ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ
АКАДЕМИЯСЫ» РҚБ

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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

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ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК РЕСПУБЛИКИ
КАЗАХСТАН»

N E W S

OF THE NATIONAL ACADEMY
OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN

SERIES

OF GEOLOGY AND TECHNICAL SCIENCES

2 (470)

MARCH – APRIL 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

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«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).

Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

Мерзімділігі: жылына 6 рет.

http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

NEWS of the National Academy of Sciences of the Republic of Kazakhstan
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 2. Number 470 (2025), 209–224

https://doi.org/10.32014/2025.2518-170X.451

UDC 504.064.36 + 622.83

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POLLUTION OF ABANDONED COAL MINES: ASSESSMENT OF SCALE AND MONITORING USING MODERN TECHNOLOGIES

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Abstract. The article analyses the environmental condition of territories adjacent to abandoned coal mines in Russia based on long-term monitoring data. The study demonstrates that despite the restructuring of the coal industry, the accumulated problems related to water, soil and air pollution remain relevant. The causes and consequences of intensive coal mining, mass mine closure and insufficient land reclamation are described. The paper discusses in detail the environmental monitoring methods used in the production and environmental safety centres of various coal basins in Russia, including traditional methods such as water, soil and air sampling, gas, geodetic and thermal monitoring. Special attention is paid to modern technologies, including the use of quadrocopters for aerial surveys, thermal imaging and remote monitoring of gas emissions.

The results of the research showed significant pollution of water bodies with heavy metals, phenols, hydrogen sulphide and bacteria, as well as deformation of the earth surface in areas of slump zones. The most problematic region is the Kizelovsky coal basin, where extreme levels of pollution have been identified. Despite the presence of positive changes in the 2020s, due to the introduction of modern monitoring technologies and some methods of reclamation, the environmental situation remains difficult and requires further efforts to solve the accumulated problems. Recommendations are offered on how to use the monitoring results to develop environmental safety management strategies, including the application of modern cleaning and reclamation methods, as well as raising environmental awareness among the population.

Keywords: environmental monitoring, coal mines, reclamation, water pollution, heavy metals, quadrocopters, mine workings, Kizelovsky basin, geodynamic monitoring.

Acknowledgements. *This work was performed within the framework of the State Assignment of the Ministry of Science and Higher Education of the Russian Federation, project No. FZWN 2024-0011 Development of an adaptive and variable complex of unmanned aircraft systems for infrastructure tasks based on digital twin technology. The study was carried out on the equipment of the High Technology Center of the Belgorod State Technological University*

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ЖАБЫҚ КӨМІР ШАХТАЛАРЫНЫҢ АУМАҚТАРЫНЫҢ ЛАСТАНУЫ: ЗАМАНАУИ ТЕХНОЛОГИЯЛАРДЫ ПАЙДАЛАНА ОТЫРЫП, МАСШТАБТЫ БАҒАЛАУ ЖӘНЕ МОНИТОРИНГ

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Аннотация. Мақалада көпжылдық мониторинг деректері негізінде Ресейдің жабық көмір шахталарына іргелес аумақтардың экологиялық жағдайы талданады. Зерттеу көмір өнеркәсібін қайта құрылымдауға қарамастан, су ресурстарының, топырақтың және ауаның ластануымен байланысты жинақталған мәселелер өзекті болып қала беретінін көрсетеді. Қарқынды көмір өндірудің, шахталардың жаппай жабылуының және жерді қалпына келтірудің жеткіліксіздігінің себептері мен салдары сипатталған. Жұмыста Ресейдің әртүрлі көмір бассейндерінің өндірістік және экологиялық қауіпсіздік орталықтарында қолданылатын экологиялық мониторинг әдістері, соның ішінде су, топырақ және ауа сынамаларын алу, газ, геодезиялық және жылу мониторингі сияқты дәстүрлі әдістер егжей-тегжейлі қарастырылған. Аэротүсірілім, жылу түсірілімі және газ шығарындыларын қашықтықтан бақылау үшін квадрокоптерлерді пайдалануды қоса алғанда, заманауи технологияларға ерекше назар аударылады.

Зерттеу нәтижелері су объектілерінің ауыр металдармен, фенолдармен, күкіртті сутегімен және бактериялармен айтарлықтай ластануын, сондай-ақ құлау қаупі бар аймақтардағы жер бетінің деформациясын көрсетті. Ең проблемалы аймақ – Кизелов көмір бассейні, онда ластанудың экстремалды деңгейі анықталды. 2020 жылдардағы оң өзгерістерге қарамастан, заманауи мониторинг технологиялары мен кейбір қалпына келтіру әдістерін енгізу арқылы экологиялық жағдай күрделі болып қала береді және жинақталған мәселелерді шешу үшін қосымша күш-жігерді қажет етеді. Экологиялық қауіпсіздікті басқару стратегияларын әзірлеу, соның ішінде тазарту мен рекультивациялаудың заманауи әдістерін қолдану, сондай-ақ халықтың экологиялық хабардарлығын арттыру үшін мониторинг нәтижелерін пайдалану бойынша ұсыныстар берілді.

Түйін сөздер: экологиялық мониторинг, көмір шахталары, рекультивация, судың ластануы, ауыр металдар, квадрокоптерлер, тау-кен қазбалары, киселов бассейні, геодинамикалық мониторинг.

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ЗАГРЯЗНЕНИЕ ТЕРРИТОРИЙ ЗАКРЫТЫХ УГОЛЬНЫХ ШАХТ: ОЦЕНКА МАСШТАБОВ И МОНИТОРИНГ С ИСПОЛЬЗОВАНИЕМ СОВРЕМЕННЫХ ТЕХНОЛОГИЙ

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Аннотация. В статье анализируется экологическое состояние территорий, прилегающих к закрытым угольным шахтам России, на основе данных многолетнего мониторинга. Исследование демонстрирует, что, несмотря на реструктуризацию угольной промышленности, накопленные проблемы, связанные с загрязнением водных ресурсов, почв и воздуха, остаются актуальными. Описаны причины и последствия интенсивной добычи угля, массового закрытия шахт и недостаточной рекультивации земель. В работе подробно рассмотрены методы экологического мониторинга, применяемые в центрах производственной и экологической безопасности различных угольных бассейнов России, включая традиционные методы, такие как отбор проб воды, почвы и воздуха, газовый, геодезический и тепловой мониторинг. Особое внимание уделено современным технологиям, включая использование квадрокоптеров для аэросъемки, тепловизионной съемки и дистанционного мониторинга газовых выбросов.

Результаты исследований показали значительное загрязнение водных объектов тяжелыми металлами, фенолами, сероводородом и бактериями, а также деформации земной поверхности в районах провалоопасных зон. Наиболее проблемным регионом назван Кизеловский угольный бассейн, где выявлены экстремальные уровни загрязнения. Несмотря на наличие позитивных сдвигов в 2020-х годах, благодаря внедрению современных технологий мониторинга и некоторых методов рекультивации, экологическая ситуация остается сложной и требует дальнейших усилий для решения накопленных проблем. Предложены рекомендации по использованию результатов мониторинга для разработки стратегий управления экологической безопасностью, включая применение современных методов очистки и рекультивации, а также повышение экологической осведомленности населения.

Ключевые слова: экологический мониторинг, угольные шахты, рекультивация, загрязнение воды, тяжелые металлы, квадрокоптеры, горные выработки, кизеловский бассейн, геодинамический мониторинг.

Introduction. In the process of restructuring the Russian coal industry, which began in the 1990s, one of the key areas of focus was the creation of an environmental monitoring system. This system is designed to track and assess the consequences arising in the territories of former mine workings and liquidated mines. This step was necessary because the socio-economic development of the 20th and 21st centuries, with its emphasis on rapid economic growth, has led to significant damage to the environment and generated a whole range of environmental problems. The technogenic model of economy based on continuous consumption of natural resources has caused the formation of global environmental challenges, which can be conditionally divided into several interrelated groups.

Firstly, environmental problems arise. Continuously growing anthropogenic load reduces the ability of ecosystems to preserve their structure and functional integrity. This manifests itself in the depletion of biodiversity, pollution of soils, water and the atmosphere, and disruption of natural cycles of substance cycling. In Russia and Kazakhstan, for example, vast areas are subject to degradation due to intensive land use in agriculture and extractive industries, leading to desertification and loss of fertility (Gladkov, et.al., 2024; Volneikina, et.al., 2023; Tynchenko, et.al., 2023). Pollution of rivers and lakes by industrial effluents and emissions from industries has become a serious problem in many regions, including large river basins such as the Volga and Ural in Russia and the Syr Darya and Irtysh in Kazakhstan.

Secondly, economic development is achieved through constant consumption of natural resources and development of new territories, which leads to the depletion of natural reserves and creates the problem of environmental pollution by industrial waste. In Russia, especially in regions with developed extractive industries, there is an accumulation of huge amounts of waste, which negatively affects the soil cover and groundwater (Klyuev, et.al., 2022). In Kazakhstan, which is also a major mineral producer, the situation is similar, with the added problem of waste disposal from radioactive materials. Improper management of mining and processing wastes leads to land contamination with heavy metals and other toxic substances (Suprun et.al., 2024; Chernykh, et.al., 2023; Tynchenko, et.al., 2023).

Thirdly, urbanisation intensifies all negative processes affecting the environment due to the concentration of transport, industrial plants and a large number of people in cities. This leads to increased air pollution, noise pollution and more household waste. Large cities in Russia and Kazakhstan face problems of smog and air pollution from motor transport and industrial emissions, especially during the heating season. The problem is aggravated by insufficient implementation of environmentally friendly technologies and lack of effective waste treatment systems (Skeeba, et.al., 2016; Vidayev, et.al., 2014).

The realisation of the catastrophic consequences of the current situation in the 1990s led to the development of environmental management strategies that provided for a change in priorities: subordination of economic and political interests to environmental ones (Ardashkin, et.al., 2014; Pashkov, et.al., 2014). To ensure sustainable development of mining production in the context of environmental safety and socio-economic prosperity, the need to restructure the coal industry has arisen. The environmental impact of the coal industry remains one of the most significant in the mining sector. Key areas of negative impact include pollution of water bodies by mine, open pit, industrial and domestic wastewater, which also leads to disruption of the hydrological regime of surface water and the hydrodynamic, as well as hydrochemical regime of groundwater. In addition, the air basin is polluted by emissions from mining and transport equipment, industrial and municipal boiler houses, aspiration systems and from burning rock dumps (Kondratev, et.al., 2020; Kondratev, et.al., 2019; Gurov, et.al., 2019). Land withdrawal from land use and its subsequent disturbance and pollution by coal mining and processing wastes are also serious environmental problems. In both countries, Russia and Kazakhstan, these factors are pressing issues that require close attention and implementation of modern methods of environmental monitoring and reclamation of disturbed lands. The need to transition to more sustainable development models and the introduction of green technologies is an obvious challenge for both countries.

Materials and methods. The analysis presented in this article is based on data collected during the long-term work of the industrial and environmental safety monitoring centres established in various coal basins of Russia. These centres, such as the Kuzbass Monitoring Centre, the Eastern Donbass Monitoring Centre, the Urals Monitoring Centre and others, have accumulated information on the state of the environment in the areas of abandoned coal mines. The main data set used in the analysis includes the results of observations and studies in the following areas: hydrogeological, gas, geodynamic, land resources monitoring, thermal survey of waste dumps, microelement analysis of soil, hydrogeomechanical and geochemical monitoring (Kulikova, et al., 2024).

Hydrogeological monitoring included measurements of the flooding level of the mine workings and analyses of mine, ground and surface water quality. Wells located near or directly within abandoned mines were used to determine flooding levels. Water samples were taken from wells, boreholes, rivers and lakes for subsequent laboratory analysis. Indicators such as pH, suspended solids, iron, sulphate, chloride, phenols, and the presence of bacterial contamination were analysed (Kukartsev, et.al., 2023). These data allowed assessing the degree of water pollution and the risk of waterlogging in the areas.

Gas monitoring included control of the surface release of harmful gases such as methane and carbon dioxide (Kulikova, et al., 2023). Measurements were made both in open areas and in residential and industrial buildings located near abandoned mines. Gas analysers were used to determine the concentration of gases in the air. Particular attention was paid to monitoring gas emissions in slump zones.

Geodynamic monitoring was conducted to identify deformations of the earth's surface that may be caused by the collapse of mine workings. Observations were carried out at life support and livelihood facilities, as well as in areas at risk of failures. Geodetic measurements and levelling methods were used to determine vertical and horizontal displacements of the earth's surface. Land resources monitoring included identification of failures and defects in the insulation of previously closed excavations, as well as assessment of disturbed land areas. Visual surveys and remote sensing, such as aerial surveys, were conducted to identify disturbances. Soil sampling was also carried out to analyse for contaminants such as heavy metals and petroleum products.

Thermal surveys of rock dumps were carried out to identify burning centres that are a source of air pollution. Thermal imaging cameras were used to detect anomalous temperatures. Microelement analysis of soil around the dumps was carried out to determine the degree of contamination with heavy metals and other toxic elements that may have migrated from the dumps into the soil. Hydrogeomechanical monitoring was aimed at determining the chemical contamination of soils in the territories of industrial sites of abandoned mines. Soil samples were taken and analysed for the presence of pollutants. Geochemical monitoring included observation of geochemical parameters of natural and anthropogenic landscapes, for which water, soil and air samples were analysed.

The methods of environmental monitoring used in the article include: water, soil and air sampling for laboratory analysis, gas monitoring using gas analysers, geodetic measurements to track earth surface deformations, remote sensing, thermal imaging using thermal imaging cameras. In addition, statistical analyses of collected data are used to identify trends and patterns in environmental changes.

As a modern method of environmental monitoring, this paper proposes monitoring with the help of small autonomous vehicles (SAV) in the format of copter-type unmanned aerial vehicles (UAVs) of serial production, used and modernised for effective solution of special environmental monitoring tasks in the field of life safety and technological processes:

• Aerial survey and mapping: Quadcopters with high-resolution cameras can create orthophotos and 3D terrain models. These data are used to monitor land surface deformations, identify failures and landslides (Klyuev, et al., 2023), and estimate the area of disturbed land (Anisimov, et al., 2024). The use of quadrocopters provides up-to-date data with high accuracy and timeliness.

• Thermal imaging: Quadcopters equipped with thermal imaging cameras can detect burning areas of waste rock dumps and heaps, as well as assess thermal pollution of water bodies. This is especially important for monitoring spontaneous combustion of waste dumps and identifying sources of thermal pollution.

• Gas monitoring: Some quadcopter models can be equipped with gas analysers, allowing remote monitoring of harmful gases such as methane, hydrogen sulphide and carbon dioxide. This is particularly relevant for monitoring areas of abandoned mines, where hazardous gases can escape to the surface.

• Air and water sampling: Specialised quadcopters can be equipped with devices for air and water sampling in hard-to-reach locations. This allows air and water pollution to be monitored without the need for personnel access to these locations, reducing risks and increasing efficiency.

• Multispectral imaging: Quadcopters with multispectral cameras can capture information on vegetation conditions. Multispectral imagery data can be used to assess plant establishment during remediation of disturbed land, determine the extent of vegetation degradation and identify areas susceptible to anthropogenic impacts.

• Video monitoring and inspection: Quadcopters can be used for visual monitoring of infrastructure such as pipelines, dams and canals, as well as for assessing the condition of industrial facilities, detecting violations and illegal activities such as unauthorised dumps.

The authors investigated and improved the technology of AMTS modernisation from the position of meta-subject approach, which includes consideration of typical processes and associated motion parameters, providing effective solution of special tasks of environmental monitoring; the study of modern component and element base used by serial manufacturers of UAVs of copter and aircraft type was carried out; digital and full-scale prototyping of the device was implemented, providing rational choice of technical, technological, interoperability and design elements of AMTS.

Analysed by the degree of practical applicability and technological feasibility, the perfected elements of the meta-technology of modernisation of hardware-software, component and constructional parts of AMTS in the format of customizable UAVs of copter and aircraft type, including typical processes and associated motion parameters, constructive and functional components contribute to both rational operation and resource-efficient maintenance of MATS, used in solving special tasks of monitoring the environment

Results and discussion. The environmental situation in the areas of abandoned coal mines in Russia continues to be extremely tense despite the completion of the main phase of coal industry restructuring in 2015. Decades of intensive coal mining followed by massive mine closures accompanied by insufficient attention to environmental aspects have resulted in significant and long-term negative environmental impacts (Zinovieva, et al., 2023). Studies conducted by various monitoring centres covering regions such as Kuzbass, Eastern Donbass, Kizelovsky coal basin and others have revealed a set of serious environmental problems that continue to worsen over time. These problems are caused not only by the direct impact of mining operations, but also by the consequences of mine flooding and insufficient reclamation of disturbed lands, which creates long-term environmental risks (Fig 1 a,b).

The situation was aggravated by the fact that in the period from 1993 to 2000, under conditions of economic crisis and insufficient funding, dynamically changing environmental parameters were practically not controlled. This led to the fact that in the following years, after 2002-2004, as a result of mass flooding of mine workings and lack of proper control, new environmental problems began to manifest themselves, which became evident and widespread in the 2010s. One of the most acute manifestations of environmental disadvantage is the pollution of water bodies. Analysis of monitoring data, conducted both by traditional methods and using modern technologies such as drones and quadrocopters, has shown that all abandoned mines are classified as 'potentially hazardous' in terms of surface and groundwater pollution. Traditional methods of water sampling from wells, rivers and lakes, as well as analyses of drone samples, confirm that the concentration of suspended solids in water reaches extreme values - up to 61 mg/l. Exceedances of maximum permissible concentrations (MPC) for iron are more than 5 times, which leads to deterioration of water quality. Also, a significant excess of MPC for hydrogen sulphide was recorded, while its MPC is 0.003 mg/l, and in the studied samples the concentrations significantly exceeded this indicator. Practically in all investigated mine wastewaters phenol is present, with maximum concentrations reaching 5 MPC. In addition to chemical pollution, bacterial pollution is observed in the surface waters of rivers, indicating a disturbance of the biological balance. Mine waters spontaneously pouring to the surface through boreholes and workings enter natural watercourses, aggravating the already difficult situation (Kulikova, et al., 2024).

a b

Fig.1. Impacts of mining activities on the ecological state of the environment: a - Rock dumps in the Kizelovsky coal basin; b - Acidic rivers in the Kizelovsky coal basin

In the Kizelovsky coal basin, the environmental situation is characterised as extremely unfavourable, as mine conservation has not been carried out properly and attention to this region was insufficient until the 2010s (Fig. 1 a,b). In addition to traditional methods, drone and quadrocopter data are being actively used in this region, allowing for more accurate assessment of the extent of contamination and disturbance. Drones equipped with high-resolution cameras and thermal imaging sensors survey the terrain to accurately define the boundaries of spoil heaps, estimate the area of disturbed land and identify burn areas. The total area occupied by spoil heaps and waste rock dumps is about 15 hectares, with more than 2 million tonnes of rock. Dumps have either not been rehabilitated or insufficiently rehabilitated, resulting in the leaching of harmful substances by rainwater into local water bodies. Analyses of water samples in the region show that iron and manganese concentrations exceed the MAC by a factor of 10,000, which is extremely high and indicates heavy pollution. In addition, other hazardous metals such as zinc, lead, nickel and cadmium are also significantly above the MAC, posing a serious threat to public health and ecosystems. Studies using modern methods show that concentrations of harmful substances, including iron and aluminium, exceed MAC by two thousand times, turning water into a toxic liquid unsuitable for supporting biological life. This is evidenced by the chemical layering at the mouth of the North Vilva River, where more than 50,000 tonnes of sediment containing iron hydroxide have accumulated. Contaminated mine water seeping from the depths of flooded mines brings to the surface sulphuric acid, which is formed as a result of chemical reactions of sulphur.

Geodynamic monitoring, conducted using both traditional geodetic methods and modern technologies such as laser scanning with drones, reveals deformations of the earth's surface. In the Kizelovsky basin, 796 hectares of fall-prone areas have been recorded, which is a significant figure. In the 2020s, thanks to more active introduction of remote sensing technologies and geoinformation systems, it became possible to monitor the dynamics of these processes more effectively, although the problem of their occurrence is still not solved.

In the 2010s, the environmental situation in the areas of abandoned coal mines remained extremely unfavourable, which was confirmed by numerous studies and publications, both scientific and socially significant. This decade was the period when the accumulated consequences of inadequate conservation and reclamation of mines began to manifest themselves in full measure. The impact of these processes on water, soil and air resources was catastrophic, and monitoring data collected by various centres indicated serious exceedances of maximum permissible concentrations (MPCs) for a number of hazardous substances. During this period, despite the efforts of individual organisations, there was no significant improvement in the overall environmental situation.

In particular, in the Kizelovsky coal basin, which was one of the most problematic regions, the situation was close to an ecological disaster. Analyses of water samples, conducted both by traditional methods and using modern technologies, revealed extremely high concentrations of heavy metals that pose a serious threat to human health and the environment. The concentration of iron in mine water during this period exceeded the MAC by 10,000 times, and at some points where water seeped to the surface, values exceeding the MAC by 12,000 times were recorded. This made the water completely unusable and posed a serious threat to aquatic ecosystems. Manganese, another toxic metal, was also present in mine water at concentrations 8,000 times the MPC, and some samples were above 9,000 times. In addition, significant concentrations of zinc, lead, nickel, and cadmium were found in mine water, exceeding the MAC by hundreds or thousands of times. For example, zinc concentrations in some water samples were as high as 50 MAC, while lead exceeded MAC by 150 times and nickel and cadmium exceeded MAC by 200 times in some places. Such pollution levels indicated that mine water was actively dissolving and leaching heavy metals from rock dumps and mine workings.

In addition to heavy metals, high concentrations of sulphates and sulphides were recorded in mine waters and soils near mine dumps. Chemical reactions in the rocks and dumps produced sulphuric acid, which, when released into water bodies and soil, changed the pH of the environment, leading to the death of living organisms and rendering the areas unusable. Measurements of pH in water samples in the 2010s showed values ranging from 2.5 to 3.5, which corresponds to an acidic environment and is destructive to most species of flora and fauna.

The situation was aggravated by the fact that as a result of the lack of an effective system of reclamation of rock dumps and slag heaps, hazardous substances with precipitation were released into local rivers and water bodies. Studies conducted in the 2010s showed that the content of heavy metals in the bottom sediments of the rivers flowing near the Kizelovsky coal basin exceeds the MAC by tens and hundreds of times. In particular, in the bottom sediments of the Kosva River the concentration of iron exceeded the MPC 800 times, manganese 500 times, zinc 70 times, lead 40 times and cadmium 20 times.

In general, the environmental situation in the areas of closed coal mines in the 2010s was critical, which was confirmed by monitoring data. High concentrations of heavy metals, acid pollution and vast areas of disturbed land created serious risks to public health and the environment. During this period, in spite of localised measures, there was no significant improvement of the situation, which indicated the need for a comprehensive and systematic approach to solving environmental problems. The increase in the level of pollution by toxic substances affected not only the state of water resources, but also soil resources, making them unsuitable for agricultural use. In addition, hazardous gases such as methane and hydrogen sulphide continued to be emitted from the mines, creating additional risks for the population living near the closed coal mines.

In the 2020s, although the environmental problems accumulated in previous decades have not been fully resolved, there have been some positive changes in the areas of abandoned coal mines, including the Kizelovsky coal basin. These changes were made possible by a number of factors, including increased attention to environmental issues, the introduction of new monitoring technologies and some targeted actions to mitigate the effects of pollution. While a dramatic turnaround has not yet been achieved, some progress, particularly in monitoring and localising pollution sources, has certainly been made.

One of the key factors contributing to positive changes has been the wider adoption of modern environmental monitoring technologies. In particular, in the 2020s, drones and quadrocopters equipped with high-resolution cameras, thermal imagers and gas analysers were actively used. This made it possible to conduct more detailed and rapid surveying of territories, identify pollution hotspots and failures, and obtain information on the state of vegetation and water bodies in hard-to-reach areas. The use of drones significantly reduced the time and costs of monitoring surveys, as well as increased the accuracy and completeness of the data collected. As a result, it became possible to react more quickly to changes in the environmental situation and take necessary measures.

Another important aspect has been the introduction of improved methods of data analysis. In the 2020s, geographic information systems (GIS) are being actively used to visualise and analyse monitoring data, identify trends and patterns, and forecast developments. GIS allow the overlaying of different layers of information (e.g. pollution data, terrain, location of settlements), which makes analyses more complete and informative. In addition, mathematical modelling techniques for predicting the spread of pollutants and simulating different scenarios have become more common during this period. This allows for more effective planning of measures to localise and eliminate pollution.

In addition to technological advances, some practical steps were taken in the 2020s to reduce the negative environmental impact of abandoned mines. In particular, some regions have begun to apply artificial geochemical barrier methods to reduce the acidity of mine water. These methods include the use of alkaline wastes, such as soda waste, to neutralise acid mine waters and reduce the concentration of heavy metals. Experimental studies have been conducted that have shown the effectiveness of using these wastes to treat mine water, raising pH to neutral values and reducing pollutants to acceptable concentrations. In some cases, attempts have been made to localise the spread of pollutants with surface runoff and groundwater. For this purpose it was proposed to use barium compounds and crushed carbonate rocks placed in trenches in the runoff zone from dumps. The use of limestone, as a relatively inexpensive reagent, was also considered as a promising option.

Also, in the 2020s, biological remediation methods for greening waste heaps and spoil heaps began to be used more actively. These techniques include the planting of contaminant-resistant plant species that help to consolidate soil, prevent erosion and reduce leaching of contaminants. Studies have been conducted that have shown the effectiveness of using microbiological remediation to restore soil cover on disturbed land.

Modern research, including visual, multispectral and intelligent study of large territories is expedient to be carried out using small AMTS in the format of copter-type UAVs. For these purposes, the technology of rational UAV acquisition is proposed, taking into account the required flight characteristics and operating conditions of the device that optimally realises the monitoring objectives. The acquisition scheme includes the achievement of the device parameters to solve the tasks of geoinformation modelling, spatial scanning and remote sensing. The efficiency of geo-information modelling tasks depends on the UAV's positioning accuracy and flight duration, for which the kitting scheme has been rationalised to include a sealed body for weather protection, an electric motor for quiet operation, fixed wings for stability and placement accuracy, high energy density lithium-ion batteries, a digital video transmitter for high quality images and, optionally, high bandwidth fibre optic connectivity for transmission of large amounts of data to the UAV. The tasks of spatial scanning, requiring high manoeuvrability and uninterrupted operation in hard-to-reach places, determined the rational equipment of the UAV with heavy duty electric motor, folding beams for easy transportation, flexible blades for better manoeuvrability, analogue video transmitter to simplify and lighten the apparatus and radio frequency communication device for operation in the absence of ground infrastructure. The tasks of remote sensing are more rationally solved by using an aircraft-type UAV, which is resistant to atmospheric loads and operates at high altitudes. For this purpose, a hull adapted to the extreme environment, a high-power internal combustion engine for high heading speed and range, rigid blades for flight stability in a thin atmosphere, a digital video transmitter for high-quality images, and a high-speed communication channel for the transmission of large amounts of data were proposed. The UAV's attachments for monitoring tasks include a lidar (laser rangefinder) used to create three-dimensional models of objects and surfaces, optimised in terms of resolution, operating distance and data transmission speed; a thermal imaging camera that searches for thermal anomalies and temperature changes, rationalised in terms of the range of recorded temperatures, sensor resolution and temperature sensitivity; a multispectral camera that collects data in several wavelength ranges and is adapted to the needs of the UAV; and a multispectral camera that collects data in several wavelength ranges.

Despite all these positive developments, it must be emphasised that the environmental problems resulting from the closure of coal mines remain serious and require further efforts to fully address them. Pollution levels, although reduced in some places, remain high and pose risks to public health and ecosystems. Further improvement of environmental monitoring methods, the introduction of effective water and soil treatment technologies, and the development of comprehensive programmes for the remediation of disturbed land are required. In addition, continuous monitoring of the situation and timely response to emerging problems are required, as well as strengthening of state control over the implementation of environmental protection measures. Overall, the 2020s was a period in which the path to a more sustainable and environmentally friendly future was charted, but there is still much work to be done to achieve significant results and full rehabilitation of the areas affected by the coal industry.

Conclusion and recommendation

Analysis of the environmental condition of the territories adjacent to abandoned coal mines has revealed an extremely complex and multifaceted problem that continues to have a negative impact on the environment and public health. Decades of intensive coal mining and subsequent mass mine closure have resulted in significant pollution of water resources, soil and air. The main factor aggravating the situation is insufficient conservation and reclamation of disturbed lands, which leads to long-term negative consequences.

The use of both traditional methods of environmental monitoring and modern small AMTS in the format of UAVs of copter and aeroplane type allowed to obtain a detailed picture of the scale of pollution. Traditional methods, including water, soil and air sampling for laboratory analysis, gas monitoring, geodetic measurements and thermal surveying, provide fundamental data on the state of the environment. At the same time, modern technologies such as remote sensing and the use of quadrocopters allow for more rapid and detailed assessment of the condition of large areas, including hard-to-reach locations. These methods make it possible to identify pollution hotspots, assess the area of disturbed land and monitor deformations of the earth's surface.

Monitoring data show that the most serious problem is the pollution of water bodies, where the concentration of suspended solids, iron, manganese and other heavy metals, as well as phenols and hydrogen sulphide, significantly exceeds the maximum permissible concentrations. In some cases, the exceedance of MPCs for certain elements reached ten thousand times, which makes water unfit for use and threatens aquatic ecosystems. In addition, bacterial contamination is observed, as well as the release of hazardous gases such as methane, creating additional risks.

The introduction of modern monitoring technologies, such as copter- and aircraft-type UAVs with adaptable technical characteristics and attachments, has made it possible to identify pollution hotspots more quickly and assess the scale of disturbance. Geo-information systems and mathematical modelling methods have contributed to more accurate data analysis and forecasting of pollutant distribution. In addition, practical steps have been taken to reduce the negative impact of abandoned mines, including the use of artificial geochemical barrier techniques to reduce the acidity of mine water, the use of alkaline waste to neutralise acidic mine water, and biological reclamation for landscaping.

The developed methodologies can be used to develop environmental safety management strategies in areas with similar problems. This includes the use of monitoring data to identify priority areas for remediation, the application of modern methods to conduct more accurate environmental assessments, and the use of new technologies to clean up contaminated water and soil. In addition, the research results can be used to develop educational programmes and raise environmental awareness among the population, as well as to develop a regulatory framework for environmental protection. The tested technology of customisation of UAVs of copter and aircraft type, rationalised for varying in a wide range of parameters of technical and flight assignments when solving industry monitoring tasks allows to reduce the resource intensity of material support of monitoring, increase the frequency of its production, reliability of the received data flow, relevance of the formed information flow and automation of documentation of the results of monitoring work, providing a basis for the creation of automated monitoring systems with the following features.

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www:nauka-nanrk.kz
http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Директор отдела издания научных журналов НАН РК *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Ж.Ш.Әден*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 15.04.2025.
Формат 70x90 1/16. Бумага офсетная. Печать – ризограф.
14,5 п.л. Заказ 2.

РОО «Национальная академия наук РК»
050010, Алматы, ул. Шевченко, 28, т. 272-13-19