

Hydrogeological and Hydrogeochemical Characteristics of the Lo Tri Coal Mine in Cam Pha, Vietnam

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Abstract

This study investigated the hydrogeological and hydrogeochemical characteristics of the Lo Tri coal mine in the Cam Pha coalfield, Vietnam. Groundwater levels, flow directions, hydrostratigraphic units, and temporal hydrogeochemical variations were analyzed using historical and recent monitoring data, including 57 water samples and pumping-test results from exploration boreholes. Three hydrostratigraphic units were identified: a Quaternary porous aquifer, a fractured aquifer within coal-bearing Triassic sediments, and water-bearing fault zones. Groundwater generally flows in a north-to-south direction. Hydrogeochemical analyses revealed that the groundwater was generally fresh, but locally acidic, dominated by Na-Mg-Ca-SO₄-HCO₃ and Na-Mg-SO₄ types. These results provide a scientific basis for mine water management and environmental effect assessment in the Lo Tri coal mine.

Keywords: Hydrogeology, hydrogeochemistry, underground coal mining, Lo Tri coal mine, Cam Pha

Introduction

Coal mining in Cam Pha, Quang Ninh province, Vietnam, has been conducted on a large scale since the late 19th century and is one of the country's most important coal production areas (Nguyen 2025). In recent decades, mining activities have progressively extended to deeper levels, raising considerable hydrogeological and hydrogeochemical challenges. Groundwater inflow into underground workings, water-rock interaction processes, and the quality of mine drainage are increasingly critical issues affecting mining safety, operational costs, and the surrounding environment (Le 2021). The present study focuses on the Lo Tri coal mine, operated by Thong Nhat Coal Company-TKV, covering approximately 2.91 km² in the Hon Gai-Cam Pha coalfield (Fig. 1).

Underground coal extraction is currently conducted at depths ranging from approximately -35 to -150 m and to -350 m in the next few years (Thong Nhat Coal Company-TKV 2023). The terrain is characterized by coastal mountains and extensive waste dumps, with elevations generally between 200 and 300 m, and a

maximum elevation of 439.6 m above sea level (a.s.l.). The southwestern part of the mine area is relatively lower, forming a valley shaped by historical and ongoing open-pit mining activities. A large waste dump with variable thickness ranging from 1.0 to 50 m is distributed in the central area. Vegetation cover is sparse due to long-term mining. Surface drainage in the area is controlled by watershed divides in the north of the mine. An artificial freshwater reservoir (Bara Lake) is located in the northeastern part of the mine area and serves industrial and domestic purposes. The mine is situated in a tropical monsoon climate zone with distinct rainy (from April to October) and dry (from November of the previous year to March of the following year) seasons. Air temperature ranges from 37–38 °C (in summer) to 8–15 °C (in winter) (Cua Ong Meteorological Station 2025). Geologically, the mine area is dominated by the Hon Gai Formation (T₃n-rhg), which is divided into the lower unit (T₃n-rhg₁) and upper unit (T₃n-rhg₂) (Vu 1987). The lower unit mainly consists of conglomerate and breccia interbedded with sandstone, siltstone, and claystone.

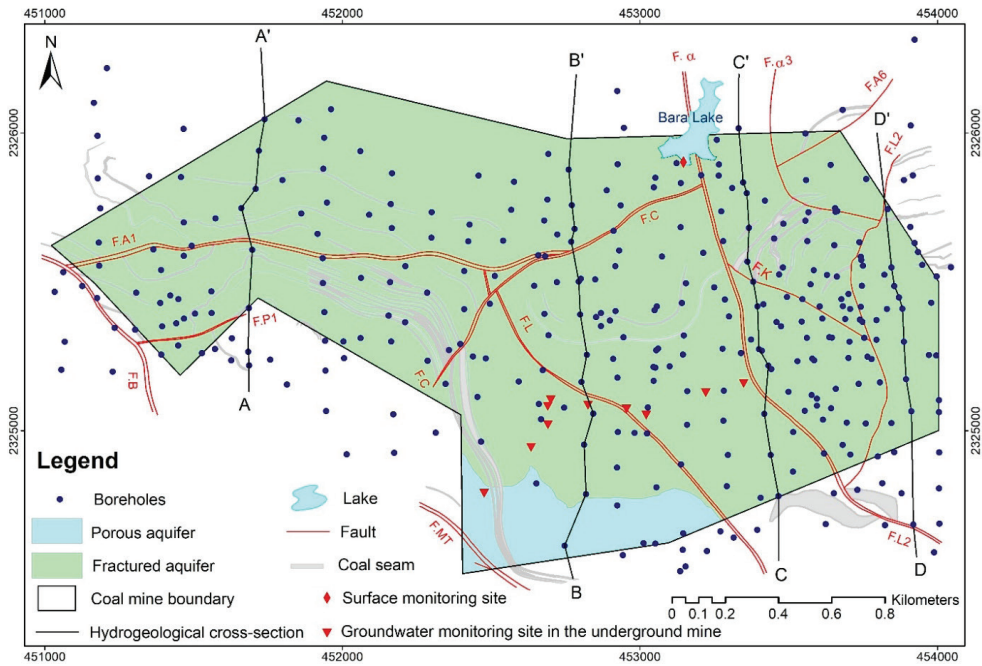


Figure 1 The hydrogeological map of the Lo Tri coal mine with cross-sections (after Dao et al. 2023).

The upper unit is widely distributed and comprises conglomerate, breccia, sandstone, siltstone, claystone, and industrial coal seams (Le 1997; Nguyen *et al.* 2022). Quaternary sediments are locally distributed along faults, slopes, and valleys and consist of pebble, gravel, sand, clay, and organic matter. The geological structure of the Lo Tri mine is complex, with multiple folds and fault systems dividing the area into northern, central, and southern structural blocks (Thong Nhat Coal Company-TKV 2023). These structural features play an important role in controlling the occurrence and flow patterns of groundwater. Although mining operations have been ongoing for decades, studies that address both hydrogeological conditions and groundwater chemistry at the Lo Tri mine remain limited. Thus, this study aims to characterize the hydrogeological conditions and hydrogeochemical properties of groundwater in the Lo Tri coal mine, which is important for supporting future deeper mining activities. The results are expected to provide a scientific basis for improved mine water management and to contribute

to a better understanding of groundwater behavior in the area.

Methodology

Data collection

Data were collected from an exploration project conducted to upgrade the Lo Tri coal mine (Thong Nhat Coal Company-TKV 2023). These included geological and hydrogeological reports, borehole logs, and an exploration report, all prepared by Thong Nhat Coal Company-TKV and Vinacomin Information, Technology, and Environment Joint Stock Company (VITE). The data included pumping test results, borehole stratigraphy, water levels, and water analysis results. This study used monitoring data from one surface monitoring site (Bara Lake) and ten groundwater monitoring sites in the underground mine (located along the drainage channels in the underground mine galleries, flowing towards the pumping stations) (Fig. 1). The static water level was measured in 65 boreholes, including 37 boreholes before 2020 and 28 boreholes from 2020 to 2022. Water samples were analyzed at



the VITE laboratory using titration methods, an atomic absorption spectrophotometer (AA-7000, Shimadzu, Japan), and a UV-Vis spectrophotometer (UV-1900i, Shimadzu, Japan).

Data processing

The lithological units, their depths, and hydrogeochemical data were processed using Excel, AutoCAD, ArcGIS 10.8, and Geochemist's Workbench software. Based on lithological units, the respective hydrostratigraphic units were verified and classified. The borehole data, which included XY coordinates, depth, elevation, and thickness for each hydrostratigraphic unit, were imported into ArcGIS. Moreover, to determine groundwater flow, water level data were processed and interpolated in ArcGIS using the Kriging technique. Potential metric maps were derived from the interpolated heads to determine the flow direction. Aquifer hydraulic characteristics were calculated from pumping tests.

Results and Discussion

Aquifer characterization

Three hydrostratigraphic units were identified in the Lo Tri coal mine area: a porous aquifer in Quaternary sediments (q), a fractured aquifer in the Hon Gai Formation (T_3), and a fault-related water-conducting zone. The porous aquifer is primarily distributed in the southern part of the area (Fig. 1). Four hydrostratigraphic cross-sections were constructed across the mine area to illustrate the hydrostratigraphic framework (Figs. 1 and 2). The cross-sections show the spatial configuration of the hydrostratigraphic units. For instance, the fractured aquifer in the T_3 sediments can be divided into three layers: (1) the fractured aquifer in the overlying strata of the Day coal seam, (2) the fractured aquifer in the Day coal seam, and (3) the fractured aquifer in the underlying sediments beneath the Day coal seam (Fig. 2). The porous aquifer pinches out northward against the fractured aquifer (e.g., cross-section BB').

Cross-sections show that the strata overlying the Day coal seam (1) are widely distributed, extending from the central part of the mine towards the north and northeast.

This distribution has been locally modified by open-pit mining and waste disposal activities (Fig. 2). The north-south cross-sections (BB', CC', and DD') reveal the presence of fault zones. Fractured conglomerate and sandstone constitute the main water-bearing formations, in which groundwater is primarily stored and transmitted through fracture systems. In contrast, siltstone and claystone contain only minor fractures, which are commonly filled with clay minerals. Therefore, they exhibit poor water-bearing capacity and generally act as aquitards or aquicludes. Several layers of fractured conglomerate and sandstone form aquifers up to 70 m thick. Due to unstable sedimentary conditions, impermeable and water-bearing layers occur as discontinuous lenses. Consequently, the groundwater in these layers is hydraulically connected through hydrogeological windows, resulting in unconfined or weakly confined conditions. Moreover, based on the pumping test results obtained from borehole TN146 in this layer, three pumping stages were conducted with different flow rates. The pumping rates (Q) were 0.38, 0.35, and 0.32 L s⁻¹, corresponding to specific discharge (q) values of 0.0189, 0.0238, and 0.0315 L s⁻¹ m⁻¹ and permeability coefficients (K) ranging from 0.0105 to 0.0142 m d⁻¹ for tests 1, 2, and 3, respectively. These values suggest that the formation is weak water-bearing and has very low permeability (Bindeman 1963; Kruseman and de Ridder 1994; Singhal and Gupta 2010).

In the Day coal seam (2), the coal seams rarely crop out at the surface (Figs. 1 and 2). This sequence is characterized by well-developed cyclothem, with a lithology dominated by siltstone, mudstone, and coal seams. According to the results of pumping tests, the specific discharge (q) ranges from 0.00406 to 0.320 L s⁻¹ m⁻¹ (Table 1), indicating that, according to Bindeman's classification (Bindeman 1963), the aquifer varies from very poor to poor in terms of groundwater abundance. The permeability coefficient (K) ranges from 0.0015 to 0.013958 m d⁻¹, indicating very low permeability (Kruseman and de Ridder 1994; Singhal and Gupta 2010). In addition, water inflow from mine roadways excavated at the +13 and -35 m levels in this stratigraphic unit is minimal.

Table 1 Results of pumping tests from boreholes in the Day coal seam sediments.

Borehole ID	Borehole collar elevation (m)	Static water level (m)	S (m)	Q (L s ⁻¹)	q (L s ⁻¹ m ⁻¹)	K (m d ⁻¹)
1071	248.6	131.4	1.21	0.178	0.320	0.006
196b	371.4	1.5	7.1	0.021	0.147	0.0015
TN121	157.2	92.9	16.7	0.0679	0.00406	0.00375
			11.7	0.0538	0.00460	0.00400
			6.6	0.0346	0.00524	0.00410
TN160	154.5	121	10.8	0.0553	0.00512	0.012929
			7.4	0.0428	0.00580	0.013958
				0.0272	0.00648	0.013684

In many locations, water is either absent or present only as minor seepage (Thong Nhat Coal Company-TKV 2023). These observations indicate that the rock and coal layers in this unit generally function as a water-poor formation due to their low water-bearing capacity.

The strata underlying the Day coal seam (3) are exposed in the southeastern and southern parts of the mine (Figs. 1 and 2). Field observations and previous drilling data suggest the presence of a siltstone layer directly beneath the coal seam. From a hydrogeological perspective, this siltstone

layer is laterally continuous across the region, acting as an aquitard that restricts groundwater flow. Beneath this layer are coarse-grained rocks such as conglomerate and sandstone, which are locally interbedded with thin lenticular layers of fine-grained siltstone and claystone. Currently, no borehole pumping tests have been conducted in these sediments. However, observations from an inclined shaft at the -35 m level suggest that, where the shaft intersects conglomerate layers, groundwater flows continuously along the shaft walls and floor. At the -140 m level, the inflow of water into the underground workings was

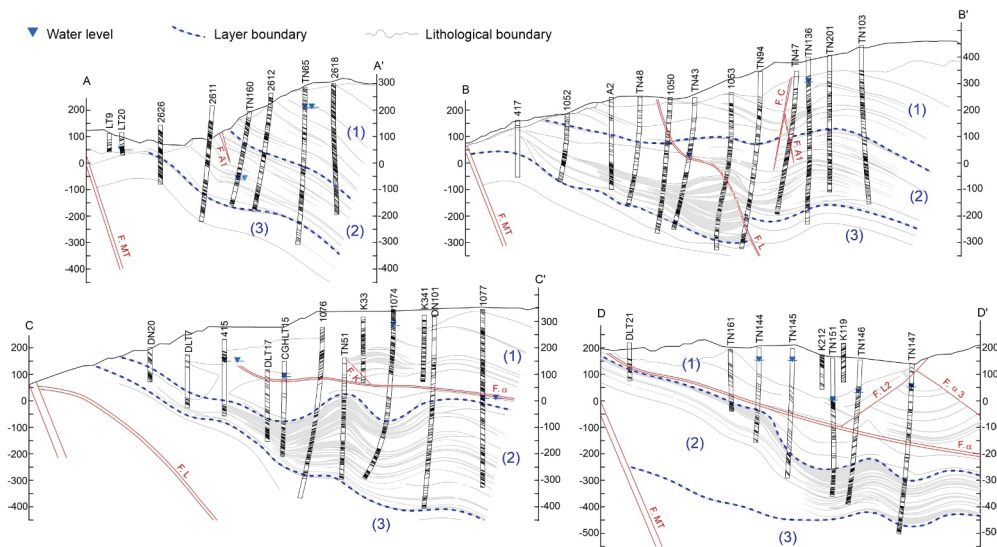


Figure 2 Hydrogeological cross-sections from the transects in Figure 1: (1) the strata overlying the Day coal seam, (2) the Day coal seam, and (3) the strata underlying the Day coal seam.



most pronounced. The maximum inflow into the mine during the rainy season reaches $839 \text{ m}^3 \text{ h}^{-1}$, causing flooding of mine workings that disrupts production and results in economic losses. Overall, this aquifer has relatively high groundwater potential.

Also, a fault-related water-bearing zone occurs in relatively wide tectonic fault damage zones, e.g., F.A1, F.C, F.L (Figs. 1 and 2). In addition to being encountered in exploration boreholes, these fault zones have also been exposed in underground roadways during coal mining operations (Thong Nhat Coal Company-TKV 2023). No pumping tests have been conducted in boreholes intersecting this zone in the Lo Tri coal mine. Potential recharge sources for the mine might be water from the overlying strata, previously mined-out areas, and precipitation. Therefore, the hydrogeological characteristics of these fault zones require further investigation.

Regional groundwater flow pattern and dynamics

Groundwater flow shows temporal variations and is influenced by mining activities. In general, groundwater flows from north to south in the central part and from west to east in the eastern part (Fig. 3). In the central part of the mine, the groundwater flow pattern during 2020–2022 was similar to that observed before 2020, with flow predominantly directed from north to south. Groundwater levels increase progressively towards the north due to the topographic influence of Khe Sim Mountain. However, during the upgrade exploration period (2020–2022), the groundwater flow pattern in

the eastern part of the mine differed from that observed before 2020 (Fig. 3a and 3b).

In addition, faults, such as F.C and F.L, act as conduits for the downward flow of groundwater in the overlying strata of the Day coal seam. Mining activities, including blasting in the longwall face and controlled roof caving, have fractured the strata immediately above the Day coal seam. This process creates hydraulic connections between aquifer layers, allowing groundwater to flow into the mine workings at the +13 and -35 m levels. According to mine water monitoring data collected at drainage points in the mine, the average inflow at the -35 m level was $116.6 \text{ m}^3 \text{ h}^{-1}$ in 2021 (Thong Nhat Coal Company-TKV 2023).

Regarding groundwater dynamics, monitoring results from mine workings indicate that both groundwater levels and mine inflow increase during the rainy season and decrease during the dry season. For example, at the +13 m adit, the coefficient of variation (CV) of annual discharge in the hydrological year ranged from 1.51 in 2015 to 18.58 in 2019. The CV was 6.84 in 2020 and 8.13 in 2021. At the -35 m level, monitoring of monthly mine drainage discharge shows that the CV of flow rate in the hydrological year increased from 1.61 in 2016 to 5.38 in 2021. Surface water monitoring results indicate that the water volume of Bara Lake ranged from approximately 508.4 m^3 to about 146.6 m^3 . However, the lake's water level fluctuates only slightly, ranging from 328.3 m in the dry season (2013) to 328.9 m in the rainy season (2014). Precipitation is considered the main source of recharge for

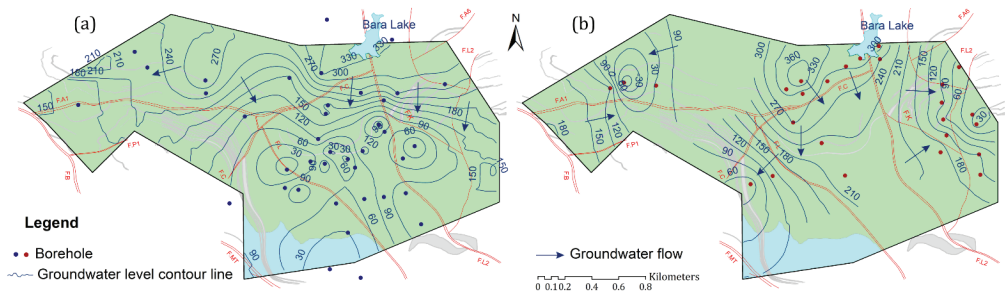


Figure 3 Groundwater potentiometric surface and flow pattern in the Lo Tri coal mine area: (a) before 2020 and (b) during the exploration upgrading period 2020–2022.

the lake (Bara Lake monitoring statistics; Thong Nhat Coal Company-TKV 2023).

Hydrogeochemical characteristics

Hydrogeochemical facies

In general, the pH values of the groundwater at the Lo Tri coal mine ranged from 2.15 to 6.60, indicating acidic water. A Durov diagram (Durov 1948) was plotted for the groundwater samples to categorize the hydrogeochemical types (Fig. 4). The dominant cations follow the order of $Mg^{2+} > (Na+K)^+ > Ca^{2+}$, whereas the major anions follow the order of $SO_4^{2-} > Cl^- > HCO_3^-$.

However, as mentioned above, the water type differed between water-bearing layers. For example, in the Day coal seam, the average pH value of the groundwater was 6.5, indicating slightly acidic water. The TDS value was 0.77 g L^{-1} , corresponding to fresh water (Freeze and Cherry 1979). The water was characterized as Na-K-Mg- SO_4 - HCO_3 water type. In contrast, the average pH value of the groundwater was 4.3, indicating acidic water, and the TDS value was 0.34 g L^{-1} , corresponding to fresh water, with the Na-K-Mg- SO_4 type in the underlying

strata beneath the Day coal seam. The low pH values were likely related to the oxidation of sulfide minerals associated with the coal seams. The Fe^{2+} concentration also differed between the strata (Table 2).

Engineering implications of groundwater chemistry

In the Day coal seam, the average water hardness was $17.9 \text{ }^\circ\text{dH}$, indicating hard water. The water exhibited strong effervescence and contained a considerable amount of sediment with hard deposits. It was also corrosive and had a high soap consumption capacity, ranging from 6,905 to $10,283 \text{ g m}^{-3}$. In contrast, groundwater in the underlying sediments of the Day coal seam had an average hardness of $6.37 \text{ }^\circ\text{dH}$, which is classified as soft water. The water exhibited normal foaming characteristics, produced little residue, and had a low tendency for scale formation. Its soap consumption capacity ranged from 986.4 to $8,832 \text{ g m}^{-3}$ (Fig. 5). These characteristics may influence mine drainage operations, pumping equipment performance, underground water systems, and maintenance conditions in underground mine workings.

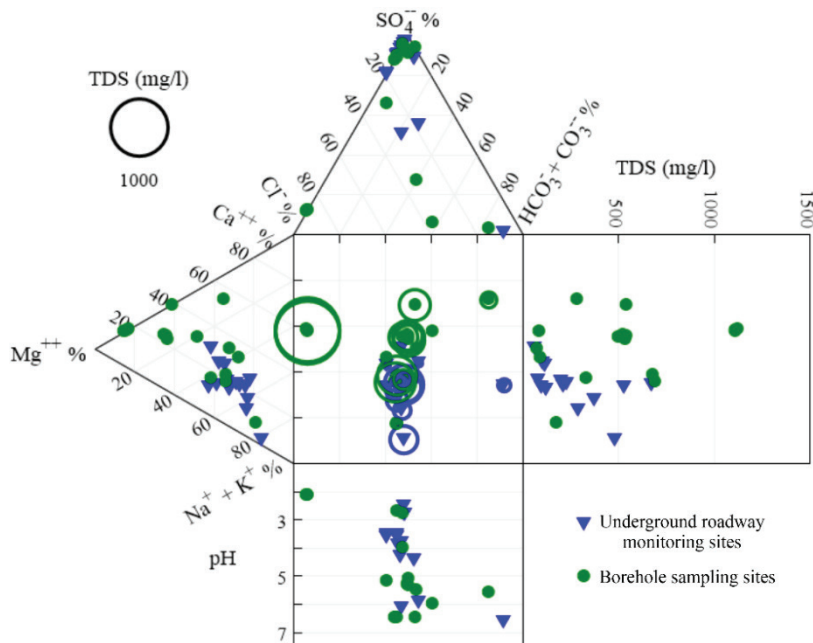


Figure 4 Durov diagram of groundwater hydrogeochemistry in the Lo Tri coal mine.



Table 2 The chemical characteristics of groundwater.

Parameter	Unit	Concentration (Day coal seam)			Concentration (below the Day coal seam)		
		Average	Max	Min	Average	Max	Min
pH	-	6.5	6.5	6.5	4.3	6.6	2.5
TDS	g L ⁻¹	0.73	0.77	0.70	0.34	0.876	0.095
Cl ⁻	mg L ⁻¹	27.9	44.55	0	10.4	19.85	0.92
SO ₄ ²⁻	mg L ⁻¹	422.2	446.4	378.9	176.5	493.8	1.23
HCO ₃ ⁻	mg L ⁻¹	12.2	30.51	3.05	35.3	192.82	0
Ca ²⁺	mg L ⁻¹	48.1	61.52	38.88	15.0	38.65	2.95
Mg ²⁺	mg L ⁻¹	48.4	58.96	42.7	19.1	60.05	2.74
(Na + K) ⁺	mg L ⁻¹	73.6	114.37	0.925	33.8	130.53	0.069
Fe ²⁺	mg L ⁻¹	2.67	8	0	4.31	40.2	0.55

Conclusions

This study provided an integrated hydrogeological and hydrogeochemical characterization of the groundwater conditions at the Lo Tri underground coal mine. The results revealed that the occurrence and flow of groundwater were mainly controlled by fractured Triassic coal-bearing strata and tectonic fault zones, whereas the Quaternary porous aquifer plays only a limited role locally. Mining

activities and fault structures created hydraulic connections that facilitated the inflow of groundwater into the underground workings. Hydrogeochemical analyses revealed that the groundwater is generally fresh, albeit slightly to moderately acidic. These findings improved the understanding of groundwater behavior in the mine, providing useful information for mine water management and future deeper mining operations in the Cam Pha coalfield.

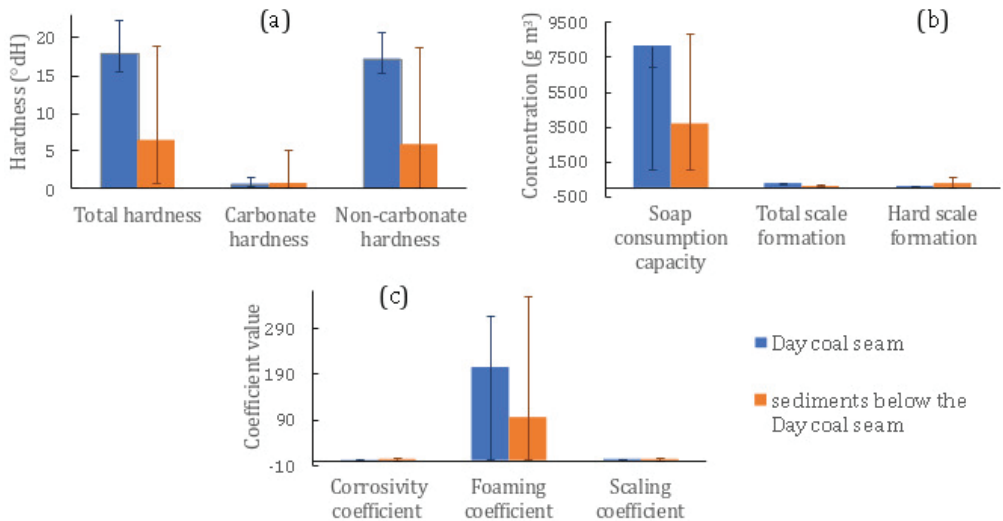


Figure 5 Engineering-related groundwater characteristics in the Lo Tri mine: (a) hardness indices, (b) scale formation potential, and (c) corrosion-related coefficients for groundwater in the Day coal seam and underlying sediments.



Acknowledgements

This research was funded by the National Foundation for Science and Technology Development (NAFOSTED), Vietnam, under grant number 105.99-2025.40. The authors would like to thank Hanoi University of Mining and Geology and Thong Nhat Coal Company-TKV for their support. The authors also thank Dr. Phuc Quang Le (Hanoi University of Mining and Geology) for his assistance with the field investigation.

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