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Modeling of mine water pollution due to corrosion of flooded metal equipment: Ukrainian case

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ABSTRACT

This study presents an assessment and long-term forecast of corrosion processes in the flooded "Centralna" coal mine, located in Myrnohrad, Donetsk region, Ukraine. This mine is currently in the zone of active military operations. Coal mining has stopped and mining equipment is subject to uncontrolled flooding by groundwater. This flooding has resulted in significant hydrogeological and geochemical changes within the underground workings and adjacent aquifers. The research focused on evaluating the chemical composition of groundwater and its influence on the corrosion of metallic equipment flooded in the mine. Laboratory analyses of groundwater were conducted on 130 parameters, with key indicators including pH (7.7), electrical conductivity (3610 μS/cm), chlorides (267 mg/l), and sulfates (1030 mg/l). The composition of metal structures, including structural, carbon, alloy and high-strength steels, was studied. The total mass of the flooded metal equipment in the mining and development sections is approximately 3,300 tons. Despite the slightly alkaline pH, elevated concentrations of chlorides and sulfates, combined with high water conductivity, were found to significantly increase the corrosion potential of mine water. Expert assessments using an integral scoring system identified chlorides as the dominant corrosion factor (16.2 points out of 20), followed by conductivity (13.2) and sulfates (12.5). A predictive model was developed to estimate long-term corrosion rates and the corresponding increase in ferrous iron (Fe^{2+}) concentrations in the groundwater. Three corrosion rate scenarios (0.05, 0.1, and 0.15 mm/year) were examined over a 30-year period. Results indicated a gradual acidification of mine water, with pH decreasing to 6.67 and Fe^{2+} concentrations potentially reaching 325 mg/l. These processes are consistent with patterns observed in other flooded coal mines in Eastern Europe. The findings emphasize the importance of long-term monitoring of hydrochemical conditions in flooded mining environments to predict potential ecological risks associated with groundwater contamination by metals.

Keywords: groundwater, coal mine, flooded metal equipment, corrosion scenarios, forecast.

INTRODUCTION

Flooding of coal mines in the territories of military actions in Ukraine causes significant environmental problems related to water quality and the mobilization of heavy metals, including the release of metal into aquifers [Shvets et al., 2025; Bohomaz et al., 2025]. One of the key issues is the gradual long-term release of iron from flooded metallic equipment [Zbykovskyy et al., 2025].

Metallic equipment and structures in coal mines are always under aggressive corrosion attacks due to the humid atmosphere and abundant underground water streams [Fachikova et al., 2022]. The corrosion rates experienced in a mine can vary greatly depending on environmental variables and it is thus critical to characterise these variables to understand corrosion potential [Preston et al., 2019]. In underground mine workings, there are conditions that contribute to the occurrence of various types of corrosion. They have different intensities, depending on the type of equipment material, groundwater chemistry, the mineralogy of the strata, quality of mine air, temperature, presence of biological agents, and time of exposure to corrosive phenomena [Ciosmak and Parzniewski, 2023; Craig et al., 2015]. Among the main components that affect the corrosion rate of flooded metal equipment, the main ones are sulfates, carbonates, carbon oxides, sulfur oxides, chlorides, and nitrates. The main contributions to the corrosion aggression are due to existence of chloride and sulphate ions as a consequence of various technologies applied in the mining industries. Combinations of such aggressive components of aqueous media is stronger when pH is slightly lower than 7.0 or neutral [Farinha, 2011; Hassell et al., 2004]. The quality of mine water after flooding can vary considerably within the same geologic section due to many factors, such as the presence of carbonates, the length of time since mine closure and others [McAdoo et al., 2023]. The natural aggressive environment of mine waters is aggravated by the use of explosives and other chemicals in the mine, which accelerate and facilitate the mining processes [Fachikova et al., 2022].

The mine water may be acidic or neutral depending upon the pyrite content in the coal as inorganic impurities [Tiwary, 2001]. After mine closure, water pumping stops and the voids in the mines fill with water. As a result, the mine water is contaminated with substances that migrate into the water from the materials and equipment left in the mine. One of these substances is iron oxides [Cheong et al., 2012]. Metal equipment left in flooded mines corrodes under aerobic and anaerobic conditions. The corrosion processes are inhibited by some natural environmental factors, such as oxygen dissolved in mine water [Peng and Timms, 2020].

After mine closure and flooding, abandoned metal devices and equipment, as well as iron-containing minerals (e.g. pyrite) form a double iron pollution system in mine water. This water will remain acidic for a long time due to the continuous release of iron. The results of the experiments showed that at temperature below 25 °C and pH above 3.5, the rate of iron release decreases [Zhou et al., 2023]. The rocks of the mine workings come into contact with mine water. The acid-base balance of the mine water changes depending on the chemical composition of the rocks [Jiang et al., 2022]. The interaction of rock and water in flooded coal mines over long periods of time changes the pH of the mine water. This process affects the dynamics of Fe and Al dissolution in water. A mature mine-pool water quality is near equilibrium with iron sulfide, iron carbonate, and iron oxyhydroxide mineral phases [Perry, 2001]. Mine water is contaminated with heavy metals due to natural mineralization, coal mining, and other activities in the area. Elevated iron levels can also be caused by corrosion of metal mining equipment [Mahato, et al., 2014]. In regions with intensive underground coal mining, mixing of groundwater with contaminated mine water is a key factor in groundwater degradation [Siegel et al., 2022].

Temperate continental climate of the study area causes seasonal fluctuations in groundwater recharge and temperature, which further modulate corrosion kinetics and metal mobilization rates. Understanding the interaction between hydrogeochemical parameters and corrosion dynamics is essential for predicting the long-term behavior of metal contaminants and assessing risks to environment. Determination and monitoring of the chemical characteristics of mine waters is very important and plays a key role in understanding anthropogenic impacts on groundwater quality [Akburak et al., 2020].

Most studies of corrosion processes are devoted to finding the most resistant materials and metals. These approaches aim to improve safety, reduce production delays, and provide more accurate forecasts of mining equipment costs over a mine's lifespan. Studies have shown that corrosion-resistant alloys like Hastelloy G30 perform better than nickel-chromium-iron alloys in acidic mine water [Hango et al., 2014]. Research efforts include field studies with corrosion coupons, atmospheric monitoring, and laboratory evaluations to understand corrosion rates and develop mitigation strategies. Field observations suggest that corrosion rate as a function of resistivity depends on local rock mass formation [Chambers et al., 2019]. A methodology is proposed to contribute to the selection and design of support systems in corrosive environments [Dorion and Hadjigeorgiou, 2014]. In a coal mine, depending on underground conditions, the corrosion rate of galvanized parts can range from 0.01 mm/year to 0.70 mm/year [Wu et al., 2017].

Corrosion of metal structures and components affects the geochemistry of mine waters and creates long-term sources of pollution [Starovoit et al., 2021]. Abandoned or destroyed coal mines are significant environmental threats due to endangers water quality in surrounding aquifers

[Zbykovskyy et al., 2024]. The "Centralna" mine in Donetsk region of Ukraine is one such example where corrosion of flooded infrastructure may lead to prolonged iron leaching into groundwater systems.

Modeling of metal corrosion processes in mines is based on different approaches and scales. The methods and techniques for modeling corrosion processes cover first-principle, semi-empirical and empirical models. They are based on the electrochemical nature of corrosion. The absence of real long-time corrosion data derived from field testing, laboratory experiments and high-confidence models (mostly absent in the current literature) necessitates the development and application of mostly empirical approaches [Vachtsevanos, 2020]. Modeling of corrosion of underground mine degassing pipelines showed that the high level of corrosion processes in underground pipelines is the result of the interaction of the metal, which acts as an electrode, with groundwater, which acts as an electrolyte [Yegorchenko et al., 2024]. Atomistic modeling can be used to study the complex chemical reactions involved in metal corrosion processes. Computational modeling of atomistic processes allows to directly assess the applicability of various corrosion mechanisms to a particular materials/environment combination [Taylor, 2012]. Hydrogeological modeling showed that the dissolved oxygen mainly affected the uniform corrosion rate, while erosive ions increase local corrosion rates [Wu et al., 2023].

The aim of the study is to assess the impact of hydrogeological conditions of the "Centralna" coal mine on the corrosion processes of metal equipment, which was abandoned in the mine during its uncontrolled flooding as a result of military actions, as well as to predict the quality of groundwater in a region where there is a lack of drinking water sources.

MATERIALS AND METHOD

Study area

The study area encompasses the flooded "Centralna" coal mine, located in Myrnohrad, Donetsk region, Ukraine (Fig. 1).

This mine is currently in the zone of active military operations. Coal mining has stopped and all mining equipment has been left in the mine workings. Donetsk Coal Basin was one of the most intensively mined coal regions in Eastern Europe [Zbykovskyy and Shvets, 2022]. The "Centralna" mine, which operated throughout the 20th century, was closed due to the end of extraction activities in recent decades and decommissioned. The mine is currently susceptible to progressive groundwater flooding and surface water infiltration. This flooding has resulted in significant hydrogeological and geochemical changes within the underground workings and adjacent aquifers. Geologically, the area consists of Carboniferous coal seams interlayered with sandstones and shales. Several aquifers, separated by impermeable layers, are hydraulically connected to the flooded mine.

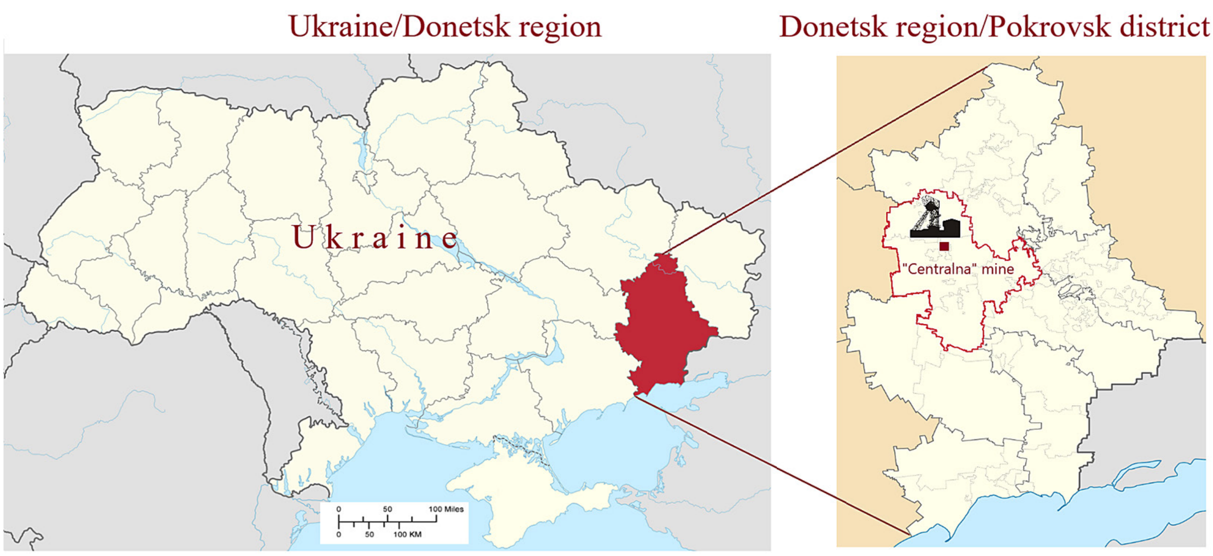

Figure 1. Location of the study area: "Centralna" mine, Donetsk region, Ukraine

Materials and methodology

The groundwater of the "Centralna" mine, where the mining and tunneling equipment was flooded, was studied according to 12 groups of parameters at the Chemical Veterinary Research Laboratory (CVUA) in Stuttgart, Germany. The total number of studied parameters was 130 [Bohomaz et al., 2025]. Table 1 shows the physical and chemical parameters of groundwater that influence the corrosion processes of mine metal equipment and contribute to an increase in the concentration of iron, aluminum, copper and other metals in mine water.

The assessment was based on information about the main and auxiliary equipment of the mining section (Table 2) and the development section (Table 3) of the "Centralna" mine and the characteristics of the metal it is made of. Metal equipment in a coal mine varies by type, purpose and materials. For subsequent assessment of corrosion processes, the equipment of the sections is classified into functional categories.

The mine equipment includes various metal components subjected to long-term flooding. The metal equipment of the flooded coal mine consists mainly of structural, carbon, alloyed, and high-strength steel, copper and aluminum. The chemical resistance of materials was analyzed based on their alloying characteristics, content of alloying elements and type of metal.

Based on the equipment data at the mining section, an inventory of abandoned equipment, its material composition, and the total mass of flooded metal were calculated. In the mining area of the "Centralna" mine, the total mass of metal equipment is 3,300 tons.

Table 1. Physical and chemical parameters of the "Centralna" mine groundwater

Parameter	Unit	Result
PH value	-	7.7
Electrical conductivity	μS/cm	3610
Chlorides	mg/l	267
Sulfates	mg/l	1030
Sodium Na	mg/l	620
Potassium K	mg/l	7.03
Calcium Ca	mg/l	121
Magnesium Mg	mg/l	78.5
Ammonium NH_4^+	mg/l	0.064
Nitrates	mg/l	1.47

RESULT AND DISCUSSION

Hydrochemical conditions in flooded mine

An analysis of the physical and chemical parameters of the groundwater in the "Centralna" mine showed that the metal equipment in the flooded mine is in a slightly alkaline environment with a pH of 7.7. The Pourbaix diagram (potential-pH diagrams) was used to predict the stability of metals and their corrosion products in aqueous solutions. This diagram is used to define the corrosion and passivation regions for metallic materials [Muñoz-Portero and Farinos, 2013; Hernández, 2012]. According to the Pourbaix diagram, the main product of iron oxidation will be Fe^{2+} and its oxyhydroxide. Thus, the aqueous environment with pH 7.7 of the "Centralna" mine promotes a low rate of metal corrosion.

On the other hand, there are factors that significantly accelerate the corrosion processes of the metal equipment of the "Centralna" mine. One of them is the high mineralization of the mine water. Mineralisation of water significantly affects its corrosivity [Astrelin et al., 2019]. For the "Centralna" mine, the electrical conductivity of the mine water is high and is 3610 μS/cm. This fact indicates the presence of a significant amount of dissolved salts capable of accelerating electrochemical corrosion processes since the ionic conductivity is high.

The main anions in mine water are chlorides (267 mg/l) and sulfates (1030 mg/l). Due to the pitting effect, ions such as SO_4^{2-} and Cl^- ions can cause corrosion of iron by destroying the passivation layer in the form of an oxide film on its surface [Yang et al., 2021; Wang et al., 2020]. The presence of chlorides is especially dangerous for metal structures in mine, as it promotes localized metal destruction. Chlorides promote an increase in electrical conductivity, which increases corrosion currents in electrochemical cells (anode-cathode), accelerating the destruction of the metal. Chlorides are especially dangerous for stainless steel and aluminum. High sulfate content will increase the overall corrosive effect, especially when interacting with different grades of steel. Among the cations, sodium dominates (620 mg/l), in combination with calcium (121 mg/l) and magnesium (78.5 mg/l). This ratio of ions indicates a significant salt composition of the water, which further increases its corrosive activity. The content of ammonium (0.064 mg/l)

Table 2. Metal equipment used at the mining section of the “Centralna” mine

Equipment/model	Number	Mass, tons		Metal used in equipment
		unit	total	
Longwall mechanized support and main workings support				
Section of mechanized support, model M103	120	3.2	384	High-strength steel
Arched metal yielding support	2240	0.35 t/set	784	Structural steel
Main mining equipment				
Longwall Shearer, model 1K101	1	11	11	Alloy Steel
Stage Loader, model PTK1	1	14.5	14.5	Structural steel
Winch, models LVD, LGKN	2	0.36	0.72	High-strength steel
Transportation and logistics				
Belt conveyor in the longwall gate, model 2L80U	1	410	410	Structural steel
Chain conveyor in the longwall with suspended equipment, model SP	1	52	52	Carbon and low-alloy steel
Rail track, model Rails R24	3280	0.024 t/m	78.72	Carbon steel, cast iron
Power supply and water drainage systems				
Power and control cables, model KGESH	1860	0.045 t/m	83.7	Copper, PVC, rubber
Water drainage and fire-fighting pipelines	2630	0.065 t/m	170.95	Structural steel
Other infrastructure				
Oil station, model SNT32	1	3.2	3.2	Carbon and stainless steel, aluminum
Local transformer substation, model TSVP	1	1.8	1.8	Copper, carbon steel
Set of starting and protection equipment	1	3.8	3.8	Carbon steel
Dust suppression system, model NUMS200	1	0.24	0.24	Carbon and low-alloy steel
Total mass of equipment			1998,63	-

and nitrates (1.47 mg/l) in mine water is insignificant and does not have a significant effect on corrosion processes. Photographs of groundwater in the coal mining area (Fig. 2a) and metal mining equipment left in the mining area (Fig. 2b) show their condition at the initial stage of flooding of the “Centralna” coal mine.

High mineralization, the presence of chlorides and sulfates create conditions for accelerated corrosion of flooded metal mining equipment. Even at a neutral pH, long-term exposure to this water will lead to gradual destruction of metal structures and increased transfer of iron ions into the aquatic environment. In the first years after flooding, the following processes are possible: an increase in the concentration of Fe^{2+} in the water, slight acidification of the water (due to hydrolysis of Fe^{2+}), a slight decrease in pH (to 6.5–7.2) and acceleration of the formation of $Fe(OH)_2$.

Integral score of groundwater parameters

Based on the analysis of the parameters of groundwater at the “Centralna” mine, an expert assessment of the degree of influence of each parameter on the corrosion of flooded mine equipment was carried out. The assessment of groundwater parameters at the “Centralna” mine was carried out in points from 0 to 20. The minimum score of 0 means no influence of the parameter. The maximum score of 20 means the maximum influence of the parameter. The evaluation was performed under conditions of anaerobic and slightly alkaline environment with a pH of 7.7, high mineralization, flooded carbon and alloy steel equipment. The influence of all parameters was assessed for three types of corrosion: uniform, pitting and crevice. The results of the expert assessment of the influence of water parameters on the corrosion processes of metal equipment for three types of corrosion are shown in Figure 3.

To calculate the integral score of groundwater parameters influence on corrosion processes, the weight coefficients of the significance of corrosion types were used in relation to flooded mine metal equipment (Table 4). The value of the weight coefficients was estimated from 0 to 1.

As a result of the calculation, integral score for each parameter was obtained. The calculation showed that the chloride content (16.2) has the greatest influence on the corrosion activity. Conductivity (13.2) enhances the action of chlorides

Table 3. Metal equipment used at the development section of the “Centralna” mine

Equipment/model	Number	Mass, tons		Metal used in equipment
		unit	total	
Main support of the workings				
Arched metal yielding support	1725	0.35 t/set	603.8	Structural steel
Main tunnelling equipment				
Road-Header, model GPKS	1	21	21	Alloy Steel
Trailer-Bridge Reloader	1	5.5	5.5	Structural steel
Winch, models LVD, LM	2	0.29	0.6	High-strength steel
Transportation and logistics				
Trolleys, model VG-1.5	5	1.1	5.5	Structural steel
Belt conveyor on a drift in a tunnel, model 2L80U	1	485	485	Structural steel
Rail track, model Rails R24	1 380	0.024 t/m	33.1	Carbon steel, cast iron
Power supply, ventilation and water drainage systems				
Ventilation Valve	1 380	0.0105	14.5	PVC Fabric
Ventilator for the local airing	2	0.52	1.0	Structural steel
Power and control cables, model KGESH	1 460	0.045 t/m	65.7	Copper, PVC, rubber
Water drainage and fire-fighting pipelines	1 380	0.065 t/m	89.7	Structural steel
Other infrastructure				
Local transformer substation, model TSVP	1	1.8	1.8	Copper, carbon steel
Set of starting and protection equipment	1	2.4	2.4	Carbon steel
Dust suppression system, model NUMS200	1	0.28	0.3	Carbon and low-alloy steel
Total mass of equipment			1 329,9	-


a)


b)

Figure 2. Condition of groundwater: (a) and corroded metal equipment, (b) at the initial stage of flooding of the “Centralna” coal mine

and other electrolytes. Sulfates (12.5) enhance localized corrosion, especially in anaerobic environments. Other components have a minor effect but can contribute to the formation of deposits. Figure 4 illustrates the integral score of the influence of groundwater parameters on corrosion activity

Corrosion of the flooded equipment

At the “Centralna” mine, the flooded equipment and structures consist of various metals, the mass of which exceeds 95% of the total mass of the equipment. The main metals are various types of steel (structural, carbon, alloyed and high-strength), copper and aluminum. Under normal conditions, structural steel has moderate corrosion resistance. When in constant contact with mine water, it is subject to hydraulic and chemical corrosion. Carbon steel is mainly subject to general corrosion and begins at welded and mating areas. Equipment made of alloy steel is more resistant to general corrosion, but in the early stages

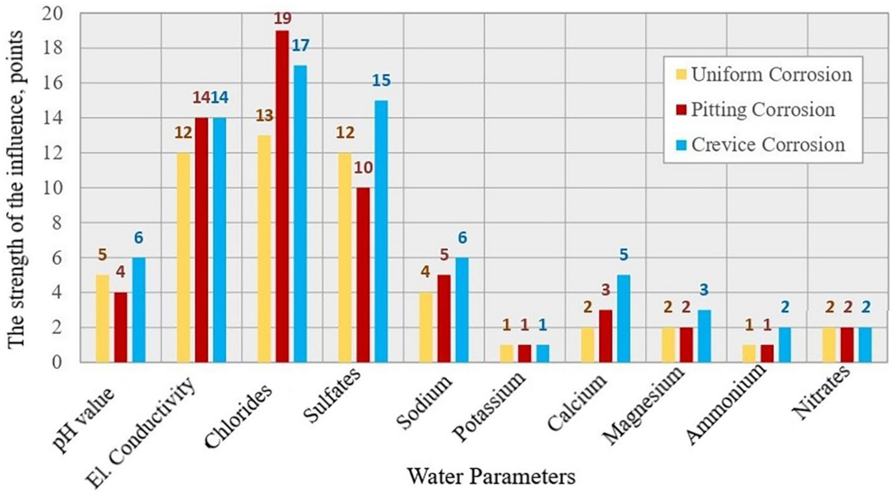

Figure 3. Evaluation of the influence of groundwater parameters of the "Centralna" mine on the corrosion of metal equipment for three types of corrosion

Table 4. Weighting factors for different types of corrosion

Type of corrosion	Weighting factor	Comment
Uniform	0.4	Basic type, especially for large surfaces
Pitting	0.3	Dangerous for alloy steels, risk of destruction
Crevice	0.3	Particularly dangerous under sediment and at slightly alkaline pH

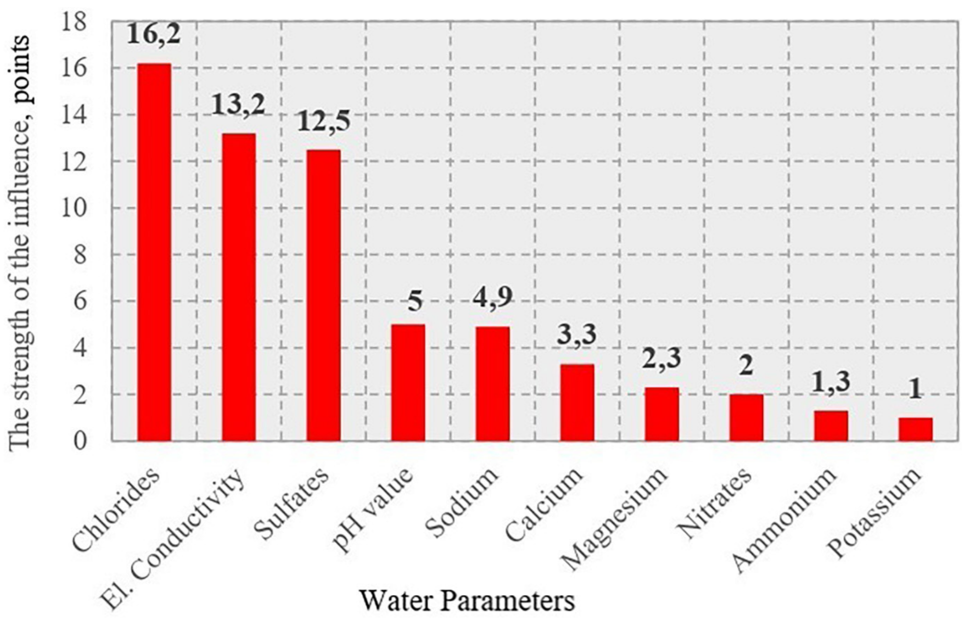

Figure 4. Integral score of the influence of the "Centralna" mine water parameters on corrosion activity

of flooding it is also subject to local corrosion, especially in areas of welded joints and microcracks. At the first stages of flooding, an oxide film forms on the surface of the flooded equipment, which prevents the occurrence and spread of corrosion. Subsequently, Cl^- ions present in mine water destroy the oxide film and the corrosion rate increases. Equipment that has high wear as a result of prolonged mechanical loads is highly susceptible to corrosion. These are tunneling and cutting machines, rails, conveyors, etc. Structural steel and carbon steel in worn-out equipment demonstrate high rates of general corrosion. The absence of anti-corrosion coating on equipment accelerates the corrosion of structures.

Forecast of pH level

After a mine is flooded, the pH of the groundwater may change due to oxidation-reduction processes and precipitation-dissolution processes occurring in the metal-water system [Fortes et al., 2017]. During the corrosion, H^+ ions will be formed, which will lead to a slight decrease in pH. The most significant factor in reducing pH is reactions with sulphide minerals (pyrite FeS_2), which are present in coal and rock:

$$FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (1)$$

However, this process will be limited by the buffer capacity of the system, as well as the formation of iron hydroxide sediment, which will reduce acidity. Under these conditions, the pH will gradually decrease, but sharp acidification of the groundwater is not expected. To predict the processes of corrosion and dissolution of iron in groundwater, it is important to calculate the expected pH level, which will determine the intensity of these processes. For this purpose, calculations of the predicted pH level in the metal-water system of the flooded "Centralna" mine were carried out. Empirical equations of pH level depending on the time of flooding were used. For calculations, a forecast horizon of 30 years was adopted. Correction factors in the equations are adopted on the basis of similar conditions of flooded coal mines [Blowes et al., 2014; Kavalsky and Viswanathan, 2024]. Approximation of the pH trend was carried out using the equations:

- for 1–15 years

$$pH_n^{1-15} = pH_0 - k_1 \times n \quad (2)$$

- for 16–30 years

$$pH_n^{16-30} = pH_{15} - k_2 \times (n - 15) \quad (3)$$

where: $k_1 = 0.05$, $k_2 = 0.02$ – empirical pH correction factors (rate of pH decrease per year); n – year; pH_0, pH_n – groundwater pH for the initial and n year.

Forecast of pH level of groundwater in the "Centralna" mine is shown in Figure 5.

According to the calculation results, the minimum predicted pH level will be 6.67. These processes correspond to real scenarios of coal mine flooding that took place in the Donetsk region in previous years. Rapid Acidification Zone (0–15 years) is characterized by a relatively intensive decrease in pH (from 7.7 to 6.95). This process is explained by acidification of the environment as a result of hydrolysis of Fe^{2+} ions. At the same time, pH decreases as a result of active corrosion of metal equipment, dissolution of salts and ion exchange. Slow Acidification Zone (16–30 years) is characterized by a slow decrease in pH (from 6.95 to 6.67). In this zone, the area of corroding surfaces decreases, the corrosion rate slows down due to the formation of $Fe(OH)_2$ deposits, hydrolysis processes and the buffering action of the solution are stabilized.

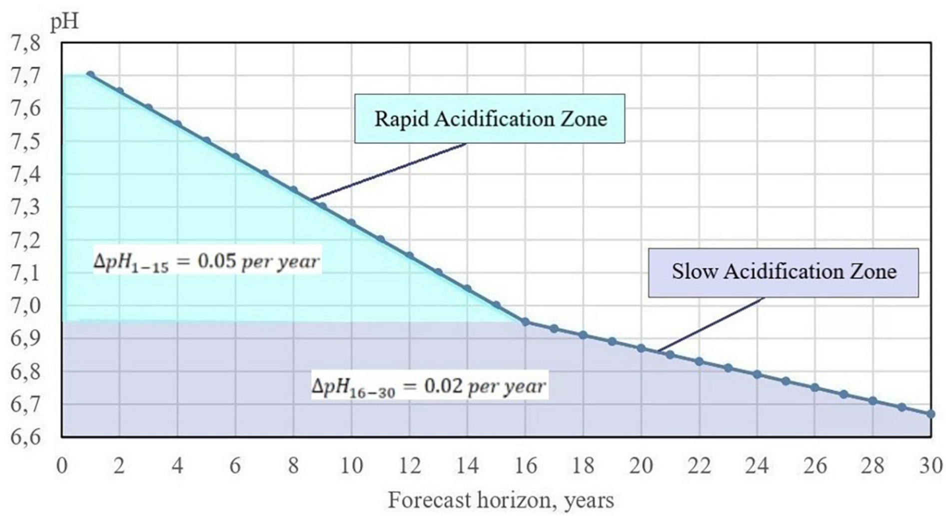

Figure 5. Forecast of pH level of groundwater in the "Centralna" mine

Forecasting methodology of corrosion processes

The forecast was developed based on a corrosion mass balance model that involves hydrodynamic, chemical and geochemical processes specific to flooded coal mines. Three corrosion scenarios were modelled to assess the projected accumulation of ferrous iron (Fe^{2+}) in the groundwater of the flooded "Centralna" coal mine. These scenarios were considered depending on the corrosion rate of the metal surfaces of the flooded mine equipment: 0.05 mm per year, 0.1 mm per year, and 0.15 mm per year. The temperature of the rocks in the mining area is approximately 40°C. Considering the fact that the corrosion rate increases 2–3 times for every 10 °C, then at 40 °C the corrosion rate will be 3–5 times higher than at a normal temperature of 10–15 °C [Zhang et al., 2022]. At these groundwater parameters and a temperature of 40°C, the typical corrosion rate of carbon steel without protective coatings is 0.1 mm/year [Preston et al., 2019]. The specific area of this equipment, taking into account large equipment and pipelines, is approximately 15 m^2 per 1 ton. The total surface area of flooded metal equipment in the mining section is 30,000 m^2, and in the development section is 20,000 m^2. Thus, the total area of the flooded metal equipment is approximately 50,000 m^2. The key input parameters of the hydrogeochemical conditions of the "Centralna" mine were used. The values of these parameters are given in Table 5.

For each year of the forecast horizon, the predictable parameters were calculated using the following equations.

Annual loss of metal mass:

$$\Delta M_n = S_n \times CR \times \rho \tag{4}$$

where: S_n – surface area, cm^2; n – flood period, years.

Reduction of corroding surface area:

$$S_{n+1} = S_n \times \frac{1 - \Delta M_n}{M_n + \Delta M_n} \tag{5}$$

where: M_n – mass of steel structures.

Dissolved Fe^{2+} contribution (considering precipitation):

$$Fe^{2+}_{dissolved} = \Delta M_n \times (1 - f_{os}) \tag{6}$$

- Precipitated Fe^{2+}:

$$Fe^{2+}_{precipitated} = \Delta M_n \times f_{os} \tag{7}$$

- Concentration Fe^{2+} in groundwater:

$$C_n = \frac{Fe^{2+}_{dissolved} \times 10^6}{V_n} \tag{8}$$

The change in pH is modelled as a gradual linear decline under the influence of cumulative Fe^{2+} release and pyrite oxidation, with empirical adjustments based on typical acidification trends in flooded coal mines.

Corrosion scenarios

As a result of calculations for three scenarios of dependence on the corrosion rate of metal surfaces of flooded mine equipment (0.05 mm per year, 0.1 mm per year and 0.15 mm per year), characteristics and patterns of corrosion processes were obtained. Among them are the following: annual mass loss, cumulative mass loss, dissolved Fe^{2+}, precipitated Fe^{2+} (Fig. 6).

The results obtained highlight the significant influence of corrosion rate on both the mass loss of metal structures and the subsequent release and behavior of Fe^{2+} in mine water. Analysis of annual mass loss (Fig. 6a) demonstrates a steady decline over time across all scenarios, directly related to the progressive reduction of the reactive metal surface area. The cumulative mass loss (Fig. 6b) increases

Table 5. The key input parameters of the hydrogeochemical conditions of the "Centralna" mine

Input parameter	Symbol	Value
Initial mass of steel structures	M_0	3300 metric tons
Initial corroding surface area	S_0	50,000 m²
Steel density	ρ	7.85 g/cm³
Corrosion rate scenarios	CR	0.05, 0.10, and 0.15 mm/year
Annual inflow of water (gradually reduced to zero by year 5)	V_o	5.694 million m³
Precipitation rate of Fe^{2+}	f_{o_s}	80% (range 70–90%)

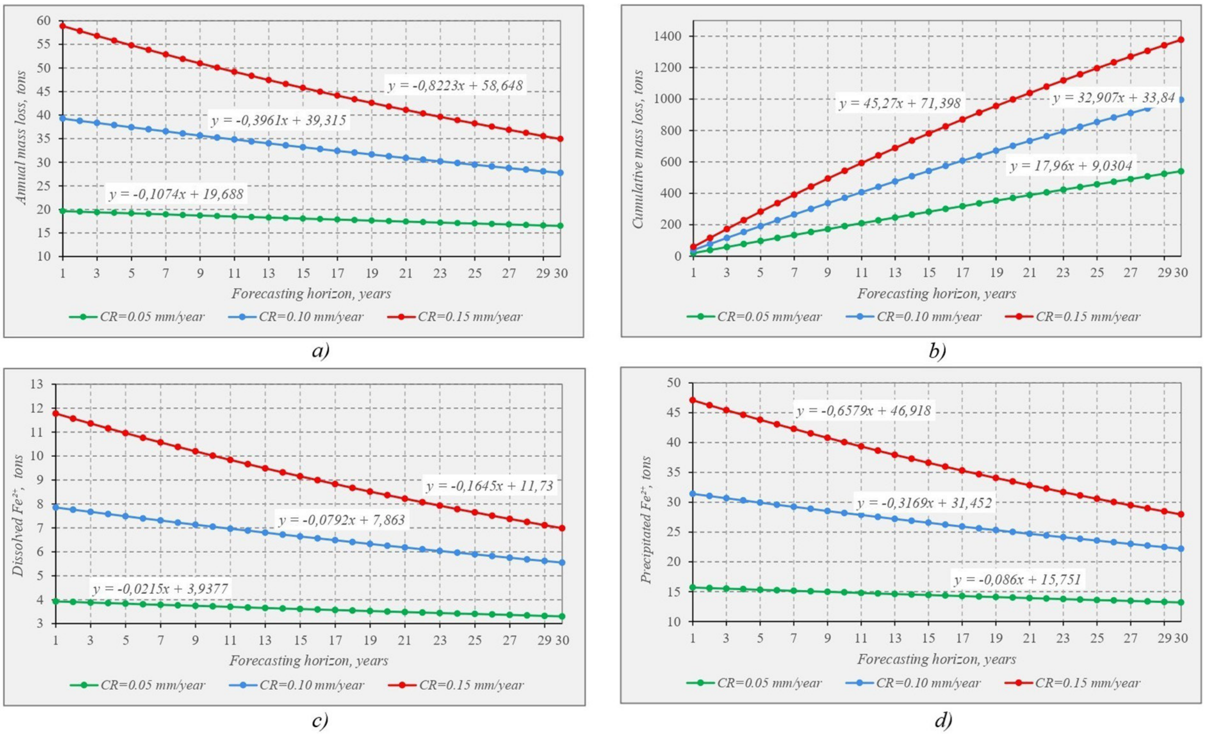

Figure 6. Models for predicting annual mass loss (a), cumulative mass loss (b), dissolved Fe^{2+} (c), precipitated Fe^{2+} (d) under three scenarios of corrosion rate of flooded metal equipment at the "Centralna" mine

linearly throughout the forecasting period. Under high corrosion conditions, up to one-third of the total mass of submerged metallic equipment may dissolve within three decades, posing a long-term environmental threat to groundwater quality. The forecast for dissolved Fe^{2+} concentration (Fig. 6c) also reveals a gradual decline in total dissolved mass over time. This reduction correlates with both the decreasing availability of metallic iron and partial precipitation processes occurring in the flooded mine environment. The precipitated Fe^{2+} (Fig. 6d), mainly in the form of $Fe(OH)_2$ under prevailing slightly alkaline conditions, shows a similar downward trend, particularly significant for the scenario with the highest corrosion rate. Overall, the modeling results emphasize that the flooded mine environment is characterized by an initially high but gradually declining intensity of iron release and precipitation processes. Moderate corrosion leads to significant cumulative inputs of iron into the aquatic system over the long term.

In terms of the total surface area of the flooded metal equipment, the mass rate of metal loss in the first year of flooding will be 39.25 tons. In this case, 7.85 tons of iron will dissolve in the mine water, and 31.4 tons of iron will precipitate in the form of $Fe(OH)_2$. By the 30th year, the rate of metal mass loss will decrease to 27.74 tons per year. With a total annual groundwater inflow into the "Centralna" mine of 5.694 million cubic meters, the increase in iron concentration in groundwater may reach 325 mg/l. The findings emphasize the importance of long-term monitoring of hydrochemical conditions in flooded mining environments to predict potential ecological risks associated with groundwater contamination by metals.

CONCLUSIONS

The study provides a comprehensive assessment of the hydrochemical conditions and corrosion processes in the flooded "Centralna" coal mine. The groundwater is slightly alkaline conditions with high mineralization, creating a favorable environment for corrosion of flooded metal equipment. The analysis revealed that while the initial pH of the groundwater is slightly alkaline, the presence of elevated concentrations of chlorides, sulfates, and high electrical conductivity significantly enhances the corrosive potential of the mine water.

Based on the analysis of the groundwater parameters at the "Centralna" mine, an expert assessment of each parameter influence on the corrosion of flooded mine equipment was carried out. Expert assessments using an integral scoring system identified chlorides as the dominant corrosion factor (16.2 points out of 20). Conductivity (13.2) enhances the action of chlorides and other electrolytes. Sulfates (12.5) enhance localized corrosion, especially in anaerobic environments.

The total flooded metal mass of 3,300 tons, combined with the high surface area of metal structures, leads to a significant potential for iron release into the aquatic environment. The developed predictive model demonstrates that over the next 30 years, corrosion processes will lead to substantial metal loss from the flooded mining equipment, contributing to the gradual enrichment of the groundwater with ferrous iron. The mass balance forecast model predicts that under typical conditions (0.1 mm/year corrosion rate), up to 7.85 tons of iron may dissolve annually in the initial years of flooding. Over 30 years, the concentration of dissolved Fe^{2+} in groundwater may increase up to 325 mg/l.

The predicted decrease in pH from 7.7 to 6.67 over 30 years indicates mild acidification, primarily stabilized by the precipitation of $Fe(OH)_2$ and buffering from the geological environment. The process will proceed in two phases: relatively rapid acidification during the first 15 years and a slower decrease thereafter.

The findings demonstrate the environmental risks of long-term groundwater contamination by metals in flooded coal mines, especially under elevated temperatures and ongoing anaerobic conditions. The study's findings can serve as a basis for designing groundwater monitoring programs and environmental mitigation strategies for flooded mining sites.

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