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Predictive modelling of iron leaching from mining waste: Civil protection and environmental safety implications

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Highlights

- Predictive model links precipitation to iron leaching from coal-mining waste.
- Laboratory column tests on argillite simulated rainfall-driven leaching.
- Dimensional analysis and similarity theory defined key dimensionless groups.
- Linear relation found: +1 mm rain → 0.01 kg Fe leached per $Mm^3 \cdot y^{-1}$.
- The model supports environmental safety and civil protection decision-making.

Abstract: Coal waste piles pose significant risks to water quality, ecosystem health, and community well-being. In Ukraine's Lviv–Volyn coal basin, the Chervonohrad concentrating plant's waste pile exemplifies these challenges: unchecked physical processes can mobilise iron, contaminating groundwater and surface waters. No prior study has systematically linked precipitation to iron leaching in this context.

This research creates and tests a predictive model relating precipitation to annual iron leaching from coal-mining waste. Laboratory column experiments on argillite flushed with deionised water under controlled flow generated empirical data for calibration. Using similarity theory (π-theorem) and regression analysis, we derived a simple linear relation for a unit spoil volume (1 Mm^3): each additional millimetre of year precipitation mobilises 0.01 kg $Fe \cdot Mm^{-3} \cdot y^{-1}$. Under the mean annual precipitation of 607.9 mm, the model indicates 24.8 kg $Fe \cdot Mm^{-3} \cdot y^{-1}$; scaled to the Chervonohrad waste volume (48.89 Mm^3), this equates to 1212 $kg \cdot y^{-1}$.

Environmental and civil safety specialists and regulators, based on local precipitation data and the model we developed, can calculate seasonal or annual iron loading without large-scale field sampling. Civil protection agencies can likewise use these predictions for early warning and readiness during wet years. The approach developed by the authors is accurate, easy to apply, and can be used in other mining regions with similar climatic and geological conditions. It provides a compact rule-of-thumb for monitoring design, optimisation of containment and treatment, and policy-relevant thresholds to protect aquatic resources-bridging laboratory science and on-the-ground decision-making under changing precipitation patterns.

Keywords: civil protection, emergency, environmental safety of mining regions, forecasting, mathematical modelling, mining waste, monitoring

INTRODUCTION

Trends in the development of global energy show that organic fuel reserves are composed of 67% coal, 18% oil, and 15% natural gas. In Ukraine, these figures are 95.4%, 2.0%, and 2.6%, respectively. The country's total coal reserves amount to 117.5 bn Mg. Coal extraction and processing in Ukraine have declined sharply because of ongoing military actions, increasing risks to both people and the environment. Operations that once managed ecological and fire safety measures at coal mining and processing facilities have been halted. The coal sector remains one of the pillars of Ukraine's industrial potential, and the nation ranks among the world's top 10 countries by coal reserves. Consequently, mining regions have become hotspots of intense anthropogenic pressure on natural ecosystems (Hrinov, Khorolskyi and Kaliushchenko, 2019; Petlovanyi *et al.*, 2023).

Industrialisation in mining regions degrades and alters ecosystems (Hnatush *et al.*, 2018; Moroz *et al.*, 2018; Popovych *et al.*, 2021). Recent studies highlight that contaminants from coal waste significantly dictate the structure of microbiota in nearby sediments and soils (Zhang *et al.*, 2023). This introduces pollutants into soils (Proshad *et al.*, 2025), sediments (Loboichenko *et al.*, 2024), surface and groundwater (Bagriy *et al.*, 2020; Al-Janabi *et al.* 2025), and the atmosphere. Furthermore, multi-element data plays an essential role in interpreting elevated element concentrations in areas impacted by both natural and anthropogenic influences (Petrović, Medunić and Fiket, 2023). These activities also heighten the risk of environmental emergencies (Petlovanyi *et al.*, 2023; Kochmar, Karabyn and Kordan, 2024). In such contexts, international emergency coordination mechanisms – such as those of United Nations Disaster Assessment and Coordination (UNDAC), International Search and Rescue Advisory Group (INSARAG), North Atlantic Treaty Organization (NATO), and the European Union's Civil Protection Mechanism (UCPM) – have proven effective in supplementing national responses to environmental hazards and disasters (Gromek, Feltynowski and Wojakowska, 2024). The accumulation of hazardous wastes generated by coal mining and beneficiation further exacerbates environmental damage. Over 100 mln m^3 of waste rock have been deposited in waste piles covering more than 270 ha, and nearly half of this volume – 48.89 mln m^3 – resides at the Chervonohrad Concentration Plant (CCP) dump.

Almost all of Ukraine's coal reserves lie in the Donetsk and Lviv–Volyn basins. Given its distance from the front line, the Lviv–Volyn Basin (LVB) has acquired strategic importance during the war. The LVB is divided into three districts based on territorial affiliation, geological structure, and coal content: the Novovolynsk Coal District, the Chervonohrad Coal District (CCD), and the Southwestern Coal Area. The CCD alone contains 694.5 mln Mg of hard coal – 70–90% of the basin's total reserves. Over decades of operation, more than 100 mln m^3 of mining and beneficiation waste have accumulated within the basin, primarily in the waste piles of the CCD's concentration plant.

Over nearly seventy years of mining activity in the LVB, ecosystems have become heavily contaminated with heavy metals (Bosak *et al.*, 2020; Kochmar, Karabyn and Karabyn, 2022; Skrobala *et al.*, 2022). Persistent heavy-metal pollution poses a significant threat to all forms of life and increases the likelihood of environmental emergencies (Lennon *et al.*, 2024). This is particularly evident in studies of superhigh-organic-sulphur coal (SHOS) ash and slag deposits, where mineralogical and geochemical constraints determine the mobility of metals and metalloids (Petrović *et al.*, 2022). Heavy metals from mining and improperly stored solid industrial waste are often highly bioavailable due to their soluble and reactive forms (Sutherland, Chittoo and Samlal, 2023; Proshad *et al.*, 2025). In the study area, an emergency situation was declared at the end of the last century due to groundwater contamination with heavy metals, which led to a significant incidence of fluorosis (Tkachenko *et al.*, 2021). Kochmar and Karabyn (2023) underscore that leachates from coal waste pose not only environmental safety risks but also civil protection challenges in the region. Predictive modelling of such contaminant release can therefore serve as a tool for civil protection authorities, enabling early warnings and timely measures to safeguard community water supplies before contamination reaches critical levels (EC, 2023).

Leachates from coal waste pose not only environmental safety risks but also civil protection challenges in the region. Therefore, predictive modelling of such contaminant release can serve as a tool for civil protection authorities, enabling early warnings and timely measures to safeguard community water supplies before contamination reaches critical levels (Kochmar and Karabyn, 2023).

Research hypothesis. We hypothesise that the amount of iron leached from the Chervonohrad Concentration Plant waste pile (CCPWP) is directly proportional to the amount of atmospheric precipitation and can be accurately predicted using a mathematical model. Hereinafter, "iron leaching" (also termed "iron mobilisation" or "iron flux") will be used to describe the mass of dissolved iron released from solid waste into the aqueous phase. Contact between water and iron sulphide or carbonate compounds initiates oxidation reactions that produce soluble iron forms, and thus increased precipitation should yield proportionally greater iron mass, following an expected linear relationship rooted in well-known biogeochemical mechanisms.

In this study, our primary objective was to create and validate a well-founded mathematical model able to forecast the annual mass of iron mobilised from the CCPWP under projected global warming conditions. To achieve this, we used similarity theory to derive key dimensionless criteria governing the leaching process and conducted controlled laboratory column experiments – flushing argillite samples with deionised water – to generate empirical data for model calibration. By integrating dimensional analysis with linear regression of the experimental results, we established a highly predictive relationship between precipitation volume and iron release, ensuring the model's applicability for environmental planning and risk assessment in coal mining regions.

MATERIALS AND METHODS

MODELLING APPROACH

We used analytical, comparative, and synthesis methods to generalise and systematise information on iron leaching processes. Modelling iron leaching from the waste pile is challenging due to the multifactorial and time-dependent nature of the processes. While previous models (Qi and Wu, 2022; Vladyko *et al.*, 2022) addressed mining contexts, our model incorporates key similarities and critical differences. To avoid model overcomplexity, we applied similarity theory, which replaces dimensional variables with dimensionless similarity criteria, or π-groups. This approach relies on dimensional analysis and the method of analogies. Geometric similarity between the physical heap and its laboratory model allowed for controlled experiments and numerical simulations. All linear dimensions and material property ratios were preserved to ensure valid scaling. Similarity theory was integrated with numerical modelling and statistical data analysis to yield comprehensive insights into iron migration within the heap.

STUDY AREA

Commissioning of the Chervonohrad Concentration Plant (CCP) in 1979 marked the beginning of the beneficiation of low-grade coal from all mines in the basin. The primary waste pile reaches 68 m in height, covers 0.8638 km^2, and contains 48.89 mln m^3 of rock (Ivanov, Kovalchuk and Bilanyuk, 2024) with an average density of ρ = 2680 kg·m^{-3}. The petrographic, mineralogical and geochemical characteristics of the dump rocks are described in more detail in the Supplementary Material.

Located in the Western Polissya region of Ukraine, the local climate is temperate (Dfb, due to Köppen–Geiger climate classification) (Myslyva *et al.*, 2023). Meteorological precipitation drives the migration of heap components into the environment; thus, accurate precipitation data are essential. At the Volodymyr meteorological station, annual precipitation in recent years has ranged from 511 to 829 mm, with an average of 607.9 mm (Tab. S1).

MATHEMATICAL MODEL FORMULATION

Waste piles consist of highly heterogeneous materials, and the chemical and physical processes governing the distribution and speciation of iron within them are extremely complex. To address such complexity, mathematical modelling of earth processes is essential for enhancing eco-technology and civil safety (Starodub *et al.*, 2020). Similarity theorems help simplify these processes by reducing them to an analysis of dimensionless parameters. According to the fundamental principles of dimensional analysis, the transition from experimental data to dimensionless models allows for the systematic scaling of physical phenomena (Longo, 2021).

From the π-theorem, we construct the following dimensionless groups:

$$\frac{m_{\mathrm{Fe}}}{m_p} \tag{1}$$

$$\frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}} \tag{2}$$

$$\frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}} \tag{3}$$

where: m_{Fe} = mass of iron leached from the waste pile (kg), m_p = mass of meteoric precipitation (kg), ε = infiltration velocity of precipitation through the heap material (m·h^{-1}), t = total leaching time (h), S_{ore} = cross-sectional area of the waste pile (m^2), P_{ore} = porosity of the heap material, V_{ore} = volume of the heap material (m^3), m_{ore}= mass of the heap material (kg), ρ_{ore} = density of the heap material (kg·m^{-3}).

Equation (1) quantifies the influence of meteoric precipitation on iron leaching. Equation (2) relates the parameters of infiltration velocity and leaching duration together with the heap's physical properties, to the mass of leached iron. Equation (3) links the heap's geometric and material characteristics with the mass of meteoric precipitation as the leaching agent.

The derivation of these equations relies on the calculation of the "null space" of the dimensional matrix, which provides the formal mathematical basis for transforming quantitative models into a dimensionless form (Price, 2005). By applying similarity theory, we then obtain the governing equation in nondimensional form. This approach is consistent with the theory of intermediate asymptotics, where self-similar solutions emerge in complex systems regardless of the specific initial conditions (Barenblatt, 1996).

By applying similarity theory, we then obtain the governing equation in nondimensional form.

$$m_{\mathrm{Fe}} = f\left(V_p,\ V_{\mathrm{ore}}, \varepsilon, t, S_{\mathrm{ore}}, P_{\mathrm{ore},}\ \rho_{\mathrm{ore}}, m_p, e_f, k_{\mathrm{sorb}}\right) \tag{4}$$

$$\frac{m_{\mathrm{Fe}}}{m_p} = f\left(\frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}}; \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}}\right) + \varphi\left(\frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}}; \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}}\right) \tag{5}$$

where: V_p = cumulative precipitation volume that falls onto the active infiltration area (S) during t (m^3), S_{ore} = cross-sectional area of the waste pile (m^2), e_f = effective surface of grains with the leached Fe (m^2), k_{sorb} = effective adsorption/distribution coefficient (m^3·kg^{-1}).

In general, the mass of the leachate and the mass of the source material are mutually independent. Consequently, the functional relationship may be represented as the sum of a linear term and a nonlinear term, each multiplied by an appropriate regression coefficients.

$$\frac{m_{\mathrm{Fe}}}{m_p} = a \cdot \frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}} + b \cdot \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}} + \left(c \cdot \frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}} + d \cdot \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}} + e \cdot \frac{P_{\mathrm{ore}} \cdot e_f \cdot k_{\mathrm{sorb}}}{m_{\mathrm{ore}}} \right)^{\delta} \quad (6)$$

where: a, b, c, d, e = regression coefficients.

Using the Maple software package to analyse our experimental data, we determined the numerical values of these coefficients.

The additional term represented by Equation (7) is small compared to the magnitude of the linear function in Equation (8) and can therefore be neglected. Consequently, we arrive at Equation (9).

$$\varphi = \left(c \cdot \frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}} + d \cdot \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}} + e \cdot \frac{P_{\mathrm{ore}} \cdot e_f \cdot k_{\mathrm{sorb}}}{m_{\mathrm{ore}}} \right)^{\delta} \quad (7)$$

$$f = a \cdot \frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}} + b \cdot \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}} \quad (8)$$

$$\frac{m_{\mathrm{Fe}}}{m_p} \approx a \cdot \frac{\varepsilon \cdot t \cdot S_{\mathrm{ore}} \cdot P_{\mathrm{ore}}}{V_{\mathrm{ore}}} + b \cdot \frac{m_{\mathrm{ore}}}{\rho_{\mathrm{ore}} \cdot V_{\mathrm{ore}}} \quad (9)$$

RESULTS AND DISCUSSION

EXPERIMENT AND MATHEMATICAL MODELLING

To quantify iron-leaching rates under controlled conditions, we conducted a laboratory-scale experiment using an apparatus designed by the Laboratory of Ecological Safety, Lviv State University of Life Safety. The setup comprised a vertical column and a recirculation pump maintaining continuous flow (Fig. S1). Argillite samples (100 g, 10 cm length) were placed in a column with a diameter of 36 mm and flushed with 8.5 dm^{-3} of deionised water over 24 h at a constant flow rate of 300 $cm^3 \cdot min^{-1}$. The sample's cross-sectional area is $S = \pi(0.018 \text{ m})^2 = 0.00101787602 \text{ m}^2$, yielding a sample volume of $V = S \cdot h = 0.00101787602 \text{ m}^2 \cdot 0.10 \text{ m} \approx 0.0001018 \text{ m}^3$ (101.8 cm^3).

Over 24 h, a total of 0.3 $dm^3 \cdot min^{-1} \cdot 60 \ min \cdot h^{-1} \cdot 24 \ h = 432 \ dm^3$ of water passed through the sample, corresponding to approximately 50.8 cycles of 8.5 dm^3 each.

Iron concentrations in the pre- and post-flushing filtrates were determined using an ElvaX Light SDD X-ray fluorescence analyser, which offers 0.01% sensitivity across elements from sodium (Na) to uranium (U). After 24 h (432 dm^3 of water), the non-thermally altered argillite filtrate contained 0.0022 $mg \cdot dm^{-3}$ of Fe (0.0187 mg total), while the thermally altered argillite filtrate contained 0.037 $mg \cdot dm^{-3}$ of Fe (0.3145 mg total) (Kochmar *et al.*, 2024). Assuming equal volumes of altered and unaltered material in the Chervonohrad Concentration Plant waste pile (CCPWP), we take the average filtrate concentration to be 0.02 $mg \cdot dm^{-3}$ of Fe, corresponding to a total leached iron mass of 0.17 mg ($1.7 \cdot 10^{-7}$ kg).

Using these experimental data, we calculated the model coefficients a and b and derived the empirical relationship governing the dependence of leached iron mass on precipitation volume.

The modelling results reveal a clear relationship between the mass of iron leached per hour from the CCPWP and the volume of precipitation (Fig. 1).

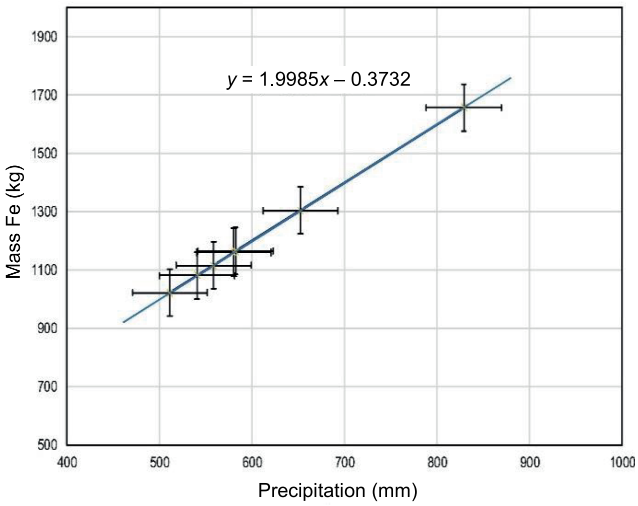

Fig. 1. Relationship between precipitation and the mass of iron leached from the Chervonohrad Concentration Plant (CCP) waste pile; source: own study

This dependence is described by the linear equation:

$$P = 1.9985 m_{\mathrm{Fe}} - 0.3732 \quad (10)$$

where: P = precipitation (mm), m_{Fe} = the mass of leached iron (kg).

Equation (10) can be rearranged to:

$$m_{\mathrm{Fe}} = \frac{P + 0.3732}{1.9985} \quad (11a)$$

or:

$$m_{\mathrm{Fe}} = 0.5004P + 0.1867 \quad (11b)$$

Assuming a mean annual precipitation of 607.9 mm, the model predicts that roughly 1212.5 kg of iron is leached from CCPWP per year or 24.8 kg of iron is leached per Mm^3 per year (0.0248 $Mg \cdot Mm^{-3} \cdot y^{-1}$). This corresponds to approximately 14.03 $kg \cdot ha^{-1} \cdot y^{-1}$ or 1.403 $kg \cdot km^{-2} \cdot y^{-1}$. Such leaching rates are environmentally significant, since even moderate concentrations of dissolved iron can alter the chemical composition of groundwater and affect ecosystem health through iron's role in biogeochemical cycles.

To find the intensity of change, you need to find the derivative:

$$\frac{dm_{\mathrm{Fe}}}{dP} = \frac{d}{dP}(0.5004P + 1.1867) \quad (12)$$

Based on the calculations using Equation (12), it can be stated that with every 1 mm increase in the mean annual precipitation, the mass of iron leached from the entire waste-pile volume (m_{Fe}) increases by approximately 0.5 kg per year, corresponding to a leaching intensity of 0.01 $kg \cdot Mm^{-3} \cdot y^{-1}$. The established linear dependence can be used to predict iron leaching rates under changing climatic conditions (increased precipitation) and to inform the design of environmental control and mitigation measures.

The following discussion places these findings in a broader global context.

GLOBAL EVIDENCE, LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Welch, Barbour and Hendry (2021) synthesised international data on metal leaching from coal-mine waste piles, demonstrating that iron losses depend strongly on pH, climate, and heap geometry. Under a neutral pH of 7.3, a volume-to-surface ratio (V:S) of 101, and a Dfc climate (Line Creek Operations, Canada), iron losses are very low (~0.00028 $Mg{\cdot}Mm^{-3}{\cdot}y^{-1}$). At pH 4.2, V:S of 7.4, and a Cfb climate (Morrison Busty, England), losses increase to 0.072 $Mg{\cdot}Mm^{-3}{\cdot}y^{-1}$; and under acidic conditions (pH 2.8), V:S of 2, and an Et climate (Bjørndalen, Norway), they rise to 3 $Mg{\cdot}Mm^{-3}{\cdot}y^{-1}$.

For the CCPWP (Dfb climate, V:S = 56.6), measured pH values of 7.07–7.52 place it close to Line Creek Operations, while its climate and V:S situate it between the Canadian and English sites. The observed iron-leaching rate of 0.0248 $Mg{\cdot}Mm^{-3}{\cdot}y^{-1}$ is therefore consistent with ranges reported for Morrison Busty and Line Creek Operations (Welch, Barbour and Hendry, 2021).

Key sources of uncertainty include analytical error in iron concentration measurement (±0.01 $mg{\cdot}dm^{-3}$), environmental variability (e.g.: pH fluctuations between 3.6 and 4.8 and temperature swings of ±3°C), and the inherent heterogeneity of heap materials. Forecasting iron leaching under various climate scenarios remains a critical practical concern: given potential increases in precipitation intensity, the derived relationship can be applied to estimate future contaminant fluxes.

Future research should expand the model to incorporate additional factors, such as soil moisture, pH, and temperature regimes, and to simulate the leaching of other potentially hazardous metals (e.g. copper, cadmium) from waste piles, while field monitoring and laboratory experiments conducted under varied climatic conditions will be valuable for validating the model. Given the likelihood of more intense precipitation events under climate change, it is essential to assess the impact of extreme weather on metal mobilisation dynamics. Characterising the chemical composition of spoil-heap filtrates and tracking its evolution over time will improve ecotoxicological risk assessments and support the development of effective neutralisation strategies.

Equally important is the incorporation of these insights into civil protection planning. The ability to forecast surges in iron (and co-contaminant) release during extreme rainfall events means that emergency services can be better prepared – for example, by pre-deploying water treatment units or issuing timely public warnings. Integrating predictive modelling into contingency planning can substantially reduce the risk of heavy-rainfall-induced leaching escalating into a public health emergency. A similar approach to predictive risk assessment has been successfully demonstrated in other environmental emergencies; for instance, operational oil-spill models are used to support civil protection authorities in preventing and responding to riverine or marine pollution events (CMS, CMCC, 2023; Kuzyk *et al.*, 2023).

CONCLUSIONS

This study developed and implemented a mathematical model of iron leaching from the Chervonohrad Concentration Plant waste pile using similarity theory to represent the underlying physical processes. The model confirmed a clear linear relationship between precipitation and the mass of leached iron, thus addressing the stated problem of predicting precipitation-driven iron mobilisation from coal-mining waste.

Laboratory column experiments on argillite, combined with dimensional analysis (π-theorem) and regression of the experimental results, yielded a concise predictive relationship for a unit spoil volume. Under the mean annual precipitation of 607.9 mm, the model indicates approximately 24.8 kg $Fe{\cdot}Mm^{-3}{\cdot}y^{-1}$. Scaled to the site volume (48.89 Mm^3), this corresponds to about 1,212 $kg{\cdot}y^{-1}$.

The mathematical model developed by the authors and the proposed method of its implementation provide a tool for quickly assessing the iron content in coal-mining areas. This supports environmental management, water-quality planning, and – critically – civil protection applications that require early warning, readiness for wet years, and timely mitigation to safeguard local supplies. This predictive approach helps civil protection agencies identify periods of highest contamination risk so they can take action to safeguard communities and water resources. In this way, the model contributes not only to long-term environmental management but also to acute emergency readiness in mining regions.

The approach abstracts complex geochemical behaviour into a transferable, volume-normalised metric while acknowledging limitations: microbial influences, pH variability, temperature effects, and heterogeneity were not explicitly parameterised, and field-scale hydrology may introduce additional uncertainty. Future work should extend the framework to multi-metal leaching, incorporate sensitivity to hydro-biogeochemical drivers, and validate predictions across contrasting spoil geometries and climatic conditions.

SUPPLEMENTARY MATERIALS

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_70_Karabyn.pdf.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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