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

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

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).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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GEOPHYSICAL INVESTIGATION OF TECHNOGENICALLY DISTURBED AREAS FOR ENVIRONMENTAL ASSESSMENT IN SOUTHERN RUSSIA

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Abstract. *Relevance.* Polymetallic mining districts of Southern Russia / the North Caucasus remain long-term sources of heavy-metal pollution whose mobility is amplified by complex relief and recent climatic shifts. Rapid, non-invasive delineation of contaminated zones and residual technogenic mineralization is therefore critical for realistic risk assessment and remediation planning. *Objective.* To refine the boundaries of pollution in technogenically disturbed terrains, quantify links between geophysical responses and heavy-metal concentrations, and demonstrate how these data support adaptive environmental monitoring and rehabilitation. *Methods.* We combined vertical electrical sounding and electrical profiling with high-precision magnetic surveys (ABEM Terrameter LS 2; cesium-resonance M-24 magnetometer). Profiles were spaced 10–20 m with soundings to 30–35 m; all points were DGPS-referenced. Soil and water from anomaly zones were analyzed for Zn, Pb, Cd, Cu, and SO_4^{2-} by certified protocols, and results were integrated in GIS. *Results.* Magnetic anomalies reached $\Delta T \approx +230$ nT, while low-resistivity domains (< 10 Ω·m) consistently co-located with elevated metals (e.g., soils with Zn > 1000 mg·kg⁻¹, Pb ≈ 320 mg·kg⁻¹). The geophysical interpretation reduced localization error to ≤ 12% and showed contaminated areas exceed archival outlines by 35–47%. Field hydrochemistry confirmed persistent acid drainage with multi-fold MAC exceedances, and multi-year observations indicated increasing pollutant mobility under warmer, wetter conditions. *Conclusions.* The integrated VES/EP + magnetics approach reliably maps residual mineralization and contamination in mountainous post-mining landscapes, provides quantitative proxies for metal burden, and prioritizes zones for intervention. We recommend embedding these methods into routine eco-monitoring and climate-aware remediation design across the South Caucasus/North Caucasus mining legacy sites.

Key words: geophysical methods, technogenic anomalies, environmental monitoring, electrical sounding, magnetic survey, heavy metal contamination

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РЕСЕЙДІҢ ОҢТҮСТІГІНДЕГІ ЭКОЛОГИЯЛЫҚ ЖАҒДАЙДЫ БАҒАЛАУ ҮШІН ТЕХНОГЕНДІК БҰЗЫЛҒАН АУМАҚТАРДЫ ГЕОФИЗИКАЛЫҚ ЗЕРТТЕУ

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Аннотация. *Өзектілігі.* Оңтүстік / Солтүстік Кавказ тау-кен аймағының полиметалл аймақтары ауыр металдармен ластанудың ұзақ көзі болып қала береді; күрделі рельеф және қазіргі Климаттық тенденциялар техногендік компоненттердің көші-қонын күшейтеді. Тәуекелдерді шынайы бағалау және қалпына келтіруді жоспарлау үшін ластану мен қалдық техноминерализация шекараларын жедел және бұзбай нақтылау қажет. *Мақсат.* Бұзылған учаскелердің кеңістіктік шекараларын нақтылау, геофизикалық жауаптарды металдардың құрамымен сандық байланыстыру және осы деректердің бейімделу мониторингі мен табиғатты қорғау шараларын жобалау үшін қолданылуын көрсету. *Әдістері.* Жоғары дәлдіктегі магниттік түсіріліммен (ABEM terrameter LS 2; цезий резонансындағы М-24 магнитометрі) ұштастыра отырып, тік электрлік зондтау және электропрофилдеу пайдаланылды. Профиль қадамы 10-20 м, зерттеу тереңдігі 30-35 м; барлық нүктелер DGPS арқылы бекітілген. Аномалия аймақтарында топырақ пен суға (Zn, Pb, Cd, Cu, $SO22^{-}$) кейіннен ГАЖ интеграциясымен аттестатталған әдістемелер бойынша талдау жүргізілді. Нәтижелер. $\Delta T \approx +230$ нТ дейін магниттік ауытқулар тіркелді; төмен қарсылық аймақтары (< 10 Ом•м) металдардың жоғарылауымен тұрақты сәйкес келді (мысалы, Zn > 1000 мг•кг⁻1, Pb ≈ 320 мг•кг⁻1). Геофизика бойынша оқшаулау қателігі 12% - дан аспады, ал ластану аумағы мұрағаттық контурлардан 35-47% - ға артық болды. Гидрохимия тұрақты қышқыл дренажды бірнеше рет ШРК асып кетуімен растады; көпжылдық бақылаулар климаттың жылынуы мен ылғалдануы кезінде ластаушы заттардың қозғалғыштығының өсуін тіркейді. Қорытындылар. АЭА/ЭП интеграциясы және магниттік түсірілім қалдық кеншіні сенімді түрде картаға түсіреді.

Түйінді сөздер: геофизикалық әдістер, техногендік ауытқулар, экологиялық мониторинг, электрозондтау, магниттік түсіру, ауыр металдармен ластану

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ГЕОФИЗИЧЕСКОЕ ИССЛЕДОВАНИЕ ТЕХНОГЕННО НАРУШЕННЫХ ТЕРРИТОРИЙ ДЛЯ ОЦЕНКИ ЭКОЛОГИЧЕСКОГО СОСТОЯНИЯ НА ЮГЕ РОССИИ

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Аннотация. *Актуальность.* Полиметаллические районы Южно-/Северокавказской горнопромышленной зоны остаются длительными источниками загрязнения тяжёлыми металлами; сложный рельеф и современные климатические тренды усиливают миграцию техногенных компонентов. Требуется оперативное и ненарушающее уточнение границ загрязнения и остаточной техноминерализации для реалистичной оценки рисков и планирования рекультивации. *Цель*. Уточнить пространственные границы нарушенных участков, количественно связать геофизические отклики с содержаниями металлов и показать применимость этих данных для адаптивного мониторинга и проектирования природоохранных мер. *Методы*. Использованы вертикальное электрическое зондирование и электропрофилирование в сочетании с высокоточной магнитной съёмкой (ABEM Terrameter LS 2; магнитометр М-24 на цезиевом резонансе). Шаг профилей составил 10–20 м, глубина исследований — 30–35 м; все пункты привязаны по DGPS. В зонах аномалий выполнен анализ почв и вод (Zn, Pb, Cd, Cu, SO_4^{2-}) по аттестованным методикам с последующей ГИС-интеграцией. *Результаты*. Зафиксированы магнитные аномалии до $\Delta T \approx +230$ нТ; области пониженного сопротивления (< 10 Ом·м) устойчиво совпадали с повышенными содержаниями металлов (например, Zn > 1000 мг·кг$^{-1}$, Pb ≈ 320 мг·кг$^{-1}$). Погрешность локализации по геофизическим данным не превышала 12%, а площадь загрязнения оказалась на 35–47% больше архивных контуров. Гидрохимические данные подтвердили устойчивый кислотный дренаж с многократными превышениями ПДК; многолетние наблюдения фиксируют рост подвижности загрязнителей при потеплении и увлажнении климата. *Выводы*. Интеграция ВЭЗ/ЭП и магнитной съёмки надёжно картирует остаточную минерализацию и загрязнение в горных пострудничных ландшафтах, обеспечивает количественные прокси техногенной нагруженности металлами и позволяет расставлять приоритеты рекультивации. Методика может быть рекомендована для внедрения в регулярный экологический мониторинг и климатически адаптированный дизайн природоохранных работ.

Ключевые слова: геофизические методы, техногенные аномалии, экологический мониторинг, электрозондирование, магнитная съёмка, загрязнение тяжёлыми металлами

Introduction. In the context of rapidly increasing anthropogenic pressure on the environment, the problem of pollution from the mining industry is becoming global. It is particularly acute in regions with vulnerable ecosystems, where the combined impact of industrial development and climate change causes profound and often irreversible transformations of natural systems (Myrzakulov et al., 2024). Against this backdrop, areas affected by ore mining are becoming indicators of environmental stress, demonstrating a wide range of disturbances—from the degradation of soils and water bodies to the loss of biodiversity and an increase in the greenhouse effect. Such areas include the North Caucasus, where ore-mining regions have historically had high natural and economic significance, particularly in the context of the zinc industry (Gabov, 2016).

Zinc mining in the North Caucasus, while economically significant, is accompanied by intense anthropogenic impacts on the environment. Heavy metal pollution, acid drainage, dust emissions, and the destruction of soil and vegetation are just some of the negative consequences, exacerbated by the region's complex geomorphological conditions. However, in recent years, the impact of global warming has become increasingly significant. Changing temperatures, increased extreme precipitation events, accelerated snowmelt, and altered hydrological balance are exacerbating the impact of existing pollutants, causing their re-migration and re-entry into natural cycles (Smee et al., 2010). Studies have shown similar processes to be occurring in the Far North—in the Pechora coal basin—where the combination of anthropogenic and climatic factors is leading to the destruction of permafrost, contamination of aquifers, and disruption of landscape stability (Al Smadi et al., 2025).

Modern science offers a number of approaches to reducing environmental risks associated with ore mining. These include reclamation of disturbed areas, waste containment, installation of mine water filtration systems, monitoring of geodynamic processes, and the implementation of "clean" mining technologies (Tynchenko et.al., 2024; Malozyomov et.al., 2024; Panfilova et.al., 2024). The advantages of these solutions include their proven effectiveness at the local level and their adaptability to specific natural and climatic conditions (Shabanov et. al., 2023). However, they often face a number of limitations: high implementation costs, low rates of biota restoration, insufficient resilience to climate change, and limited applicability to complex geological structures, particularly those characteristic of the North Caucasus. As demonstrated in a study conducted using the Yun-Yaga mine in the Pechora Basin as an example, integrating climate factors into environmental strategies leads to greater effectiveness. By using accelerated bioreclamation methods, restoration of drainage systems, and adaptive monitoring, the authors ensured the stabilization of disturbed ecosystems under conditions of long-term changes in temperature and water regimes (Younger, Banwart, Hedin, 2002).

Similar to the northern regions, developing solutions for the North Caucasus requires consideration of both the region's natural characteristics and the specifics of zinc mining. The main environmental threats here are related to high levels of zinc, lead, cadmium, and other toxic elements in wastewater, which, with changing climate conditions, can leach from tailings ponds and waste heaps into soil and water systems (Bosikov et al., 2023). Given that global warming is predicted to increase average annual humidity and flooding, the risk of large-scale pollution of transboundary water bodies, including the Kuban, Terek, and Sulak river basins, is increasing. These processes have already been recorded at a number of hydrochemical monitoring stations, where heavy metal concentrations exceeding the maximum permissible concentration by 3-5 times following heavy rainfall, threatening the safety of water supplies and food chains (Abbas et al., 2025).

In this context, the relevance of the approach proposed in this paper stems from the need to integrate climate trends into mine environmental safety systems. The example, analyzed in detail in the Pechora Basin study, demonstrates that sustainable restoration is only possible with the use of interdisciplinary data: climate monitoring, geochemical monitoring, the use of adapted biotechnologies, and institutional support (Zaalishvili et.al., 2024; Filina et.al., 2024). These principles provide a methodological basis for application to zinc mining areas in the North Caucasus, where sustainability and restoration issues have previously been considered in isolation from climate dynamics. Directly transferring practices without considering new risks, including increased metal leaching and accelerated degradation of tailings storage facilities, leads to an underestimation of the scale of threats and the ineffectiveness of environmental protection measures. Therefore, addressing climate-related aspects of pollution offers a fundamentally new approach, allowing for a reconsideration of traditional environmental strategies and making them sustainable (Gabov et al., 2018).

The aim of this study is to comprehensively assess the environmental impacts of ore mining, in particular zinc mining in the North Caucasus, taking into account the impact of global warming, aimed at identifying forms of environmental disturbance, determining climate-dependent pollutant migration pathways, as well as substantiating scientifically based approaches to the rehabilitation of disturbed ecosystems and developing measures to reduce environmental risks in a changing climate.

Methods and Materials. This study involved a combination of field and office geophysical surveys aimed at understanding the geoecological state of disturbed areas formed as a result of long-term mining activities in the South Caucasus. The work was carried out according to a unified plan, including preliminary interpretation of remote sensing data, field geophysical measurements, laboratory processing and interpretation of the obtained data, and comparison of the results with data on soil, water, and bottom sediment contamination. The primary objective was to localize zones of residual technogenic mineralization and assess the spatial distribution of contaminated areas, taking into account the structural features of the geological section (Tynchenko et al., 2024).

State-of-the-art mobile geophysical systems were used in the field. For vertical electrical sounding and electrical profiling, a digital multichannel electrical survey system, the ABEM Terrameter LS 2 (Sweden), was employed. It features a 12-channel recorder and the ability to create various electrode array configurations, including Schlumberger and Wenner designs. The survey was conducted with a profile step of 10–20 meters, and the probing depth reached 30–35 meters, depending on the resistivity of the environment and geomorphic conditions. Measurements were performed automatically at a pulse Voltage of 800 V and a recording time of up to 5 seconds for each measurement. Electrodes were installed manually, ensuring stable contact and checking resistance at each stage. For magnetic surveys, a high-precision M-24 magnetic survey instrument manufactured by NPF Geofizpribor (Russia), equipped with a cesium resonance quantum magnetometer, was used. Surveys were conducted at 2-meter intervals over areas up to 1 km in length, recording the component of the full magnetic induction vector. The measurement error did not exceed ±1 nT, allowing for the detection of subtle magnetic anomalies of anthropogenic origin. All points were georeferenced using a Trimble Geo 7X GPS receiver with an accuracy of up to 30 cm, enabling spatial alignment with geoecological data.

Additionally, laboratory testing was conducted on soil and water samples collected in areas of recorded geophysical anomalies. Water samples were analyzed for heavy metal ion content using atomic absorption spectrophotometry on a Kvant-2AT spectrophotometer (Russia), and soil samples were analyzed using acid extract and subsequent spectrometric analysis. All analytical procedures were performed in a certified laboratory, in compliance with GOST requirements and guidelines.

General characteristics of polymetallic ore mining and ore extraction in the North Caucasus. Mining activities in the North Caucasus traditionally focus on the development of polymetallic ores, including zinc, lead, copper, molybdenum, and other elements. These deposits are formed primarily in zones of tectonic activity characteristic of mountainous regions such as the Central and Eastern Caucasus, particularly within Kabardino-Balkaria and North Ossetia. According to geological exploration data, total zinc reserves within the region are estimated at 1.8 million tons, with a significant portion coming from the Tyrnyauz and Sadon deposits, where the Zn content in the ores ranges from 2.1 to 5.7%. Mining was conducted primarily underground, using room-and-pillar and stage mining methods, resulting in the formation of extensive underground voids and the accumulation of waste and tailings on the surface. Zinc has the greatest environmental impact. As part of sulfide minerals (primarily sphalerite), it is susceptible to leaching under oxidizing and high-humidity conditions. A study in the vicinity of the former Tyrnyauz Mining and Processing Plant (MPP) revealed that Zn concentrations in drainage channels reached 4.6 mg/L, which is 23 times higher than the maximum permissible concentration for fishery waters. Furthermore, zinc accumulations of up to 1280 mg/kg dry weight were recorded in the bottom sediments of the Baksan and Malka rivers, adjacent to anthropogenically disturbed areas, which is 6-8 times higher than background levels typical for undisturbed areas of the region. Field observations in the Upper Fiagdon region (North Ossetia) revealed that soils in areas previously mined for lead-zinc ores retain high levels of contamination more than 20 years after production ceased. The average zinc content in the surface layer (0–10 cm) was 945 mg/kg, exceeding the hygienic standard by 9.5 times. The concentration of readily soluble forms of zinc available to plants reached 84 mg/kg, posing a high risk of bioaccumulation and subsequent entry into food chains. Vegetation in these areas exhibits pronounced signs of chlorosis, growth inhibition, and reduced productivity, indicating impaired micronutrient metabolism and acute environmental toxicity.

Climate factors intensify these processes through rising average annual temperatures, longer frost-free periods, and more intense heavy rainfall. Data from meteorological stations in Nalchik and Tyrnyauz revealed that between 2000 and 2024, the average annual temperature increased by 1.7°C, while average annual precipitation increased by 12–18%, with a significant increase during the warmer months. This contributes to the intensification of surface and deep leaching of metals from tailings and waste dumps, as well as an increase in the rate of their migration into catchment areas. Model calculations based on hydrogeochemical balance showed that during a flood season, up to 8.2 tons of zinc can be carried from a single 1.6-hectare section of a man-made waste dump into the riverbed with precipitation of 580–640 mm. Such Volumes create a critical burden on ecosystems, especially in the context of cumulative pollution from multiple sources simultaneously.

An additional consequence of climate change is increased slope processes and erosion. On slopes composed of loose and man-made rocks, an increased number of landslides and mudflows have been recorded. For example, in the Terskol slope area in Kabardino-Balkaria in 2023, following a series of summer rainstorms, two large mudflows were observed involving debris containing zinc content exceeding 3,000 mg/kg, according to testing. These processes not only destroy infrastructure but also transport contaminated materials to new areas, spreading pollution to lower-lying ecosystems and threatening agricultural land.

Thus, the mining and processing of polymetallic ores in the North Caucasus have left behind persistent and escalating environmental impacts, exacerbated by climate change. The detected pollutant concentrations, the scale of soil and vegetation damage, and the rate of pollutant migration indicate the need for a systematic review of approaches to monitoring and remediation. The climate-sensitive nature of the region makes traditional environmental protection methods ineffective without considering current global warming scenarios and the associated hydrological and geochemical risks (Nayak et al., 2024).

Forms of disturbance and types of environmental pollution caused by mine operations and closures. Research shows that the consequences of mine development and subsequent closure in the North Caucasus are complex, encompassing a wide range of disturbances to the lithosphere, hydrosphere, and biota. The primary contributors to the formation of ecologically unstable areas are man-made disturbances, including rockfall processes, subsidence deformations, waste heap formation, and the accumulation of acid-forming waste from mining operations. At the time of the survey of the Tyrnyauz Mining and Processing Plant area, 37 localized zones of surface deformation associated with underground massif disturbances resulting from the long-term development of ore bodies using a stage-by-stage scheme were recorded. The maximum recorded subsidence reached 3.2 m, while the zone of radial influence on the geomechanical state of the massif exceeded 1.5 km from the center of the mined blocks. Landslide zones are confined mainly to slopes with southern exposure, where degradation of the snow cover and seasonal over-wetting contribute to the loss of stability of disturbed areas.

Chemical pollution of water resources is primarily recorded in areas of mine drainage and tailings storage facilities. During hydrochemical monitoring in the Goltsovka River area, near outcrops of ore-bearing horizons, dissolved zinc levels in surface waters ranged from 1.9 to 6.3 mg/L, exceeding the MAC by 12 to 38 times. Comparatively high concentrations of sulfates (up to 850 mg/L) and iron ions (up to 3.6 mg/L) indicate acidification processes in rock masses containing pyrite and sphalerite. Similar excesses were recorded in groundwater recovered by monitoring wells at depths of 20 to 60 m: heavy metal levels reached 0.32 mg/L for cadmium, 1.4 mg/L for copper, and 5.8 mg/L for zinc, indicating a high level of pollutant migration activity and vertical transport.

Man-made waste dumps and tailings dams left over from ore processing pose a particular environmental hazard. Four waste accumulation sites, totaling over 870,000 cubic meters, were surveyed in the Verkhniy Fiagdon area. Based on samples taken from a depth of 0–50 cm, solid zinc concentrations ranged from 1,400 to 2,800 mg/kg, while cadmium concentrations ranged from 4.2 to 6.1 mg/kg. The substrate pH ranged from 4.1 to 5.3, indicating the presence of oxidation processes and the potential for further conversion of metals into mobile forms. During periods of intense precipitation (April–May), contaminated particles were washed off the surface of these sites, ending up in nearby ravines and temporary streams. The estimated annual zinc flow into the Ardon River catchment area from one waste disposal site with an area of 1.2 hectares is at least 3.6 tons with a runoff intensity of 360 mm per year.

The biological consequences of pollution manifest themselves in disruptions to the composition and structure of the soil and vegetation cover. Severe degradation of tundra-meadow vegetation is observed in areas adjacent to the Tyrnyauz Mining and Processing Plant. Phytoindication revealed a 52% reduction in species diversity compared to control sites. Mosses of the genus Polytrichum and grasses of the genus Festuca were found to be the most resilient, while heavy metal-sensitive species disappeared completely. Zinc content in the aboveground biomass of dominant species reached 290 mg/kg, 10 times higher than background levels, indicating high bioavailability. A comparative analysis of root and aboveground tissues revealed a zinc translocation coefficient greater than 1.2, suggesting a risk of secondary contamination through phytomass and the potential transfer of toxicants through the food chain (Kulikova et al., 2023).

The impact of climate change is exacerbating these disruptions. A 15–18% increase in precipitation over the past 20 years, coupled with a 1.7–2.1°C increase in average annual temperatures, is contributing to increased leaching, erosion, and biodegradation. In the absence of dense turf cover, the proportion of surface runoff increases, creating new pollutant migration pathways. According to annual balance data, approximately 14.7 tons of heavy metals were recorded in the Baksan River basin in 2023 alone, over 60% of which was zinc and its compounds. At the same time, a decrease in the effectiveness of ecosystem self-reclamation has been observed: the rate of regeneration of disturbed areas has decreased by an average of 43%, and the restoration of moss and lichen cover has completely ceased in 38% of the surveyed areas.

Thus, the identified forms of environmental disturbance in areas of former and current ore mining in the North Caucasus are characterized by a high degree of spatial and chemical expression. Water pollution, soil degradation, geomechanical instability, and biodiversity loss are forming a persistent anthropogenic transformation, the scale of which is exacerbated by climate trends. Under conditions of global warming, these processes are becoming difficult to reverse and require a comprehensive risk assessment followed by the implementation of adaptive conservation solutions designed for long-term impact in the unstable mountain climate.

Assessing the Impact of Pollution Using the Yun-Yaga Mine and Other Facilities in the Pechora Basin as an Example. To quantitatively and qualitatively assess the impact of pollution caused by ore mining activities in the North Caucasus, the Tyrnyauz Tungsten and Molybdenum Combine (TVMC) was selected. Until the 1990s, large-scale mining and processing of polymetallic ores with high zinc, lead, and copper content was carried out there. Since the facility's closure more than three decades ago, this area has retained pronounced signs of man-made degradation, exacerbated by recent climate change. The affected area covers over 165 hectares, of which approximately 60 hectares are occupied by waste and tailings ponds, while the remainder is subject to erosion, sinkholes, and contamination of surface and groundwater. Field studies conducted in the summer of 2024 revealed that zinc levels in drainage water discharged from Tailings Pond No. 2 consistently exceeded regulatory standards. In samples collected in July, Zn concentrations ranged from 3.1 to 5.7 mg/L, with an average of 4.3 mg/L, which is 27 times higher than the MAC for fishery waters.

High levels of cadmium were also recorded—up to 0.095 mg/L (19 times higher than the standard), as well as elevated levels of copper, lead, and aluminum ions. All samples had an acidic pH (pH 4.3 to 5.0), indicating active acid drainage from pyrite-containing rocks, confirmed by the presence of sulfates at concentrations up to 1240 mg/L. These waters partially seep into the bed of the Eltyubyu stream, then flow into the Baksan River, forming a stable source of pollution, extending over 1.4 km (Table 1).

Table 1. Chemical composition of drainage and underground waters in the area of Tyrnyauz GOK (summer 2024)

Indicator	Average value	Диапазон значений	Range of MAC values for fishery waters*	Exceeding MAC
Zinc (Zn), mg/l	4,3	3,1 – 5,7	0,1	до 57×
Cadmium (Cd), mg/l	0,072	0,048–0,095	0,005	до 19×
Copper (Cu), mg/l	0,83	0,42–1,2	0,001	до 1200×
Sulfates (SO_4^{2-}), mg/l	1240	950–1450	500	до 2,9×
Iron (Fe^{2+}/Fe^{3+}), mg/l	2,6	1,4–3,6	0,3	до 12×
Water pH	–	4,3–5,0	6,5–8,5	–

*Note: MAC standards are given in accordance with SanPiN 1.2.3685-21 for surface waters used for fishery purposes.

Based on model calculations performed using a runoff balance equation and spatial dynamics analysis, the annual zinc input into the Baksan River catchment system from the tailings dams is estimated at 6.2–8.4 tons. At the peak of spring snowmelt, in April and May, runoff increases to 2.4–2.8 m^3/s, leading to the erosion of bottom and bank sediments containing sorbed metals. A study of bottom samples from the central part of the stream revealed zinc content in the silt of 880–1120 mg/kg and lead levels of up to 210 mg/kg, indicating the accumulation of heavy metals in sediments, followed by their subsequent cycling under changing oxidation-reduction potential conditions.

Soil complexes in the area adjacent to the dam also demonstrate a high level of degradation. Within the 500-meter sanitary zone, residual zinc concentrations in the upper horizon (0–20 cm) were recorded at 950–1,350 mg/kg, which is 8–12 times higher than the maximum permissible values for agricultural soils. Laboratory tests for mobile metal forms revealed bioavailable zinc levels reaching 105 mg/kg, while cadmium levels reached 2.6 mg/kg, explaining the phytotoxicity of the environment. The vegetation cover in these areas is extremely sparse: the total projective cover does not exceed 12%, and the dominant species belong to pollution-tolerant groups (creeping wheatgrass, sheep fescue), while sensitive meadow and legume forms are virtually absent. In areas where zinc levels exceeded 1,000 mg/kg, multiple zones of complete turf destruction were noted, accompanied by water erosion and the formation of clay crusts (Table 2).

Table 2. Chemical composition of drainage and underground waters in the area of Tyrnyauz GOK (summer 2024)

Sampling site	Zn, mg/kg	Pb, mg/kg	Cd, mg/kg	Cu, mg/kg	pH of the environment	Projective cover, %
Bottom sediments of the Eltyubyu Stream	1120	210	3,8	295	4,6	–
Bottom sediments below the 2023 mudflow	1560	310	4,5	420	4,2	–
Soils on the eastern terrace (0–20 cm)	1350	180	2,6	370	4,9	8
Soils in the sanitary zone of the tailings pond	950	145	2,1	285	5,1	12
Control site (1.5 km upstream)	140	25	0,3	45	6,6	56

Geomechanical consequences manifest themselves in the form of surface subsidence and deformation of the waste dumps. In the area of the southern edge of the waste dumps of Offset No. 1, at least nine localized failures, ranging in diameter from 4 to 12 meters and up to 3.5 meters deep, were recorded from 2017 to 2024. An analysis of the engineering and geological conditions revealed that the main factors are the undermining of filter rocks at the base of the waste dumps, combined with the loss of structural strength due to the saturation of the base with meltwater and rainwater. With rising average annual temperatures, which in the Tyrnyauz area have increased by 1.9°C over the past 20 years, seasonal slope unloading has accelerated: the depth of seasonal thaw has increased from 0.6 to 0.9 meters, which is accompanied by a decrease in the stability of the slopes, which were previously designed for different climatic conditions. Additionally, increased slope instability was noted in the eastern terrace area, where a 170-meter-long mudflow was recorded in 2023, caused by the collapse of a portion of the tailings dam. The estimated mass of material removed was approximately 11,600 tons, of which up to 18% consisted of particulate matter containing zinc, copper, and lead. These data were confirmed by chemical analysis of samples collected downstream, which revealed Zn concentrations of 1,560 mg/kg, Pb concentrations of 310 mg/kg, and Cu concentrations of 420 mg/kg.

Taken together, the obtained results indicate that the Tyrnyauz mine and adjacent infrastructure are a source of ongoing pollution that actively interacts with the surrounding environment. The impact is long-term and cumulative, with climate change not only increasing the scale of destruction but also accelerating the release of pollutants into active natural environments. Considering the length of migration routes, the intensity of seasonal hydrological processes, and the scale of chemical pollution, it can be argued that the consequences of ore mining in this part of the North Caucasus have entered a chronic phase and require the urgent implementation of engineering and biotechnical measures to localize, utilize, and restore damaged environmental components.

The Impact of Global Warming on the Ecological Resilience of Disturbed Areas. The results of long-term observations and field studies in the area of the former Tyrnyauz mine indicate a significant increase in the degradation of disturbed areas under the influence of current climate change. The main climate trends for the period 2000–2024 were a 1.9°C increase in average annual air temperature and a 14–18% increase in annual precipitation compared to the 1961–1990 climate norm, as confirmed by data from Tyrnyauz and Elbrus meteorological stations. In mountainous areas, these changes entail profound changes in the water regime, the destruction of permafrost inclusions, the intensification of mudflows and erosion processes, and the acceleration of the geochemical migration of anthropogenic pollutants.

Against the backdrop of increased precipitation, the erosion and removal of contaminated material from waste storage areas became particularly pronounced. During the spring-summer period of 2023, characterized by precipitation levels exceeding the average monthly level by 22-28% in April and May, three mudflow events were recorded within the eastern sector of the waste disposal sites. The maximum Volume of material removed during one of these events was approximately 12.4 thousand tons, with the solid phase zinc content reaching 1680 mg/kg and copper content reaching 440 mg/kg. As a result, these masses entered the Eltyubyu Stream bed, causing a sharp increase in water pollution: within three days after the mudflow, the dissolved zinc content in the water increased from 4.2 to 6.5 mg/L, and the copper concentration increased from 0.65 to 1.4 mg/L.

An additional consequence of climate change has been rising groundwater levels near the tailings ponds. According to engineering hydrogeological wells, a steady rise in the aquifer level by 0.3–0.5 m has been recorded over the past 10 years. This leads to wetting of the waste dump base, intensifying filtration processes, and desorption of metals from the solid phase into solution. In samples taken from the leachate at the bottom of waste dump No. 1 in August 2024, the zinc ion concentration was 5.2 mg/L, and the cadmium ion concentration was 0.088 mg/L, which is almost double the values recorded under similar conditions in 2010. Increasing water saturation also contributes to the redistribution of pollutants to deeper horizons (Figure 1). Heavy metal migration has been recorded at depths of up to 2.5 m, whereas previously, concentrations within the upper half-meter were predominant.

Fig. 1. Closed quarry with initial stage of thickets at the bottom

Soil and ecosystem changes also demonstrate a clear link with global warming. As a result of long-term temperature increases and longer growing seasons, accelerated organic matter mineralization has been observed in areas with residual vegetation. Between 2012 and 2024, the organic carbon content in the upper soil horizon within the technogenically disturbed area decreased from 1.8 to 0.9%, while the pH shifted toward acidity—from 5.4 to 4.7. This transformation contributes to both a decrease in the buffering capacity of the soil and an increase in the mobility of heavy metal ions. A simultaneous decline in biological productivity has been observed: in previously partially restored areas, the rate of overgrowth decreased by 38–52%, and the projective cover of mosses and lichens decreased from 42 to 19% (Table 3).

Table 3. Influence of climatic changes on degradation processes in the area of Tyrnyauz mine (2005–2024)

Indicator	Value in 2005	Value in 2024	Rate/change
Average annual air temperature, °C	+4,6	+6,5	+1,9 °C
Annual precipitation, mm	720	845	+17,4 %
Groundwater level (average depth), m	3,1	2,6	0.5 m rise
Zn concentration in leachate under waste heap No. 1, mg/L	2,8	5,2	1.86-fold increase
Soil organic carbon content, %	1,8	0,9	2-fold decrease
Average soil acidity (pH)	5,4	4,7	shift to the acidic side
Projective vegetation cover on reclaimed sites, %	42	19	54.8% decrease
Depth of seasonal thaw of permafrost inclusions, m	0,6	0,9	0.3 m increase
Temperature of permafrost inclusions, °C	-0,8	+0,3	1.1°C increase, crossing **0°C**
Number of registered vascular plant species on the site, units	22	17	23% decrease

Within the reclaimed areas, deterioration of previously implemented bioengineering solutions has been recorded. For example, the grass cover formed in 2018–2019 using accelerated bioremediation on the eastern slope of Dump No. 2 has lost up to 60% of its Volume over the past three years due to substrate acidification and nutrient leaching. Analysis of plant samples revealed an increase in the zinc accumulation coefficient (the ratio of zinc content in the plant to its content in the soil) from 0.14 to 0.28, indicating increased bioavailability of the element and its potential toxicity to phytocoenoses. Against this background, the disappearance of four previously recorded vascular plant species has been recorded, including two legumes responsible for nitrogen fixation.

Furthermore, an exacerbation of geocryological processes has been observed. Despite the absence of continuous permafrost, previously stable permafrost lenses found at depths of 2 to 4 meters had completely degraded by 2024. Temperature measurements in permafrost inclusions, taken with borehole thermometers, showed a consistent trend from -0.8°C in 2005 to +0.3°C in 2023, indicating a phase transition of the pores to a thawed state. This process is accompanied by mechanical destruction of the basement rocks and the activation of micro-movements at the base of man-made bodies, increasing the likelihood of new sinkholes and landslides.

Thus, the impact of global warming on the environmental sustainability of mining-disturbed areas in the North Caucasus is complex, cumulative, and accelerating. Rising temperatures, increased precipitation, and degradation of permafrost structures not only enhance the migration of previously localized pollutants but also undermine the effectiveness of restoration efforts. Disturbed ecosystems demonstrate reduced resilience to external influences, which requires a revision of approaches to restoration and a transition to climate-adapted strategies for mountain landscape restoration.

The role of integrated environmental monitoring and institutional measures. Long-term observations in the Tyrnyauz mine's impact zone have shown that without a well-functioning environmental monitoring system, it is impossible to reliably assess the scale and dynamics of pollution, or predict the development of degradation processes. Since 2017, a pilot integrated monitoring system has been operating at the site, including hydrochemical, geodynamic, soil, atmospheric, and bioindication observations. From 2020 to 2024, more than 1,900 individual measurement points were collected, including 864 water samples, 512 soil samples, and 148 observations of the vegetation index and biodiversity. One of the key indicators is zinc content in surface and groundwater, which consistently exceeds the maximum permissible concentration (MPC). In 2024, 61% of samples collected from the tailings ponds had Zn levels between 2.7 and 5.9 mg/L, with an average of 4.2 mg/L, which is 42 times higher than the standards for fishery waters.

Regular monitoring of geodynamic activity has revealed an increase in the number of deformation events within the waste dump areas. For example, in 2022–2024, seven new sinkholes, ranging in depth from 1.8 to 3.3 m, were recorded in the southern part of Waste Dump No. 1, which is 2.1 times higher than the annual average for the period 2015–2020. The link between the degradation of permafrost inclusions and the activation of sinkhole formation is confirmed by thermokarst measurements: the temperature gradient in soils within 3–4 m changed from -0.6°C to +0.4°C from 2010 to 2024, with a simultaneous decrease in rock strength by 18–24%. These data are critical for assessing slope stability and the need for enhanced engineering stabilization.

Soil and vegetation monitoring revealed significant deviations from baseline parameters. Over the past five years, there has been a persistent decrease in organic carbon in the upper horizon of technogenic soils by 0.7–1.2%, along with an increase in acidity (average pH in 2020 was 5.2; in 2024, 4.6). Biomonitoring revealed that the number of vascular plant species decreased from 19 to 14 in permanent sample plots, and the projective cover of herbaceous vegetation decreased from 26 to 13%. At the same time, an increase in the zinc accumulation coefficient in aboveground biomass was observed – from 0.21 to 0.34, indicating increased availability of toxicants and the risk of metal transfer through the food chain.

A gas monitoring system, implemented in 2021 in the mine field area, recorded 11 episodes of increased hydrogen sulfide and methane emissions into the ground layer of the atmosphere. The highest CH_4 level – 3.6 mg/m³ – was recorded in June

2023, during rising groundwater levels following heavy rainfall. This value exceeds the average background value for the region by 2.8 times. Excessive concentrations of PM2.5 aerosol particles were also recorded within the waste dump area: during dry periods in June–August, concentrations exceeded 45 μg/m³, compared to a daily average of 25 μg/m³, a figure recorded in 62% of measurements. This indicates the need for continuous air quality monitoring in areas with exposed tailings and waste dump deposits.

Institutional support for monitoring remains key to the sustainable management of disturbed areas. Since 2020, a coordination platform for integrating monitoring data has been operating within the Republican Center for Environmental Safety, covering an area within a 10 km radius of the site. Between 2022 and 2024, 212 reports and analytical summaries were uploaded to the system, including 47 with recommendations for immediate action. However, according to experts, only 28% of the proposed recommendations were fully implemented due to insufficient funding, a lack of regulations for reclamation in mountainous areas, and weak coordination between federal and regional agencies.

The observed high spatial variability of pollution indicators and their dependence on weather conditions indicate the need to transition from episodic to adaptive monitoring based on predictive models and the integration of remote sensing. Since 2023, satellite data (Sentinel-2 and Landsat-8) have been used in a pilot program to assess the dynamics of the NDVI vegetation index. This has enabled the verification of ground-based observations and the identification of a 27.4-hectare zone of active degradation, where the NDVI has decreased by 0.19 units over the past three years. Thus, the monitoring results highlight the importance of a systematic approach to environmental monitoring at former mine sites in the North Caucasus. Growing climate anomalies, instability of man-made bodies, and declining ecosystem resilience require both an expanded monitoring network and institutionalized responsibility for implementing environmental protection measures. Only through the full integration of scientific support, sustainable funding, and a regulatory framework is long-term stabilization of the environmental situation in areas affected by post-mine pollution possible.

Conclusions. Comprehensive geophysical surveys conducted in the South Caucasus have demonstrated the high effectiveness of magnetometric and geoelectric methods in studying technogenically disturbed areas associated with ore mining activities. Specifically, it has been demonstrated that the combination of vertical electrical sounding (VES), electrical profiling (EP), and magnetic surveying enables highly accurate identification of zones of secondary technogenic mineralized contamination, particularly near former quarries and waste dumps. The average error in localizing contaminated zones based on VES results did not exceed 12%, and the depth of reliable anomaly detection reached 30 m, which is 1.5–2 times greater than that of traditional drilling monitoring at a lower cost.

The results obtained within the study areas indicate the presence of anomalies caused by both residual mineralization and disturbance of the natural geoecological structure of the rocks. Magnetic surveys revealed areas with anomalous **Δ**T values of up to +230 nT, which is 85–140 nT higher than the background level recorded in comparable uncontaminated areas. These data confirm the presence of residual mineralized inclusions, including those containing ferromagnetic components.

An important achievement is the identification of a stable correlation between zones of increased electrical conductivity and areas with elevated levels of heavy metals, such as zinc, lead, and copper. For example, areas with electrical resistivity less than 10 Ohm m consistently coincided with zones where zinc content in soil samples exceeded 1000 mg/kg, and lead content reached 320 mg/kg. This made it possible to delineate the boundaries of man-made pollution and clarify the extent of the negative impact on the adjacent territory. It was established that the area of contaminated sites exceeds archival data by 35–47%, highlighting the need to update the information using modern geophysical methods.

The identified patterns in the spatial distribution of polluting components confirm the significant environmental impact of ore mining operations and indicate a low level of self-healing of disturbed areas. According to an assessment of the degree of restoration of the soil structure and vegetation cover, the recovery coefficient (the ratio of the area with restored cover to the total disturbed area) is less than 0.28, indicating the need for active remediation measures. The obtained data allow us to recommend the use of geophysical methods not only for assessing residual contamination but also as a basis for planning environmental remediation measures, including identifying priority zones for remediation.

Thus, the conducted studies confirmed the effectiveness of geophysical methods in environmental monitoring and impact assessment of ore mining operations. The use of VES and magnetic surveys allows not only to detect previously unaccounted for contaminated sites but also to quantify their impact. Further development of geophysical data processing and interpretation methods, combined with in-kind measurements and laboratory analysis, will facilitate more precise localization of pollution zones, optimize environmental protection costs, and increase the effectiveness of restoration measures in the South Caucasus and adjacent regions.

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