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CLIMATIC VARIABILITY AND ITS IMPACT ON HYDRAULIC LOAD AND OPERATIONAL RISK IN ACID MINE DRAINAGE TREATMENT IN AN OPEN-PIT COPPER MINE

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ABSTRACT

This study presents a long-term assessment of acid mine wastewater treatment at an open-pit copper mine in the Republic of Bulgaria, with the aim of evaluating treatment efficiency, the influence of climatic factors on hydraulic loading, and associated operational risks. A comprehensive dataset covering the period 2015 - 2025 was analysed, including pH, concentrations of Cu, Mn and SO_4^{2-}*, mine water flow, and key meteorological parameters. The results demonstrate stable neutralization and consistently high removal efficiency of copper and manganese (> 93 %), with effluent concentrations remaining below regulatory limits. In contrast, sulfate removal remains limited and variable, reflecting the inherent constraints of neutralization-based treatment processes. A moderate positive relationship between monthly precipitation and generated mine water flow was identified (r = 0.5592, Pearson), enabling the development of an empirical regression model for predicting hydraulic loading. Based on this relationship, a three-tier hydraulic risk classification was proposed, incorporating a conservative safety factor to define operational thresholds under variable precipitation conditions. The proposed approach enables the use of forecasted precipitation as an early indicator of hydraulic load, supporting proactive and adaptive management of treatment facilities. The results highlight the importance of integrating monitoring and meteorological data to improve predictability, optimize resource use, and ensure stable system performance under changing climatic conditions.*

Keywords: *acid mine drainage, open-pit copper mining, water treatment, statistical modelling, hydraulic risk assessment.*

INTRODUCTION

Acid mine drainage (AMD) is one of the most serious environmental problems associated with the extraction and beneficiation of sulfide ores, due to its low pH and elevated concentrations of dissolved metal ions [1]. In open-pit mining environments, the generation of acid mine water is strongly influenced by both the mineralogical composition of the ore and the waste rock, as well as by climatic factors that control infiltration, surface runoff and the seasonal dynamics of water flow [2]. The resulting effluents often contain high levels of toxic elements such as copper and manganese, which can cause severe ecological damage through bioaccumulation and disruption of aquatic biota, while elevated sulfate concentrations contribute to salinization and alteration of the geochemical balance in receiving waters and soils. The treatment of acid mine water is typically based on neutralization and precipitation of metal hydroxides, which processes are highly efficient at removing Cu, Mn, and other metal ions but provide limited effectiveness in sulfate ions reduction [3, 4]. The conventional treatment of acid mine drainage primarily involves alkaline neutralization followed by precipitation of metal hydroxides, the most widely used and well-documented approach [5 - 7]. By adding an alkaline reagent (most often $Ca(OH)_2$ or CaO), the hydrogen ions in the acid waters are neutralized according to the general reaction presented in Eq. (1):

$$H^+ + OH^- \rightarrow H_2O \quad (1)$$

The increase in pH creates conditions for the subsequent precipitation of dissolved metal ions as sparingly soluble hydroxides [6, 8]. The primary mechanism for the removal of copper, iron, and manganese, involving the formation of solid hydroxide phases, can be described as in Eq. (2 - 4):

$$Cu^{2+} + 2OH^- \rightarrow Cu(OH)_2\downarrow \quad (2)$$
$$Mn^{2+} + 2OH^- \rightarrow Mn(OH)_2\downarrow \quad (3)$$
$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3\downarrow \quad (4)$$

Iron and copper are effectively precipitated at pH values of 6.0 - 8.0, whereas manganese precipitation requires higher pH values and/or longer contact times, which explains the observed greater variability in Mn removal efficiency [7, 9]. Recent studies have highlighted that climatic variability plays a crucial role in the formation and behaviour of acid mine drainage in open-pit mining environments [10 - 12]. Variations in temperature, precipitation, and evaporation directly influence the oxidation rate of sulfide minerals, the solubility and mobility of metal ions, and the hydrological balance within mine waste systems. Increased rainfall and extreme weather events can enhance infiltration and runoff, leading to larger volumes of AMD with fluctuating chemical composition, while prolonged dry periods may promote oxidation processes followed by the sudden release of highly acidic drainage during first-flush events. These dynamics also affect the performance and stability of treatment systems, as changes in hydraulic load, temperature, and influent chemistry can alter the efficiency of metal removal and the precipitation behaviour of hydroxides and sulfates. In this context, the integration of climatic data into operational risk assessment frameworks has been increasingly recognized as an important direction for improving system management [13].

Unlike metal cations, sulfate ions (SO_4^{2-}) do not participate directly in the precipitation reactions during neutralization and remain dissolved in the aqueous phase. Their partial removal may be due to dilution at increased water volumes, co-precipitation with calcium compounds, and changes in the mineralogical composition of the incoming water, while efficient sulfate removal generally requires dedicated treatment technologies [14 - 16]. This explains the lower and more variable efficiency in sulfate reduction compared to metal pollutants. The effectiveness of hydroxide precipitation for metal removal in AMD systems has been widely confirmed in experimental and field studies, particularly for copper and iron, while manganese removal remains more sensitive to process conditions [17, 18].

Despite the substantial body of literature, relatively few studies have applied an integrated approach combining long-term monitoring data, climatic variability, and risk assessment for operational treatment facilities. The present study contributes to this direction by analyzing ten years of monitoring data on acid mine water from open-pit copper mining, with a focus on the influence of precipitation on hydraulic load and the potential for risk prediction under changing climatic conditions, consistent with seasonal variability patterns reported for similar systems [19].

EXPERIMENTAL

The study is based on a long - term dataset covering the period 2015 - 2025, obtained from the operational monitoring of an active treatment facility for acid mine drainage generated in an open - pit copper ore mine in the Republic of Bulgaria. The monitoring program was carried out in accordance with national and European regulatory requirements for surface water and effluent quality control. Sampling was performed monthly at two points: (I) inflow of untreated acid mine drainage entering the treatment plant, and (II) treated effluent discharged from the facility.

Key meteorological indicators were obtained from a departmental meteorological station. pH values, dissolved metal concentrations (Cu^{2+}, Mn^{2+}) and SO_4^{2-} ions were determined in an accredited independent laboratory using inductively coupled plasma optical emission spectrometry (ICP - OES, VARIAN VISTA - MPX) following internationally accepted analytical standards.

To ensure data reliability, established QA/QC procedures were applied, including the use of field blanks, duplicate samples and certified reference materials. The analytical precision and accuracy were within acceptable limits for environmental monitoring studies. The limit of detection for heavy metals (Cu, Mn, Fe) was 0.001 mg L^{-1}.

The relationship between precipitation and the volume of generated mine drainage was evaluated using the Pearson linear correlation coefficient (r). A simple linear regression approach was applied to derive an empirical relationship between monthly precipitation and mine drainage volume. Given the natural variability of the system, the obtained relationships are interpreted as indicative rather than strictly predictive.

Treatment efficiency (η, %) for each parameter was calculated according to Eq. (5):

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \qquad (5)$$

where C_{in} and C_{out} are the concentrations of the studied component before and after treatment, respectively.

A qualitative risk classification was developed by combining the empirical relationship with a conservative safety factor to define operational thresholds corresponding to varying hydraulic loads of the treatment facility. This approach allows the translation of climatic variability into operationally relevant risk levels.

For visualization of seasonal patterns, a representative hydrological year was selected from the dataset. The selected year reflects typical intra-annual variability while also capturing recent climatic conditions characterized by increased temperature anomalies and precipitation variability, consistent with long-term trends (1979 - 2025) [20]. This year is used solely for illustrative purposes, while all statistical evaluations and interpretations are based on the full dataset covering the period 2015 - 2025.

RESULTS AND DISCUSSION

The analysed meteorological data exhibits pronounced seasonal patterns in precipitation and air temperature, which directly influence the hydraulic loading and operational behaviour of the treatment system [20]. As shown in Fig. 1, precipitation displays a clear seasonal distribution, with a primary maximum during spring (March - May), associated with rainfall and snowmelt, and lower values during the summer period. A secondary increase is observed during late autumn and early winter. These seasonal precipitation patterns are directly reflected in the inflow dynamics of the treatment system (Fig. 2), where periods of increased precipitation correspond to higher inflow volumes, while reduced hydraulic loading is observed during drier periods. This correspondence confirms the dominant role of precipitation as a controlling factor for hydraulic load.

Air temperature follows a typical continental regime (Fig. 1), with winter minima and summer maxima, resulting in a seasonal amplitude exceeding 30°C (max. 35°C). While temperature influences evaporation processes and reaction kinetics, its effect on hydraulic loading is secondary compared to precipitation, which is consistent with observations reported in similar studies on acid mine drainage systems [10 - 12].

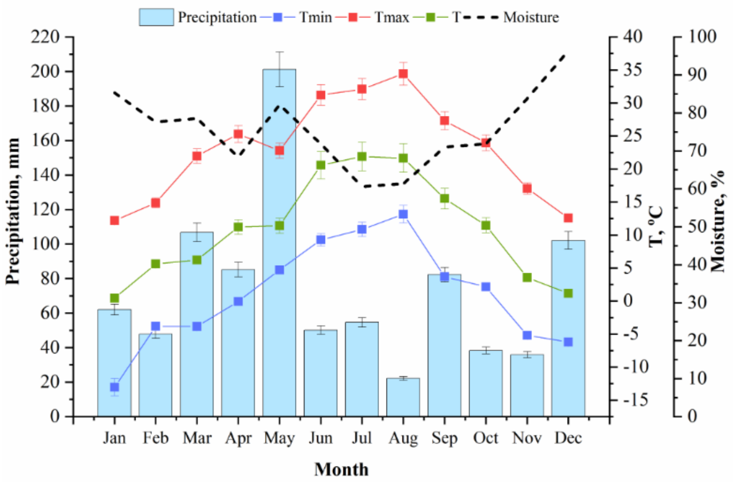

Fig. 1. Seasonal variation of precipitation and air temperature (2015 - 2025).

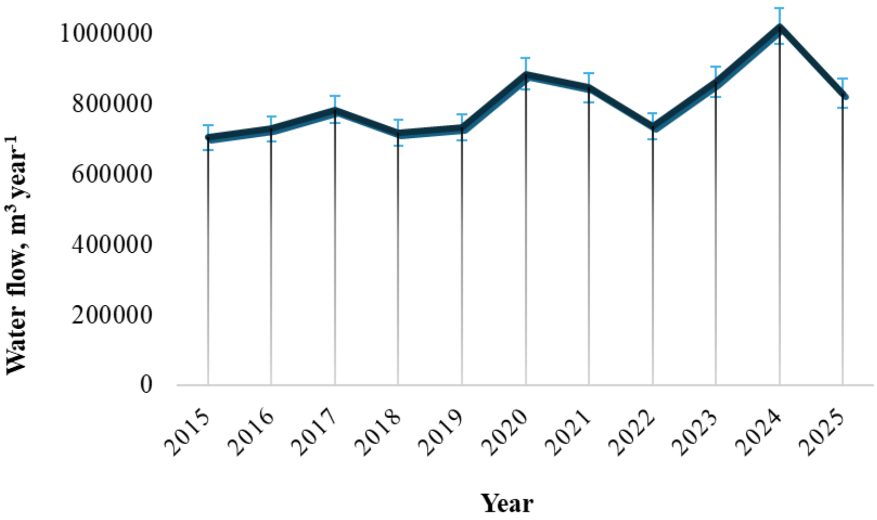

Fig. 2. Annual cumulative inflow of mine water to the treatment facility (2015 - 2025).

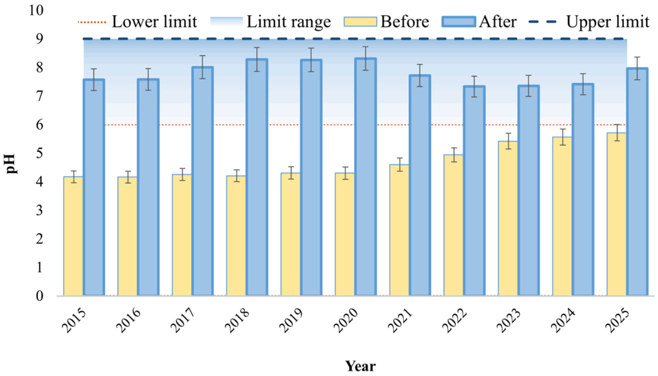

Fig. 3. Annual average pH values of acid mine drainage before and after treatment (2015 - 2025).

Fig. 2 presents the annual cumulative inflow of mine water to the treatment facility for each year within the period 2015 - 2025.

The annual inflow values (Fig. 2) exhibit moderate interannual variability, ranging approximately between 7.0×10^5 and 1.0×10^6 m^3 year^{-1}. Periods of increased inflow generally correspond to years with higher precipitation and enhanced surface runoff, confirming the dominant role of climatic forcing on hydraulic loading. Despite these variations, the system demonstrates relatively stable long-term behavior, indicating effective hydraulic management under variable environmental conditions.

The average annual pH values of acid mine drainage before and after treatment are presented in Fig. 3.

Prior to treatment, pH values range approximately between 4.2 and 5.7, characteristic of moderately acidic mine waters. Following treatment, pH stabilizes within the range of 7.3 - 8.3, consistently meeting regulatory requirements (pH 6.0 - 9.0). The low interannual variability indicates stable and reliable operation of the neutralization process, largely independent of climatic fluctuations.

Fig. 4 presents the annual average concentrations of Cu^{2+}, Mn^{2+} and SO_4^{2-} in mine water before and after treatment.

A consistent decrease in dissolved metal concentrations is observed over the study period, with effluent values remaining below permissible limits throughout. Copper removal is particularly effective, with concentrations in treated water remaining well below the regulatory limit of 0.5 mg L^{-1} and decreasing to

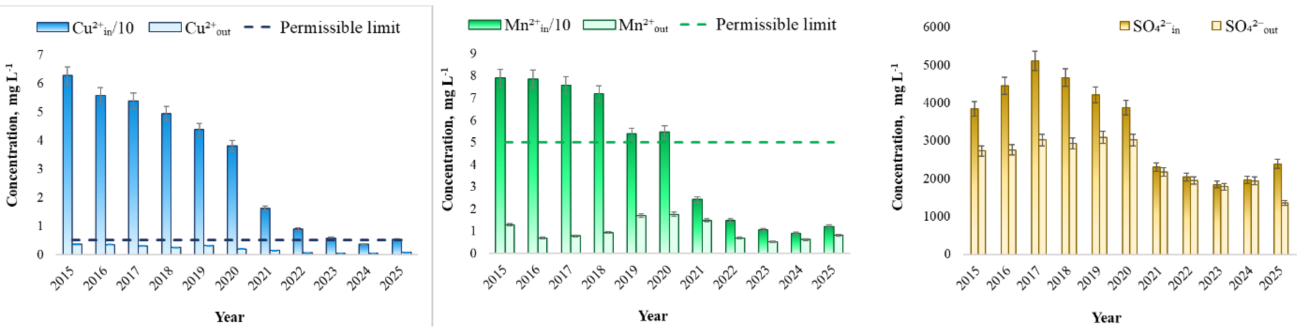

Fig. 4. Annual average concentrations of Cu^{2+}, Mn^{2+} and SO_4^{2-} in mine water before and after treatment (2015 - 2025).

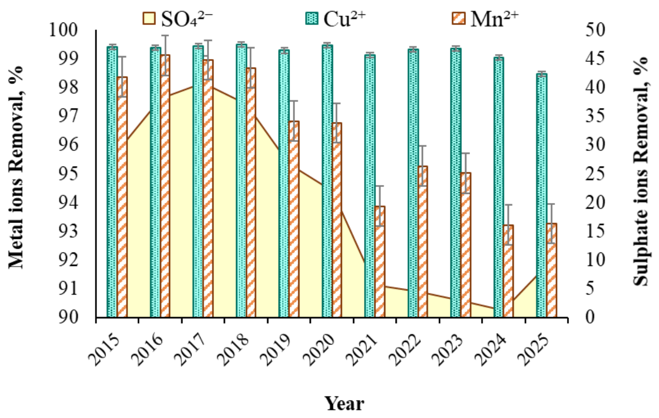

Fig. 5. Treatment efficiency for Cu^{2+}, Mn^{2+} and SO_4^{2-} removal, expressed as annual percentage reduction (2015 - 2025).

below 0.1 mg L^{-1} in the later years. Manganese exhibits greater interannual variability, reflecting its more complex precipitation behaviour and higher neutralization pH requirements. Nevertheless, Mn concentrations show a clear decreasing trend over time, stabilizing at approximately 1 mg L^{-1} or lower in the final years and remaining below the regulatory limit of 5 mg L^{-1}. In contrast, sulfate concentrations display higher variability, influenced by hydrological and geochemical factors. Treated effluent sulfate concentrations range approximately between 1400 and 3100 mg L^{-1}, with a gradual long-term decrease. The comparatively low sulfate removal efficiency is expected, as the applied treatment is based on neutralization and metal hydroxide precipitation rather than sulfate-specific removal mechanisms, which typically require advanced processes such as adsorption, membrane separation or layered double hydroxides [14 - 16].

The treatment facility demonstrates consistently high efficiency in dissolved metal removal from acid mine drainage (Fig. 5). Copper removal efficiency remains particularly high throughout the study period, ranging from 98.5 % to 99.5 %, resulting in effluent concentrations well below the regulatory limit of 0.5 mg L^{-1} and decreasing to below 0.1 mg L^{-1} in the later years.

Manganese removal efficiency shows slightly greater variability, consistent with its more complex precipitation behaviour and higher pH requirements, but remains above 93 % due to effective control of alkalinity, aeration and residence time. In contrast, sulfate removal efficiency is considerably lower (1.3 - 41 %) and more variable, as sulfate does not participate directly in

Table 1. Pearson correlation coefficients between mine water flow and climatic variables.

Relationship between variables	Correlation coefficient, r	Interpretation
Water flow - Precipitation	0.5592	Moderate positive correlation
Water flow - Temperature	- 0.3383	Weak negative correlation
Water flow - Humidity	0.4792	Moderate positive correlation
Precipitation - Temperature	- 0.1951	Very weak negative correlation
Precipitation - Humidity	0.3957	Weak positive correlation
Temperature - Humidity	- 0.8677	Strong negative correlation

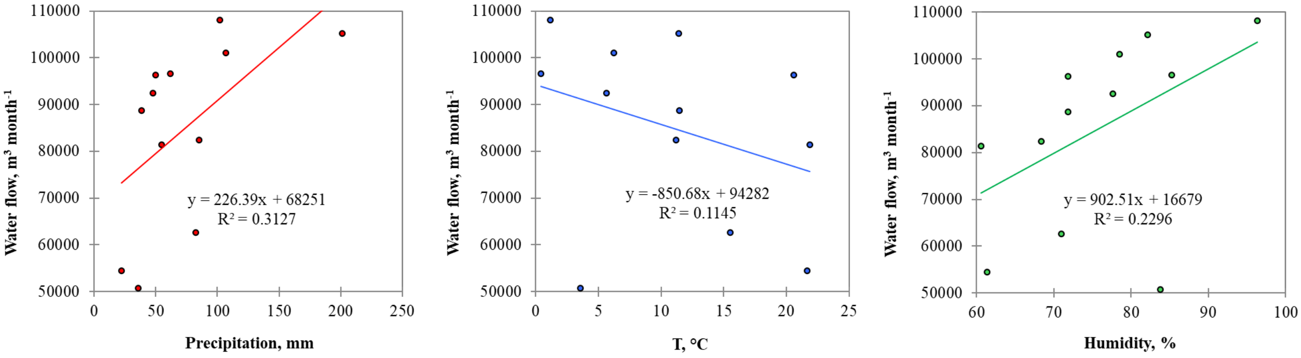

Fig. 6. Regression relationships between climatic variables (precipitation, temperature, and humidity) and mine water flow.

hydroxide precipitation. Partial sulfate attenuation may occur through dilution effects or co-precipitation with calcium or trace metals under specific conditions [14 - 16]. The observed behavior is consistent with literature data for neutralization-based treatment systems.

The combined analysis of pH evolution, metal removal and sulfate behavior indicates that the treatment system operates under stable geochemical conditions, where process efficiency is primarily controlled by alkalinity and hydraulic regime, rather than by short-term climatic variability.

The treatment process is based on conventional alkaline neutralization with lime, followed by sedimentation of the formed metal hydroxide sludge. The system operates under continuous flow conditions, ensuring sufficient mixing, pH control, and residence time for effective metal removal under varying hydraulic loads.

To quantitatively assess the influence of climatic variability on system behaviour, a statistical analysis was performed linking hydrometeorological parameters with generated mine water flow. The relationships were evaluated using Pearson correlation analysis (Table 1) and further explored through linear regression models (Fig. 6).

The results indicate that precipitation exhibits the strongest relationship with mine water flow (r = 0.5592), suggesting a moderate positive association. In contrast, temperature shows a weak negative correlation (r = - 0.3383), while humidity demonstrates a moderate positive relationship (r = 0.4792). A strong inverse correlation between temperature and humidity (r = - 0.8677) is observed, indicating potential multicollinearity between these variables.

Overall, the results confirm that precipitation is the primary climatic driver controlling hydraulic load, while temperature and humidity exert secondary and indirect effects. The moderate strength of the correlation reflects the influence of additional hydrogeological and operational factors, which is consistent with observations reported for similar mine water systems [10 - 12]. To further quantify these dependencies, linear regression models were developed for each climatic variable (Fig. 6). Among them, precipitation shows the most pronounced influence on mine water flow.

The Pearson correlation coefficient (r = 0.5592) corresponds to $R^2 = 0.3127$, indicating that approximately 31 % of the variability in water inflow can be explained by precipitation. However, the associated p-value ($p = 0.059$) indicates marginal statistical significance, suggesting that the relationship, although physically meaningful, does not strictly meet the conventional 95 % confidence threshold, although it remains physically meaningful. This reflects the complex and multivariate nature of the system, where additional hydrogeological and operational factors contribute to flow generation.

The empirical relationship between precipitation and mine water flow is described by Eq. (6):

$$Y = aX + b \tag{6}$$

where Y represents mine water flow (m^3 $month^{-1}$), X is precipitation (mm), and a and b are regression coefficients. Based on the analysed dataset, the relationship is expressed as in Eq. (7):

$$Y = 226.39X + 68251.22 \tag{7}$$

In contrast, the regression model for temperature shows a weak and statistically insignificant relationship ($r = - 0.3383$, $R^2 = 0.1145$, $p = 0.282$), indicating that temperature does not exert a direct control on flow variability. Similarly, although humidity exhibits a moderate correlation ($r = 0.4792$), its effect is likely indirect and linked to its interaction with precipitation and evaporation processes rather than acting as an independent controlling factor.

From an operational perspective, the empirical relationship obtained for precipitation allows estimation of potential hydraulic loading conditions. Considering the design hydraulic capacity of the treatment facility ($Q_{max} = 80$ L s^{-1}), corresponding to approximately 6912 m^3 day^{-1} or 207360 m^3 $month^{-1}$, this value represents a threshold above which hydraulic overloading may occur. Using Eq. (7), the precipitation level associated with potential exceedance of system capacity was estimated at approximately 615 mm $month^{-1}$, equivalent to ~21 mm day^{-1}.

For practical applicability, the relationship was further expressed in daily form (Eq. (8)):

$$Q = 2.42P + 26.27 \tag{8}$$

where Q is the flow rate (L s^{-1}) and P is the daily precipitation (mm day^{-1}). The corresponding correlation ($r = 0.535$, $R^2 = 0.286$) confirms a moderate dependence typical for real hydrological systems.

The relatively large scatter of the data around the regression line (Fig. 6) indicates the presence of additional controlling factors, such as hydrogeological conditions, delayed infiltration processes, and operational variability, which are not captured by precipitation alone. A key limitation of the applied regression approach arises from the use of monthly averaged data aggregated across different seasonal regimes. As illustrated in Fig. 1, the hydrological response of the system is not uniform throughout the year, as precipitation-runoff relationships are strongly influenced by seasonal factors such as temperature, evapotranspiration, and soil moisture conditions.

The use of monthly averaged data results in the superposition of distinct hydrological regimes within a single dataset. As a result, the observed variability can be partially attributed to the superposition of distinct seasonal behaviours within a single linear model. This effect is particularly relevant under temperate climatic conditions, where precipitation patterns and hydrological responses vary significantly between seasons. Therefore, the proposed regression model should be interpreted as an integrated annual approximation rather. This model is useful for identifying general trends and estimating hydraulic loading under average operating conditions.

The obtained relationship between precipitation and mine water flow provides a practical basis for estimating hydraulic loading under varying hydrometeorological conditions. Based on the design hydraulic capacity of the treatment facility ($Q_{max} = 80$ L s^{-1}), a critical precipitation threshold of approximately 22 mm day^{-1} (P_{crit}) was identified, above which there is an increased probability of hydraulic overload.

By introducing a conservative safety factor (SF = 0.8), an effective operational threshold of $Qeff = 64$ L s^{-1} was defined, corresponding to a warning precipitation level of approximately 15.7 mm day^{-1} (P_{warn}). These thresholds form the basis for the hydraulic risk classification presented in Table 2 and provide a practical framework for operational management. Under extreme precipitation events observed in the study area (~55 mm day^{-1}), the predicted inflow reaches approximately 150 - 160 L s^{-1}, i.e., nearly twice the design capacity. This confirms the occurrence of high-risk hydraulic conditions, associated with a substantial probability of system overload and reduced treatment efficiency.

Table 2. Hydraulic risk classification based on precipitation thresholds and predicted mine water inflow.

Risk zone	Hydraulic load	Precipitation, mm day^{-1}	Predicted inflow, L s^{-1}	Operational condition	Description
Zone I - Normal	Q < 0.8 Qmax	< 15.6	< 64	Normal operation	Hydraulic load remains below the effective operational threshold (Q_{eff}). Stable treatment performance is expected.
Zone II - Warning	0.8 Qmax ≤ Q < Qmax	15.6 - 22.1	64 - 80	Elevated load	Inflow approaches design capacity. Enhanced monitoring and process control are required.
Zone III - Critical	Q ≥ Qmax	> 22.1	> 80	Overload risk	Inflow reaches or exceeds design capacity (Q_{max}), with high risk of reduced treatment efficiency.

Three qualitative operational regimes were established based on predicted hydraulic load (Table 2).

The proposed classification enables the direct translation of climatic variability into operationally relevant risk levels. Under increased precipitation conditions, the predicted inflow may approach or exceed the design hydraulic capacity, indicating a potential risk of system overload and reduced treatment efficiency.

This classification represents a practical contribution of the present study, linking climatic variability with operational decision-making through clearly defined hydraulic thresholds. The approach allows the use of forecasted precipitation data as an early indicator for expected hydraulic loading, supporting timely planning of operational measures, including adjustment of process parameters and resource allocation. Such an approach is consistent with recent studies emphasizing the need for integrating climatic information into the management of mine water systems [10 - 12] but remains rarely applied in an operationally explicit form.

By translating meteorological inputs into quantitative operational thresholds, the proposed risk zones provide a practical tool for improving system responsiveness and supporting sustainable management of the wastewater treatment facility under variable hydrometeorological conditions.

This enables a shift from reactive to predictive operation of treatment systems, which is essential for optimizing resource consumption and ensuring long-term process stability.

CONCLUSIONS

This study presents a comprehensive ten - year assessment (2015 - 2025) of an active acid mine drainage treatment system in an open-pit copper mine, demonstrating consistently high removal efficiency of dissolved metals (> 93 %) and full compliance with regulatory discharge standards. In contrast, sulfate removal remains limited and variable (up to 40 %), confirming the inherent limitations of neutralization-based treatment processes.

The results identify precipitation as the primary climatic factor controlling hydraulic loading, with a moderate correlation (r ≈ 0.56) between precipitation and mine water inflow. This confirms the dominant role of hydrometeorological conditions in governing system inflow dynamics. A contribution of the present study is the development of a three-tier hydraulic risk classification (normal, warning, and critical), based on precipitation thresholds and predicted inflow rates. This classification enables the translation of climatic variability into operationally relevant decision criteria. Model projections indicate that extreme precipitation events (~ 55 mm day^{-1}) may result in inflow rates exceeding 150 L s^{-1}, approaching nearly twice the design capacity of the treatment facility, and thus representing a significant risk of hydraulic overloading and reduced treatment efficiency.

The integration of meteorological data with empirical modeling provides a practical tool for supporting predictive and adaptive management of treatment systems. This approach allows the use of forecasted precipitation as an early indicator for operational planning, including optimization of process conditions and resource consumption. Overall, the proposed methodology contributes to improving system resilience and supports the sustainable operation of wastewater treatment facilities under conditions of increasing climatic variability.

Authors' contributions

The initiators of the proposed article are A.G. and S.L. and contributed equally to the final manuscript. All authors considered the final manuscript and made valuable additions. The authors contributed significantly to the article and confirmed the presented version.

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