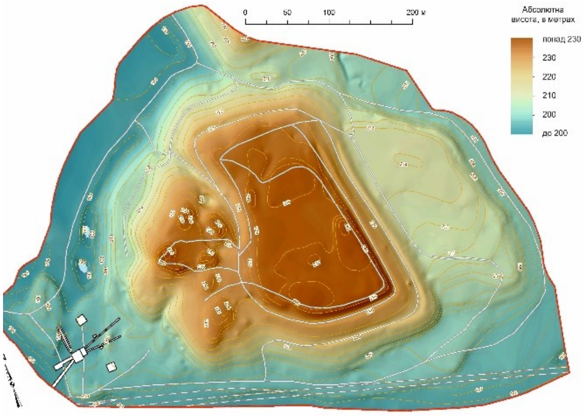
In 1960-1980, the old conical dumps burned heavily, as a result of which the rocks crystallized. Intense physical weathering led to the formation of metamorphosed residual rocks. More than 70 chemical elements, the content of which is usually up to 0.1%, have beenfound in hard coal and industrial waste raised to the surface during coal mining (Toxic and hygienic..., 1992). It should be noted that the waste contains pyrite, which quickly oxidizes. As a result, sulfuric acid is formed, which reduces the reaction of aqueous solutions (pH) of rock and infiltrates to 2.0-3.5 (Knysh, Kharkevich, 2003).

There are no useful components and microelements in the rocks of mine dumps suitable for extraction. A mixture of sandstones, claystones, and siltstones from separate dumps is used for the production of building materials, filling dams, ballasting roads, etc. Mine liquidation projects envisage the partial disassembly of rock dumps followed by the mining and biological stages of reclamation. Today, reclamation works at liquidated mines are at various stages of implementation. Some of the dumps have been rehabilitated, others are being actively prepared, and fertile soil is being bulked. However, the majority of waste dumps remain unrecultivated, processes of formation of post-mining geosystems take place on them.

Even after the closure of the mines and the completion of reclamation, the rock dumps will remain the main sources of environmental pollution. The high content of environmentally hazardous elements in the rocks of mine dumps will lead to contamination of the soil cover, soil and underground water, degradation of the vegetation cover and will affect human life. Along with rock dumps in each mine, there was an open coal storage, which is a powerful source of environmental pollution. At liquidated mining enterprises, warehouses are covered with a layer of soil mixture. On the territory of closed mines, there are sedimentation ponds that require lowering or pumping out mine waters, dewatering bottom sediment (sludge), filling residual voids with rocks from neighboring dumps, dismantling equipment, recultivation of industrial sites with renewal of soil and vegetation layer (Rudko, Ivanov, Kovalchuk, 2019).

To analyze the prerequisites for the formation of post-mining geosystems, a model site was chosen within the rock dump of the “Vizeyska” mine (old name - No. 8 “Velykomostivska”), which ceased coal mining in 2009 and is currently liquidated. The examined area covers three interconnected dumps with an area of 0.36 km^2. For the morphometric analysis of the territory, a digital model of the terrain was created (Fig. 1a). The mine liquidation project (Project..., 2001) envisages carrying out the mining engineering stage of reclamation of the rock dump with the creation of new leveled relief forms (Fig. 1b). However, this will lead to the transformation of existing forms of relief, compaction of the upper layers of rocks, reduction of their filtration capacity, activation of linear erosion, destruction of existing packs of fine soil, soil and plant cover (Fig. 1c). That is why we believe that it is worth carrying out the reclamation of the rock dump and the formation of post-mining geosystems, taking into account the already existing forms of relief. Phytomelioration should be carried out without mining leveling of its surface.

From a landscape point of view, the rock dump should be considered as a part of the post- mining area (the rock dump of PJSC “Lviv Coal Company” is adjacent to the heap dump). Taking into account the different time of formation of conical and flat dumps (30-65 years), the difference in the lithology of rocks and their operational condition, the development of relief forms, soil and vegetation cover is uneven, which determines the specificity of the formation and development of post-mining geosystems. Complex tracts formed on gentle, very steep and steep slopes of various exposures (over 50% of its area) predominate within the rock dump (Fig. 1d, g). At the same time, horizontal, mostly plateau-like and hilly surfaces account for 30-35% of the rock dump area (Ivanov, Andreychuk, Knysh, 2018).



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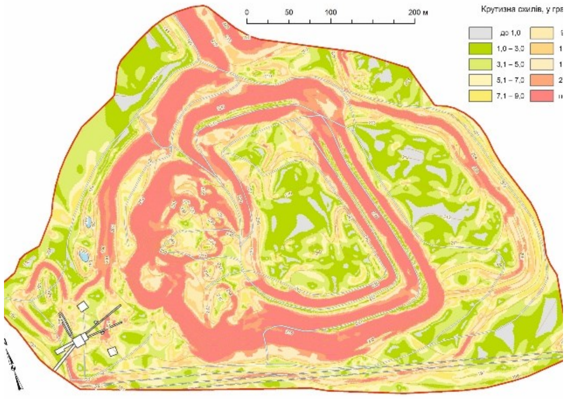

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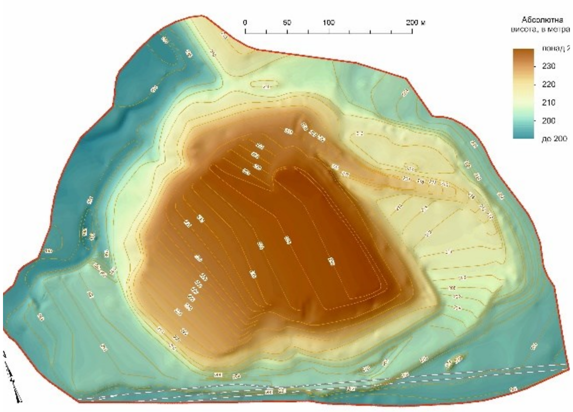

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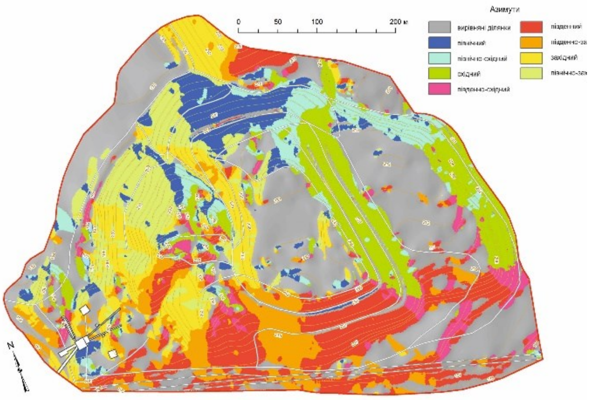

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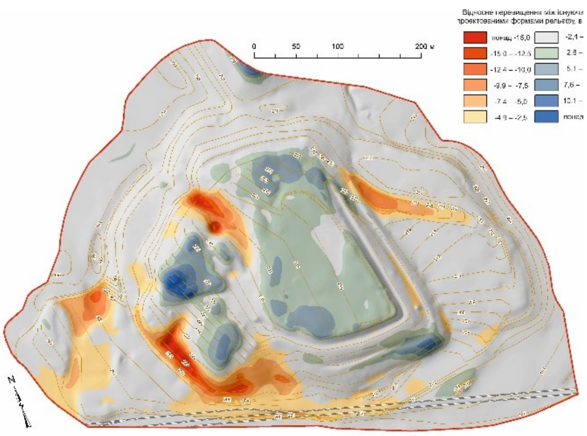


c)

digital relief model (relief forms as of 2007);

digital relief model (relief forms as of 2020);

transformation of landforms as a result
of the technical stage of reclamation;

steepness of slopes (relief forms as of 2007);

exposure of slopes (relief forms as of 2007).

Fig. 1. Transformation of post-mining geosystems of the rock dump of the “Vizeyska” mine

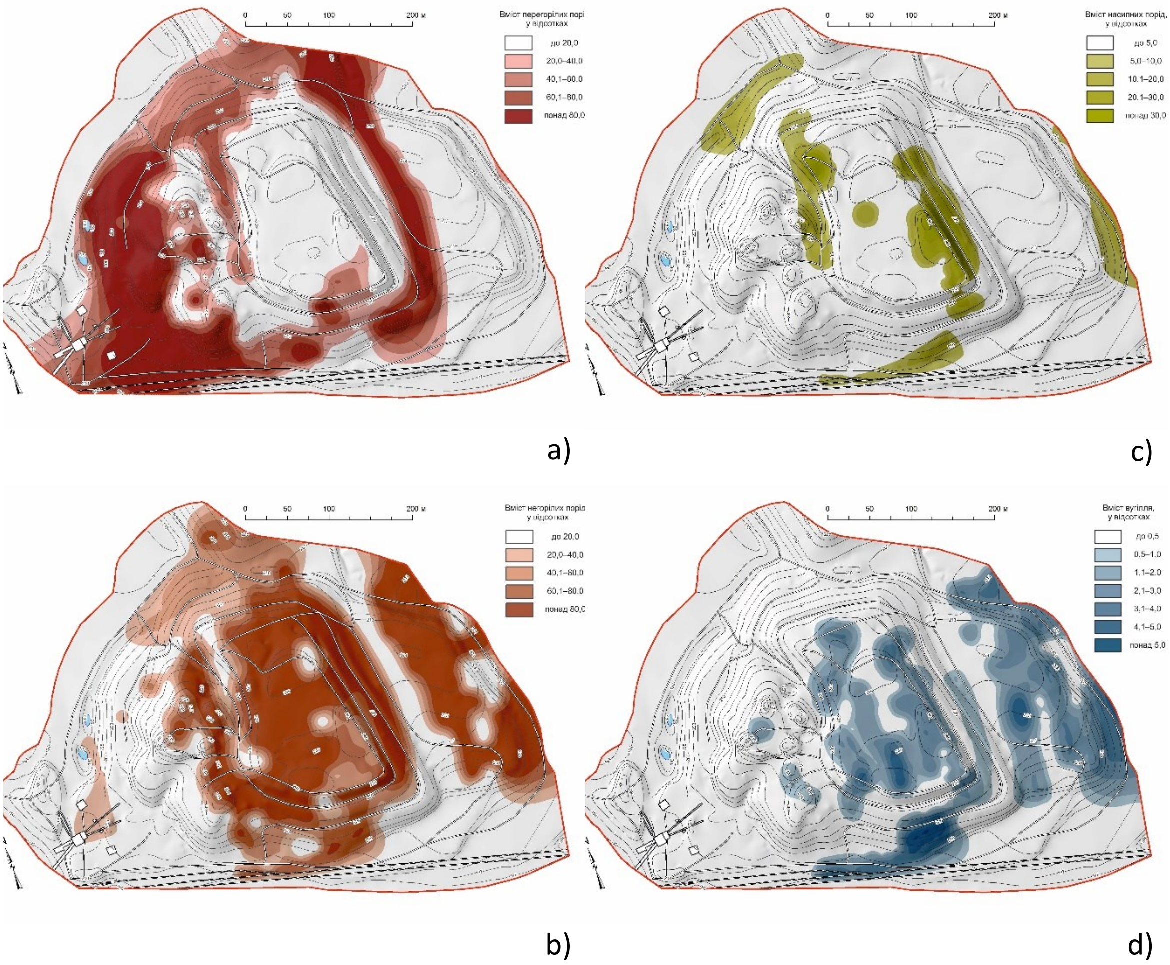


Fig. 2. The composition of lithological deposits within the rock dump of the "Vizeyska" mine: a) content of burnt rocks; b) content of unburnt rocks; c) bulk rock content; d) coal content

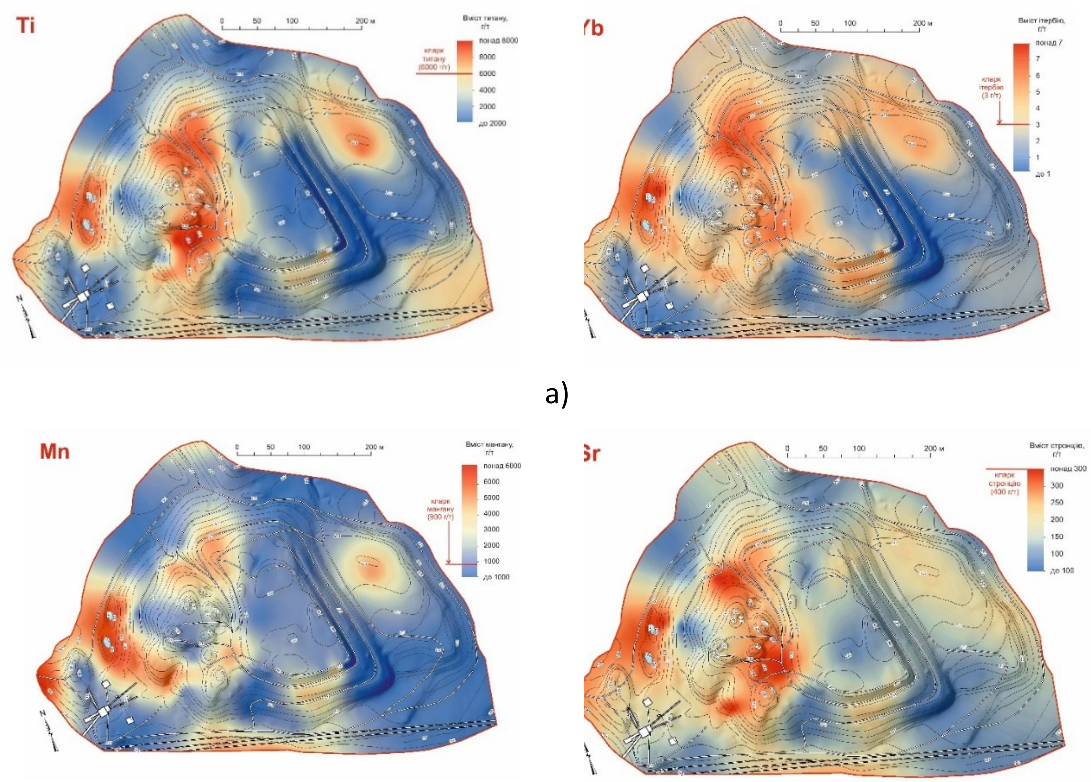
Mine rock dumps are composed of argillites (66%), siltstones (22%), sandstones (10%), coal shale, hard coal and pyrites (up to 2%) (Toxic and hygienic .., 1992). The rock is formed by various fragmental and granular formations, the size of fragments of which is up to 150-200 mm. The mineral part is represented by a mixture of metamorphosed clay minerals, compacted and recrystallized under the influence of high temperatures and pressure in the body of the rock dump. 39% of the mass of sediments in the composition of the rock dump belongs to the burnt brownish-red substrate of various shades, which indicates the complexity of lithological transformations during the burning of the rock dump (Fig. 2a). Such a composition of rocks is characteristic of an old conical dump. Unburned rocks, which make up the rest of the post-mining geosystems of the rock dump, make up 61% of the volume thereof (Fig. 2b). Black and gray colored masses are typical for them. The near-surface layer of sediments has a variegated grain size and is represented by coarse-grained material, mainly stones and gravel. Their share accounts for 60-75% of the total mass of near-surface rocks. Individual slopes of flat dumps are covered with a 1.5-2.0 m layer of loose sand deposits (Fig. 2c). Areas with unburnt and loose rocks are characterized by a high content of coal

(3-5%), which complicates the formation of soil and vegetation cover (Fig. 2d) (Rudko, Ivanov, Kovalchuk, 2019).

According to the geochemical conditions of the migration of substances, the natural landscapes around the rock dump of the "Vizeyska" mine belong to the area of free migration and intensive removal of pollutants, where acidic (H) and acid-glay (H-Fe) classes of elementary landscapes of accumulative plains with low and medium capacities predominate chemical absorption. The site is a potentially dangerous area of intensive contamination of soil and underground water due to lack of surface runoff. Among dump rocks, the best accumulators of chemical elements are argillites, carbonaceous shale, coal and pyrites. In turn, siltstones are transitional between sandstones and mudstones, and sandstones are characterized by indicators close to the values of the geochemical background. Both burned and unburned rocks are accumulators of chemical elements and lead to the formation of anomalies on the surface of rock dumps. The model site is characterized by significant fluctuations in the content of titanium, manganese, phosphorus, copper, nickel, vanadium, ytterbium, beryllium and other chemical elements over the area with systematic excesses of the geochemical background level and MAC (maximal allowed concentration) values (Fig. 3). The maximum values of chemical contamination were recorded in the western part of the rock dump (near the coal warehouse) and the lower parts of the slopes of the old conical dump. The maximum levels of chemical pollution for many chemical elements are 25–250 (!) times higher than the MAC (Toxic-hygienic..., 1992). At the transition from unburnt to burnt rocks, the level of chemical contamination increases. Most likely, this is due to the fact that burnt rocks are denser and less capable of leaching chemical elements. Unburnt rocks are unstable to weathering, so they lose the gross content of chemical elements more easily. The level of the exposure dose within the rock dump ranges from 8 to 12 μR/h and in some places reaches 25-30 μR/h. The average gross content of strontium is 175-180 g/t (Knysh, 2008) (Fig. 3d).

The lithological composition of fine soil and soil mixtures differs in individual dumps, which depends on its natural and anthropogenic origin: bulk, biotic-lithogenic, and crystalline-lithogenic (Fig. 4a). The largest capacity of fine soil is within the old conical dump. There are practically no signs of fine soils on young (10-15 years) rock dumps, outcrops, and in former open pit developments. Productivity of biologically stable of plantations on dumps, their species composition and the direction of development of post-mining geosystems depend on the strength of the embryo. On slopes with a steepness of 20-25°, this layer is 0.2-0,5m. The formation of humus reaches its maximum within geosystems with optimal hydrothermal parameters in closed depressions as a result of better development of vegetation under such conditions, as well as due to the additional introduction of fine soil from the surrounding slopes (Ivanov, 2007).

Denudation processes develop within the territory, forming separate meso- and microforms, which are the basis for post-mining geosystems. Among the slope relief-forming processes, the most active are rock shedding and shifting, linear erosion and planar washout (Fig. 4b). Numerous landslides and rockfalls are confined to very steep and precipitous slopes of the conical dump. The washout processes are characteristic of the entire rock dump, which is associated with the significant steepness of the slopes, the low water permeability of the rocks, and the poverty of the vegetation. It also contributes to the formation of a large number of erosion forms. The topography of the dumps is complicated by modern man-made processes, namely, reclamation works, quarrying of deposits for the production of construction materials, dumping of flooded and waterlogged areas, and extinguishing of dumps.

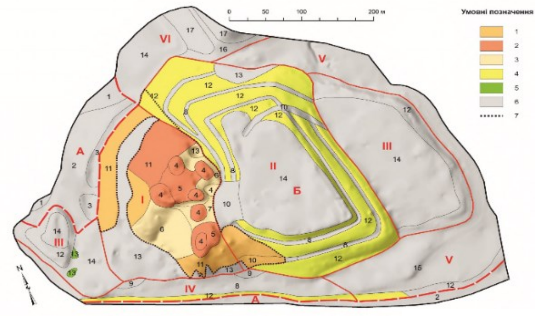


a) c)

b) d)

Fig. 3. The content of chemical elements in the lithological deposits of the rock dump of the "Vizeyska" mine: a) thecontent of titanium (Ti); b) manganese (Mn) content; c) ytterbium (Yb) content; d) content of strontium (Sr)

In the processes of distribution of ecological characteristics of post-mining geosystems, the leading role is played by the steepness, exposure and shape of the slopes and their length. They determine the peculiarities of radiation, heat and water balance and the microclimate of geosystems. For dumps with slopes of 40-45°, the values of the absolute values of the total radiation on the slopes of the southern exposure are tens, and in some cases, hundreds of percent more than on the slopes of the northern exposure. Another important factor that determines the thermal regime of the earth's surface of the rock dump is the presence of combustion centers. Areas of more than 100 m have been registered on the surface of the old dump with the temperature to 65-80 °C, and in some cases up to 125 °C. Thermal "islands" stand out from the environment in the winter period of the year, which should be taken into account during phytoremediation (Ivanov, Andreychuk, Knysh, 2018).



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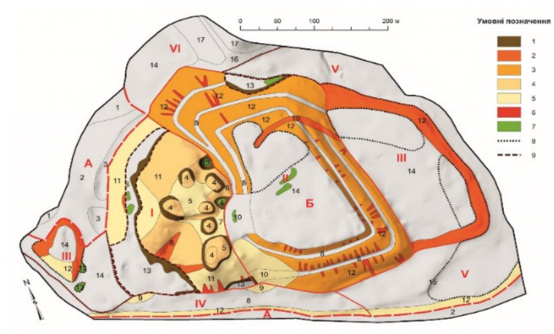


b)

Legend for scheme a: Fine soils: 1 – biotic-lithogenic; 2 – crystalline-lithogenic; 3 – fragmentary; 4 – sand-lithogenic; 5 – sod soils; 6 – areas without signs of soil formation; 7 - zones of formation of technic soils

Legend for scheme b: 1 – fallout (rock fall); 2 – landslides; 3–5 – strong, medium or weak washout; 6 – forms of linear erosion; 7 - accumulation of debris.

Legend for scheme c: Plant groups: 1–2 – forest; 3 – meadow-shrub; 4 – moss meadows; 5 – areas without vegetation; 6 – single trees-

Fig. 4. Features of the formation and development of post-mining geosystems within the limits of the rock dump of the “Vizeyska” mine: a) soil formation; b) relief-making processes; c) formation of vegetation cover.

Vegetation on the exposed near-surface layer of rocks of the dumps has a mosaic character and includes various groups. These are primarily pioneer grass formations or groups of one to three types of trees, mainly Scots pine, pedunculate oak and warty birch, shrubs, grass or moss in the form of separate patches. Over time (in 5-10 years), individuals of other types of vegetation join their composition, which leads to the formation of more complex groups and a more stable vegetation cover. The sequence of stages of development of the vegetation cover on the dumps looks like this: woody, woody-moss, woody-herbaceous, woody-cereal and woody-shrub-cereal. These stages mostly end with a pine-oak association, the peculiarity of which is the edaphic determination of the dominance of Scots pine or pedunculated oak from the origin of fine soil. The most complex plant formations are common within the old conical dump. They correspond to the wood-moss stage of self- recovery of slope surfaces and the wood-grass stage of pre-dumping surfaces and upper plateaus of dumps. Background species include Scots pine and petiole birch. Black alder and white acacia are found on the wooded and terraced slopes of the dumps. In the groups around the rock dump, trees are drying up, which is caused by flooding and waterlogging, in the first stage of which the crowns of Scots pine dry, then the undergrowth also dries. At the same time, the recovery of aspen can be traced as a reaction to lighting and excess moisture, and ruderal species appear in the grass cover. Adventitious plants that form segetal and ruderal phytocenoses are widespread in places with significant subsidence of the earth's surface (Rudko, Ivanov, Kovalchuk, 2019).

Vegetation cover of the rock dump of the "Vizeyska" mine, which arose as a result of the process of its self-growth (Fig. 4c). It is advisable to plant forest crops resistant to the natural conditions of the region and geochemical pollution, namely: Scots pine, black alder, and white acacia in combination with the sowing of leguminous grasses. The carried out phytoremediation will make it possible to preserve the formed landscapes, weaken the activity of the manifestation of natural and anthropogenic processes and create prerequisites for the formation of cultural post-mining geosystems, which over time (after 50-100 years), after lowering the levels of chemical and radioactive pollution, can be used as a recreation and rest area .

Formation and development of post-mining geosystems in areas of inundation and submergence.

Intense inundation and underflooding are manifested within the Lviv-Volyn basin. The development of these processes is largely determined by the landscape structure of the territory. Even before the development of hard coal deposits, the Malopolissya part of the basin was characterized by a high degree of waterlogging and the presence of numerous depressions that were periodically filled with water. This is due to the flatness of the surface with a small dismemberment of the relief, a small depth of groundwater and a significant amount of precipitation (650-700 mm/year). Since the beginning of the development of coal deposits in the basin, the processes of flooding and overflooding of lands caused by man-made factors have acquired a wide development. Among these factors, we single out the insufficiently substantiated conduct of mining operations, unsuccessful selection of places for rock dumps, heaps and tailings, uncontrolled flooding and closure of coal mines (Ivanov, Kobelka, 2006).

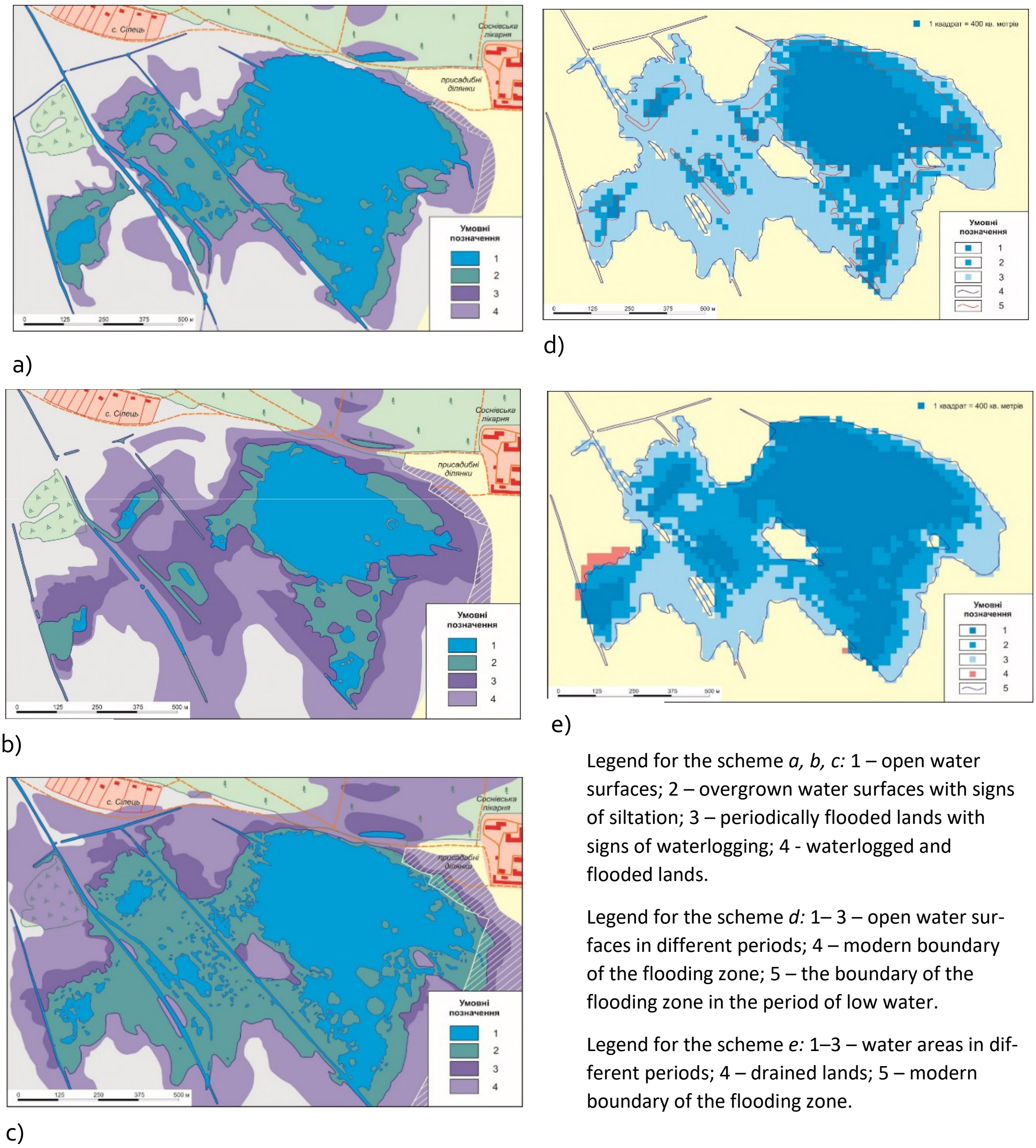
In many places of the basin, new reservoirs have formed - flooded depressions of a rounded, oval or elongated shape with a diameter of 100-150 m, which are constantly filled with surface and ground water. The largest bodies of water created as a result of flooding have a diameter of up to 500–800 m and an area of more than 10 hectares (Ivanov, 2007). Part of the reservoirs appeared on the site of former wetlands, others appeared on those fields where wetlands were not observed before and which were occupied by arable land, hayfields, pastures or forests. Flooded and inundated areas were recorded within residential or industrial areas of the cities of Chervonograd and Sosnivka, the village of Hirnyk, the villages of Mezhiryche, Bendyuga, Silets and Volsvyn. Flooding of low-lying natural areas with a shallow depth of groundwater begins after subsidence of the earth's surface by 1.5-2.0 m or under the conditions of artificial formation of a drainageless area. Significant areas of settlements, which are located within the local flat surface floodplain of the Zapadny Bug, Rata, and Solokia rivers and the rest of the first floodplain terrace and have experienced intense subsidence (2.0-2.5 m), cause the floods every year and cause significant losses to agriculture and people lose their dwellings (Ivanov, 2007).

We will consider the features of the emergence and development of post-mining geosystems in areas of inundation and submergence using the example of the Sosnivka model site. A plot of land with an area of 1.68 km^2 laid within the depression of the ground surface of the "Vizeyska" and "Nadia" mines. As a result of the development of four coal seams in the city of Sosnivka, Lviv region and its surroundings, there was an uneven subsidence of the earth's surface and the formation of a mould with a diameter of more than 1000 m and a depth of 1.6-2.2 m (Ivanov, Kovalchuk, 2003). The mould emerged 20 years ago in a relatively short period of time. Within two years, a young water body was formed in the place of pastures, hayfields and homesteads, which approached the forest massif. At the same time, two smaller flooded and waterlogged areas appeared in the forest, which is located within the boundaries of a slightly elevated interfluve, complicated by eolian humps. Their formation, along with intensive subsidence of the earth's surface, was determined by the drainageless nature of the area (Rudko, Ivanov, Kovalchuk, 2019).

Based on the decoding of space photos Landsat ETM+ we have been identified the stages of the reservoir area formation of post-mining geosystems (Fig. 5a, b, c). In particular, open water areas are highlighted; overgrown and muddy water surfaces that are covered with swamp vegetation; periodically flooded and heavily waterlogged areas with signs of waterlogging; flooded and waterlogged areas. The average values of the depth of the flooding zone are insignificant (0.75-1.70 m). At the same time, small deep areas were formed in the reservoir, and the maximum depth is 4.5 m.

In the zone of inundation by surface and ground water, significant fluctuations of the water level are noted, which are of a seasonal nature: the lowest level occurs in August-September (October), and the highest in March-April. It was found that during the low-water period, the water level dropped by 0.32 m, which led to a halving of the water surface area (Fig. 5d). In 2014, the maximum water level in the flood zone is lower than in 2009 (by 0.14 m) and is explained by a year with little snow (Ivanov, Kovalchuk, Tereshchuk, 2006). The expansion and gradual movement of the water area in the eastern and southeastern directions was also revealed (Fig. 5e). The average speed of movement of the inundation zone is 1.4-3.0 m/year and is caused by the expansion of the subsidence mould in the direction of the city (Rudko, Ivanov, Kovalchuk, 2019).

In recent years, we have observed the formation of numerous islands and underwater uplands overgrown with reeds and cattails. These cells are completely or partially submerged every season. At the same time, small open water spaces and zones with a low density of rush-reed communities were formed within the overgrown areas. We can note significant changes in the coastal strip of water bodies, where there is intensive waterlogging and overgrowth of watercress. In general, the ecological situation within the model area changed radically after the liquidation of the Vizeyska mine, the processes were reactivated due to a significant rise in the level of underground and groundwater. Flooding and flooding poses a danger to human life and causes the transformation of post-mining geosystems.



Legend for the scheme *a, b, c:* 1 – open water surfaces; 2 – overgrown water surfaces with signs of siltation; 3 – periodically flooded lands with signs of waterlogging; 4 - waterlogged and flooded lands.

Legend for the scheme *d:* 1– 3 – open water surfaces in different periods; 4 – modern boundary of the flooding zone; 5 – the boundary of the flooding zone in the period of low water.

Legend for the scheme *e:* 1–3 – water areas in different periods; 4 – drained lands; 5 – modern boundary of the flooding zone.

Fig. 5. Formation and development of post-mining geosystems within the subsidence mould of the earth's surface of the "Vizeyska" and "Nadia" mines (fragment of the map diagram): a) as of April 20, 2009; b) as of August 26, 2012; c) as of March 29, 2014; d) mosaic formation of open water surfaces; e) comparative mosaic dynamics of flooding of natural and economic systems.

Unfortunately, anti-flood measures do not have the proper effect. Today project documentation has been developed for the construction of a canal between the Rata and Zahidniy Bug rivers in order to divert excess water from settlements. The project is designed to save their residents from the annual flooding of houses, outbuildings and gardens. The channel must cross the model area, the flood zone and adjacent flooded and swampy areas, which complicates its construction. We consider this design decision to be unreasonable from the point of view of hydro-ecological feasibility, which is expensive and ineffective. Due to insufficient funding, the project was not implemented.

Conclusions.

On the basis of landscape and ecological studies conducted within In the Lviv-Volyn coal basin, the specifics of the functioning and development of various post-mining geosystems, which were formed within the bedrock dupms of coal mines, were studied. It is important to analyze the level of anthropogenic transformation of the geosystems of coal mining areas, to assess the current state and the intensity of the subsidence of the earth' surface, its flooding and submergence. At the same time, the landscape bases for carrying out optimization works within the limits of various coal mining facilities are substantiated. We analyzed the existing approaches and proposed the new ones to improve the current ecological situation in the basin, reclamation and phytomelioration of coal fields and dumps, optimizing the use of inundation and submergence zones, establishing a system of effective monitoring of the state of the environment, etc. are considered.

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The concept of the "Mining and Postmining" program for the training of bachelors with the specialty "Mining" at the National Technical University of Ukraine "Ihor Sikorskyi Kyiv Polytechnic Institute" in the context of cooperation with TH Georg Agricola

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Abstract

The relevance of the creation of the educational program "Mining and Postmining" to ensure the sustainable development of transforming mining regions by specialists was revealed. The conceptual foundations and features of the new bachelor's program are presented. The content of the program is described, the characteristics of the main groups of educational components, competencies and expected learning prospectives are provided. The steps to provide the program with educational and methodical literature are shown, taking into account the world and Ukrainian experience of restructuring mining enterprises. Prospects of cooperation with TH George Agricola, as a leading higher education institution for post-mining issues, are being discussed.

Environmental and climate protection is one of the global challenges of the 21st century and occupies a special place in modern world politics and society. The coal industry, which in the 18th century started the industrial era and until the end of the 20th century remained a basic element of world energy, entered a period of large-scale transformation and purposeful production reduction, step by step yielding to low-carbon energy technologies. The world community realized the need to find "green" ("clean") energy sources and methods of their widespread use. Modern world energy and

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climate policy requires acceleration of the processes of transformation of mining regions. The European green course and vector of decarbonization of the economy and energy systems involves the use of low-carbon resources, which is directly related to the reduction of fossil coal production. For countries that have undertaken to achieve carbon neutrality (including Ukraine), large-scale restructuring of the coal industry and transformation of mining regions is a priority task. Within 10 years, it was planned to close about 30 state mines and some private mines in Ukraine. Similar processes, but mainly for economic reasons, also apply to a part of the mining enterprises of the ore industry, which complete the development of profitable reserves of their ore fields. The long stage of post-mining, that is, a complex of measures of a technological, ecological and social nature to ensure the sustainable development of mining regions that are being transformed, is becoming a relevant mining activity for Ukraine in the coming decades [1, 2]. Educational processes of professional training must correspond to significant changes in the mining industry and provide the post-mining stage with highly qualified personnel of bachelors and masters.

As a consequence at the National Technical University of Ukraine "Ihor Sikorskyi Kyiv Polytechnic Institute" in 2021, the certificate program "Mining and Postmining" was developed and approved3 as a specialization component of the basic educational program "Geoengineering", the basis of which is geotechnologies of underground construction for the bachelor's level of higher education (specialty 184 "Mining"). The purpose of the certificate program is to train highly qualified, competitive experts in the field of mining, who are able to solve complex problems that arise during and after the closure of mining enterprises, in particular, to carry out post-mining taking into account environmental protection legislation and Ukraine's international obligations on decarbonization.

The certificate program is designed for full-time students to shape their individual trajectory of obtaining higher education. Enrollment in the program takes place during the period when students exercise their right to freely choose academic disciplines for the next academic year/semester. The prerequisites for mastering the certificate program are the acquisition of basic knowledge in higher mathematics, physics, chemistry, geology, which is the basis for further study of the educational components of the certificate program. It is filled with unique content and author's courses, which are characterized by the practicality and relevance of information, which allows you to gain additional knowledge and skills, expand the range of career opportunities in the field of mining.

The concept and structure of the new educational program was based on the principle that post-mining issues can be effectively solved only by specialists who have properly mastered the basics of mining, modern mining technologies and geoconstruction technologies. That is why the name and content of the program consists of two components "Mining and Postmining". Another con-

[3] The authors of the article are the developers of the program.

ceptual position was the comprehensive disclosure of the tasks and methods of postmining: technological, ecological, economic, social, which was reflected in the corresponding names and contents of the disciplines. In addition, the main competencies and expected learning outcomes had to comply with the approved Higher Education Standard for specialty 184 “Mining” [3].

The educational components of the program are presented in the table. 1.

Educational components of the certificate program	Number of ECTS credits	Final control form	Study semester
Technologies of underground development of mineral deposits	4	Test	V
Technologies of open development of mineral deposits	4	Test	V
Mineral processing and purification technologies	4	Test	V
Geotechnological methods of mineral extraction and processing	4	Test	V
Geoecology	4	Test	VI
Environmental impact assessment for mining activities	4	Test	VI
Economics of deposit use	4	Test	VI
Investment policy and management in mining	4	Test	VI
Climate change and decarbonization of the mining sector	4	Test	VI
Mining waste disposal and circular economy in mining	4	Test	VII
Development of energy resources by non-traditional methods	4	Test	VII
Technical and economic justification of liquidation and conservation of mining enterprises	4	Test	VII
Post-mining of coal-mining regions	4	Test	VIII
Post-mining of ore and non-ore mining enterprises	4	Test	VIII
The total amount of ECTS loans	**56**		

The cycle of professional disciplines providing the mining-technological component of the program includes: “Technologies of underground development of mineral deposits”, “Technologies of open-pit development of mineral deposits”, “Technologies of processing and purification of minerals”, “Geotechnological methods of extraction and processing of minerals”, “Development of energy resources by non-traditional methods”. They reveal modern methods and production processes of underground and open mining of minerals, in particular the technology of underground development of stratified coal deposits; open, underground and combined development of ore deposits; extraction of conventional oil and gas fields; borehole geotechnologies of mineral deposit development (transfer of solid minerals into a mobile state); non-traditional development methods (shale gas and oil production, seabed gas hydrates, Earth’s deep heat, solar energy, wind, etc.). An important aspect of the content of the courses is the disclosure of environmental and man-made risks of the application of mining technologies for the extraction of various minerals and ways of minimizing risks during the exploitation of deposits. The content of the technological cycle is focused on the first part of the program (“Mining”), although certain technologies can also be used during the restructuring of mining enterprises (for example, during the liquidation of coal mines, residual reserves, tailings can be worked out by underground gasification of coal).

The cycle of environmental disciplines is equal in scope to the technological cycle and consists of the following educational components: “Geoecology”, "Environmental impact assessment for mining activities”, “Utilization of mining waste and circular economy in mining” and “Climate change and decarbonization of the mining industry sector”. They will reveal types of nature use and their ecological consequences; theoretical foundations and methodical methods of geoengineering studies of environmental problems and situations at the local and regional levels; features of connections and interaction between geology, mining technologies and ecology. Existing geo-ecological problems, features of deposit protection during the development of underground space, methods of reducing the negative impact on the environment will be considered, “circular economy” models for mining enterprises and regions. Special importance is attached to climate change and decarbonization of the energy sector. Green (low-carbon) technologies in industry, ecologization of mining transport and transport infrastructure, energy-saving geo-building technologies, prevention of pollution of atmospheric air and water bodies, disposal of mining waste, etc. will be considered. An important approach to the meaningful filling of these disciplines is the disclosure of the features of environmental protection not only of mineral extraction, but also issues of liquidation of mining enterprises and transformation of mining regions.

The cycle of economic disciplines includes: “Economics of deposit use” and “Investment policy and management in mining”. The following will be studied here: the economic mechanism of deposit use, environmental management and audit, ecological and economic effectiveness of environmental protection measures and environmental insurance, the development of science and technology as a factor in the profitability and sustainability of deposit use, the principles of investment policy for the development of mineral deposits, financial support for investment projects and international cooperation, modern tools of project management in mining, etc. These disciplines cover economic and organizational issues of both components of the “Mining and Postmining” program.

The most significant for the second part of preparation is the final cycle of post-mining, which includes: “Post-mining of coal-mining areas”, “Post-mining of ore and non-ore mining enterprises”, “Technical and economic justification of liquidation and conservation of mining enterprises”. A set of technological, ecological and social measures to ensure the sustainable development of mining enterprises and transforming regions is considered here. Features of the final period of operation and liquidation of mining enterprises, consequences of mining operations and projects of ecological rehabilitation of territories (in particular, landscape restoration works) are shown. A typical mine liquidation project and its components, safety issues during mine liquidation and in the post-liquidation period are considered. The peculiarities of post-mining technologies for coal mines, ore mines, non-metallic mineral extraction enterprises (underground and open pit mining) and technical and economic reasons for their liquidation and conservation are analyzed. New production possibilities of mining regions in accordance with the development of “green technologies” have been revealed. The possibilities of revaluation of the surface complex of mining enterprises and the use of tools for preserving the cultural and industrial heritage of miners (museumification of mining objects), as well as ways to overcome the socio-economic consequences of the closure of mining enterprises, are shown. New production possibilities of mining regions in accordance with the development of “green technologies” have been revealed. The possibilities of revaluation of the surface complex of mining enterprises and the use of tools for preserving the cultural and industrial heritage of miners (museumification of mining objects), as well as ways to overcome the socio-economic consequences of the closure of mining enterprises, are shown. New production possibilities of mining regions in accordance with the development of “green technologies” have been revealed.

Among the expected learning outcomes related to the post-mining component, it should be noted the ability to: develop projects for the liquidation or conservation of mining enterprises, provide technological and environmental components of the restructuring of coal mines, carry out ecological rehabilitation of the territories of mining enterprises, apply mining waste disposal technologies, develop social and ecological directions for targeted transformation of mining regions, provide new production capabilities of industrial enterprises in accordance with the development of “green technologies”, create circular production cycles for the decarbonization of the industrial sector, preserve the cultural heritage of miners and tourist-important industrial objects, carry out technical management of post-mining processes.

It should be noted that the considered cycles of educational components are provided with methodical and educational literature to varying extents, which required the teachers to prepare relevant postmining lecture notes. In the future, it would be expedient to combine the efforts of Ukrainian and German specialists to prepare a joint textbook on post-mining, which would reveal various aspects and extensive international experience of restructuring mining enterprises and transformation of industrial regions. In the case of a significant need for post-mining specialists, the “Mining and Post-Mining” certificate program can become the basis for a separate educational program, which will have a universal character for Ukrainian technical universities, where specialists are trained in the specialty 184 Mining. For the development of such a universal program and its educational and methodological support, it would be expedient to involve international educational experience, in particular, the experience of German specialists like THGA in Bochum. Thus, the development and improvement of this educational direction requires international cooperation and the involvement of the best practices of countries with large-scale successful post-mining experience.

On the basis of the Letter of Intention (LOI) dated 09.09.2021, signed between the TH George Agricola and the State Enterprise “OK Ukruglerestructurizatsiya” on participation in a joint scientific project dedicated to the problem of restructuring the coal regions of Ukraine, German and Ukrainian experts exchanged knowledge in the field, the basis of this work advanced German experience lay. TH George Agricola was chosen by Ukrainian colleagues as the leading mining technical high school in Germany, which was founded in 1816 and has been providing engineering education in the main mining disciplines for over 200 years.

In the course of cooperation, there was a need to expand the scope of cooperation in matters of education of experts in the field of post-mining. Currently, the possibilities of cooperation between the TH George Agricola and the National Technical University of Ukraine “Ihor Sikorskyi Kyiv Polytechnic Institute” are being discussed for the purpose of developing a unified training program for post-mining experts.

The Center for Post-Mining Research at the TH George Agricola (THGA) is the world’s first scientific institution that investigates all aspects of post-mining. The life cycle of a mine is not only the preparation of the deposit, but also the work after the cessation of production. Post-mining is, in other words, how to create a new life for a former mining enterprise and coal region with an emphasis on technical and environmental issues.

Main directions of research [4]:

- eternal tasks and mine water management;
- geomonitoring;
- materials science for the preservation of industrial heritage;
- reuse and just transition.

In Germany, the last coal mine closed in 2018. RAG Stiftung is engaged in solving “eternal challenges”[5] at the post-mining stage. It should be noted that these “eternal tasks” are, however, related to the issue of water resources: water pumping, polder activities, groundwater purification, etc.

All this experience is currently very necessary for Ukraine to secure new modern approaches in post-mining issues. The German government very actively supports Ukrainian-German scientific cooperation in the field of ecology. Despite the fact that Ukraine is currently at war with Russia, the issue of ecological closure of illiquid mines is urgent, because with inappropriate approaches to the problem of mine closure, the negative consequences can last for decades, for this we need appropriate specialists with competencies that correspond to the current state of technical of knowledge.

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Underground coal gasification as the technology on the transition between the coal industry and decarbonization

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Abstract

Reasonable expediency of using underground gasification of coal in the period of transformation of the coal industry. The historical development and directions of improvement of underground gasification technology are shown. The features of new methods of using autonomous wells, ensuring the mobility of the blasting point, utilizing the thermal energy of the underground gas generator, the possibility of a sharp increase in the hydrogen content in the generator gas, etc. are disclosed. New possibilities of effective application of underground gasification of coal according to the principles of "green energy" are shown.

Introduction

Environmental and climate protection is one of the global challenges of the 21st century. and occupies a special place in modern world politics and society. The coal industry, which in the 18th century started the industrial era and until the end of the 20th century. remained a basic element of world energy, entered a period of transformation and purposeful production reduction, step by step yielding to low-carbon energy technologies. The world community realized the need to find "green" ("clean") energy sources and methods of their widespread use. However, the "abandonment of coal" (the period of decarbonization of the world economy) will last several decades, which requires solving the issues of safe and environmentally efficient development of coal deposits during this period. Large-scale environmental problems of traditional mining.

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Today, only borehole underground gasification of coal is the closest to "clean" energy technologies, since most environmentally harmful substances remain underground during its use. At the same time, the possibility to significantly increase the hydrogen content in the generator gas (instead of carbon oxides) through a special regime of periodization and composition of the blasting or the use of plasma-chemical transformations in high-temperature flows significantly minimizes CO_2 emissions during the consumption of generator gas and meets the requirements of climate policy.

In addition, borehole technologies of thermochemical processing of coal seams ensure a high level of safety of mining operations (since these are "unmanned technologies") and can be used in conditions where traditional underground development is economically impractical or dangerous for miners. In view of this, the development and improvement of the borehole technology of underground gasification of coal (in particular, obtaining generator gas with a predominance of hydrogen), the use of thermal energy of the underground gas generator, monitoring and control of technological processes represent an important complex scientific and technical challenge, the solution of which can provide ecological and a socially acceptable way of developing coal deposits during the transformation of the coal industry, in particular in China and other Asian countries.

Historical overview

The predecessor of the technical idea of underground coal gasification (UCG) was the technology of coal gasification at illuminating gas plants. From the beginning of the 19th century. certain streets of London were already lit by lamps that used artificial gas obtained during the processing of hard coal at gas plants [1]. In 1868, the German and British engineer Karl Wilhelm Siemens put forward the idea of the possibility of underground gasification of coal at the place of its occurrence, similar to gasification processes at gas plants [2]. Independently of Siemens, this idea was formulated and developed in the early 1880s by the famous Russian chemist Dmytro Mendeleev, who came to it while researching methods of fighting coal seam fires in the mines of the Donetsk coal basin. The scientist proposed to manage the process of burning layers and productively use the released gases. Seeing the significant prospects of this method, Mendeleev wrote: "Probably, with time, even such n era will come when coal will not be dug out of the ground, but there, in the ground, they will be able to turn it into combustible gases and will distribute them over long distances through pipes. " He also formulated a general technical solution to the problem: "After drilling several holes into the formation, one of them should be designated for the inhaust, even blowing in air, the other for the exhaust, even pumping out (for example, with an injector) combustible gases, which can then be easily carried even over long distances to the furnaces" [3].

The first official patent for the method of underground gasification of coal was received in Great Britain in 1909 by the American Alan Betts. In 1912, the outstanding Scottish chemist William Ramsay proposed the first project of underground gasification of coal, but it was not possible to implement it in practice – the technical problem turned out to be much more difficult than the general ideas about its solution. The world's first industrial-research works on underground gasification of hard coal were carried out in 1933 in Ukraine at the Lysychansk station "Pidzemgaz" (project of 1928), but the first scheme of gasification turned out to be unsuccessful. The experience gained made it possible to find a rational scheme for igniting the formation and successfully use it at the station in Horlivka, where in 1935 it was possible to obtain stable gas formation. This became possible thanks to the development by a group of former students of the Donetsk Coal Chemical Institute P. Skafa, V. Matveev and D. Filippov with the support of prof. I. Korobchanskyi and V. Krym of the so-called "current method of gasification" [4].

For several decades, three underground gasification stations operated in Ukraine in Lysychansk, Horlivka, and Synelnikovo, which made it possible to accumulate significant scientific and technological experience in conducting work (in particular, in 1954, the world's first hydraulic fracturing of a coal seam was successfully carried out), which proved the possibility of process management underground gasification and the expediency of further development of this direction. It should be noted that some problems of the technology, in particular the relatively low calorific value of the obtained generator gas - up to 3-4 MJ/m^3, have not been found an acceptable solution for a long time. In the 1960s, the widespread development of gas fields in Western Siberia began, and the cheap gas that arrived in the European part of the former USSR led to the loss of industrial interest in underground gasification.

Technological level of the 21st century. opened a new stage in the development of underground coal gasification technology, which became possible thanks to the solution of a number of important technical problems, in particular directional drilling of boreholes, obtaining generator gas of increased calorific value (up to 10-12 MJ/m^3), management of gasification processes and control of the spread of fire works, improvement of environmental safety, etc. [5-8]. At the same time, technologies for the complex use of gasification products were developed: co-generation energy systems (with the inclusion of generator gas in the combined cycle of power plants), specialized enterprises for converting generator gas into a liquid for obtaining synthetic oil, motor fuels, oils and other chemical raw materials [9-11].

At the beginning of the XXI century. in the world, there were more than 20 large underground coal gasification enterprises, most of which were concentrated in Australia and China, some stations - in the USA, Canada, South Africa, and Central Asia. Significant interest in this issue is evidenced by the large number of new station projects (more than 50) recently developed by global companies, in particular industry leaders - Linc Energy (Australia), ENN Coal Gasification Mining, Shandong energy Xinwen mining Refco Group (China) and others, as well as the exit of individual companies to the world stock exchanges. The competitiveness of modern underground gasification technology is evidenced by the cost of generator gas, which, when recalculating its calorific value to the level of traditional natural gas, ranges from $39 to $295 per thousand cubic meters in various companies.

In 2015, the Ministry of Energy and Coal Industry of Ukraine and the Australian companies Linc Energy and Bond Bros Contracting signed a Memorandum of Understanding regarding the start of preparation of a joint underground coal gasification project in Ukraine, but the continuation of the

Russian aggression against Ukraine suspended these plans. The Dnipro lignite and Lviv-Volyn coal basins are the most promising for the implementation of underground coal gasification projects.

The main areas of improvement of underground gasification of coal

Over the last period, industrial-experimental studies of underground gasification of coal allowed us to identify several directions of intensification and management of thermochemical processes. The traditional approaches were: increasing the temperature of the underground gas generator (in particular, in the recovery zone) and increasing the gas flow rate in the gasification channel, which is achieved by reversing (periodically changing the direction of incoming and exhausting gas); an increase in pressure in the underground gas generator, which shifts the balance of chemical reactions towards the formation of methane; the use of pulsating (ensures a better opening of the reaction surface) and periodic (increases the formation of hydrogen) blasting; management of water inflows to the underground gas generator; backfilling of used (burnt) space; optimization of the composition of the blasting (air, oxygen, steam), etc. [6, 12]. The process of transforming a carbon-containing heterogeneous medium into gas under the influence of plasma energy should be considered a promising direction of research, which dramatically increases the hydrogen content in the generated generator gas and opens up environmentally acceptable opportunities for its consumption in the framework of "green energy" [13].

Of particular importance for increasing the efficiency, competitiveness and environmental friendliness of the use of products of thermal processing of coal seams is the problem of utilization of a significant amount of heat released in the process of coal gasification and spent on unproductive heating of the rock mass (losses - up to 30-40%). Possibilities of using thermal energy released during the burning of coal seams were investigated by Prof. Yu. Dyadkin, Acad. V. Rzhevsky, prof. O. Kolokolov [6], but all of them involved the use of a gaseous heat-carrying agent that filled the burnt space, had unstable characteristics and was used only in heat exchange processes.

The latest scientific and technical achievements in the field of geothermal energy technologies have opened fundamentally new opportunities for the use of liquid heat-carrying agent for electricity generation, bringing the efficiency of hydro-steam turbines closer to the efficiency of high-temperature steam units. Modern hydro-steam turbines (in particular, the American corporation Energent) use superheated water (T=110–2500C) as a working heat-carrying agent, have compact dimensions and a power of up to 100 kW [13]. For the first time, Ukrainian scientists proposed the idea of combining modern hydro-steam turbines with a heat-carrying agent that circulates in a hermetic pipe collector at the bottom of a coal seam during its thermochemical processing, and developed the concept of a power plant using the thermal energy of an underground gas generator [6, 11, 15].

In order to combine the new technology with the traditional borehole technology of coal gasification, a method is proposed that allows to obtain generator gas and superheated water for electricity generation using gas and steam turbines. The method is carried out as follows, fig. 1:

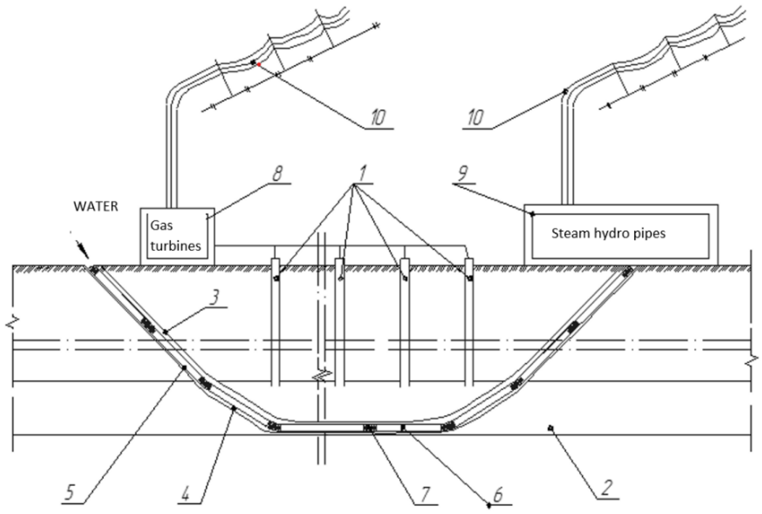

Fig. 1. Scheme of implementation of the method for horizontal layers

According to the selected method of gasification and/or burning of the coal seam, a system of air supply and gas removal boreholes 1 are drilled from the surface, reaching the coal seam 2. In addition, transfer boreholes 3 with bypass cavities 4 are drilled, and the boreholes pass at the bottom of the coal seam 2 and come to the surface. Sealed pipelines 5, which are formed by combining rigid sections of the pipeline 6 with flexible intermediate elements 7 (for example, with metal corrugated sleeves), are pulled into the transfer boreholes 3. The length of the rectilinear rigid sections 6 is determined taking into account the curvature of the transfer borehole 3 and the dimensions of the bypass cavity 4, in which the pipeline goes in the bottom of the coal seam. After the installation of the pipeline, gasification and/or burning of the coal seam is carried out, diverting generator gas to gas turbines 8 with electric generators. At the same time, a liquid heat-carrying agent (water) is supplied at the entrance of the pipeline 5, regulating the speed of the heat-carrying agent with a pump, the temperature of which should be 150-2000C at the outlet (optimal parameters for hydro-steam turbines). The heat-carrying agent (superheated water) enters the hydro-steam turbines 9 with electric generators. Electricity produced by gas and hydro-steam turbines is supplied by power lines to 10 consumers.

The inclined lying of coal seams allows, when using borehole technology, to drill straight boreholes from the surface directly along the seam (Fig. 2), which greatly simplifies the formation of a pipe collector.

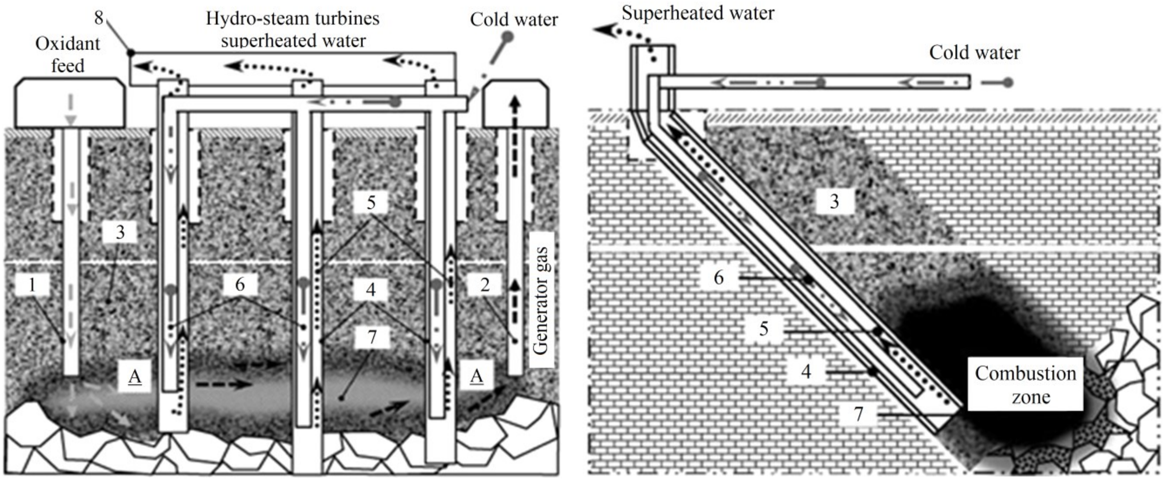

Fig. 2. Scheme of implementation of the method of thermal energy utilization for inclined seams: 1,2 – air input and productive boreholes; 3 – coal seam; 4 – heat removal boreholes; 5 – pipe sleeve; 6 – feed sleeve; 7 – seam gasification zone; 8 – hydro-steam turbines

In contrast to the method described above, the rectilinear hermetic collector (pipe sleeve) 4 is made with a closed outlet and an internal injection sleeve 6 is placed in it, through which a liquid (cold) heat-carrying agent is supplied to the bottom part of the collector, which is directed through the combustion zone of the formation 7 (where it is heated). to the mouth of the borehole for feeding to hydro-steam turbines.

Thus, the method ensures the utilization of thermal energy generated during underground thermochemical processing of coal and allows its use for additional electricity production, which significantly expands the possibilities of effective application of borehole technology and increases the productive capacity of the underground power unit.

Ways to ensure the mobility of the injection point

A new stage in the development of underground coal gasification technology is associated with the idea of ensuring the mobility of the injection point (CRIP method), which was first implemented in a series of UCG Centralia tests in the state of Washington [17]. According to this method, the coal seam is entered with a vertical borehole, which is used for gas removal, and an inclined-horizontal borehole, the horizontal part of which is drilled in the bottom of the seam and lined with a metal pipe. Through it, the blasting is supplied. Since when some part of the formation is outgassed, the fire face moves away from the point of the blast supply (the end of the pipe), heat losses increase, and the calorific value of the generator gas decreases. To change the situation, a flexible tube with a torch was inserted into the horizontal borehole, which was used to cut the tube at the appropriate distance, ensuring that the air mixture reaches the fire face moved along the borehole. This allows a new area of the formation to be involved in the gasification process, and when the process is repeated, the entire area of the formation along the borehole. It should be noted that cutting a pipe with a torch at a long distance underground is a rather difficult task and the method requires improvement. The CRIP method with a mobile (controlled) blasting point has been tested at several experimental underground coal gasification stations, in particular in Teruel (Spain). The further development of the method was its use for parallel boreholes with the possibility of formation of new reaction channels between them (as the fire breaks out between the boreholes) [5].

The authors associate the prospects for the evolving of the CRIP method with the combination of functions of oxidizing supply and generator gas removal in one borehole equipped with a tubular recuperator with heat-carrying agent circulation [6, 16]. According to the developed method, the fire heading face is formed not between parallel boreholes, but along them, forming the complete autonomy of each of the boreholes (Fig. 3). The oxidizing agent is supplied to the combustion zone by a sleeve located in the tubular recuperator and protected from burning by the liquid heat-carrying agent (superheated water) circulating through the recuperator. Generator gas is exhausted through the free space between the borehole wall and the pipe recuperator (gas flow zone). The heat carrier is supplied by a separate sleeve, which is also placed inside the pipe recuperator. Such a solution simultaneously provides the specified characteristics of the supply of liquid heat carrier and oxidizer for coal gasification processes, removal of generator gas and thermal energy of the underground gas generator.

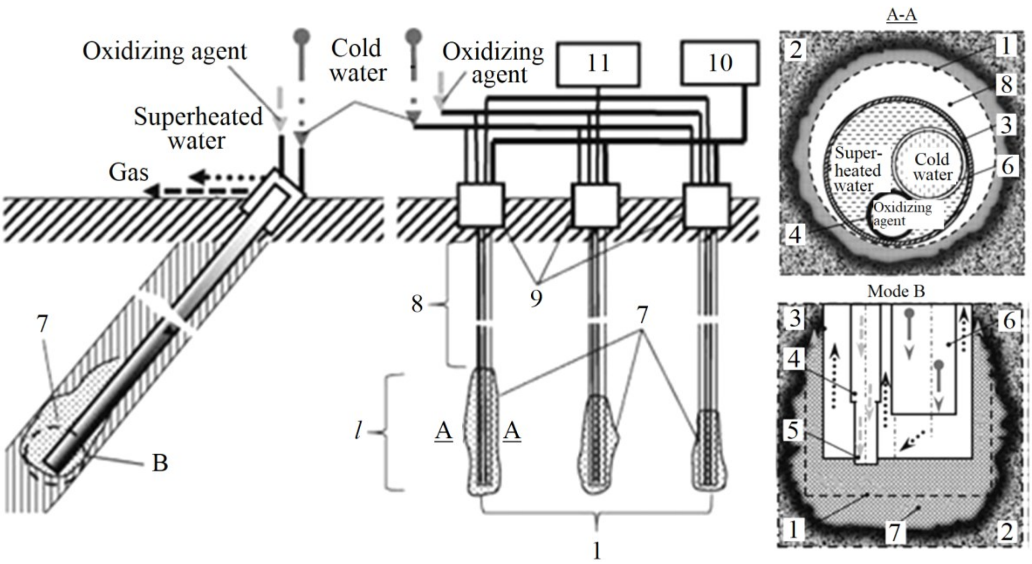

Fig. 3. Method of gasification of coal by autonomous boreholes: 1 – system of autonomous boreholes; 2 – coal seam; 3 – pipe recuperator; 4 – sleeve for supplying the oxidizer, 5 – nozzle; 6 – sleeve for supplying the heat-carrying agent, 7 – gasification zone; 8 – generator gas flow zone through the well; 9 – conductor; 10 – gas turbines; 11 – hydro-steam turbines

The authors have developed a system for bypassing the oxidizer in the sections of the pipe recuperator for the timely supply of the air mixture to the combustion cell of the formation during the movement of the fire heading face along the borehole, which increases the total volume and quality (heat-generating capacity) of the generated generator gas, and ensures the process of coal gasification along the entire length of the well. Thus, the CRIP method has found a new development for coal gasification by autonomous boreholes.

Conclusions

The processes of decarbonization of the world economy and energy systems and the transformation of the coal industry caused by them require the search for alternative technologies for the ecological and safe development of coal deposits for this period. The potential of underground gasification of coal, which for various reasons did not receive wide industrial application during the development of the coal industry, may find wide application in the transition period, as it largely corresponds to the ecological and social principles of the transformation of coal regions, modern climate policy. Scientific developments of the last period, in particular, the use of autonomous boreholes, methods of ensuring the mobility of the blasting point, the utilization of thermal energy of the underground gas generator, the possibility of a sharp increase in the hydrogen content in the generator gas, etc.

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Results of the joint German-Ukrainian project “Managing the Change: Tasks of Post-Mining in Ukraine”.

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Dipl.-Ing. N. Lubenska[1]

Introduction

Since 2014, after the annexation of Crimea and Eastern Donbass, Ukraine has been forced to defend its territories from Russian military aggression. On February 24, 2022, the war moved into a full-scale phase.

Many large cities have been destroyed, the country’s energy system and infrastructure have suffered from the war actions. When it comes to survival, environmental issues fade into the background. However, you need to understand that if you neglect the solution of these issues, it will have irreparable consequences in the future. There are many industrial places in Ukraine that due to the war stay without proper environmental monitoring. One of such problems is the flooding of coal mines on uncontrolled territories, highly mineralized water comes to the surface, goes to rivers, polluting them and the surrounding territories. The methane gas displaced by rising water collects in the basements of houses, creating an explosion hazard. The situation is complicated by the fact that many industrial sites are mined, which postpones the possibility of visiting them by experts, even after the end of the war, for an indefinite period.

As a support to Ukraine, our team of German and Ukrainian authors tried to draw parallels between the restructuring of the coal industry in Germany and Ukraine, offering a catalog of measures that can be implemented now and that can be implemented only after the end of the active phase of the war.

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Restructuring of the German coal industry in the post-war period and the "eternal tasks" of post-mining

Coal, steel and energy were needed to rebuild Germany after World War II. In the 1950s, North Rhine-Westphalia was considered the leading economic zone of Germany and all of Western Europe. Here is the largest Ruhr coal basin (according to the toponym of the Ruhr River), where coal has been mined since the 12th century. In the middle of the 20th century, mining was carried out at an average depth of 1500 m, and during the years of active mining, subsidence of the earth's surface in some areas reached 25 m. In the most active years of mining, about 500,000 miners worked in the period from 1930 to 1960, peak production reached 125 million tons per year.

In the mid-1950s, an oil boom broke out in the energy market. The first mines went bankrupt and closed in 1959. In total, about 13.000 miners were left without work. To resolve issues **of** social insurance for miners, mine management and, in general, economic survival on the 27th of November 1968, the Ruhrkohle AG in Essen (later RAG) was founded. As a result, this joint-stock company included 23 coal associations with approx. 120 mines. The basis for the creation of this company was the law on the adaptation and rehabilitation of the German coal regions.

In the 1970s, a special energy tariff was introduced, the so-called "coal pfennig", which was supposed to ensure the existence of the coal industry in Germany, since without state support it would not be competitive. In 1975, the amount of subsidies in today's terms was about 4.5 billion euros. In 1995 the "coal pfennig" law was repealed.

On February 7, 2007, an agreement was reached between the German government, the coal-mining federal states of North-Rhine Westphalia and the Saarland, the company RAG AG, as well as the Industrial Union of the Coal, Chemical and Energy Sector (IG BCE) regarding the closure of coal mines in Germany. In December of the same year, a law on the financing of coal enterprises was adopted. RAG has committed to phasing out coal production, taking into account social aspects, by the end of 2018. **During this time, the number of mines has decreased from 128 in 1958 to 7 in 2000 and to 2 in 2018.** On December 21, 2018, the last coal mine in Germany, the Prosper-Haniel mine, was closed.

However, since the company is still liable for mining damage for 30 years, RAG AG will continue to regulate this. In addition, RAG AG rehabilitates old shafts that are still within its area of responsibility, rehabilitates former coking plant sites.

RAG Foundation was created for the realization of so-called perpetual tasks in accordance with the long-term lease agreement: failures and subsidence of the surface; gas release to the surface; polder and mine water management; reclamation of waste dumps that includes mine drainage, polder construction and drinking water monitoring on the Rhine and Ruhr.

The income of the fund is provided by the property and assets of RAG AG. The largest chemical company Evonik Industries was capitalized on the market, the amount from the sale of sharesamounted to 261.3 million euros. The main income of the fund comes from this and from the income from the sale of property, which is handled by Vivawest GmbH. The fund also owns 100% RSBG, which invests in technology enterprises. As of the end of 2021, the value of the assets of the RAG Fund is 21 billion euros, while the stake in Evonik Industries is 56.8% (7.5 Mrd.), Vivawest 40% (2.5 Mrd.), RSBG100% (1,8 Mrd.). The following percentage distribution of the budget for the "eternal tasks" of post-mining is provided: 65% for maintaining the operation of drainage systems, 31% for polder activities and up to 4% for groundwater treatment.

If the fund's money is not enough to solve the "eternal tasks", further fulfillment of obligations is guaranteed by the Federal Government and the Federal State.

Key figures

BALANCE SHEET
In EUR million

	31/12/2016	31/12/2017	31/12/2018	31/12/2019	31/12/2020	31/12/2021
Fixed assets	5,200.8	6,488.0	7,430.9	8,546.2	9,903.4	**10,754.8**
Current assets	899.5	712.7	2,053.1	1,127.3	1,286.2	**718.0**
Total assets	**6,100.3**	**7,200.7**	**9,484.0**	**9,673.5**	**11,189.6**	**11,472.8**
Equity	2.0	2.0	2.0	2.0	2.0	**2.0**
Provisions	4,925.3	5,364.6	7,909.2	8,012.6	8,596.1	**9,019.1**
Liabilities[1]	1,169.6	1,834.1	1,572.8	1,658.9	2,591.5	**2,451.7**
Total equity and liabilities	**6,100.3**	**7,200.7**	**9,484.0**	**9,673.5**	**11,189.6**	**11,472.8**

[1] Liabilities including deferred income.

INCOME STATEMENT
In EUR million

	31/12/2016	31/12/2017	31/12/2018	31/12/2019	31/12/2020	31/12/2021
Net annual profit (= allocation to the provisions for perpetual obligations)	392.8	430.6	911.8	413.6	858.5	**665.0**

Fig. 1. Key figures of the RAG Foundation at the state of 12/31/2021, Source https://rag-stiftung.de/

Water management of RAG AG

After the end of subsidized hard coal mining and the closure of mines, the eternal tasks remain, including mine water drainage, polder measures above ground, as well as mine water purification and mine water monitoring.

Mine water is the rainwater that seeps through the ground and dissolves the minerals or other harmful substances present in the rock. Potential hazards of surging include the following: methane gas outcome at the surface; raising the surface of the day; danger of cracks or earth and contamination of drinking water resources.

One of the most important elements of the current RAG water management concept is the approach that the mines should be flooded in a controlled manner. The pump height should be kept as low as possible and the dewatering systems should be converted to “well water systems” with modern submersible pumps. Pumping will take place from the surface. This eliminates the need for underground engine rooms and ventilation, resulting in cost and energy savings and CO_2 reduction.

Since the mines are hydraulically connected underground and in that case can be viewed as one vessel, they are divided into water provinces, with the help of the special software box model from DMT GmbH & Co. KG it is calculated at which location is most favorable pump out the mine water.

So that it would be possible to influence the mine water in case of need, reserve wells are provided. And with the planned flooding, a safe distance from drinking water sources is always provided for.

Changes in approaches to the closure of mines in Ukraine in the future must necessarily take into account the system of division into water provinces with the transition to central drainage systems.

The role of Research Center of Post-Mining

The TH Georg Agricola University (THGA), Bochum/Germany, has established the Research Center of Post-Mining (FZN) for sustainable management of mining impacts. The scientific researchers work with all mining issues related to the former coal extraction, for example rebound of mine waters, mine gas emissions, rehabilitation of abandoned mines, reuse of dump hills and alternative energy sources as thermal energy etc.

Each deposit has its own peculiarities, that’s why it is profitable to develop such research centers national wide that have the modern understanding of post-mining challenges and would have experience on the working with local coal mines.

Profitability of coal mines in Ukraine

As of 12/31/2021, there were 148 coal mines in Ukraine, of which 102 are state-owned and 46 are private, 2 mines are in the process of liquidation, while 33 mines are in the territory under the control of Ukraine and 67 coal mines in the territory not under the control of Ukraine. After the occupation of Donbass, where the majority of Ukrainian coal mining enterprises are concentrated, production has significantly decreased. The following coal production statistics are given without taking into account mines in non-government controlled areas (Fig. 2), while the higher productivity of private mines is clearly seen (Fig. 3). In most cases, the higher productivity of private mines is due to investments in modern equipment and staff training.

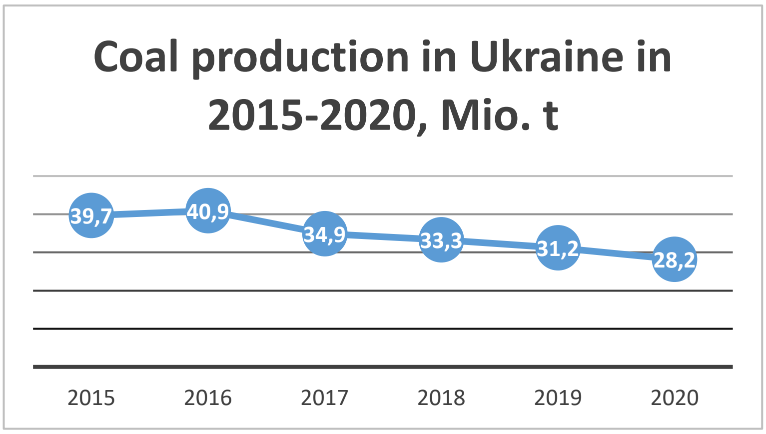

Fig. 2. Coal production in Ukraine in 2015-2020, Mio.t, without coal mines on the uncontrolled territory (infographics is based on the Statistics of the Ministry of Energy of Ukraine)

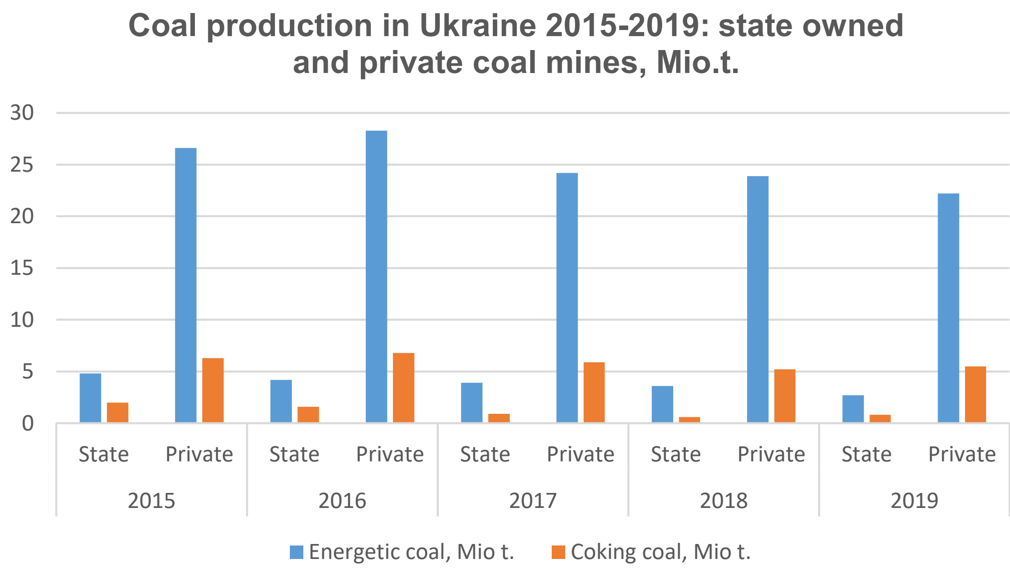

Fig. 3. Coal production of state-owned and private coal mines in Ukraine in 2015-2019 (infographics is based on the Statistics of the Ministry of Energy of Ukraine).

According to the Accounts Chamber for 2017, only Nadiya Mine PJSC and Krasnolimanskaya Coal Company closed the financial year with a profit. In the crisis year of 2020, the economic crisis worsened as a result of the consequences of the COVID pandemic, only Lvivvuhil enterprises showed positive results. As of 2020, the number of employees in the coal industry was approx. 35 thousand people, so the closure of unprofitable state mines is not possible in a short time. The state continues to subsidize the cost of production until 2019. The overall level of state support for the coal industry continued to grow (Fig.3).

State-owned mines in Ukraine mean a large number of jobs, for the employment of people it is necessary to develop a comprehensive program, and here the example of Germany can serve as a guide.

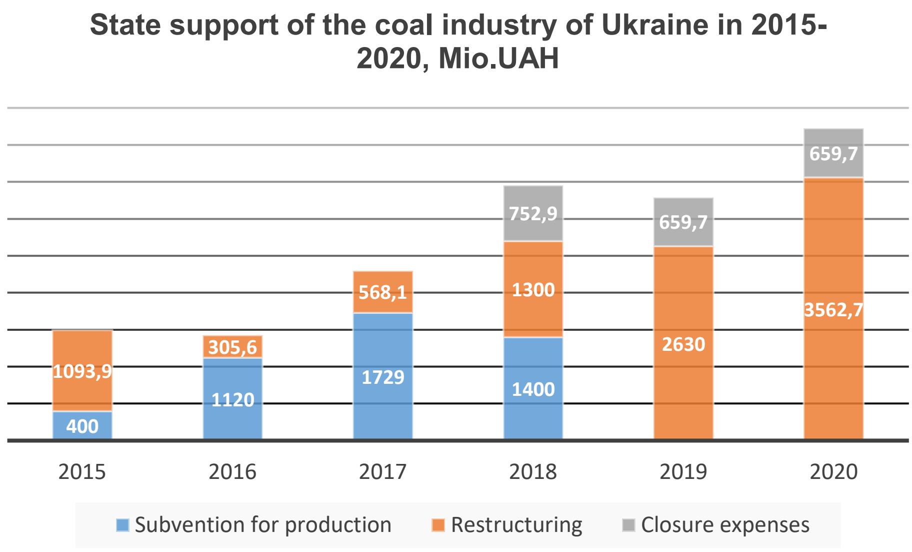

Fig. 4. State support of the coal industry of Ukraine in 2015-2020, Mio.UAH

Chronology of the restructuring process in Ukraine

As of 1991, there were 276 state mines in Ukraine, which in total produced 193 million tons of coal. Massive closure of state mines followed. The state's wage arrears led to almost annual strikes by miners from the late 1980s to the late 1990s.

The second attempt at restructuring was made in Ukraine back in 2005 (Decree of the Cabinet of Ministers of Ukraine under No. 236-r of 07.07.2005). At the first stage (2006-2010) it was planned to renew the stock of equipment, create attractive conditions for the privatization of state-owned mines, and in 2010 reach a production of 90.9 million tons per year. At the second stage (2011-2015), it was planned to reach production of 96.5 million tons and construction of 3 new mines. At the third stage (2016-2030), it was planned to reach production of 112 million tons per year. In general, for the implementation of the three stages of the concept, it was planned to attract funding from both private companies, foreign investors and the state. The concept was not implemented.

In 2008, the third reform attempt was made, which also set ambitious plans to increase the production of thermal coal and was also purely declarative.

In 2017, the Concept for the Reform and Development of the Coal Industry for the period up to 2020 was approved, although the concept did not set ambitious goals, the planned production level in 2019 and 2020 (taking into account the occupation of the South-East of Ukraine) provided for approx. 10 million tons per year, it was also not implemented.

The latest up-to-date concept of the State Target Program for the Fair Transformation of Coal Regions for the period up to 2030 (Resolution of the Cabinet of Ministers of Ukraine No. 1024 of September 22, 2021) identified the main causes of the crisis: low investment attractiveness; un-profitability of state mines; inefficient state policy in the coal regions; poorly developed infrastructure; environmental problems in coal regions. The results of the implementation of the concept provided for the transformation of 20 coal communities. In connection with the military aggression of the Russian Federation, it is clear that this concept will not be implemented either.

Conclusions

Ukraine has decided to follow Europe's green path for the restructuring of the coal industry. All attempts to reform it until 2022 were unsuccessful. On February 24, 2022, they became almost impossible.

In pre-war times, the best option for reforming the coal industry could be the example of the RAG fund. It is now clear that the revival of Ukraine is possible only with the support of the world community. As at one time Germany was restored according to the Marshall Plan, it will be necessary to develop a similar plan for Ukraine, where the restoration of coal regions should be a separate chapter. And if some aspects, for example, the size of the destruction, cannot be assessed before the ceasefire, then the concepts for eliminating the negative consequences of coal mining need to be developed now.

Table 1. Proposals for a comprehensive approach to the restructuring of the coal industry in Ukraine, taking into account the military aggression of the Russian Federation:

Activities before the end of hostilities	Activities after the end of hostilities
• Revision of the rules for the liquidation of coal mines, taking into account the "eternal tasks";	• Updating the energy strategy of Ukraine;
• Development of a pilot project on "Water Management" on a group of Ukrainian mines belonging to one "water province".	• Assessment of the state of coal mines, taking into account the destruction during the military conflict;
• Development of a training program for university students in the direction of post-mining;	• Assessment of accumulated environmental damage from coal mining in the past;
• Creation of the post-mining center, similar to Research Centre of Post-Mining at THGA in Bochum, Germany.	• Inclusion of recommendations for the transformation of coal regions in the overall plan for the recovery of the country.

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