



The Use of Hydrochemical Zoning to Predict Water Hazards: The Example of the Olkusz-Pomorzany Zn-Pb Mine

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Abstract

A water hazard is one of the greatest dangers in mining and tunneling operations and the issue of predicting water hazard zones has been extensively discussed in the literature. However, the currently used methods require a highly detailed understanding of hydrogeological conditions or have major limitations and often produce unreliable results. This paper describes the use of hydrogeochemical anomalies as an indicator of impending mine water hazard zones. The proposed method uses the concentration of Cl ions in water extracts from Permian rock samples collected from the face of the mine workings. The concentration of Cl ions in the water extracts strongly correlated with the concentration of this ion in the pore solutions extracted from the same rock samples. Additionally, the concentration of Cl ions in the pore solutions exhibited a very strong correlation with the concentration from the Permian leaks. Thus, the decreasing concentration of Cl ions in the water extracts was deemed a reliable signal of an approaching water hazard zone. In the hydrogeological conditions present in the Olkusz-Pomorzany mine, this method enabled the detection of the moment when a water hazard zone was ≈ 200 –250 m away.

Keywords Water inrush · Prediction method · Mining · Water extract · Hydrogeochemical anomalies

Introduction

A water hazard is defined as the possibility of water or a mixture of water and loose rock material entering mine workings, creating a danger to the health and life of workers or the continuity of mine operations (Rogoż 2004). Next to rock mass failures and gas explosions, these are the most dangerous events in underground mines. Inrush of water into underground excavations, both in mines and tunnels constructed using mining methods, often results in the loss of many lives (Kong et al. 2022; Sun et al. 2015; Tajduś 2022; Zhang et al. 2020). Prevention of water hazards primarily involves reliable prediction of their location and taking appropriate actions to minimise the risk. The location of a water inrush, however, is exceedingly challenging to predict. First of all, the complicated hydrogeological

conditions near the mine workings is typically too poorly recognized to make predictions sufficiently reliable (Wang et al. 2022). Challenges related to predicting potential water inrush zones in mining excavations are extensively discussed in the literature (e.g. Li et al. 2017, 2023a; Liu et al. 2011; Ma et al. 2022a; Rogoż 2004; Xie et al. 2023; Zhang 2005).

Hydrochemical methods can be used to forecast the inrush of water or quicksand into mine workings. Descriptions of such cases are rare in the hydrogeological literature, likely because the use of these methods requires a marked difference in the chemical composition of water at the source of the hazard compared to the surroundings of the mining excavations. An example is the use of this method for predicting zones of possible water inrushes in mine workings from the overburden (Motyka et al. 1972), or for predicting sudden increases in water and mud inflows into mine workings (Pirc and Uhan 1991).

In this study, the first case of utilizing hydrochemical zonation to predict potential water inflows into excavations accessing zinc and lead ore deposits in the Olkusz-Pomorzany mine in the Olkusz region (SW Poland) is discussed.

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The mine was closed at the end of 2021 due to the depletion of ore resources.

Conventional Approaches to Water Inrush Risks

Various methods are used in mining to predict the locations of water inrush zones. The fundamental approach involves analyzing the geological structure of the rock mass, with particular emphasis on the identification of fault zones, from which water or quicksand inrushes into mining excavations may occur (e.g. d'Obryn et al. 2021). In the case of carbonate rocks, where karst systems may be developed, analysis of the geological structure as a whole is insufficient. Reconnaissance on a local scale (in each individual pit) is then necessary. For both fault zones and karst systems, common practice involves advance boreholes of up to several tens of meters in length. These drillings are carried out along the excavation axis and are occasionally supplemented with additional boreholes, drilled from the mine working face, spanning a few meters in length.

To identify water hazard zones, geophysical methods such as geoelectric and seismic methods are employed. The transient electromagnetic method (TDEM) is also used (Han et al. 2011). These methods can help locate permeable fault zones and areas with an increased density of fractures and karst channels. In certain cases, tracer methods (Vincenzi et al. 2008) can assist in identifying sources of water inrush; this has proven to be effective under certain conditions (Chen et al. 2019; Luo et al. 2022).

A separate group, proposed mainly by Chinese hydrogeologists, consists of calculation methods, GIS techniques, and simulation methods. Calculation methods include empirical equations (Cao et al. 2022; Dong et al. 2021; Li et al. 2023b; Shi et al. 2014; Wang et al. 2016; Zhao et al. 2023a; Zhang 2005), statistical methods of trend analysis and extrapolation (Hingley and Nicolas 2006), and mathematical models based on linear and nonlinear equations of filtration and geomechanics (Huang 2016; Hou et al. 2020; Hu et al. 2019; Kang et al. 2019; Li et al. 2017; Liang et al. 2023; Peng et al. 2020; Wang et al. 2012; Xiao et al. 2010; Xiang et al. 2011; Yin et al. 2022; Zhang and Zhong 2012). Empirical formulas and statistical methods tend to be less reliable in complex groundwater flow conditions. The use of mathematical models requires the acquisition of a large amount of data regarding geological structure and hydrogeological conditions, which greatly limits the use of these methods. A large volume of input data is also essential when employing discriminant analysis methods (Dong and Zhang 2023; Xue et al. 2023). Simulation methods such as similar materials simulation experiments (Sui et al. 2014; Wang et

al. 2020; Zhang et al. 2018), mechanical similarity experiments (Pang et al. 2014), or numerical simulations (Ma et al. 2022b; Wu et al. 2015) are also used. However, these methods often require simplifications of the hydrogeological conditions of the study area, which affects the quality and certainty of the developed predictions.

In the literature, researchers have also attempted to use the analytic hierarchy process (AHP) expert method, which involves a group of experts assigning subjective numerical weights to selected factors that affect the formation of water hazards in the mine workings (Song et al. 2021; Sun et al. 2014; Zhao et al. 2023b). The results thus obtained makes it possible to assess the degree of danger from the possibility of water intrusion into the workings. The results obtained in this manner enables an assessment of the threat level of a potential water inrush. However, a major drawback of this method is the subjective nature of the assessment, which, depending on the choice of experts, can vary within broad limits.

There have also been attempts to use GIS methods to locate water hazard zones (Dai et al. 2018; Liu et al. 2021; Wang et al. 2023; Wen et al. 2010; Wu et al. 2011). When combined with neural networks, they give satisfactory predictive results, but they are limited by the need to consider numerous factors and a complicated modeling process.

Rapid increases in water inflows into mines or their operational fields due to heavy rainfall are also considered within the category of a water hazard (Gao et al. 2018). To forecast such threats, rainfall infiltration models are used, with an example being the rainfall-runoff model (Kang et al. 2019; Luo et al. 2022). However, this model requires precise determination of the catchment area boundaries and parameters, making it less commonly applied in practice.

Hydrogeological and Hydrogeochemical Setting

The Olkusz zinc and lead ore mining region is part of the Silesian-Kraków monocline, consisting of Mesozoic formations that are slightly inclined in the NE direction. Paleozoic rocks, including Devonian, Carboniferous, and Permian, underlie the Mesozoic sediments, which are covered by Quaternary sediments. There are four identified aquifers in this area: Quaternary, Jurassic, Triassic, and Paleozoic (Carboniferous-Devonian) (Wilk and Motyka 1977).

The Quaternary aquifer primarily consists of medium-grained fluvioglacial sands with interbeds of gravel and weathered rock debris. It locally contains silts and clays. The thickness of the Quaternary water-bearing formations depends on the shape of the older bedrock and can reach several tens of meters in the axial parts of buried river

valleys formed in the pre-glacial period (Motyka 1988). The geometric mean value of the permeability coefficient, determined from the results of pumping tests, is 2.5×10^{-4} m/s (Motyka and Wilk 1976).

Jurassic formations are found in the northern and eastern parts of the Olkusz region (Fig. 1). The water-bearing strata are composed of Upper Jurassic limestones, which form the aquifer level of the Malm. These limestones are underlain by poorly permeable marls of the lower part of the Malm and the upper Dogger. Locally, marlstones and sandstones of the Middle Jurassic form a separate aquifer level (Różycki 1953; Tokarski 1958). Jurassic limestones serve as a fractured-karst type aquifer with a thickness up to ≈ 200 m. The geometric mean value of the permeability coefficient of Jurassic limestones, determined from the results of pumping tests, is 1.5×10^{-5} m/s (Motyka and Wilk 1976).

The Triassic aquifer in the Olkusz zinc and lead ore mining region is lithologically bipartite. In the lower section, it consists of sands and sandstones from the Middle and Lower Bunter Sandstone, often interbedded with claystones. In the upper part, it is composed of carbonate rocks from the Upper Bunter Sandstone (Rhaetian) and Muschelkalk. The Lower Bunter Sandstone formations occur as patches with a thickness of up to several meters, and thus have a limited effect on groundwater flow conditions. The dolomites and limestones of the Upper Bunter Sandstone (Rhaetian) and Muschelkalk constitute a fractured-karst-porous groundwater reservoir (Motyka 1998). Its total thickness reaches 130 m, and the geometric mean value of the hydraulic conductivity, calculated from the results of pumping tests, is equal to 6.5×10^{-5} m/s (Motyka and Wilk 1976). The dolomites of the Middle Triassic serve as the host rocks for lead and zinc

ore (ore-bearing dolomite). The presence of karst void systems in them has been the cause of localized water inrushes with a maximum discharge of ≈ 1 – 1.5 m³/s (Fig. 2).

The Paleozoic aquifer is composed of Lower Carboniferous limestones and Devonian dolomites and limestones interbedded with marls. The hydrogeological properties of this aquifer are poorly recognized. Only two pumping tests have been conducted in the carbonate rocks of the Paleozoic, yielding permeability coefficient values of 7.6×10^{-6} m/s and 7.0×10^{-5} m/s. In several boreholes, the presence of voids, likely karstic, ranging from 0.6 to 4.9 m in height, and karstic forms filled with fine-grained, laminated sediments, has been observed. Based on the current hydrogeological investigation results, the Paleozoic carbonate rocks are classified as a fractured-karst aquifer.

Predominantly in the area of the Olkusz zinc-lead ore mining region, the Triassic aquifer is underlain by Permian conglomerates. It is a typical Permian molasse, developed mainly as a monotonous series of poorly-sorted, red terrestrial conglomerates (Fig. 2), with insets of sandstones and mudstones. Permian deposits, with a thickness of up to 300 m, constitute a low-resource porous-fractured aquifer. On a regional scale, the Permian molasse has been interpreted to be an aquitard sandwiched between the overlying Triassic aquifer and the underlying Paleozoic aquifer. However, during mining operations in these rocks, zones with locally increased permeability (usually fracture systems) were often encountered, with water outflows ranging from tenths of L/min to several hundred L/min. In the Permian conglomerates, six pumping tests were conducted in two monitoring wells, and 26 slug tests were performed in 12 drilling wells. The permeability coefficient value of Permian

Fig. 1 Geological map of the Olkusz area

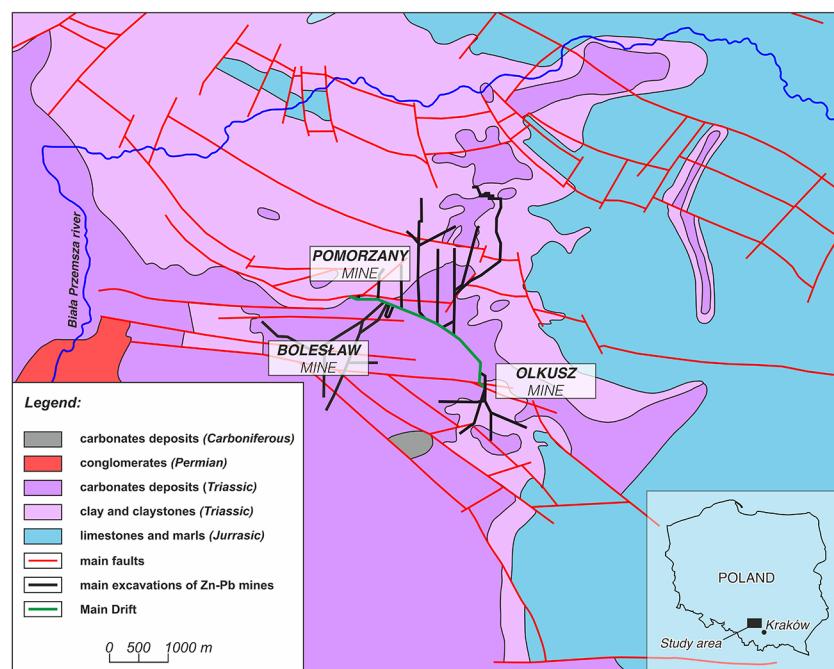
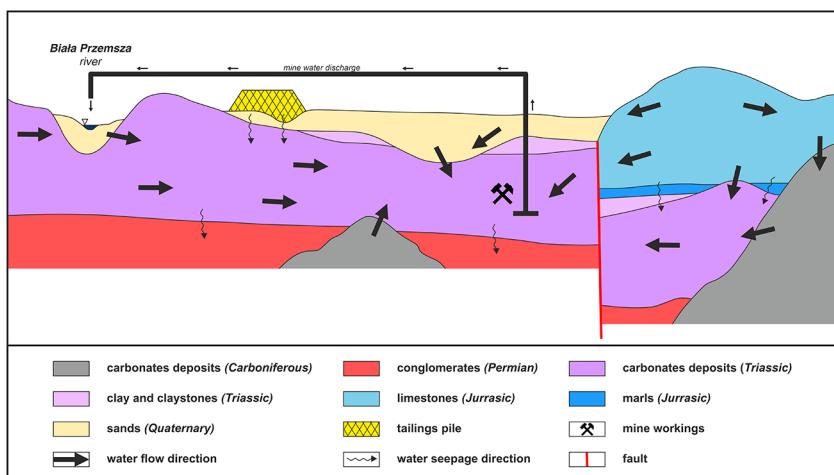


Fig. 2 Water inrush from ore bearing dolomites ca. $1.0 \text{ m}^3/\text{s}$ (Photo by J. Leśniak)



Fig. 3 Groundwater flow scheme in the Olkusz area under mining drainage conditions (based on Adamczyk and Motyka 2000)



rocks, determined from the results of these tests, fell within a wide range of values, i.e. from 2.5×10^{-8} to $5.4 \times 10^{-5} \text{ m/s}$ (Adamczyk et al. 1978).

Groundwater flow conditions in the Olkusz zinc and lead ore mining region are highly complex due to the diverse types of hydraulic connections between various aquifers (Fig. 3).

The primary hydraulic contacts of sedimentary-facial and sedimentary-transgressive types, as well as secondary contacts of erosional and tectonic types, have the greatest influence on water exchange between various aquifers. The Triassic aquifer, containing zinc and lead ores that were mined in the Olkusz region until 2020, is recharged through such hydraulic connections.

From the perspective of the issues discussed in this study, the chemical composition of groundwater in Triassic and Permian formations is of great importance. Natural

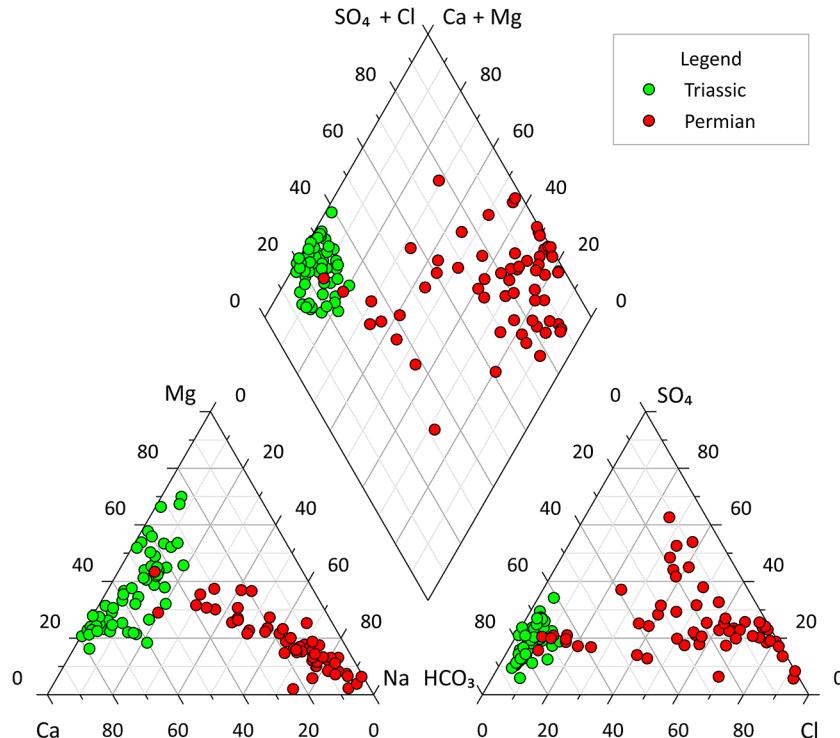
groundwater in carbonate Triassic formations in the Olkusz region have total dissolved solids (TDS) concentrations ranging from 100 to 590 mg/L, averaging about 280 mg/L (Różkowska et al. 1975). They are mostly of the Ca-Mg-HCO₃ or Ca-Mg-HCO₃-SO₄ type. According to Adamczyk and Wilk (1976), the average TDS of natural groundwater in carbonate Triassic rocks in the Olkusz region was about 340 mg/L.

Analyses of the chemical composition of natural waters from inflows into the mine workings within carbonate Triassic rocks in the Olkusz-Pomorzany mine have confirmed the results presented in the previously cited works. The TDS of these waters is most often 200–400 mg/L (Table 1) and they are, as localized in the environment of dolomites and limestones hosting zinc and lead ores, most commonly of the Ca-Mg-HCO₃ type and occasionally of the Ca-Mg-HCO₃-SO₄ type (Fig. 4).

Table 1 Aggregate results of Triassic water analyses

Parameter	Unit	Minimum	Maximum	Mean	Median	Std. dev.	Number of observations
Ca	mg/L	22.04	83.20	52.69	54.10	12.48	63
Mg		10.10	39.64	20.24	17.15	8.42	63
Na + K ¹		0.23	23.91	8.56	7.13	6.27	62
Cl		0.51	48.86	10.14	8.86	6.73	63
SO ₄		11.93	74.27	43.19	43.20	13.92	63
HCO ₃		152.55	283.74	213.68	216.62	25.17	63
TDS		244.00	409.00	348.38	347.00	34.39	63
pH	-	7.00	8.35	7.70	7.65	0.41	21

¹The analyses date back to the 1960s and 1970s, when Na and K ion content was determined as a combined value. Applies also to Table 2

Fig. 4 Piper diagram for Triassic and Permian water unaffected by mining activities**Table 2** Aggregate results of Permian water analyses

Parameter ¹	Unit	Minimum	Maximum	Mean	Median	Std. dev.	Number of observations
Ca	mg/L	4.48	1,483.00	154.50	56.11	255.84	60
Mg		10.21	538.92	85.35	41.34	113.51	60
Na + K		13.00	6,349.38	883.53	407.15	1,286.87	60
Cl		15.96	12,232.66	1,347.25	381.19	2,325.13	60
SO ₄		39.09	2,750.00	537.10	314.78	605.86	60
HCO ₃		6.10	366.10	238.18	250.18	67.12	60
TDS		369.34	21,669.80	3,250.07	1,665.42	4,408.57	60

¹pH values were not determined for Permian water samples

The hydrochemical type of Permian waters changed depending on the TDS (Table 2). Fresh waters, i.e. with TDS below 1000 mg/L, were multi-ionic, with different combinations of proportions of major ions. Within this group of waters, the following hydrochemical types were identified: Ca-Mg-Na-Cl-SO₄-HCO₃, Na-Mg-Ca-Cl-SO₄-HCO₃, Na-Ca-Mg-HCO₃-Cl-SO₄, Na-Mg-Ca-HCO₃-Cl,

and Ca-Mg-HCO₃. A discernible pattern emerged, wherein an increase in TDS corresponded to a rise in the proportion of magnesium and sodium among cations, at the expense of calcium. Simultaneously, among anions, there was an elevation in the proportion of sulfates and chlorides, at the expense of bicarbonates.

In Permian water samples with a TDS ranging from 1 to 10 g/L, sodium predominated among cations, while at lower TDS, magnesium, and calcium were present at higher concentrations. Among anions, bicarbonates dominated in waters with TDS of about 1 g/L, and as TDS increased, sulphates became more prevalent, with chlorides exhibiting the highest mmol/L percentage in waters with a TDS of about 10 g/L. Consequently, the majority of waters in this TDS group exhibited a Na-SO₄-Cl, Na-Cl-SO₄, and less frequently Na-SO₄ type. In the group of saline waters with a TDS > 10 g/L, sodium and chloride ions dominated. In waters with a TDS slightly > 10 g/L, elevated concentrations of sulphate ions were observed, and they were of the Na-Cl-SO₄ type. Waters with higher TDS were characterized as a Na-Cl type. The proportions of concentrations of individual ions in Permian conglomerate waters under natural conditions varied depending on their TDS. For cations, a distinct trend was evident with the shift from Ca, Mg → Na, while for anions, two less pronounced trends were observed: HCO₃ → Cl and Cl → SO₄ (Fig. 4).

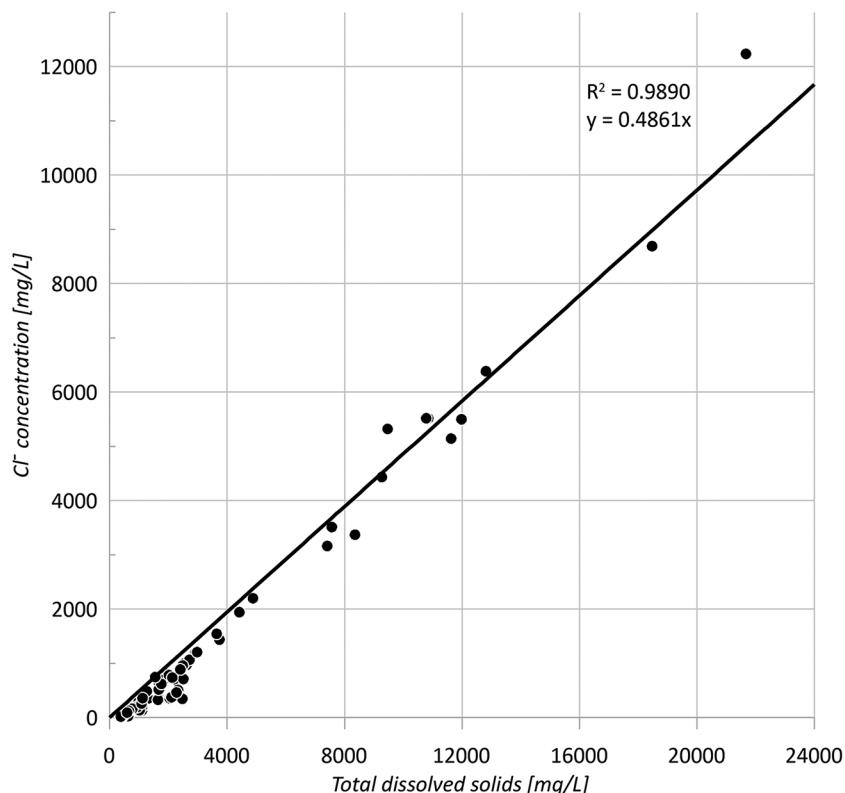
Methods and Method Description

A typical method for identifying water hazard zones in Poland has been the drilling of advance boreholes parallel to the direction of mining operations. According to current Polish safety regulations, they must advance the front of the excavation by at least 50 m. Within these boreholes, measurements are taken of

water flow rates, if such flows occur, as well as the pressure of the outflowing water. Drilling such boreholes poses a logistical challenge as it needs to be synchronized with the pace of mining progress. In practice, it may be necessary to temporarily halt mine workings to allow boreholes to advance the face of the gallery by the required 50 m. In addition, drilling advance boreholes is also expensive. The hydrochemical method for predicting water inrush zones is practical and much more cost-effective than drilling. However, certain hydrogeological conditions must be met to allow its application.

The hydrochemical method can be applied under conditions characterized by a distinct difference in concentrations of easily measurable components in the water within the aquifer posing the risk of water inrush and in the formations in which the mining works are carried out. This condition was met in the described case of the main excavation accessing the zinc and lead ore deposit (Main Drift) at the Olkusz-Pomorzany mine, particularly for Cl⁻, which are easily measurable conservative ions. In the poorly permeable Permian conglomerates, mineralized waters were present at the Main Drift level, while in the adjacent carbonate Triassic rocks, freshwater was found. The waters of the Triassic aquifer, from which water inrush into the Main Drift could occur, had low Cl⁻ concentrations (Table 1). In the Permian conglomerates water outflows, the Cl⁻ concentration exhibited a wide range, from 16 to 12,200 mg/L (Table 2). This ion's concentration strongly correlated with TDS (Fig. 5), making it a suitable TDS indicator for the discussed hydrochemical method.

Fig. 5 Relationship of Cl⁻ concentration to TDS in leakage water from Permian rocks



The discussed hydrochemical method was developed based on comprehensive studies carried out in workings located in Permian conglomerates. These studies involved analyses of the chemical composition of water leaks, analyses of Cl^- concentrations in pore solutions extracted using a hydraulic press from Permian rock samples collected as the face advanced, and analyses of Cl^- concentrations in water extracts at a liquid/solid ratio (L/S) of 5:1 from rock samples. One part of the samples underwent hydraulic pressing, while the other part was used to prepare a water extract. The moisture content of each rock sample was determined before preparing the water extract. The concentration of Cl^- in leaks, pore solutions, and water extracts was determined using the argentometric titration method. Considering the moisture weight (M_w) of the sample and the L/S ratio and assuming that the entire Cl ion content was present in the rock in the form of an aqueous solution in the pore space, the Cl_e concentration (mg/100 g) from the eluate was converted to the Cl_p concentration in the pore solution, according to the formula:

$$Cl_p = 10 \frac{Cl_e}{M_w} \quad (1)$$

The concentration of Cl^- in water samples collected from leaks in excavations drilled in Permian shales increased with depth, measured from their roof, and clearly aligned

along two distinct trends. One of these trends represented a set of leaks where the concentration of Cl^- increased following the expected pattern of TDS growth with depth. The other trend included a collection of leaks with anomalously low concentrations of the discussed ion, showing slight variations with depth (Fig. 6).

Leaks with anomalously low concentrations of Cl ions occurred near faults or close to the roof of Permian formations. They also exhibited much higher outflow rates than those aligning along the normal trend of hydrochemical zonation. Therefore, they indicated areas of potential water hazard for excavations located in Permian rocks. These patterns formed the basis for the proposed method of identifying such zones, with the assumption that it should be straightforward and practical in application. These conditions were met by the aforementioned method using water extracts. The validity of applying this method was verified in two steps.

In the first stage, the relationship between the Cl^- concentration in pore solutions and the concentration of these ions in water leaks was examined, considering only rock samples taken to obtain pore solutions in the vicinity of individual leaks. The Cl^- concentration values in pore solutions and leaks demonstrated an almost deterministic relationship (Fig. 7A). In the second stage, the correlation between the Cl^- concentration in water extracts and the concentration of these ions in pore solutions was checked, revealing a very

Fig. 6 Changes in Cl^- concentration in water from leaks in the Main Drift with depth, measured from the Permian roof

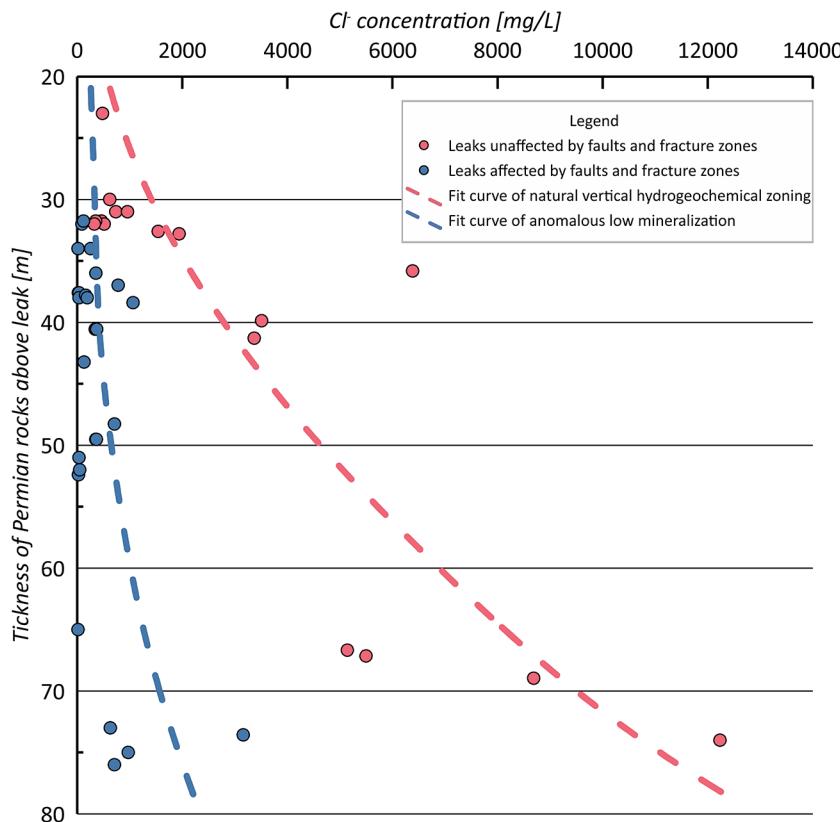


Fig. 7 (A) Relationship of Cl^- concentration in seepage waters to Cl^- concentration in pore solutions; (B) Relationship of Cl^- concentration in water extracts to Cl^- concentration in pore solutions

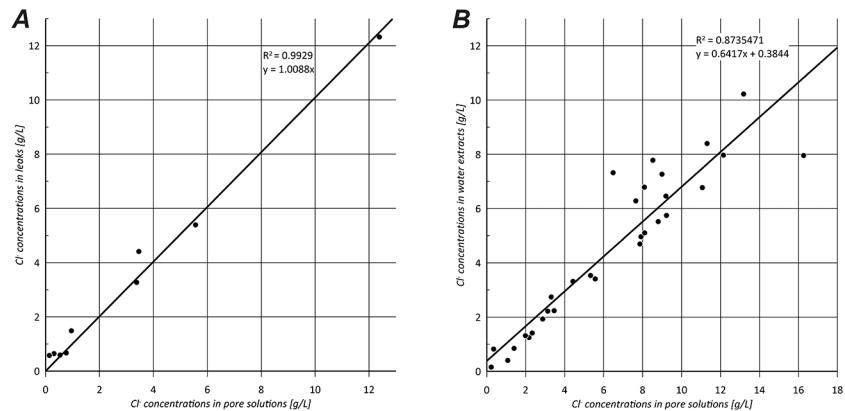
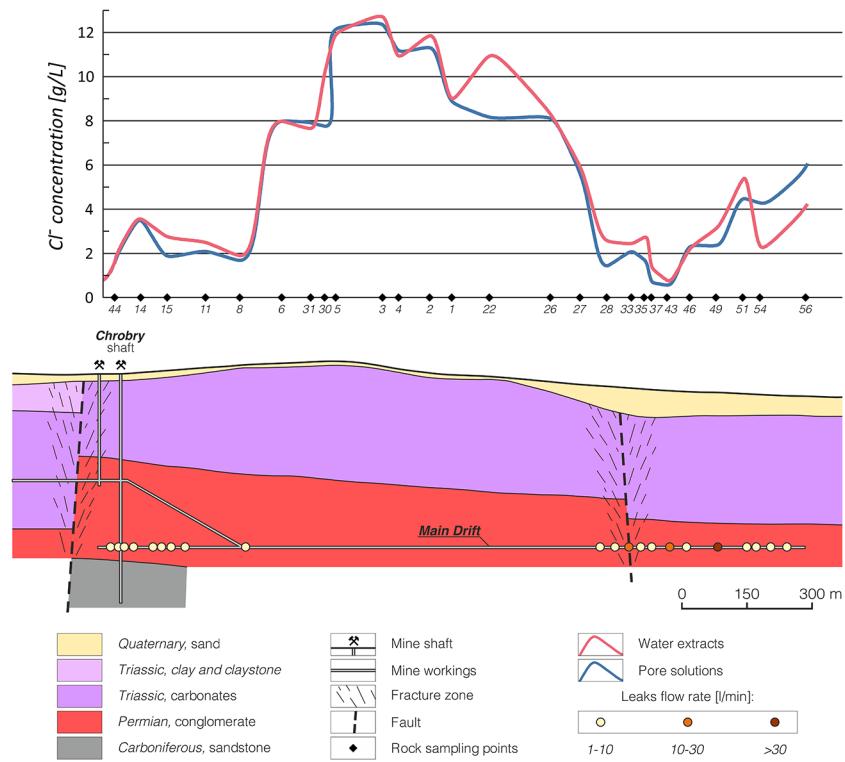


Fig. 8 Changes in Cl^- concentration in pore solutions and water extracts from Permian conglomerates along the initial section of the Main Drift



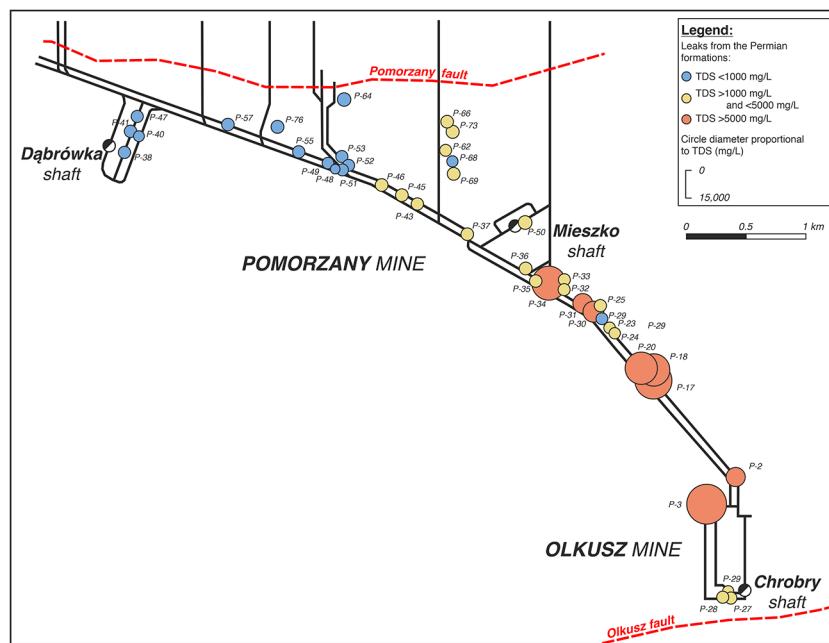
strong relationship as well (Fig. 7B). Thus, the Cl^- concentration in samples of Permian conglomerates collected during mining works could be applied to predict water hazard zones.

The discussed method for predicting water hazard zones was tested on the initial section of the Main Drift. A visible decrease in the Cl^- concentration in pore solutions and water extracts was observed in the areas of fractures accompanying faults, even with minimal throw (Fig. 8). At the same time, these zones hosted water leaks with higher outflow rates and lower TDS. A reduction in Cl^- concentration was also associated with the drift approaching the roof of Permian formations due to the inclination of the strata. This pattern was confirmed in other excavations carried out in Permian rocks (Fig. 9).

The conducted research has revealed favorable conditions for the application of the proposed hydrochemical method in the Olkusz-Pomorzany mine to detect faults and fracture zones that pose a water hazard to mining activities carried out in Permian rocks. A decrease in Cl^- concentrations in pore solutions and water extracts from these rocks, which is indicative of a decrease in TDS value due to the influence of freshwater from the overlying strata, signals the approach of the excavation to a potential water inrush zone. This signal appears ≈ 200 – 250 m ahead of the water hazard zone (Fig. 8). This range is notably greater than that achieved with costly advance boreholes, which had a length of ≈ 100 m.

The assessment of the impact of freshwaters on waters with higher TDS could also benefit from EC measurements.

Fig. 9 TDS diagrams for water from leaks from the Permian formations at the Pomorzany and Olkusz mines



It can be presumed that the correlation between TDS and EC would be as significant as with chlorides. However, during the measurements conducted at the Olkusz-Pomorzany mine in the 1970s, conductivity meters were not available in Poland.

Conclusions

Hydrochemical methods for predicting water hazard zones in mine workings gives promising results, but a crucial requirement for their application is a noticeable difference in the chemical composition of water at the source of the hazard and in the surrounding vicinity of the mine workings. The method described in this paper, which was developed during mining operations in the Permian conglomerates at the Olkusz-Pomorzany mine, fulfills these conditions. The Permian conglomerates have low permeability and water outflows in the workings located within them occur in fracture zones, which typically surround faults. Above them, there are Triassic carbonate rocks, which form a fracture-karst groundwater reservoir. Water inrush into excavations in the Permian rocks through the aforementioned fracture zones was possible from this aquifer.

The TDS of the Triassic aquifer ranged from 200 to 400 mg/L, while in Permian rocks, it ranged from 370 to 21,700 mg/L. Notably, in water leaks with decreasing TDS, there was an increasing proportion of water from Triassic formations, indicating their association with water hazard zones. A useful indicator of the excavation's proximity to the water hazard zone was the conservative chloride ion, which exhibited a strong correlation with TDS. Additionally, the

determination of this ion using the argentometric titration method is straightforward and does not require complex equipment. In the waters of the Triassic aquifer, the Cl^- concentration ranged from 0.5 to 49 mg/L, while in Permian rocks, it ranged from 16 to 12,200 mg/L.

It was assumed that the proposed hydrochemical method for detecting water hazard zones should be simple and effective. To achieve this, the concentration of Cl^- ions in water extracts from samples of Permian conglomerates was used, which were collected from the face of the Main Drift. The concentration of Cl^- ions in water extracts showed a strong correlation with the concentration of this ion in pore solutions obtained from the same rock samples as the water extracts. The correlation of Cl^- concentration in pore solutions and in water leaks from Permian rocks was also very strong. Therefore, the decrease in Cl^- concentrations in water extracts was considered a reliable signal of approaching the water hazard zone. This signal appeared ≈ 200 –250 m ahead of the hazard zone, much earlier than in the case of horizontal advance boreholes ahead of the excavation, typically by about 100 m.

The proposed method yields good results in conditions where a marked difference in water chemistry is observed between the rocks where mining operations are conducted and those from which water may inrush into the mine workings. In the case of the Olkusz-Pomorzany mine, this contrast was evident between the Permian waters with high TDS and Cl^- content and the Triassic waters with low TDS and low Cl^- content. The influence of freshwater became apparent as the workings approached zones of fractures and faults, indicating areas of potential water hazard.

Currently, in mines prone to sudden water inrushes into workings, EC measurements could also be conducted at leaks. This would enable EC changes to be monitored, and in the event of such occurrences, prompt actions could be taken to investigate the phenomenon, especially when advance boreholes have not revealed any anomalies.

This method produced very promising results, and we suggest that it be tested in other mines and also during tunnel constructions. It represents a useful, simple, and low cost supplement to other methods such as cover drilling. The principle behind this method is to forgo pre-drilling in safe zones, where pore solutions and water extracts have high chloride concentrations. However, at sites where a potential water hazard is indicated, advance boreholes are mandatory. This approach allows for major cost savings by avoiding pre-drilling in safe zones while ensuring proactive measures were taken in areas of potential risk.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10230-024-00991-5>.

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References

Adamczyk Z, Motyka J (2000) Water inflow to lead and zinc mines in the Olkusz area (SW Poland). *Przegląd Geol* 48:171–175 (in Polish)

Adamczyk AF, Wilk Z (1976) Variation in the chemistry of underground water of mines of the Olkusz region. PAS Scientific Progress Report. Krakow Branch 20:2 (in Polish)

Adamczyk AF, Motyka J, Wilk Z, Witczak S (1978) Salt water in Permian sediments on the north-eastern border of the Upper Silesia Coal Basin. *Ann Soc Geol Pol* 48:537–558 (in Polish)

Cao Z, Gu Q, Huang Z, Fu J (2022) Risk assessment of fault water inrush during deep mining. *Int J Min Sci Technol* 32:423–434. <https://doi.org/10.1016/j.ijmst.2022.01.005>

Chen Y, Zhu S, Xiao S (2019) Discussion on controlling factors of hydrogeochemistry and hydraulic connections of groundwater in different mining districts. *Nat Hazards* 99:689–704. <https://doi.org/10.1007/s11069-019-03767-1>

d'Obryn K, Kamiński P, Motyka J (2021) Influence of hydrogeological investigation's accuracy on technology of shaft sinking and design of shaft lining—case study from southern Poland. *Energies* 14:2050. <https://doi.org/10.3390/en14082050>

Dai G, Xue X, Xu K, Dong L, Niu C (2018) A GIS-based method of risk assessment on 11 coal-floor water inrush from Ordovician limestone in Hancheng mining area, China. *Arab J Geosci* 11:714. <https://doi.org/10.1007/s12517-018-4071-8>

Dong D, Zhang J (2023) Discrimination methods of mine inrush water source. *Water* 15:3237. <https://doi.org/10.3390/w15183237>

Dong S, Zhou W, Liu Q, Wang H, Ji Y (2021) Mine water inrush mechanisms and prediction methods. *Professional Practice in Earth Sciences*. Springer International Publishing, Cham, pp 29–61

Gao R, Yan H, Ju F, Mei X, Wang X (2018) Influential factors and control of water inrush in a coal seam as the main aquifer. *Int J Min Sci Technol* 28:187–193. <https://doi.org/10.1016/j.ijmst.2017.12.017>

Han D, Li D, Shi X (2011) Effect of application of transient electromagnetic method in detection of water-inrushing structures in coal mines. *Procedia Earth Planet Sci* 3:455–462. <https://doi.org/10.1016/j.proeps.2011.09.120>

Hingley P, Nicolas M (2006) Improving forecasting methods at the European Patent Office. *Forecasting innovations*. Springer, Berlin Heidelberg, pp 191–245

Hou E, Wen Q, Ye Z, Chen W, Wei J (2020) Height prediction of water-flowing fracture zone with a genetic-algorithm support-vector-machine method. *Int J Coal Sci Technol* 7:740–751. <https://doi.org/10.1007/s40789-020-00363-8>

Hu Y, Li W, Wang Q, Liu S, Wang Z (2019) Evaluation of water inrush risk from coal seam floors with an AHP-EWM algorithm and GIS. *Environ Earth Sci* 78. <https://doi.org/10.1007/s12665-019-8301-5>

Huang H (2016) The application of fuzzy comprehensive evaluation to risk assessment of coal floor water irrigation. *Proc, 2016 international conf on advances in Energy, Environment and Chemical Science*. Atlantis, Paris, France

Kang X, Luo S, Xu M, Zhang Q, Yang Y (2019) Dynamic estimating the karst tunnel water inflow based on monitoring data during excavation. *Acta Carsologica* 48:117–127. <https://doi.org/10.3986/ac.v48i1.4654>

Kong HQ, Zhao LS, Zhang N (2022) Water inrush hazard in Shijingshan Tunnel during construction, Zhuhai, Guangdong, China. *Safety* 8:7. <https://doi.org/10.3390/safety8010007>

Li B, Zhang W, Gao B, Yuan J (2017) Research status and development trends of mine floor water inrush grade prediction. *Geotech Geol Eng* 36:1419–1429. <https://doi.org/10.1007/s10706-017-0408-4>

Li P, Wu J, Zhou W, LaMoreaux JW (2023a) In: Li P, Wu J, Zhou W, LaMoreaux JW (eds) *Mine water inrush and its prediction. Hazard Hydrogeology*. Springer International Publishing, Cham, pp 143–177

Li Y, Wu Y, Qiao W, Zhang S, Li X (2023b) The permeability evolution of sandstones with different pore structures under high confining pressures, high pore water pressures and high temperatures. *App Sci* 13:1771. <https://doi.org/10.3390/app13031771>

Liang J, Sui W, Chen G, Ren H, Li X (2023) Multi-indicator early-warning model for mine water inrush at the Yushen mining area, Shaanxi Province, China. *Water* 15:3910. <https://doi.org/10.3390/w15223910>

Liu Z, Jin D, Liu Q (2011) Prediction of water inrush through coal floors based on data mining classification technique. *Procedia Earth Planet Sci* 3:166–174. <https://doi.org/10.1016/j.proeps.2011.09.079>

Liu W, Han M, Meng X, Qin Y (2021) Mine water inrush risk assessment evaluation based on the GIS and combination weight-cloud model: a case study. *ACS Omega* 6:32671–32681. <https://doi.org/10.1021/acsomega.1c04357>

Luo M, Chen J, Jakada H, Li N, Guo X, Zhou H (2022) Identifying and predicting karst water inrush in a deep tunnel, South China. *Eng Geol* 305:106716. <https://doi.org/10.1016/j.enggeo.2022.106716>

Ma D, Duan H, Zhang J, Bai H (2022a) A state-of-the-art review on rock seepage mechanism of water inrush disaster in coal mines. *Int J Coal Sci Technol* 9:50. <https://doi.org/10.1007/s40789-022-00525-w>

Ma D, Duan H, Zhang J, Liu X, Li Z (2022b) Numerical simulation of water–silt inrush hazard of fault rock: a three-phase flow model. *Rock Mech Rock Eng* 55:5163–5182. <https://doi.org/10.1007/s00603-022-02878-9>

Motyka J (1988) Carbonate triassic sediments as a groundwater environment in the Olkusz-Zawiercie ores mining region. *Zeszyty Naukowe AGH* 1157:1–109 (in Polish)

Motyka J (1998) A conceptual model of hydraulic networks in carbonate rocks, illustrated by examples from Poland. *Hydrogeol J* 6:469–482. <https://doi.org/10.1007/s100400050169>

Motyka J, Wilk Z (1976) Vertical differentiation in the water permeability of carbonate triassic rocks in the light of a statistical analysis of the results of pumping tests (Silesia-Cracow monocline). *Geol Q* 20:381–399 (in Polish)

Motyka J, Niewdana J, Witczak S (1972) Hydrochemical method of forecasting flooded fault zones under the conditions of a zinc and lead mine. *Zeszyty Naukowe AGH* 377:141–156 (in Polish)

Pang Y, Wang G, Ding Z (2014) Mechanical model of water inrush from coal seam floor based on triaxial seepage experiments. *Int J Coal Sci Technol* 1:428–433. <https://doi.org/10.1007/s40789-014-0049-7>

Peng Y, Wu L, Zuo Q, Chen C, Hao Y (2020) Risk assessment of water inrush in tunnel through water-rich fault based on AHP-Cloud model. *Geomatics Nat Haz Risk* 11:301–317. <https://doi.org/10.1080/19475705.2020.1722760>

Pirc S, Uhan J (1991) Application of hydrochemistry for predicting water eruptions in Zasavje collieries. Proc, 4th International Mineral Water Assoc Congress, Ljubljana (Slovenia)-Portschach (Austria), pp 279–289

Rogoż M (2004) Mining hydrogeology with basics of General Hydrogeology. Central Mining Institute, Katowice. (in Polish)

Różkowska A, Różkowski A, Rudzińska T (1975) Hydrochemical characteristic of the triassic water bearing system in the Silesia-Cracow Region. *Biul Instytutu Geologicznego* 282:551–581 (in Polish)

Różycki S (1953) Upper Dogger and lower Malm of the Krakow-Częstochowa Jura. Wydawnictwo Geologiczne, Warsaw. (in Polish)

Shi L, Qiu M, Wei W, Xu D, Han J (2014) Water inrush evaluation of coal seam floor by integrating the water inrush coefficient and the information of water abundance. *Int J Min Sci Technol* 24:677–681. <https://doi.org/10.1016/j.ijmst.2014.03.028>

Song T, Zeng J, Ma J, Ma C, Li T, Xia T (2021) Water inrush risk assessment based on AHP and advance forecast approach: a case study in the Micangshan tunnel. *Adv Civil Eng* 2021. <https://doi.org/10.1155/2021/9750447>

Sui W, Hang Y, Ma L, Wu Z, Zhou Y, Long G, Wei L (2014) Interactions of overburden failure zones due to multiple-seam mining using longwall caving. *Bull Eng Geol Environ* 74:1019–1035. <https://doi.org/10.1007/s10064-014-0674-9>

Sun M, Zheng WX, Duan XB (2014) Research on deep coal seam mining floor strata water bursting influenced factors based on analytic hierarchy process. *Appl Mech Mater* 608–609:737–741. <https://doi.org/10.4028/www.scientific.net/amm.608-609.737>

Sun W, Zhou W, Jiao J (2015) Hydrogeological classification and water inrush accidents in China's coal mines. *Mine Water Environ* 35:214–220. <https://doi.org/10.1007/s10230-015-0363-3>

Tajduś A (2022) Risks in tunnel construction, part 1. *Nowoczesne Budownictwo Inżynierjne* 1:64–66 (in Polish)

Tokarski A (1958) The part of water displayed in discerning the Olkusz Jura Tectonics. *Geol Q* 2:415–419 (in Polish)

Vincenzi V, Gargini A, Goldscheider N (2008) Using tracer tests and hydrological observations to evaluate effects of tunnel drainage on groundwater and surface waters in the northern Apennines (Italy). *Hydrogeol J* 17:135–150. <https://doi.org/10.1007/s10040-008-0371-5>

Wang Y, Yang W, Li M, Liu X (2012) Risk assessment of floor water inrush in coal mines based on secondary fuzzy comprehensive evaluation. *Int J Rock Mech Min Sci* 52:50–55. <https://doi.org/10.1016/j.ijrmms.2012.03.006>

Wang WX, Sui WH, Faybushenko B, Stringfellow WT (2016) Permeability variations within mining-induced fractured rock mass and its influence on groundwater inrush. *Environ Earth Sci* 75:326. <https://doi.org/10.1007/s12665-015-5064-5>

Wang Z, Zhang Q, Shao J, Zhang W, Wu X, Zhu X (2020) New type of similar material for simulating the processes of water inrush from roof bed separation. *ACS Omega* 5:30405–30415. <https://doi.org/10.1021/acsomega.0c03535>

Wang D, Sui W, Ranville JF (2022) Hazard identification and risk assessment of groundwater inrush from a coal mine: a review. *Bull Eng Geol Environ* 81:421. <https://doi.org/10.1007/s10064-022-02925-3>

Wang D, Gao C, Liu K, Gong J, Fang Y, Xiong S (2023) A GIS-based probabilistic spatial multicriteria roof water inrush risk evaluation method considering decision makers' risk-coping attitude. *Water* 15:254. <https://doi.org/10.3390/w15020254>

Wen G, Deng Y, Xu J Research and application of coal floor water bursting forecast system based on GIS., Proc (2010) 2nd Conf on Environmental Science and Information Application Technology, IEEE

Wilk Z, Motyka J (1977) Contact between water-bearing horizons (Olkusz ore mining region near Cracow). *Ann Soc Geol Pol* 47:115–143 (in Polish)

Wu Q, Liu Y, Liu D, Zhou W (2011) Prediction of floor water inrush: the application of GIS-based AHP vulnerable index method to Donghuantuo Coal Mine, China. *Rock Mech Rock Eng* 44:591–600. <https://doi.org/10.1007/s00603-011-0146-5>

Wu Q, Liu Y, Luo L, Liu S, Sun W, Zeng Y (2015) Quantitative evaluation and prediction of water inrush vulnerability from aquifers overlying coal seams in Donghuantuo Coal Mine, China. *Environ Earth Sci* 74:1429–1437. <https://doi.org/10.1007/s12665-015-4132-1>

Xiang H, Wenquan Z, Dianzhi J (2011) Assessment method of water-inrush risk induced by fault activation and its application research. *Proc Eng* 26:441–448. <https://doi.org/10.1016/j.proeng.2011.11.2190>

Xiao J, Tong M, Fan Q, Zhu C (2010) Fuzzy neural network model applied in the mine water inrush prediction. Proc, International Conf on Image Processing and Pattern Recognition in Industrial Engineering. Xi'an, China, DOI. <https://doi.org/10.1117/12.866853>

Xie D, Du Z, Han C, Han J, Wei J, Yan J (2023) Prediction of the water inrush risk from an overlying separation layer in the thick overburden of a thick coal seam. *Sustainability* 15:13988. <https://doi.org/10.3390/su151813988>

Xue W, Hou E, Zhao X, Ye Y, Tsangaratos P, Ilia I, Chen W (2023) Discriminant analysis of water inrush sources in the Weihei Coalfield, Shaanxi Province, China. *Water* 15:453. <https://doi.org/10.3390/w15030453>

Yin H, Xu G, Zhang Y, Zhai P, Li X, Guo Q, Wei Z (2022) Risk assessment of water inrush of a coal seam floor based on the combined empowerment method. *Water* 14:1607. <https://doi.org/10.3390/w14101607>

Zhang J (2005) Investigations of water inrushes from aquifers under coal seams. *Int J Rock Mech Min Sci* 42:350–360. <https://doi.org/10.1016/j.ijrmms.2004.11.010>

Zhang CL, Zhong GS (2012) Application of cusp catastrophe model to predicting of water inrush from mine floor. *Adv Mater Res* 446–449:1546–1550. <https://doi.org/10.4028/scientific5/amr.446-449.1546>

Zhang Y, Xu Y, Wang K, Chen P, Wang X, Zheng Q, Zhang Z (2018) The fracturing characteristics of rock mass of coal mining and its effect on overlying unconsolidated aquifer in Shanxi, China. *Arab J Geosci* 11:666. <https://doi.org/10.1007/s12517-018-4034-0>

Zhang N, Zheng Q, Elbaz K, Xu YS (2020) Water inrush hazards in the Chaoyang Tunnel, Guizhou, China: a preliminary investigation. *Water* 12:1083. <https://doi.org/10.3390/w12041083>

Zhao Y, Liu Q, Lin H, Wang Y, Tang W, Liao J, Li Y, Wang X (2023a) A review of hydromechanical coupling tests, theoretical and numerical analyses in rock materials. *Water* 15:2309. <https://doi.org/10.3390/w15132309>

Zhao B, Liu Q, Zhu J (2023b) Risk assessment and zonation of roof water inrush based on the analytic hierarchy process, principle component analysis, and improved game theory (AHP–PCA–IGT) method. *Sustainability* 15:11375. <https://doi.org/10.3390/su151411375>

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