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Original scientific paper

Development of a Conceptual Model for Environmental Monitoring in Underground Coal Mining

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Abstract: Despite the implementation of various technological solutions, underground coal mining has a significant environmental impact. This paper focuses on the impact of underground coal mines on the environment, with particular emphasis on such mining activities in the Republic of Serbia and stresses the importance of monitoring as a phase of environmental protection. The current practice of environmental monitoring in underground coal mines in the Republic of Serbia lacks systematic and comprehensive procedures, making this research paper an original and significant contribution to the mining industry. The primary objective of this research is to investigate the interaction between underground mining operations and the environment, provide a realistic assessment of the environmental impacts, and emphasize the importance of measuring certain parameters. A conceptual model of environmental monitoring, encompassing global trends and research, as well as the existing institutional framework in the Republic of Serbia, has been developed in this paper. Consistent implementation of this model can help establish quality procedures to reduce the impact of underground coal mining on the environment. The research demonstrates that the parameters with the greatest direct impact on the environment are the mine air (i.e. methane), waste rock disposal, ground subsidence, and indirect impacts such as electricity consumption. These influential parameters are analysed using the example of the Soko brown coal mine.

Keywords: coal mine; environmental impact; methane

1 INTRODUCTION

Mining activities have a significant impact on the environment, leaving an ecological footprint that surpasses the ones of any other industrial activity. The magnitude of this impact varies depending on the mineral resources being extracted and the distinct phases of production, but it can have substantial effects both locally and globally [1]. According to Richards [2], mining causes three primary forms of environmental impact: soil degradation, habitat destruction, and harmful chemical effects. Soil degradation encompasses changes in land use, surface ground displacement, vibrations due to blasting, and the visual impact of surface mines or waste dumps. Habitat destruction involves damage to flora, fauna, natural watercourses, drainage, and groundwater, resulting in a lowering of the water table. Harmful chemical effects include air pollution due to dust and harmful emissions, water pollution due to surface runoff from various mining areas, and waste dumps and leaching from tailings.

Mining, especially extraction of metallic mineral resources, is one of the most problematic industries, and surface coal mining operations are worse polluters than the underground coal mines [3]. Underground mining has other impacts, such as the use of methods that lead to cave-ins of roof rock strata above mining works, resulting in ground subsidence. Mining activities often require leasing or purchasing private land beneath which mineral wealth is located, leading to the displacement of people in that area.

Mining has played a critical role in the growth of human society and continues to remain an essential industry. The primary objective of this sector is to extract mineral resources, such as coal, in an economically feasible and safe manner while minimizing the environmental impact.

In recent decades, the planet has undergone significant changes in global weather patterns, leading to weather disasters resulting from global warming. It is evident that human activity has played a significant role in causing these changes in nature. Therefore, reducing gas emissions from human activity has received substantial attention in recent years [4]. Carbon dioxide is the most well-known gas contributing to global warming, and national environmental protection agencies have directed their efforts towards reducing its emissions. However, recent studies have focused on reducing methane emissions into the atmosphere, which have contributed to a 30% increase in global warming. The energy sector, including coal production, accounts for approximately 40% of total methane emissions resulting from human activity, ranking second after agriculture in terms of methane emissions. Out of the 135 million tons of methane emitted annually as a result of energy sector activity, an estimated 42 million tons of methane are emitted directly from coal mines. The three largest emitters are the People's Republic of China, the Russian Federation, and the United States [5].

Considering the high demand for coal due to the energy crisis, it is crucial to reduce methane emissions from coal mines using new technologies. Currently, traditional sources such as coal, oil, and gas provide 78% of the world's energy [6]. Methane is considered one of the deadliest gases in underground coal mining due to the risk of explosion, posing a severe threat to both miners and the environment [7]. Mine fires and explosions caused by methane and/or coal dust are the leading cause of fatalities in Serbian underground coal mines, and similar events are the leading cause of accidents in other underground coal mines worldwide. In a study conducted by Hirschberg, methane explosions caused 45% of all accidents [8]. Robertson discovered that 42% (388 out of 918) of fatalities in Australian underground coal mines were associated with gas and ventilation parameters [9].

In Serbia, several coal mines operate, and given the industry's importance, implementing environmental protection measures based on an integrated ecological-economic assessment of the mines' impact is crucial. It is essential to consider the social and environmental needs of the population living in the affected areas. Effective environmental and economic measures must be applied in coal mines, along with advanced production technologies and innovative methods to reduce the negative impact on the environment. Emissions of harmful gases during the production process, including methane, carbon dioxide, sulphur dioxide, nitrogen oxides, and other hazardous substances, are a significant problem in coal mines. Implementing gas purification systems is essential to reduce these harmful emissions [10].

However, achieving these goals necessitates a thorough understanding of the detrimental effects that mining activities can have on the environment. Failure to mitigate these risks can lead to catastrophic long-term impacts.

This study places particular emphasis on developing a conceptual model for environmental monitoring that will enable efficient detection and prevention of the harmful effects of underground coal mining on the environment. Through the utilization of analytical and measurement methods, along with the primary and secondary documentation analysis, the authors have formulated specific recommendations for environmental protection during the process of underground coal mining. These recommendations focus on the most crucial parameters and types of pollutants.

The Soko brown coal mine has a rich history of underground coal mining dating back to 1898 and is currently operated by the Public Enterprise for Underground Coal Exploitation Resavica (original name in Serbian: Javno preduzeće za podzemnu eksploataciju uglja Resavica, JP PEU Resavica) with an average annual production of 90000 tons of commercial coal. Located in eastern Serbia near Sokobanja, area of an exceptional tourism potential and ecological significance, the mine operates under special conditions due to the increased risk of methane ignition.

2 METHODOLOGY AND DATA

When evaluating the interaction between mining and the environment, it is crucial to identify potential impacts, particularly on environmental factors such as soil, water, air, flora and fauna, climate, and landscape. In the ecological context of analysing an underground coal mine, the risks that may arise are well-known and well-documented in scientific literature. These risks include issues related to water management, air pollution, ground subsidence, soil movements, waste dumps, tailings, soil pollution, abandoned facilities, and cumulative impacts on the environment [11].

The mining industry requires the support of both the community and the government to sustain its current activities and, more importantly, to undertake future projects. The critical factor in this regard is the management of environmental risks during mine operation, closure, and post-closure. The mining industry has to restore its reputation that has suffered over the decades in relation to environmental degradation.

In this context, global research has been considered, with a specific focus on China, where the production system, auxiliary production system, life cycle system, and their unit processes in eighteen environmental impact categories were analysed [12]. The results of the Life Cycle Assessment (LCA) demonstrated that underground coal mining has significant environmental impacts. Process analysis identified key operations of underground coal mining, such as mine ventilation, and waste removal, as the primary causes of ecological damage that require attention in the future [13].

The findings of these studies have provided guidelines to authors, suggesting that due to the initial lack of all parameters that will be collected over time, the focus should be primarily on these two key operations.

2.1 Conceptual Model

The mining environment is characterized by complex geological, hydrological, and biological processes that significantly impact the quality of water, air, soil, and sediment. Therefore, geochemical modelling is a challenging task that requires a comprehensive understanding of these processes. Hence, it is crucial to develop a reliable conceptual model, which refers to a conceptualization of physical, biological, or chemical phenomena, to achieve accurate results in geochemical modelling [14].

The accuracy of geochemical models is subject to real constraints imposed by the study of geology, hydrology, and chemistry at the site under investigation. This context emphasizes that models can only be useful if they are applied correctly, based on precise input data, and a reliable conceptual model.

It is worth noting that the term "model" is frequently used inaccurately, and generating computer output using pre-existing or new programs is effortless. Therefore, it is essential to have a clear understanding of the purpose and limitations of models to avoid inaccuracies in their application.

The importance of the conceptual model cannot be overstated. As Bredehoeft emphasized, "every model has a conceptual model at its foundation" [15]. Thus, developing the conceptual model is of great value. For example, how is the conceptual model developed? There is no straightforward or satisfactory answer to this question. It is established by a blend of conventional knowledge available at the time, the modeler's level of knowledge, and their creative aptitude. It is a combination of acquired knowledge and creative reasoning.

In the development of a conceptual model, consideration is given to incorporating analytical and measurement methods in conjunction with documentation analysis. Specific recommendations for environmental protection during the process of underground coal mining were formulated and applied at the Soko brown coal mine, considering the complete life cycle of the mining activity. Ongoing measurements of geochemical data are being conducted, which will be utilized for geochemical modelling.

Data collection often involves monitoring measurements from the field, production parameters, and pollutant emissions from the coal production process. Errors in field data collection, as well as inevitable variations in data, result in a certain degree of uncertainty, which can be expressed as a range or standard deviation.

The outcomes of geochemical modelling allow the testing of hypotheses regarding geochemical processes that may account for observations and anticipate future trends. These results are only useful in the hands of experts in hydrogeochemical processes and geochemical modelling. The aim of environmental monitoring is to provide practical information for assessing changes in the environment that can be linked to mining activities [16].

In essence, establishing the conceptual model for environmental monitoring in underground coal mining is rooted in its capacity to offer a holistic, data-driven, and regulatory-compliant approach. By integrating some of LCA principles, the conceptual model ensures that monitoring efforts are strategically aligned with the full life cycle of mining activities, allowing for effective and targeted environmental protection measures.

2.2 Environmental Monitoring

The practice of environmental monitoring in coal mines involves meticulous observation and recording of environmental phenomena. It includes collecting samples for analysis, conducting measurements, and performing tests to evaluate the data and analyse the results. The purpose of this practice is to assess any changes in the environment that may be attributed to mining activities. The obtained values are then compared with a set of established directives, regulations, ordinances, and standards to determine if there are any instances of exceedance.

Essentially, monitoring serves as a means of both supervision and control, including audit, and is not solely about tracking the status quo. Supervision enables the control of activities and their direction towards achieving specific goals, such as the quantity and quality of completed work, as well as the prevention and/or mitigation of harmful impacts on the environment. Audit is typically conducted during mining operations by independent auditors.

The goals of environmental monitoring in coal mines include determining the level of threat to humans and the environment from mining activities, ensuring compliance with laws and regulations governing proposed mining activities, and implementing protective measures. Relevant pollution data is also necessary for governmental authorities and the public, in addition to developing an inventory of emissions, releases, and losses of substances from production processes.

In Serbia, environmental monitoring is a legal obligation defined by a series of laws and regulations in the field of environmental protection, including the Rulebook on the contents of the environmental impact assessment study [17]. The Environmental Impact Assessment Study (EIAS) assesses the impact of planned activities or projects on the environment and identifies potential negative environmental impacts. The goal of the EIAS is to identify and assess all possible environmental impacts that an activity or project could have, including air, water, and soil pollution, noise, vibration, impact on biodiversity, climate, and other ecosystems.

Table 1 Conceptual model of environmental monitoring

	Subject of monitoring	Monitoring parameters	Measuring sites of monitoring and control	Method and frequency of monitoring and control	Monitoring and control requirements
Instrumental and laboratory measurements	Soil/Land	The size of the horizontal and vertical deformations of the terrain	The surface of the undermined terrain of the mining area	Geodetic measurements, annually	Deformation of the terrain / rulebook
		Situation on the mining waste and ground in the area	Mining waste	Geodetic measurements, annually	Stability of mining waste disposal / design
	Water	Quality of mine water and water in the recipient	Mine water before the inflow, above and below the inflow	Laboratory tests, quarterly	They are determined / rulebook
		Quantity of water inflow in the mine	Mining premises, source	Measuring (equipment), monthly	Water inflow (m^3/min) / mine design
		Water level in wells	Wells, mining area	Handy gauge, quarterly	Water level, variability / rulebook
	Air	Concentration of gases in the mine air	Ventilation drifts, channels, and shaft	Instrumental measurements, fifteen days	Gas concentration in % / rulebook
		Emissions on an emitter	Stationary source, chimney of the boiler house	Laboratory tests	It's more emissions / rulebook
Operational control	Soil/Land	Damage to the surface facilities	The facilities benchmarks	Visual inspection, semi-annual instrumental measurement if necessary	The degree of damage and the trend of further displacement
		Pollution of harmful substances (toxic pollution)	Location of pollution	Operational control and laboratory testing, as needed	Harmful substances are measured / rulebook
		Disposal of mining waste	Working bench of waste disposal	Visual inspection, daily	Establishing of waste disposal code / design
	Waste	Type and quantity of waste, class, and category	Collection, sorting, storage, and shipping locations	Visual inspection, daily	Mining waste management plan / regulation
	Noise	Mining works are carried out underground and coal process plant is within enclosed facilities at the surface. The primary ventilation fan generates noise while in operation. Noise levels are ascertained by obtaining reference measurements and conducting subsequent measurements as necessary.			

The Republic of Serbia has mandated the development of a Plan for the measurement of air pollutant emissions through the Regulation on monitoring conditions and air quality requirements [17] and the Regulation on measurements of emissions of pollutants into the air from stationary sources of pollution [17], which define the location, time, frequency, and manner of measurements. The mining company is responsible for environmental monitoring, while the competent Government authorities oversee the enforcement of this obligation, as stipulated by these acts.

Harmful environmental impacts in coal mines should be monitored by assessing various factors, including the quality of surface and groundwater, soil quality, surface, and subsurface deformation due to excavation, quality of mine water, stationary source air quality measurements, noise level control measurements, monitoring of waste rock disposal in mine waste dumps, and waste management system control.

The authors, through the development of the Conceptual Model, have incorporated regulations, as well as theories and methodologies underlying model creation. This includes understanding the coal mine ecosystem processes, identifying key environmental impacts, selecting relevant parameters for monitoring and further analysis, as well as defining modeling goals. The conceptual model may encompass various modeling approaches, such as statistical models, simulations, or system-based modeling. In short, the conceptual model includes the theoretical framework and methodology of the model itself, while the development in later stages will represent a concrete tool used for the analysis and simulation of the impacts of coal mining on the environment.

Measuring sites of monitoring and control are integral to this approach, enabling precise observation and regulation enforcement at strategic locations within the coal mine environment.

Tab. 1 presents a conceptual model for monitoring the environmental impacts of underground coal mining based on an analysis of pollution sources, technological processes, and other relevant parameters.

The indispensability of chemical tests in monitoring water, air, soil, and waste is evident. Tests for acidity, alkalinity, heavy metals, organic, and inorganic compounds are imperative for assessing various parameters. The performance of these tests is an essential activity that cannot be overlooked. It is noteworthy that the monitoring process would be rendered dysfunctional in the absence of such tests

3 RESULTS: USING A CASE STUDY EXAMPLE

This study focuses on analysing the direct impact of environmental pollution resulting from underground coal mining activities. Specifically, the impact of mine air dominated by methane and mine waste has been analysed. Understanding the environmental impact of mining activities is crucial for developing strategies to mitigate the negative effects on the environment and human health.

3.1 Methane Emission

To gather data in Soko brown coal mine, the ADK (automatic remote control) gas-ventilation parameter system for data processing utilizes the ADROIT computer application. Continuous monitoring devices for methane concentration have been installed at specific locations in the mine, including one located at the end of the path of the entire main ventilation flow in the ventilation shaft at k + 240 m, in addition to devices that measure other gas ventilation parameters [18, 19].

The concentration of methane emitted by mine ventilation is typically low, ranging between 0,1-1%, making it difficult to utilize and causing significant emissions that constitute approximately 70% of coal-related methane emissions [20].

Regarding gas-ventilation parameters, measurements were specifically taken of the amount of air and concentration of harmful gases in the outlet air stream of the mine. However, this paper focuses on CH_4 and CO_2 gases. The dataset used was collected at the ventilation shaft location in the Soko brown coal mine between 2002 and 2021 [21-23]. This dataset is valuable as it consists of industrial real-time measured data and can be used to create models that predict an increased concentration of methane in the coal mine [24].

As shown in Fig. 1, the average annual absolute concentration of methane measured in the Soko brown coal mine over the past two decades is illustrated. The highest value of the mean annual absolute methane concentration was recorded in 2012, amounting to 6,59 m^3min^{-1}. Conversely, the lowest value was measured in 2018, which amounted to 0,56 m^3min^{-1} [21].

When compared to methane quantities from other mines such as China [12] and Poland [24], where values can reach up to 80 m^3min^{-1}, the methane emissions presented in Fig. 1 do not constitute a significant source of methane emissions that can be utilized as an energy source [25].

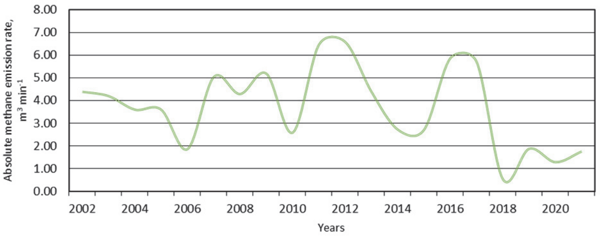

Figure 1 The recorded values of the absolute methane emission rate according to the data from [29]

However, progressively deeper depths of underground coal mining in Serbia and other countries lead to a growing discharge of methane into the air, presenting a significant challenge in the fight against air pollution.

Methane is being emitted directly into the atmosphere at the Soko brown coal mine. However, the absence of proper infrastructure at the mine is impeding efforts to mitigate air pollution and its adverse environmental effects. To convert methane into carbon dioxide, the oxidation reaction described by Eq. (1) can be utilized. Nevertheless, the unavailability of necessary resources at the Soko brown coal mine is preventing the implementation of this process.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

Eq. (2) can be used to calculate the reduced CO_2 equivalent emissions (where A denotes the reduced CO_2 equivalent emission in terms of mass per unit volume of methane, measured in kgm^{-3}).

$$A = (\mathrm{GWP}_{\mathrm{CH}_4} - \mathrm{CEF}_{\mathrm{CH}_4})\,\rho_{\mathrm{CH}_4} \tag{2}$$

where: ρ_{CH_4} is the methane density at standard conditions, 0,716 kgm^{-3}; $\mathrm{GWP}_{\mathrm{CH}_4}$ is the global warming potential of methane and measures how much a given mass of methane contributes to global warming over a specified period compared to the same mass of carbon dioxide (CO_2). The most common time horizons used for this comparison are

20 years and 100 years; CEF_{CH_4} is the amount of CO_2 released per unit mass of methane in the oxidation reaction and represents the factor by which the amount of methane (CH_4) is converted to CO_2 equivalent, usually based on the GWP and the specific time horizon, which equals 2,75 (calculated from the stoichiometric ratio of 44/16) [12].

Eq. (2) describes that the combustion of one cubic meter of methane reduces pollution by 15,90 kg of equivalent emissions.

This implies that burning the methane released in the Soko brown coal mine would result in a reduction of approximately 60 kg of A in comparison to the average absolute amount of methane, which is 3,73 m^3 min^{-1}, over a period of twenty years.

3.2 Disposal of Mining Waste from the Soko Brown Coal Mine

Pollutants generated during the mining process typically comprise waste rock, mine drainage water, suspended dust, gases, and ash [26]. Processing these pollutants constitutes a significant long-term investment for the mine.

At the Soko brown coal mine, waste rock is generated during coal processing and the construction of lateral developments in the rock mass. The amount of waste rock accumulated in the mine ranges from 24666 tons in 2013 to 6437 tons in 2016 annually [27]. This waste rock is disposed of in the main waste rock dump of the Soko brown coal mine, which is a designed waste dump that has been in use for the past ten years and is currently 56,50 % full of its intended capacity, as shown in Fig. 2.

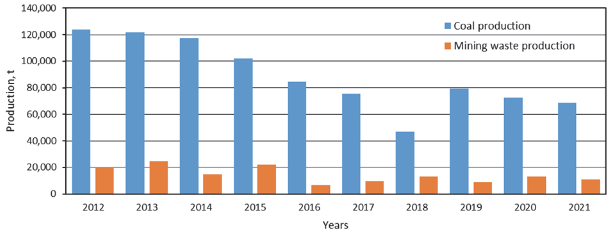

Figure 2 Mining waste and coal production over the last 10 years according to the data from [36]

The degraded surface area measures 55814 m^2, and tests conducted on the composition of the waste rock indicate that it is entirely made up of inert material. As a result, the impact of this pollutant is solely related to the degraded surface area [28]. Although the project includes reclamation of the area, this phase has yet to be implemented.

Monitoring of terrain erosion and the micro-environmental ecosystem of the landfill has not been conducted. However, such monitoring is necessary in the future to prevent further environmental pollution [29].

Not giving enough thought to how mining affects the environment might require us to pay more attention to restorations afterward. To test out a suggested approach, we take a close look at a specific example: methane emissions and waste disposal. Quickly and accurately figuring out the downsides is a big challenge but is key to making smart choices about dealing with pollution [30]. In underground coal mines, the main culprits are waste rock and methane, highlighting how important it is to manage them well to solve environmental issues.

4 DISCUSSION

The rapid advancement of economic globalization has amplified global environmental concerns. In Serbia, the primary reliance on coal in the energy consumption structure, coupled with predominantly using underground coal mining methods, poses potential environmental challenges and hazards if proper protective measures are not implemented.

While Serbia may not be a major global coal producer, its coal mines are crucial for domestic economic growth and energy production. Therefore, the authors advocate for the promotion of sustainable and responsible mining in Serbia through the implementation of innovative technology in mines, efficient resource utilization, modernization of mining methods, standardization of mine management, and ecological remediation of mining areas.

Given the presence of both surface and underground coal mining in Serbia, addressing additional environmental protection challenges may be necessary. Notably, coal mines in Serbia, particularly underground ones, differ from those in China in various aspects. Therefore, sustainable mining approaches must be tailored to these specificities and becoming examples for further studies.

Gas extraction not only ensures coal production safety but also offers economic and environmental benefits. Optimizing coal mining requires continuous research and development of methane degassing from coal deposits to reduce emissions. Promoting intelligent mining and other technologies is essential to decrease CH_4 emissions from coal mines at the source [31].

To mitigate the negative environmental impact, it is crucial to employ appropriate gas treatment technologies. Methods for utilizing methane and other gases emitted from mines, such as gas for electricity production, gasification, and synthetic gas production processes, can decrease greenhouse gas emissions. Increasing mining production efficiency and reducing gas emissions from mines are critical factors in minimizing environmental impact [32].

For the sustainability of coal mines in Serbia, a comprehensive life cycle analysis must identify key processes affecting ecological damage. Strategies for elimination or reduction should be developed, considering innovative technologies, improved mining management, and the eco-friendliness of mining environments.

Academic research supports the use of Life Cycle Assessment (LCA) in coal production [10, 11]. LCA helps pinpoint preparatory stages in the supply chain that significantly contribute to environmental impacts. It evaluates alternative strategies, identifies waste management options to protect soil and water quality [33], and suggests ways to minimize impacts on flora, fauna, and landscapes [34]. The preparatory stage involves gathering data on emissions and environmental impacts through monitoring production parameters and pollutant emissions. In cases of insufficient data, information from other countries, planned data, and relevant literature may supplement it, known as "on-site monitoring" [11]. The evaluation covers all coal mining and preparation operations, energy consumption, direct emissions, and waste management, using a functional unit.

A study conducted in underground mines in China recorded methane emissions ranging from 3,005 to 54,487 $m^3 \cdot t^{-1}$ [4]. Low concentration methane can be captured using oxidation methods and used as auxiliary fuel. Various oxidation methods, including the technology of a reactor for the reversal of thermal flow, the technology of a reactor for the reversal of catalytic flow, and catalytic monolithic reaction, can be employed [25]. Despite some progress made in low concentration gas treatment technology, it remains underutilized and not well-promoted. In most cases worldwide, low concentration methane is directly released into the atmosphere. The occurrence of other harmful gases, such as nitrate gases and gaseous products of oxidation and fires, is minimal and has been measured and documented [35].

Considering various models and studies of the mining ecosystem and utilizing the proposed conceptual model along with the chosen case study, authors assert, based on available data, that mine ventilation and waste disposal are the most critical processes contributing to environmental burdens [10-12].

Drawing on experiences from China and best practices worldwide, Serbia has the potential to develop a more sustainable approach to coal mining, setting an example for other countries in the region. However, this requires substantial dedication and collaboration among the government, mining companies, and the professional community to achieve sustainable outcomes.

The scientific contribution of this research lies in its holistic methodology for understanding and addressing the environmental challenges posed by underground coal mining. The study advances the scientific discourse on sustainable mining practices and environmental protection.

5 CONCLUSION

Mining is a pivotal activity that meets society's ever-growing demands, but it can significantly impact the environment. Therefore, innovative techniques must be employed to ensure safety, improve productivity, and implement effective environmental protection measures to prevent adverse effects on the environment. Technological advancements can contribute to safer and more efficient mining, leading to cost reduction and increased production.

In the context of the Republic of Serbia, underground coal mining will persist in the foreseeable future, making it crucial to investigate its interaction with the environment. Accordingly, research has extensively analysed the technical work processes in active coal mines, collecting data on pollution presence and distribution, emissions and immissions monitoring in air and water, pollution sources, their distribution, and hazardous substances monitoring in specific locations.

After applying a feasible conceptual monitoring model to the direct impact factors in the Soko brown coal mine, it can be inferred that methane release into the atmosphere is the primary cause of pollution. Various options are available to mitigate this pollution, with methane combustion being the most effective solution, resulting in a 60 kg reduction in emission equivalents (A). Furthermore, economically viable alternatives such as surface or mine degassing should also be considered.

The study's main contribution is the development and implementation of a feasible conceptual monitoring model, enabling efficient monitoring of environmental protection during underground coal mining. Proper monitoring, particularly chemical testing, is crucial for accurately measuring air, water, and soil quality. Therefore, implementing monitoring allows for effective assessment of underground coal mining's impact on the environment, reducing the potential detrimental effects on it.

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