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INTEGRATED ASSESSMENT OF ENVIRONMENTAL RISKS IN TAILINGS STORAGE FACILITIES BASED ON GEOCHEMICAL AND HYDROLOGICAL ANALYSIS

Vahan R. Grigoryan
Institute of Water Problems and Hydro-Engineering
Named After I.V. Yeghiazarov
125/3 Armenakyan St., 0011, Yerevan
e-mail: vahan.gvr@gmail.com
ORCID iD: 0009-0003-2277-3055
Republic of Armenia

Arevshad A. Vartanyan
M.V. Lomonosov Moscow State University
1, Kolmogorov str. 119991, Moscow
e-mail: arevshad@mail.ru
ORCID iD: 0000-0002-0317-7296
Russian Federation

Eleonora V. Avanesyan
National University of Architecture and
Construction of Armenia
105, Teryan St. 0009, Yerevan
e-mail: avanesyane@rambler.ru
ORCID iD: 0000-0002-4443-2353
Republic of Armenia

Hovhannes V. Tokmajyan
Institute of Water Problems and Hydro-Engineering
Named After I.V. Yeghiazarov
125/3 Armenakyan St., 0011, Yerevan
e-mail: tokmajyan.hovhannes@gmail.com
ORCID iD: 0000-0002-2315-7233
Republic of Armenia

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Abstract

This study presents an integrated assessment of environmental risks associated with tailings storage facilities based on field and laboratory data. The analysis focuses on pH variability, heavy metal concentrations, and hydrological processes governing contaminant migration.

The results reveal significant spatial heterogeneity of geochemical conditions. Although water samples exhibit near-neutral pH values, extremely acidic conditions (pH down to 1.32) were identified in surface layers, indicating localized acid mine drainage processes. Heavy metals demonstrate strong accumulation in soils, confirming their long-term environmental persistence.

The study highlights the need for integrated risk management combining geochemical monitoring, engineering solutions, and management strategies.

Keywords: Tailings, Acid Mine Drainage, Heavy Metals, Hydrology, Environmental Risk, Geochemistry.

Introduction

Tailings storage facilities (TSFs) represent one of the most critical and long-lasting sources of environmental risk associated with mining activities. Unlike active industrial processes, tailings remain environmentally reactive for decades or even centuries, making them persistent sources of contamination in surrounding ecosystems.

Global incidents, including the Brumadinho dam disaster and the Mount Polley tailings dam failure, have highlighted the catastrophic consequences of insufficient monitoring and management of tailings systems[1][2]. These events demonstrated that failures in tailings storage are not only engineering problems but also systemic failures involving environmental, operational, and governance factors.

Environmental significance of tailings

The environmental impact of TSFs is primarily driven by two interrelated processes:

- acid mine drainage (AMD);
- heavy metal mobilization.

AMD is generated through the oxidation of sulfide minerals, leading to the formation of sulfuric acid and a significant decrease in pH values. This process enhances the solubility and mobility of metals, resulting in long-term contamination of water and soil systems (Tabl. 1). According to David K. Nordstrom (2011), AMD represents one of the most severe forms of mining-related pollution, capable of altering entire river systems and groundwater regimes[3].

Table 1

Process	Mechanism	Environmental impact
Acid Mine Drainage	Sulfide oxidation	pH decrease, metal mobilization
Heavy metal transport	Dissolution + migration	Water and soil contamination
Hydrological flow	Infiltration and runoff	Regional pollutant spread

Heavy metals as long-term pollutants

Heavy metals such as Cu, Zn, Pb, Cd, and As are among the most persistent contaminants associated with tailings. Unlike organic pollutants, these elements do not degrade and can accumulate in soils and sediments.

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[1] The Brumadinho dam disaster was a catastrophic tailings dam failure that occurred on January 25, 2019, near Brumadinho in Minas Gerais, Brazil. The collapse released a massive wave of mining waste from Vale S.A.'s Córrego do Feijão iron ore mine, killing 270 people and causing widespread environmental destruction.

[2] The Mount Polley tailings dam failure was a major industrial accident that occurred on August 4, 2014, at the Mount Polley copper-gold mine near Likely, British Columbia, Canada. A breach in the mine's tailings storage facility released roughly 25 million m³ of water and mine waste into nearby lakes and creeks, making it one of Canada's worst mining environmental disasters.

[3] David K. Nordstrom is an American geochemist recognized for his pioneering research on acid mine drainage and aqueous geochemistry. His work has shaped scientific understanding of metal sulfide oxidation, contaminant transport, and geochemical modeling in natural and mining-impacted waters. Nordstrom's research is widely cited across environmental science and hydrology.

Studies by Katherine A. Hudson-Edwards and David W. Blowes have shown that metal mobility is strongly controlled by geochemical conditions, particularly pH and redox potential[4][5].

Low pH environments significantly increase metal solubility, which enhances their transport through hydrological systems and increases ecological risk.

Hydrological control of contamination

Hydrological processes play a crucial role in the redistribution of contaminants from tailings storage facilities. These include:

- infiltration into groundwater systems;
- surface runoff during precipitation events;
- transport through river networks

Such processes can extend contamination far beyond the original tailings site, transforming local pollution into regional environmental problems.

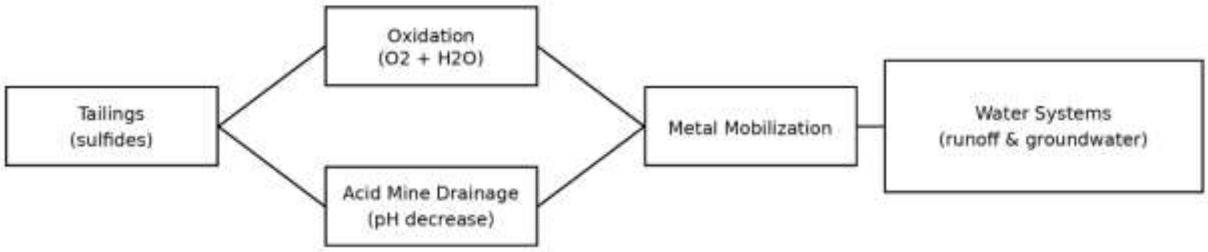

Fig. 1 Conceptual model of contaminant generation and transport in tailings storage facilities

Fig. 1 summarizes the main environmental-risk pathway in tailings storage facilities: sulfide oxidation generates acid mine drainage, which decreases pH and promotes heavy-metal mobilization. Mobilized contaminants are then transported through surface runoff and groundwater infiltration, creating exposure risks for soils, rivers, and biological receptors.

Hidden nature of environmental risk

One of the most critical challenges in assessing tailings-related risks is the discrepancy between apparent and actual environmental conditions.

Water samples may indicate near-neutral pH values, suggesting stability, while underlying soil layers can contain highly acidic zones responsible for ongoing metal mobilization.

This phenomenon has been described in multiple studies as a “hidden geochemical instability”, where contamination processes occur below the surface and remain undetected in conventional monitoring systems.

Research gap and novelty

Despite extensive research on tailings, several gaps remain:

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[4] Katherine A. Hudson-Edwards is a British environmental geochemist recognized for her expertise in the behavior and management of mine wastes. Her research focuses on metal contamination, remediation, and the environmental impacts of mining and mineral processing. She is a professor of sustainable mining and geochemistry at Birkbeck, University of London and a leading voice in sustainable resource extraction and pollution mitigation.

[5] David W. Blowes is a Canadian geochemist and environmental scientist known for his pioneering work on the geochemistry of mine wastes and groundwater remediation. A Professor at the University of Waterloo, he is recognized internationally for advancing understanding and prevention of acid mine drainage and contaminant transport in subsurface systems.

- недостаточная интеграция почвенных и водных данных;
- ограниченное внимание к локальным зонам закисления;
- недостаток комплексных моделей риска.

The present study addresses these gaps by integrating:

- pH variability;
- heavy metal concentrations;
- hydrological processes.

Tailings storage facilities (TSFs) have been widely recognized as complex environmental systems where geotechnical instability, geochemical reactivity, hydrological transport, and management failures interact over long periods. Unlike many industrial wastes, tailings remain reactive after mine closure, which makes post-closure monitoring and risk governance essential components of tailings safety.

Kossoff et al. emphasized that TSF risks are determined not only by dam construction and failure mechanisms, but also by the chemical nature of stored tailings, their long-term environmental impact, and the effectiveness of remediation measures. Their review highlights that tailings failures may generate severe downstream pollution, sediment contamination, and ecosystem degradation [1].

A major environmental mechanism associated with tailings is acid mine drainage (AMD). AMD is produced through the oxidation of sulfide minerals in the presence of oxygen and water, resulting in acidification and increased metal solubility. Blowes et al. describe AMD as a geochemical process capable of sustaining long-term contamination in mine-waste environments, especially where sulfide-rich materials remain exposed to atmospheric and hydrological conditions [2].

Heavy metal mobility is strongly controlled by pH, redox conditions, mineral composition, and hydrological pathways. Under acidic conditions, metals such as Cu, Zn, Fe, Mn, Pb, Cd, and As may become more soluble and mobile. This explains why apparently neutral water samples may not fully reflect the real environmental risk if acidic zones exist within tailings surface layers or internal deposits. This issue is especially important for the present study, where field and laboratory data show neutral-to-alkaline water pH in several cases, but highly acidic surface-layer conditions in some tailings facilities. Hydrological transport is another critical factor in tailings-related contamination. Infiltration, seepage, surface runoff, and river connectivity can transfer pollutants from tailings bodies into groundwater, soils, and downstream aquatic systems. This transforms localized contamination into a broader regional environmental risk. Therefore, tailings assessment should not be limited to chemical measurements alone, but should integrate hydrogeological context and pollutant migration pathways. From a safety-management perspective, historical analyses show that TSF failures often result from multiple interacting factors rather than a single technical cause. Azam and Li’s review of tailings dam failures over the last century indicates that vulnerability is linked to dam construction practices, sequential raising, insufficient regulation, high post-closure maintenance costs, and extreme rainfall events [3].

Recent international governance frameworks also emphasize integrated management. The Global Industry Standard on Tailings Management, developed by UNEP, ICMM, and PRI, stresses that tailings facilities must be managed throughout their full lifecycle, including closure and post-closure, with the aim of preventing catastrophic failure and reducing risks to people and the environment [4].

Tailings management frameworks have evolved significantly over the past decades, incorporating both engineering design principles and long-term environmental considerations. The classical work of Steven G. Vick emphasizes that the stability of tailings dams must be evaluated not only during operation but also during closure and post-closure phases, where environmental risks often become more pronounced [5].

In parallel, geochemical studies highlight that sulfide-rich tailings remain reactive long after deposition. According to Dold, sulfide oxidation and secondary mineral formation control the release of acidity and metals, leading to long-term contamination potential in mine-waste environments [6]. These processes are strongly influenced by environmental conditions such as moisture, oxygen availability, and temperature.

Furthermore, comprehensive assessments of mine waste systems demonstrate that environmental impacts cannot be mitigated solely through containment strategies. As noted by Lottermoser, effective tailings management requires a combination of geochemical stabilization, hydrological control, and long-term monitoring [7]. This integrated approach is particularly relevant for regions where tailings interact with surface and groundwater systems.

Hudson-Edwards, Jamieson, and Lottermoser noted that mine wastes represent one of the largest waste streams worldwide and often contain high concentrations of elements that may severely affect ecosystems and human health [8]. Their work supports the need to treat tailings as long-term geochemical systems rather than inert storage materials.

Hydrological transport is another key factor in TSF risk formation. Infiltration, seepage, surface runoff, and river connectivity can transfer pollutants from tailings into soils, groundwater, and downstream aquatic systems. Rico et al. showed that tailings failure impacts are strongly connected with downstream run-out and pollutant transport, supporting the inclusion of hydrological pathways in risk assessment [9].

Modern studies also emphasize that tailings risks have socio-environmental dimensions. Cacciuttolo and colleagues concluded that mine tailings cannot be treated as inert or harmless materials, because they may generate toxic impacts on both communities and ecosystems [10]. This reinforces the need for integrated environmental-risk assessment and long-term governance.

Recent global-scale analyses of tailings failures indicate that the consequences of TSF incidents may extend far beyond the storage area and can affect river basins, settlements, agricultural lands, and regional water security. Islam et al. considered tailings failures at a global scale and emphasized the importance of impact assessment beyond the immediate failure site [11].

International governance frameworks now require lifecycle-based tailings management. The Global Industry Standard on Tailings Management, developed by UNEP, ICMM, and PRI, stresses that tailings facilities should be managed throughout design, operation, closure, and post-closure stages to prevent catastrophic failure and minimize risks to people and the environment. This aligns with the management component of the present article [12].

At a global scale, water systems are increasingly exposed to multiple anthropogenic pressures, including mining-related contamination. According to Vörösmarty et al., freshwater ecosystems are among the most threatened environmental systems, with water quality degradation driven by industrial pollution, land-use change, and hydrological alteration [13]. The authors emphasize that contaminants introduced into river systems can propagate over long distances, affecting not only local ecosystems but also regional water security and biodiversity. This perspective is particularly relevant for tailings storage facilities, where pollutants generated within confined areas may be transported through hydrological pathways, transforming localized contamination into basin-scale environmental risks.

Table 2

Key research directions in tailings risk assessment

Research direction	Key contribution	Relevance to this study
Tailings dam failure analysis	Identifies accident causes and downstream impacts	Supports the need for integrated risk assessment
Acid mine drainage	Explains sulfide oxidation and pH decrease	Interprets acidic surface-layer conditions
Heavy-metal mobility	Links low pH with metal solubility and migration	Supports Cu, Zn, Fe, Mn, Cr interpretation
Mine-waste geochemistry	Combines pH, sulfate, conductivity, and metals	Supports multi-parameter analysis
Hydrological transport	Explains runoff, seepage, and groundwater transfer	Supports contaminant migration analysis
Socio-environmental risk	Connects pollution with communities and ecosystems	Supports broader risk interpretation
Tailings governance	Emphasizes lifecycle management and monitoring	Supports management innovation component

Conflict Setting

The reviewed literature shows that TSF risks are usually studied through separate disciplinary lenses: geotechnical failure, AMD chemistry, metal mobility, hydrological transport, or governance. However, several gaps remain. First, many monitoring approaches focus mainly on water chemistry, although soil and surface-layer geochemistry may reveal hidden acidification zones. Second, environmental data are often separated from management decision-making, which limits their practical use for risk reduction. Third, few studies combine pH, metals, hydrology, and management-oriented interpretation within one integrated framework.

The present study addresses these gaps by integrating real field and laboratory data on water and surface-layer chemistry with a broader interpretation of environmental risk and tailings safety management.

The aim of this study is to provide an integrated assessment of environmental risks in tailings storage facilities based on real field and laboratory data, focusing on the interaction between geochemical and hydrological factors.

Research Results

Study area and tailings facilities

The study was conducted across multiple tailings storage facilities (TSFs) located in mining regions characterized by long-term ore processing and waste accumulation. The selected sites represent different geochemical and hydrological conditions, allowing for comparative analysis of environmental risks. The investigated tailings facilities include: Voghji, Pukhrut, Darazor, Dastakert, Artsvanik, Terterasar, Hankasar, Sotk. These sites were selected based on their environmental relevance, variability of geochemical conditions, and availability of field data.

Sampling strategy

Field sampling was conducted to capture both spatial variability and environmental heterogeneity of tailings systems.

Two main sample types were collected:

- water samples (surface water and pore water);
- soil samples (surface layers of tailings deposits).

Sampling locations were selected to represent:

- different zones within tailings facilities;
- areas with potential acidification;
- zones influenced by water flow and runoff.

To ensure representativeness, samples were collected from multiple points within each site.

Table 3

Study sites and sampling matrix

Site	Sample type	Parameters analyzed
Voghji	Water / Soil	pH, Cu, Zn, Fe, Mn
Pukhrut	Water / Soil	pH, Cu, Zn, Fe, Mn
Darazor	Water / Soil	pH, Cu, Zn, Fe, Mn
Dastakert	Water / Soil	pH, Cu, Zn, Fe, Mn
Artsvanik	Soil	pH, metals
Terterasar	Water / Soil	pH, metals
Hankasar	Water / Soil	pH, metals
Sotk	Soil	pH, metals

Laboratory analysis

Laboratory analyses were performed using a Photolab 7100 VIS spectrophotometer, ensuring high precision in chemical measurements.

The following parameters were determined: pH; Electrical conductivity; Total dissolved solids; Heavy metals (Cu, Zn, Fe, Mn, Cr and others).

Analytical methods:

- Spectrophotometric analysis;
- Standard water and soil testing procedures;
- Calibration using certified reference solutions.

Data processing and interpretation

The collected data were analyzed using a combination of:

- comparative analysis between sites;
- range-based interpretation (minimum–maximum values);
- identification of spatial variability.

Particular attention was given to:

- correlation between pH and metal concentrations;

- differences between water and soil environments;
- identification of anomalous values.

Conceptual modeling approach

To interpret the environmental processes, a conceptual framework was applied linking:

- sulfide oxidation;
- acid generation;
- metal mobilization;
- hydrological transport

This approach allows the integration of geochemical and hydrological data into a unified environmental risk model.

Reliability and limitations

The reliability of the results is supported by:

- use of calibrated laboratory equipment;
- standardized analytical procedures;
- consistency of measurements across sites.

However, several limitations should be noted:

- spatial heterogeneity of tailings systems;
- temporal variability (seasonal effects not fully captured);
- limited number of sampling points in some locations.

pH variability and acidification processes

The analysis of pH values revealed pronounced spatial variability across the investigated tailings storage facilities. While water samples generally exhibited near-neutral conditions (pH ≈ 6.6–7.5), surface and soil layers showed significantly lower values in certain locations. The most critical conditions were identified in Dastakert and Terterasar, where soil pH reached extremely acidic values (down to 1.32), indicating active acid mine drainage (AMD) processes. Localized acidification zones act as primary drivers of geochemical instability, even when bulk water conditions appear stable.

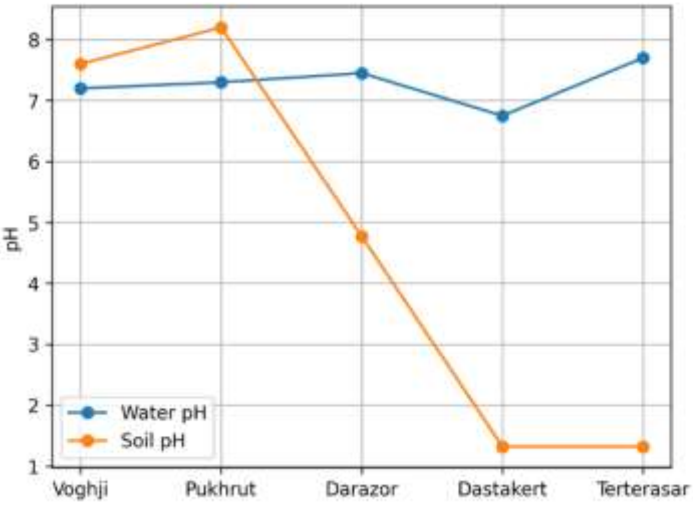

Fig. 2 Comparison of pH values in water and soil samples across tailings storage facilities

Fig. 2 compares pH values between water and soil environments across the studied tailings storage facilities. While water samples generally exhibit near-neutral conditions, soil layers show significantly lower pH values in several sites. This discrepancy indicates the presence of localized acidification zones that are not reflected in bulk water measurements.

Table 4
pH distribution in ailings systems

Site	Water pH	Soil pH	Interpretation
Voghji	6.9–7.4	7.5–7.8	Stable
Pukhrut	7.2–7.4	7.8–8.7	Stable
Darazor	7.4–7.5	4.77	Local acidification
Dastakert	6.7–6.8	1.32	Extreme AMD
Terterasar	7.4–8.0	1.32	Strong heterogeneity

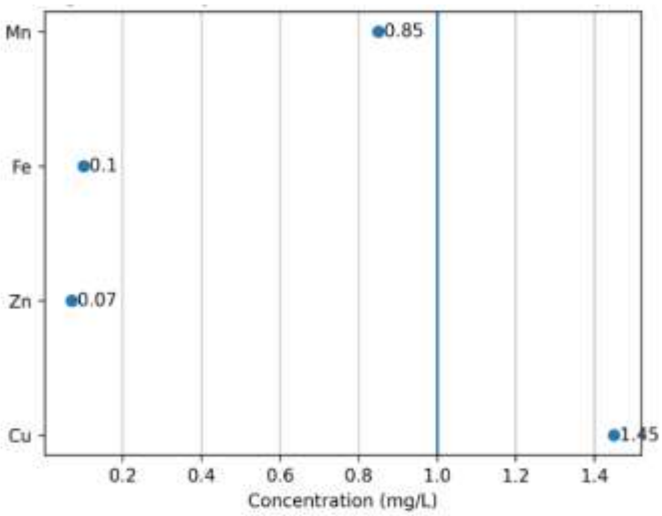

Fig. 3 Heavy metal concentrations in water samples across selected tailings storage facilities. The vertical line indicates a reference threshold level

Fig. 3 presents the distribution of heavy metal concentrations in water samples. The results show that certain elements, particularly Cu, approach or exceed reference levels, indicating active geochemical processes and potential environmental risk. The variability among metals reflects differences in mobility and geochemical behavior under site-specific conditions.

Discussion

Comparison with international studies

The results obtained in this study are consistent with international findings on tailings storage facilities, particularly regarding the dominant role of geochemical processes in environmental risk formation.

Previous studies (e.g., Kossoff et al., 2014; Dold, 2010 [1, 6]) have shown that tailings systems often exhibit significant spatial variability, where localized geochemical conditions may differ substantially from bulk measurements. The present study confirms this observation: although water samples generally display near-neutral pH values, soil layers contain highly acidic zones (pH down to 1.32), indicating active acid mine drainage processes.

This discrepancy aligns with the findings of Nordstrom (2011), who emphasized that mine waters may appear chemically stable while still carrying dissolved contaminants originating from acidic microenvironments [14].

Acid mine drainage as a controlling factor

The identification of localized acidic zones highlights the critical role of acid mine drainage (AMD) as a primary driver of contamination.

International studies have demonstrated that AMD significantly increases the solubility and mobility of metals. Blowes et al. showed that sulfide oxidation processes lead to long-term acid generation, which may persist even after mine closure [2].

The results of this study confirm that AMD is not uniformly distributed, but rather occurs in localized zones, which act as “hotspots” of contamination. This finding is important because it explains why conventional monitoring based on water sampling may underestimate environmental risk.

Heavy metal behavior and accumulation

The observed distribution of heavy metals is consistent with global research indicating that metals tend to accumulate in solid phases rather than remain in aqueous solutions.

Lottermoser (2010) demonstrated that mine wastes often act as long-term reservoirs of contamination due to metal retention in soils and sediments. Similarly, Hudson-Edwards et al. (2011) emphasized that mine tailings contain significant quantities of potentially toxic elements that can be released under changing environmental conditions [7, 8].

The results of the present study clearly show that soil concentrations are significantly higher than those in water, confirming the accumulation effect and long-term environmental persistence of metals.

Role of hydrological processes

Hydrological transport plays a crucial role in the redistribution of contaminants.
International case studies (Rico et al., 2008; Islam et al., 2021) have demonstrated that contaminants originating from tailings can be transported through river systems and groundwater, affecting large areas beyond the original source [9].

The findings of this study support this mechanism, as the presence of mobile metals in water samples indicates ongoing transport processes. This confirms that tailings-related pollution should be considered not only as a local problem but also as a regional environmental risk.

Management implications

A key implication of this study is that environmental risk in tailings storage facilities cannot be effectively mitigated through engineering solutions alone.

The Global Industry Standard on Tailings Management emphasizes the importance of lifecycle-based management, including monitoring, risk assessment, and governance.

The results of this study support this approach and demonstrate that:

- monitoring must include both water and soil;
- localized acidic zones must be identified;
- geochemical data must be integrated into management decisions.

The results demonstrate that environmental stability in tailings systems is often only apparent. While bulk water chemistry may suggest neutral conditions, underlying geochemical processes can sustain active contamination pathways.This hidden instability represents a critical challenge for environmental monitoring and risk assessment, as it may lead to significant underestimation of long-term environmental impacts.

Conclusions

Main findings

1. Tailings storage facilities exhibit high spatial variability in geochemical conditions.

2. Localized acid mine drainage zones (pH as low as 1.32) are the primary drivers of metal mobilization.
3. Heavy metals show strong accumulation in soils, confirming their long-term environmental persistence.
4. Hydrological processes enable the transport of contaminants beyond the tailings site, creating regional environmental risks.

Scientific contribution

5. This study demonstrates that environmental risk assessment must integrate water and soil data to capture hidden geochemical processes.
6. The results provide evidence that conventional monitoring approaches may underestimate environmental risk if localized acidification zones are not considered.

Practical implications

7. Effective tailings management requires:
   - integrated monitoring (water + soil);
   - identification of geochemical hotspots;
   - incorporation of geochemical data into management systems.

Future research

8. Further research should focus on:
   - quantitative risk modeling;
   - long-term monitoring systems;
   - integration of geochemical and hydrological models.

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Վ.Ռ. Գրիգորյան[1], **Ա.Ա. Վարտանյան**[2], **Է.Վ. Ավանեսյան**[3], **Հ.Վ. Թոքմաջյան**[1]

[1]Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ
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[3]Ճարտարապետության և շինարարության Հայաստանի ազգային համալսարան

Ներկայացնում է պոչամբարների շահագործման հետ կապված բնապահպանական ռիսկերի համապարփակ գնահատական՝ հիմնված դաշտային և լաբորատոր տվյալների վրա:

Հետազոտության արդյունքները բացահայտում են երկրաքիմիական պայմանների զգալի տարածական բազմազանությունը: Չնայած ջրի նմուշները ցույց են տալիս չեզոքին մոտ pH արժեքներ, սակայն մակերեսային շերտերում հայտնաբերվել են չափազանց թթվային պայմաններ (մինչև 1.32): Ծանր մետաղները զգալի կուտակում են ցուցաբերում հողերում, ինչը հաստատում է դրանց երկարատև պահպանումը շրջակա միջավայրում: Ուսումնասիրությունը ընդգծում է ինտեգրված ռիսկերի կառավարման անհրաժեշտությունը՝ համատեղելով երկրաքիմիական մոնիթորինգը, ինժեներական լուծումները և կառավարման ռազմավարությունը:

Հետազոտության արդյունքները ցույց են տալիս, որ պոչամբարներում շրջակա միջավայրի կայունությունը հաճախ միայն թվացյալ է: Չնայած ջրի քիմիան ընդհանուր առմամբ կարող է ցույց տալ չեզոք պայմաններ, հիմքում ընկած երկրաքիմիական գործընթացները կարող են նպաստել ակտիվ աղտոտման ուղիներին: Այս թաքնված անկայունությունը լուրջ մարտահրավեր է ներկայացնում շրջակա միջավայրի մոնիթորինգի և ռիսկերի գնահատման համար, քանի որ այն կարող է հանգեցնել երկարաժամկետ շրջակա միջավայրի վրա ազդեցության զգալի թերագնահատման:

Բանալի բառեր՝ պոչեր, հանքի թթվային հոսքեր, ծանր մետաղներ, հիդրոլոգիա, շրջակա միջավայրի ռիսկ, երկրաքիմիա:

V.R. Grigoryan, A.A. Vartanyan, E.V. Avanesyan, H.V. Tokmajyan

INTEGRATED ASSESSMENT OF ENVIRONMENTAL RISKS IN TAILINGS STORAGE FACILITIES BASED ON GEOCHEMICAL AND HYDROLOGICAL ANALYSIS

КОМПЛЕКСНАЯ ОЦЕНКА ЭКОЛОГИЧЕСКИХ РИСКОВ В ХВОСТОХРАНИЛИЩАХ НА ОСНОВЕ ГЕОХИМИЧЕСКОГО И ГИДРОЛОГИЧЕСКОГО АНАЛИЗА

В.Р. Григорян[1], А.А. Вартанян[2], Э.В. Аванесян[3], О.В. Токмаджян[1]

[1]*Институт водных проблем и гидротехники им. акад. И.В.Егиазарова*
[2]*Московский государственный университет им. Ломоносова*
[3]*Национальный университет архитектуры и строительства Армении*

Представлена комплексная оценка экологических рисков, связанных с хранилищами отходов обогащения, на основе полевых и лабораторных данных. Анализ сосредоточен на изменчивости pH, концентрациях тяжелых металлов и гидрологических процессах, определяющих миграцию загрязняющих веществ.

Результаты показывают значительную пространственную неоднородность геохимических условий. Хотя пробы воды демонстрируют значения pH, близкие к нейтральным, в поверхностных слоях были выявлены крайне кислые условия (pH до 1,32), что указывает на локализованные процессы кислотного дренажа шахт. Тяжелые металлы демонстрируют сильное накопление в почвах, подтверждая их долговременную стойкость в окружающей среде. Исследование подчеркивает необходимость комплексного управления рисками, сочетающего геохимический мониторинг, инженерные решения и стратегии управления.

Экологическая стабильность в хвостохранилищах часто носит лишь кажущийся характер. Хотя химический состав воды в целом может указывать на нейтральные условия, лежащие в основе геохимические процессы могут поддерживать активные пути загрязнения. Эта скрытая нестабильность представляет собой серьезную проблему для экологического мониторинга и оценки рисков, поскольку она может привести к значительной недооценке долгосрочных экологических последствий.

Ключевые слова: хвосты, кислые шахтные стоки, тяжелые металлы, гидрология, экологический риск, геохимия.

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