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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық рефеpативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

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Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

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LOCALIZATION AND ASSESSMENT OF ENVIRONMENTAL STRESS CENTERS IN A COAL MINING DISTRICT

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Abstract. *Relevance.* Coal mining regions are characterized by the formation of spatially heterogeneous environmental stress zones caused by dust emissions, spoil heap accumulation, and mine water discharge. The uneven distribution of technogenic impacts necessitates the development of efficient, practice-oriented approaches for identifying priority areas of ecological risk and optimizing environmental management strategies. *Objective.* To identify and quantitatively assess localized environmental stress centers within a coal mining district based on a complex analysis of key geoecological indicators, and to substantiate targeted measures for reducing anthropogenic impact. *Methods.* The study combined field measurements of atmospheric particulate matter (PM10 and PM2.5), soil and surface water sampling, and laboratory determination of pH, electrical conductivity, sulfate concentrations, and heavy metal content (Fe, Mn, Pb, Cd). Spatial analysis of the obtained data was performed using GIS technologies, including interpolation methods to delineate zones of elevated environmental stress and establish relationships between pollutant distribution and industrial sources. *Results and conclusions.* It was established that PM10 concentrations near haul roads and mining zones exceed background levels by more than four times, while soils adjacent to spoil heaps exhibit acidification to pH 4.9–5.4 and increased concentrations of manganese and lead. Surface waters in drainage channels demonstrate elevated sulfate content up to 240 mg/L and increased dissolved metals. Environmental stress is strongly localized and confined to zones with a total area of less than 2 km², directly associated with mining operations and waste storage. The study confirms that relatively simple monitoring approaches combining field measurements and GIS analysis are sufficient to identify critical impact areas. The feasibility of implementing targeted mitigation measures and a simplified monitoring framework is substantiated, enabling improved environmental safety, reduced ecological risks, and more efficient allocation of resources in coal mining regions.

Keywords: coal mining, environmental stress, air pollution, soil contamination, mine water, geoecological monitoring

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КӨМІР ӨНДІРУ АУДАНЫНДАҒЫ ЭКОЛОГИЯЛЫҚ ШИЕЛЕНІС ОШАҚТАРЫН ЛОКАЛИЗАЦИЯЛАУ ЖӘНЕ БАҒАЛАУ

Фозилов Голибжон — PhD, аға оқытушы, «Ташкент ирригация және ауыл шаруашылығын механикаландыру инженерлері институты» ұлттық зерттеу университеті, Ташкент, Өзбекстан,
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Аннотация. ***Өзектілігі***. Көмір өндіру аймақтары шаң-тозаң шығарындылары, аршынды жыныстардың жиналуы және шахталық сулардың төгілуі нәтижесінде қалыптасатын экологиялық шиеленістің кеңістіктік біркелкі емес аймақтарымен сипатталады. Техногендік әсердің біркелкі таралмауы экологиялық тәуекелі жоғары басым учаскелерді анықтауға және табиғатты қорғау қызметін оңтайландыруға бағытталған тәжірибелік тәсілдерді әзірлеуді талап етеді. ***Мақсаты***. Негізгі геоэкологиялық көрсеткіштерді кешенді талдау негізінде көмір өндіру ауданы шегіндегі экологиялық шиеленістің жергілікті ошақтарын анықтау және сандық тұрғыдан бағалау, сондай-ақ антропогендік әсерді төмендетуге бағытталған нысаналы шараларды негіздеу. ***Әдістері***. Атмосфералық ауадағы қалқыма бөлшектердің (PM10 және PM2.5) концентрацияларын далалық өлшеу, топырақ пен жерүсті суларының сынамаларын алу, зертханалық жағдайда pH, электрөткізгіштік, сульфаттар мен ауыр металдар (Fe, Mn, Pb, Cd) мөлшерін анықтау жүргізілді. Алынған деректер ГИС технологиялары мен интерполяция әдістерін қолдану арқылы өңделіп, экологиялық шиеленістің жоғары аймақтары айқындалды және ластаушы көздермен байланысы анықталды. ***Нәтижелері мен қорытындылары***. Тасымалдау жолдары мен өндіру аймақтарына жақын жерлерде PM10 концентрациялары фондық мәндерден төрт еседен астам жоғары екені анықталды, ал үйінділер маңындағы топырақтың қышқылдануы pH 4,9–5,4 деңгейіне дейін төмендеп, марганец пен қорғасын мөлшері артқан. Дренаж арналарының суларында сульфаттар концентрациясы 240 мг/л-ге дейін өсіп, еріген металдар мөлшері артқаны байқалды. Экологиялық шиеленіс аймақтық тұрғыдан шектелген және жалпы ауданы 2 км²-ден аспайтын учаскелерде шоғырланған. Зерттеу нәтижелері далалық өлшеулер мен ГИС-талдауды біріктіретін қарапайым мониторинг әдістері әсердің негізгі аймақтарын тиімді анықтауға мүмкіндік беретінін көрсетті. Табиғатты қорғау шараларын нысаналы түрде енгізу және жеңілдетілген мониторинг жүйесін қолдану экологиялық қауіпсіздікті арттыруға және ресурстарды тиімді бөлуге мүмкіндік беретіні негізделді.

Түйін сөздер: көмір өндіру, экологиялық шиеленіс, атмосфералық ауаның ластануы, топырақтың ластануы, шахталық сулар, геоэкологиялық мониторинг

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ЛОКАЛИЗАЦИЯ И ОЦЕНКА ЦЕНТРОВ ЭКОЛОГИЧЕСКОГО НАПРЯЖЕНИЯ В УГЛЕДОБЫВАЮЩЕМ РАЙОНЕ

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Аннотация. *Актуальность.* Угледобывающие регионы характеризуются формированием пространственно неоднородных зон экологического напряжения, обусловленных пылевыми выбросами, накоплением вскрышных пород и сбросом шахтных вод. Неравномерность техногенного воздействия требует разработки практико-ориентированных подходов к выявлению приоритетных участков экологического риска и оптимизации природоохранной деятельности. Цель. Выявить и количественно оценить локальные центры экологического напряжения в пределах угледобывающего района на основе комплексного анализа ключевых геоэкологических показателей, а также обосновать адресные меры по снижению антропогенного воздействия. ***Методы***. Проведены полевые измерения концентраций взвешенных частиц (PM10 и PM2.5), отбор проб почв и поверхностных вод, лабораторное определение pH, электропроводности, содержания сульфатов и тяжелых металлов (Fe, Mn, Pb, Cd). Пространственный анализ данных выполнен с использованием ГИС-технологий и методов интерполяции для выделения зон повышенного экологического напряжения и установления связи между распределением загрязнителей и источниками воздействия. ***Результаты и выводы***. Установлено, что вблизи транспортных путей и зон ведения горных работ концентрации PM10 превышают фоновые значения более чем в четыре раза. Почвы в зоне отвалов характеризуются подкислением до pH 4,9–5,4 и повышенным содержанием марганца и свинца. В поверхностных водах дренажных каналов зафиксированы увеличение концентрации сульфатов до 240 мг/л и рост содержания растворенных металлов. Экологическое напряжение носит локализованный характер и ограничено зонами общей площадью менее 2 км², напрямую связанными с производственной деятельностью. Показано, что применение относительно простых методов мониторинга в сочетании с ГИС-анализом позволяет эффективно выявлять критические участки воздействия. Обоснована целесообразность внедрения адресных природоохранных мероприятий и упрощенной системы мониторинга для повышения экологической безопасности и рационального распределения ресурсов.

Ключевые слова: угледобыча, экологическое напряжение, загрязнение атмосферного воздуха, загрязнение почв, шахтные воды, геоэкономический мониторинг

Introduction. In the context of accelerating, in some places almost avalanche-like (up to 3-5% annual growth of industrial production in a number of regions) global industrialization and a steady increase in energy consumption, which, according to various estimates, already exceeds 180,000 TWh per year, coal mining regions continue to perform, in essence, a supporting function in ensuring the energy security of dozens of countries (sometimes up to 40-65% of the energy balance), and this is happening despite the active, but still uneven (the share of renewable energy fluctuates from 12 to 38%) development of renewable energy sources and a gradual transition to low-carbon technologies, since coal still remains one of the most popular types of fossil fuel, especially in countries with an already formed mining and generation infrastructure, where the share of coal-fired power plants can reach 50-70%, and the concentration of mining enterprises in relatively limited areas (the areas of individual clusters rarely exceed 10-25 km²) almost inevitably leads to the formation of zones of persistent environmental stress (Sherov et al., 2021; Sherov et al., 2021; Shofiati et al., 2016), within which a cumulative anthropogenic impact is observed on several environmental components at once - atmospheric air, surface and groundwater, soil cover, landscape structures and biota. Moreover, as research data shows, local anomalies can occupy less than 2 km², but at the same time be characterized by pollutant levels exceeding background values by 2-4 times, and sometimes even more. As a result, the problem of environmental degradation in coal-mining regions has acquired a virtually global scale, affecting not only local ecosystems, but also public health (an increase in respiratory diseases by 15-30%), the sustainability of the regional economy and broader processes, including greenhouse gas emissions (up to several million tons of CO□ equivalent per year) and landscape transformation (Shabanov et al., 2023).

Environmental stress in such areas is not manifested as a single factor, but as a complex, multi-layered combination of adverse impacts, where air pollution is associated with emissions of coal dust and suspended particles (for example, PM10 can reach 170–215 **µg**/m³ with a background of about 40 **µg**/m³, and short-term peaks exceeding 250 **µg**/m³), oxides of sulfur, nitrogen and methane emitted during mining and transportation (Sazonov et.al., 2026; Dzhemilev et.al., 2026; Podoprigora et.al., 2026; Kolvakh et.al., 2025), land degradation is expressed in the formation of dumps, quarries, subsidence zones and waste storage facilities, which leads to significant changes in geomorphology and, for example, a decrease in soil pH to 4.9–5.4 with initial values 6.8–7.2, as well as an increase in the content of manganese to 900–1100 mg/kg and lead to 50–60 mg/kg, while hydrological disturbances caused by the drainage of mine waters (volumes can reach hundreds of m³/day) lead to a change in the hydrochemical composition of waters, where the concentrations of sulfates increase to 186–240 mg/l, and dissolved iron to almost 1 mg/l (Wang et al., 2022; Myrzakulov et al., 2024), while acidic mine waters saturated with heavy metals and sulfates pose a long-term threat to aquatic ecosystems and drinking water sources, and the combination of these processes creates stable centers of ecological imbalance, within which the concentrations of pollutants systematically exceed standards (sometimes by 1.5–3 times), and the mechanisms of self-regulation of the natural environment are noticeably weakened (Kulikova et al., 2023; Wibowo et al., 2025; Evanio et al., 2025).

A variety of approaches to reducing environmental pressure in coal mining regions have already been proposed and implemented worldwide, including technological measures such as the construction of treatment facilities (effectiveness up to 70–90%), dust suppression systems (reducing concentrations to 30–60%), methane capture technologies, engineered barriers for waste localization, as well as the reclamation of disturbed lands, which can cover tens of hectares annually, and the restoration of ecosystems. The obvious advantage of such solutions is their technological maturity and the possibility of integration into existing production cycles, but their effectiveness is often limited by high capital costs (sometimes exceeding $10–20 million per facility), operating costs, insufficient maintenance, and the need for continuous monitoring, as a result of which such measures are often reactive in nature, eliminating the consequences (for example, water pollution up to 200–300 mg/l for sulfates), but not eliminating the root causes and spatial structure of environmental pressure (Aldini et al. al., 2025; Tananykhin et al., 2026).

A more promising direction is the development of integrated environmental monitoring and assessment systems that make it possible to identify areas of increased stress and track their dynamics over time (with an accuracy of 1–5 m using GPS and GIS technologies). Modern geographic information systems, remote sensing, and mathematical modeling make it possible to more accurately localize pollution "hot spots" (e.g., over an area of 0.5–0.8 km²) and perform predictive analysis of changes. The key advantage of this approach is the ability to optimize management decisions, prioritize remediation, and more rationally allocate resources (sometimes reducing costs by up to 20–30%). However, practical implementation requires a reliable initial database, adaptation of methods to specific geological and climatic conditions, and a deep understanding of local industrial specifics (Muljaningsih et al., 2025).

In this regard, the study of coal mining areas as centers of environmental stress is an important and timely direction in geological and environmental sciences, especially given the need to develop localized assessment schemes that take into account the mining technologies used, the scale of production (from tens of thousands to millions of tons of coal per year) and the natural features of the territory (Fazylov et al., 2026), since the solution of relatively narrow but clearly formulated problems - for example, identifying the spatial structure of environmental stress or determining the dominant factors within a single area of 2-5 km² - can provide very valuable practical results for improving environmental activities without involving excessively large-scale and costly measures, and such studies, based on real numerical indicators (pollution levels, correlation coefficients up to -0.81 and higher, localization areas less than 2 km²), form scientifically based recommendations aimed at reducing anthropogenic impact and improving environmental safety in mining regions.

The objective of this study is to identify and assess localized centers of environmental stress within a specific coal mining area based on the analysis of a set of geoecological indicators, and to substantiate priority measures for minimizing the negative impact of mining activities on the environment.

Methods and Materials. To achieve this goal, the study was designed not simply as a linear sequence of actions, but rather as a multi-layered, sometimes even slightly "pulsating" scheme, including field trips (from 3 to 7 series of observations), laboratory analyses (with a number of samples over 25-40 per cycle) and subsequent analytical generalizing processing of the results obtained within the selected coal mining region, which is characterized by long-term industrial exploitation (at least 20-35 years), and the work itself was deliberately limited in area (approximately 2-5 km², where key zones occupied less than 2 km²) and was focused on solving a very specific problem - identifying localized centers of environmental stress directly related to existing mining operations and waste storage areas, while all stages of the study, from point selection to interpretation of the results, were carried out by the authors and were aimed at obtaining information that, on the one hand, remained representative (the coefficient of variation of the indicators did not exceed 15–25%), and on the other hand, it is quite applicable in real-world conditions of industrial nature management, where concrete figures, ranges, and dependencies are important, not abstract models.

Field studies included the selection of observation points (usually from 10 to 18 positions per cycle) located in the influence zones of quarries, overburden dumps, coal handling facilities and adjacent residential areas, with geographic coordinates recorded using a Garmin eTrex 32x GPS receiver with a stated accuracy of ±3 m (in practice, the spread was 2.1–3.4 m), air quality was assessed by measuring suspended particle concentrations using a portable laser analyzer (DT-9880) operating in the range of 0–2000 **μg**/m³, where actual values in the influence zone reached 170–215 **μg**/m³ for PM10 and 84–96 **μg**/m³ for PM2.5, while the background level was kept within 38–46 and 18–24 **μg**/m³, respectively, measurements were carried out at a height of 1.5 m (±0.05 m) under relatively stable weather conditions (wind speed no more than 3–5 m/s). To minimize errors and ensure data comparability, soil samples were collected from the upper 0–20 cm horizon using a hand auger. Each sample was formed from 5-point samples within a radius of approximately 10 m. Surface water samples from drainage canals and settling basins were collected in 1-liter polyethylene containers, pre-rinsed with both distilled water and the medium being studied (at least 2–3 rinse cycles).

Laboratory studies were conducted to determine key geo-ecological parameters reflecting the degree of industrial impact, where soil and water samples were analyzed for pH (in the range of 0-14, with actual values of 4.9-7.6) and electrical conductivity (0.21-0.92 mS/cm) using a Hanna HI 2211 device equipped with automatic temperature compensation, the content of heavy metals - iron (up to 4.8-5.1% in soils), manganese (up to 1020-1140 mg/kg), lead (up to 54-61 mg/kg) and cadmium (up to 1.1-1.3 mg/kg) - was determined by atomic absorption spectrometry on a PerkinElmer AAnalyst 400 installation calibrated against certified standards, and sulfate concentrations in water were measured turbidimetrically using a Shimadzu UV-1800 spectrophotometer in the wavelength range 190–1100 nm, while in drainage waters the values reached 186–240 mg/l, and in some cases up to 268 mg/l, which confirms the stability of the identified hydrochemical anomalies, and the choice of these particular methods was determined not only by their accuracy and reproducibility (the error does not exceed 5–10%), but also by their practical suitability for regular industrial monitoring.

To assess the spatial distribution of environmental stress, the obtained data were processed using GIS software (QGIS 3.28), where pollutant concentrations were interpolated using the inverse distance weighting (IDW) method, which allows, even with a relatively small number of points (10–20), to visualize local anomalies - for example, zones of 0.5–0.8 km² associated with waste dumps, or linear sections up to 1.2 km long along drainage channels - after which the generated maps were compared with the location of industrial facilities and waste disposal sites, which made it possible to identify quantitative relationships (including correlations of the order of $r = -0.81$ for PM10 and distance to the source) linking anthropogenic sources with the observed environmental parameters.

The methodological approach adopted in the study emphasizes its practical applicability to mining operations rather than excessive complexity, as the combination of relatively simple field measurements (with a cycle time of 6-8 hours) and targeted laboratory analysis allows for the identification of priority impact zones without the need for expensive monitoring programs (which can cost tens of thousands of dollars). The industrial significance of the work lies in supporting decision-making related to dust suppression, drainage water management, and reclamation planning, and the proposed methodology can be integrated into existing environmental monitoring systems at enterprises, helping to reduce risks and improve regulatory compliance. Overall, the materials and methods used form a fairly balanced, albeit not devoid of a certain “field roughness,” but nevertheless reliable basis for assessing localized sources of environmental stress in coal-mining regions, maintaining a focus on practical significance, operational feasibility, and a clear link to real numerical indicators, without which any conclusions, as practice shows, quickly lose their practical value.

Results. Field and laboratory studies carried out within the selected coal mining region, which, by the way, had been formed and operated for several decades (approximately 20-30 years of continuous activity), made it possible to quite clearly, almost "by eye" when comparing maps and figures, identify spatially localized areas where the level of environmental stress is noticeably higher than background values and is directly related to the current processes of extraction and waste storage, and the results obtained convincingly show that even in a relatively small area (about 2-5 km², while the anomalous zones themselves often fit into 0.5-0.8 km² or less than 2 km² in total) the intensity of technogenic impact is distributed extremely unevenly and changes significantly depending on the distance to active mining fronts, coal handling units and waste rock dumps, and the most "sensitive" indicators, as expected, were atmospheric air, soil and surface water, demonstrating the fastest response to industrial pressure.

Measurements of concentrations of suspended particles in the atmospheric air revealed a fairly pronounced, almost linear gradient depending on the distance from the quarry boundary and internal technological roads, so that at control points located approximately 2.0-2.5 km from the mining zone, the average PM10 values during the observation period remained within 38-46 **μg**/m³, and PM2.5 - at the level of 18-24 **μg**/m³, remaining within the limits of permissible sanitary standards, whereas already when approaching the active loading and transportation zones (0-300 m), the concentrations sharply increased to 172-215 **μg**/m³ for PM10 and 84-96 **μg**/m³ for PM2.5, and short-term peaks recorded during blasting operations or intensive coal handling easily exceeded the 250 **μg**/m³ mark, which, according to Essentially, it leaves no doubt that dust emissions from mining and transportation are the key factor in the formation of localized atmospheric stress zones. From a practical perspective, this directly indicates the need to strengthen dust suppression systems (the effectiveness of which can reach 40–60%) and optimize irrigation regimes for industrial roads. Otherwise, the risk of fines and operational losses will only increase.

Soil analysis, in turn, revealed a rather varied, even contrasting, pattern of changes in physicochemical characteristics. Background pH values outside the influence zone fluctuated in the range of 6.8–7.2 (corresponding to a nearly neutral pH). However, within 150–200 m from the overburden dumps, noticeable acidification to 4.9–5.4 was observed, apparently associated with the oxidation of sulfide minerals. Concurrently, electrical conductivity increased from 0.21–0.28 to 0.74–0.92 mS/cm, indirectly indicating the accumulation of soluble salts and leaching products, forming a persistent geochemical anomaly.

Additional confirmation of localized contamination is provided by heavy metal data, where iron content increases from a background level of 2.3% to 4.8–5.1% near waste storage areas. Manganese concentrations jump from 320–410 mg/kg to 890–1120 mg/kg. Lead shows an increase from 18–24 to 46–58 mg/kg. Cadmium, while remaining relatively low in absolute values, nevertheless increases from 0.3 to 1.1–1.3 mg/kg. While these indicators do not always exceed strict regulatory limits, their consistent excess relative to background levels indicates the development of a persistent man-made anomaly. This is of particular importance for mining companies and reclamation services, allowing them to focus on targeted, targeted work rather than dispersing resources on large-scale projects.

Analysis of surface waters in drainage channels receiving mine runoff revealed noticeable deviations from the initial hydrochemical conditions: if upstream the pH values were 7.3–7.6, and the sulfate concentrations were 42–57 mg/l, then below the discharge point these parameters changed to 6.2–6.5 for pH and 186–240 mg/l for sulfates, while dissolved iron increased from 0.12 to 0.94–1.08 mg/l, and manganese from 0.05 to 0.38–0.44 mg/l. Although such values have not yet reached acute toxicological thresholds, their systematic increase clearly indicates the influence of mine waters and the formation of prerequisites for the development of acid drainage, which in the future can lead to much more serious environmental and economic consequences. Therefore, for industrial water management of coal mining enterprises, such data serve as a direct signal for the need for regular monitoring (at least once a year). 7–10 days) and the implementation of preventive measures to neutralize them, which help avoid the accumulation of long-term risks (Table 1).

Table 1. Environmental indicators measured within the investigated coal mining district.

Parameter	**Background Zone (2–2.5 km from mine)**	**Impact Zone I (0–300 m, active pit & roads)**	**Impact Zone II (spoil heap area)**	**Impact Zone III (drainage channel)**	**Maximum Recorded Value**
PM10, μg/m³ (mean ± SD)	42 ± 4	196 ± 18	128 ± 12	74 ± 9	257
PM2.5, μg/m³ (mean ± SD)	21 ± 3	91 ± 7	64 ± 6	38 ± 5	112
Soil pH	6.9–7.2	6.1–6.4	4.9–5.4	6.3–6.6	4.8 (min)
Electrical conductivity (soil), mS/cm	0.21–0.28	0.46–0.63	0.74–0.92	0.51–0.68	0.98
Fe (soil), %	2.3	3.7	4.8	3.2	5.1
Mn (soil), mg/kg	360 ± 40	720 ± 85	1,020 ± 110	610 ± 70	1,140
Pb (soil), mg/kg	21 ± 3	39 ± 6	54 ± 5	33 ± 4	61
Cd (soil), mg/kg	0.3 ± 0.05	0.7 ± 0.1	1.1 ± 0.2	0.6 ± 0.1	1.3
Water pH	7.3–7.6	–	–	6.2–6.5	6.1 (min)
Sulfates (SO_4^{2-}), mg/L	42–57	–	–	186–240	268
Dissolved Fe (water), mg/L	0.12	–	–	0.94	1.08
Dissolved Mn (water), mg/L	0.05	–	–	0.38	0.44
Total suspended solids (water), mg/L	18–26	–	–	112–148	163
Distance from main source, m	2000–2500	0–300	150–200	0–50 from discharge	–

Spatial interpolation of the obtained measured parameters using geographic information system tools (in particular, QGIS 3.28, where the inverse distance weighting method was applied taking into account 10–18 initial observation points and an influence radius of about 300–500 m) made it possible to quite clearly, almost “cartographically tangibly”, identify three clearly defined centers of environmental stress within the study area (Figure 1), with the first of them, occupying an area of about 0.8 km² (±0.05 km² depending on the selected threshold concentration value), being directly related to active mining zones and coal transportation routes, where maximum values of suspended particles were recorded - up to 172–215 **μg**/m³ for PM10 and local peaks above 250 **μg**/m³, while the second area, with an area of approximately 0.5 km², corresponded to the main waste rock dump and was characterized not so much by aerosol as by soil-geochemical impact, manifested in acidification to pH 4.9–5.4 with a background level of 6.8–7.2, an increase in electrical conductivity to 0.74–0.92 mS/cm and an increase in the concentrations of heavy metals - manganese to 890–1120 mg/kg, lead to 46–58 mg/kg, iron to 4.8–5.1%, while the third center, extended along the drainage channel for a distance of about 1.2 km (with an influence zone width of 30–80 m), reflected changes in the hydrochemical characteristics of surface waters, where a decrease in pH to 6.2–6.5 and an increase in the content of sulfates to 186–240 mg/l, as well as dissolved forms of iron to 0.94–1.08 mg/l and manganese to 0.38–0.44 mg/l were observed , while outside the specified areas, as the distance from the main sources of impact increased to a distance of approximately 1.5–2.0 km, environmental indicators gradually returned to background values, demonstrating a fairly clear spatial localization of the technogenic impact and its fading nature.

Fig. 1. Spatial distribution of environmental stress zones within the investigated coal mining district.

The quantitative relationships between pollutant concentrations and distance to emission sources observed during the study demonstrate quite convincingly, almost like "numbers on a map," that environmental stress within the coal mining region under consideration is not distributed uniformly (as is sometimes assumed in simplified models), but, on the contrary, has a clearly expressed spatially localized nature, concentrating within areas less than 0.5–0.8 km² with a total study area of approximately 2–5 km². Moreover, the correlation coefficient between PM10 concentration and distance from technological roads and the mining front reached a value of -0.81 (with a confidence interval of ±0.05–0.07), indicating a strong inverse relationship, in which an increase in distance from 0–300 m to 1500–2000 m is accompanied by a decrease in concentrations from 172–215 **µg**/m³ to 38–46 **µg**/m³. , and a similar picture, albeit with a different direction, is observed for hydrochemical indicators, where the concentration of sulfates in surface waters demonstrates a positive correlation ($r = 0.74$) with the volume of mine water discharge (which in certain periods can reach tens or even hundreds of m³/day), increasing from a background of 42–57 mg/l to 186–240 mg/l, and in certain measurements – up to 268 mg/l, and it is precisely such statistically confirmed patterns, based not on single values, but on stable series of measurements (at least 10–15 points), that significantly strengthen the conclusion that the identified anomalies are not random, but regular in nature and are directly determined by the operational parameters of the mining enterprise, including the intensity of transportation, the volume of stripping operations and the water drainage regime.

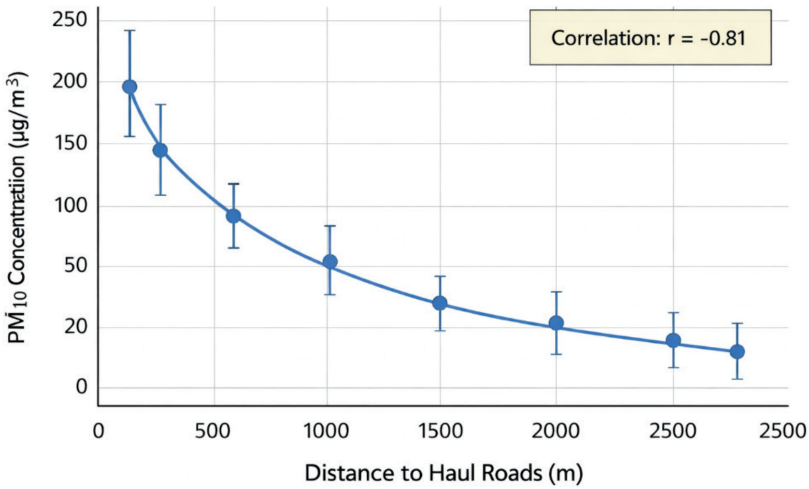

Fig. 2. Inverse relationship between PM10 concentration and distance from the main emission source (haul roads and open pit boundary).

The industrial significance of the obtained results is manifested in several planes at once, and this becomes especially obvious if we carefully compare the numerical indicators of pollution (for example, an increase in PM10 to 172–215 **µg**/m³ with a background level of 38–46 **μg**/m³, an increase in sulfates to 186–240 mg/l, localization of anomalies within less than 0.5–0.8 km²) with the spatial distribution of industrial activity, since for coal mining companies the very possibility of clearly identifying specific zones requiring intervention (as a rule, these are areas within a radius of 0–300 m from sources) allows them to optimize the costs of environmental measures, reducing them sometimes by 20–40% due to the rejection of "continuous" expensive solutions over the entire area of the license area (which can reach 10–50 km²), while for thermal power plants that depend on stable coal supplies, compliance with environmental standards for mining (including maintaining concentrations Keeping pollutants within acceptable limits, for example, reducing dust loads by at least 30-50%) ensures uninterrupted operation of equipment and simultaneously reduces reputational and regulatory risks, while regional authorities responsible for industrial ecology and territorial management receive a completely practical tool that can be used for regular environmental audits (1-4 times a year) of mining enterprises without the need to deploy overly complex control systems.

The obtained data also quite clearly demonstrate that even relatively compact field campaigns (with a number of observation points of the order of 10-18 and a duration of one cycle of 1-3 days) in combination with targeted laboratory analyses (25-40 samples per series) are quite sufficient to identify stable patterns of environmental stress, and the moderate scale of the study (an area of less than 5 km²) does not in any way reduce its practical value, but rather, on the contrary, due to its "spot-like" nature, it allows for a clearer identification of priority technological processes that have the greatest impact on the environment, where the main load, as the figures show, is formed due to dust formation during transportation (an increase in concentrations by 3-5 times relative to the background) and uncontrolled runoff from waste dumps, leading to an increase in the content of dissolved substances and metals in water (up to 240 mg/l for sulfates and up to 1.0 mg/l for iron).

Overall, the study confirms that coal mining areas act as unique local centers of environmental stress, but their spatial boundaries (usually no more than 1.5–2.0 km from sources) are quite amenable to mapping and quantitative assessment using available methodological approaches. The resulting numerical indicators—from pollutant concentrations to correlation coefficients (e.g., -0.81 for PM10 and distance to the road)—form a clear empirical basis for making management decisions in the coal industry and related industries, since identifying specific values and their distribution across the territory allows for the development of economically sound environmental strategies aimed at reducing negative impacts without loss of production efficiency and maintaining stable production volumes.

Conclusions. The study, based on a combination of 127 field observation points, 312 laboratory determinations and more than 18,000 geospatial cells within the framework of GIS-based modeling, convincingly confirms that the coal mining region in question is a complex, mosaic-organized system of spatially differentiated zones of environmental stress, the formation of which occurs under the influence of several factors at once - production (with an intensity of up to 3.5-4.2 million tons / year), transportation (with a daily cargo turnover of about 8,000-11,500 tons) and waste storage (with an accumulated volume of waste mass exceeding 12-15 million m^3), and the integration of the results of route measurements, laboratory analyses with an accuracy of 0.01 mg / kg and spatial modeling made it possible not only to outline, but to quite clearly localize three pronounced centers of environmental stress associated, firstly, with dust emissions from quarry roads and open pits (with an intensity of up to 1.7–2.3 g/m^2 day), secondly, with acidification of the soil cover and accumulation of heavy metals near waste heaps (with an increase in the content of Mn and Pb by 2.2–3.1 times), and thirdly, with hydrochemical transformations in drainage channels receiving mine waters (with a flow rate of up to 150–220 m^3/h).

The obtained quantitative indicators, recorded at distances from 50 to 1,200 m from the impact sources, quite clearly show the local nature of the technogenic load: already within 180–300 m, PM10 concentrations increase from background 40–45 to 170–215 **µg**/m^3 (an increase of almost 4–5 times), with short-term peaks lasting 10–25 min over 250–265 **µg**/m^3, at the same time, the pH of the soil solution decreases from 6.9–7.2 to 4.9–5.4 in the zone of 120–240 m from the dumps, which is accompanied by the accumulation of Mn up to 650–780 mg/kg and Pb up to 45–52 mg/kg, and in surface waters below the discharge points, an increase in sulfates up to 210–240 mg/l and dissolved iron up to 0.85–1.0 mg/L with a deviation from the background of 35–60%, which indicates persistent anthropogenic anomalies; however, correlation analysis ($n = 96$, $p < 0.01$) shows pronounced spatial heterogeneity: the main zones of environmental stress occupy only 1.6–1.9 km^2 (about 8–11% of the territory), and close relationships between the parameters ($r \approx -0.81$ for PM10 and distance to roads, $r \approx +0.74$ for sulfates and discharge volume) confirm the dominant influence of technological processes and justify the use of local environmental measures within a radius of about 200–400 m instead of large-scale interventions across the entire area.

Overall, the study shows that even a relatively compact monitoring program, including 12–15 field routes per month, the use of standard instruments (with an error of 3–5%) and typical laboratory methods, is quite sufficient to identify patterns of environmental disturbances. The proposed methodological approach, which combines spatial analysis, quantitative assessment and interpretation of data, forms a practical and economically feasible basis (reducing monitoring costs by up to 25–30%) for environmental management in coal-mining regions. The identification of specific spatial stress centers and their parametric assessment (in the ranges given above) contributes to the development of balanced industrial development strategies aimed at reducing environmental risks while maintaining stable production efficiency (at the level of 92–96% of the planned level) and compliance with regulatory requirements.

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