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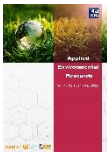

Research Article

Evaluating The Current Quality Status and Potential Health Risk of Heavy Metals in Groundwater Near a Mining Site in Ha Trung, Ha Long, Quang Ninh Province, Vietnam

Nguyen Quoc Tuan, Ta Thi Hoai, Nguyen Thi Hai*

University of Science, Vietnam National University, Hanoi, 334 Nguyen Trai, Hanoi, Vietnam

*Corresponding Email: nguyenthihai128@hus.edu.vn

Abstract

In this study, groundwater quality and the human health implications of heavy metal contamination near a coal mining site in Ha Trung, Ha Long, Quang Ninh Province, Vietnam, were examined. Ten household wells were sampled during both the wet and dry seasons (n = 20) and analyzed using multivariate statistical and quantitative methods. The results indicated that the concentrations of heavy metals (Mn, Hg, Fe, Se, Cu, Ni, Zn, Cd, Pb, and As) increased during the dry season. Specifically, the levels of Pb, Fe, and Se surpassed Vietnam's technical regulations on domestic water limits in both seasons, raising concerns about the potential health impacts on local communities. Health risk assessment revealed that children face greater exposure risks than adults do, with As and Pb being the main contributors posing the greatest noncarcinogenic and carcinogenic risk. Noncarcinogenic risk assessments revealed that 90% of the sampling sites exceeded safe exposure levels for both adults and children, indicating a potential noncarcinogenic health risk from groundwater heavy metal exposure in both age groups. The carcinogenic risks associated with As and Pb at all the sampling sites were much greater than the United States Environmental Protection Agency acceptable risk range of 10^{-6}–10^{-4} for both age groups in both seasons, suggesting that As and Pb in groundwater pose significant carcinogenic risks to the local population.

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Introduction

In peri-urban northern Vietnam, private groundwater wells remain a primary source of domestic water (Bui et al., 2018). However, groundwater quality is increasingly threatened by rapid industrialization. Ha Long city, located in Quang Ninh Province, sits above Vietnam's largest open-pit coalfield, as well as kaolin and limestone quarries that have been exploited almost continuously since the mid-20th century. The annual coal output in this area now exceeds 50 million tons, and thousands of tons of waste rock are either stored in perched spoil heaps or discharged into settling ponds (Nguyen et al., 2021).

Acid mine drainage (AMD) and seepage from these facilities trickle through highly fractured Permo-Carboniferous sandstone, mobilizing iron (Fe), manganese (Mn), zinc (Zn), cadmium (Cd), lead (Pb), and arsenic (As) before reaching the shallow weathered aquifer that supplies nearby households (Acharya and Kharel, 2020). Heavy metals are particularly concerning because they do not biodegrade and can accumulate in human tissues over a lifetime. Divalent cations, such as Mn^{2+}, Zn^{2+}, and Cd^{2+}, become significantly more mobile under the low-pH and high-salinity conditions typical of AMD, whereas metalloids such as As remain soluble under acidic, reducing groundwater conditions (Chaudhary et al., 2024; Mishra et al., 2025). Chronic ingestion of combinations of these heavy metals above guideline values has been linked to various health issues, including neurotoxicity (from Mn), nephrotoxicity (from Cd), and increased incidences of skin, bladder, and lung cancers (from As, Pb, and Ni) (Jaishankar et al., 2014).

In the Ha Long region, surface water surveys have indicated elevated metal levels; however, there has been no systematic assessment of groundwater, particularly concerning how seasonal changes affect redox states and metal migration pathways (Trang, 2004). Seasonal variations are likely to play a crucial role. The wet season (May to September) typically dilutes solutes and introduces oxidizing recharge, whereas the dry season (November to March) leads to evaporative concentration, declining water tables, and stronger reductive conditions beneath mine wastelands (Luu, 2019; Nghiem et al., 2019; 2020). Understanding how these contrasting hydrological conditions influence metal behavior is essential for risk management but remains an unresolved question for Quang Ninh. Current health risk estimates for the province rely on national default exposure parameters, which may not reflect actual local intake patterns.

In response to these conditions, this study (i) determines the concentrations and maps the spatial variation in the concentrations of ten key heavy metals (Mn, Hg, Fe, Se, Cu, Ni, Zn, Cd, Pb, and As) in well water within 0.3–2.5 km of the Ha Trung mine and (ii) characterizes the noncarcinogenic and carcinogenic health risks for adults and children during both wet and dry periods. These metals were selected because of their frequent occurrence in mining-affected groundwater and their toxicological relevance to human health risk assessment.

By delivering the first paired dry and wet season dataset for subsurface heavy metal pollution in this nationally significant mining area and by directly linking source apportionment to probabilistic health risk outcomes, this research provides actionable evidence for the Quang Ninh Department of Agriculture and Environment. The findings are expected to inform upcoming revisions of provincial groundwater quality targets, guide the placement of new observation wells, and support the design of remediation measures to safeguard community water supplies as the province moves toward mine closure and postmining land use transitions.

Materials and methods

1) Study site

The research was carried out in the Ha Trung open-pit mining corridor, which is located on the eastern outskirts of Ha Long city, Quang Ninh, in northern Vietnam.

2) Sampling design and measurements

Ten representative wells (S1–S10), with depths ranging from 10 to 65 m, were sampled twice: once during the mid-wet season (from 15th August to 18th August, 2024) and again during the peak-dry season (from 10th January to 12th January, 2025), resulting in a total of 20 groundwater samples. Sample sites were selected on the basis of the following criteria: (i) households with children under 10 years of age; (ii) wells currently used as a source of domestic water supply; (iii) spatially representative locations covering residential areas surrounding the mining zone; and (iv) informed consent from participating households, along with the provision of basic water use information (Figure 1).

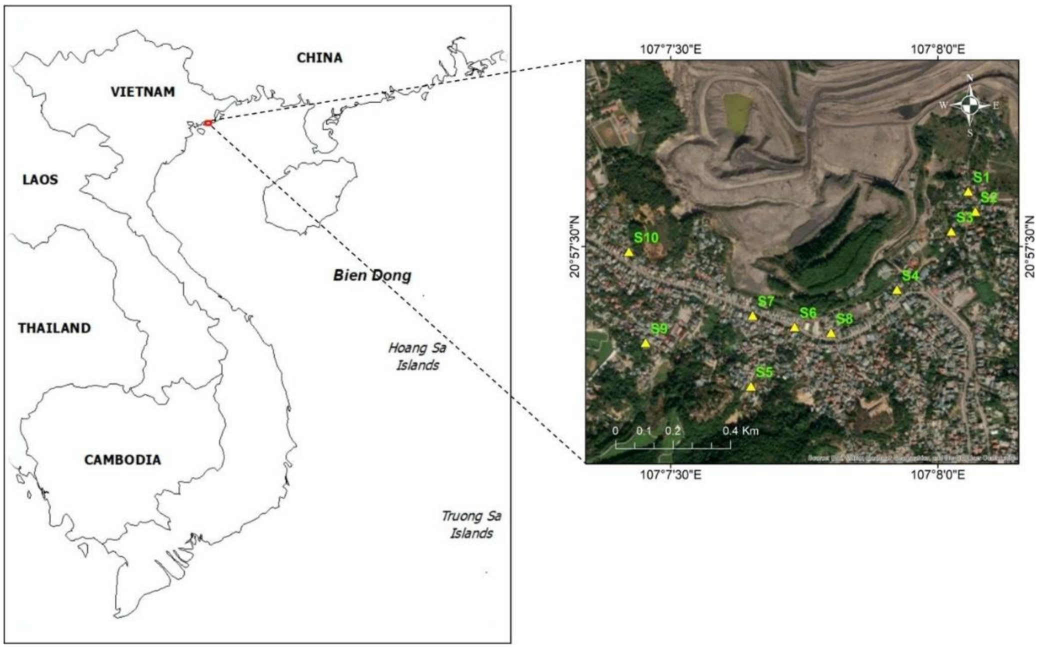

Figure 1 Study site and groundwater sampling location in the vicinity of the Ha Trung mine, Ha Long city, Quang Ninh Province, Vietnam.

Sample collection and preservation were conducted in strict compliance with Vietnamese national standards TCVN 6663-1:2011, TCVN 6663-11:2011, and TCVN 6663-3:2016. The sampling locations were systematically and spatially distributed across the study area to ensure representativeness and adequate coverage for an accurate assessment of the pollution levels. Each well was purged with more than three static volumes of water before the samples were collected in preacid-washed 1 L HDPE bottles. In situ parameters such as pH, dissolved oxygen (DO), electrical conductivity (EC), oxidation–reduction potential (ORP), salinity and total dissolved solids (TDS) were measured using a calibrated YSI EXO-2 multiparameter probe, which has a precision of ± 0.02 pH units, ±1 mV for ORP, and ± 0.5% for EC.

For heavy metal determination, water samples were filtered through a 0.45 µm nylon syringe filter (Millipore, USA) and acidified with ultrapure HNO_3 to a pH < 2. Quality assurance included the collection of duplicate samples and one field blank after every five wells. The samples were kept at approximately 2 °C and transported to the laboratory within 24 h. The concentrations of Mn, Fe, Ni, Se, Cu, Zn, Cd, Pb, and As were determined using an inductively coupled plasma–mass spectrometry system (ICP–MS; Thermo Scientific iCAP RQ). Instrumental detection limits, which are based on the manufacturer's typical performance in He-KED mode with a 3.5 mm insert, were in the low ng L^{-1} range, including 2.5 ng L^{-1} for Cr, 1.2 ng L^{-1} for Mn, 6.6 ng L^{-1} for Fe, 0.3 ng L^{-1} for Ni, 2.1 ng L^{-1} for Cu, 7.1 ng L^{-1} for Zn, 3.5 ng L^{-1} for As, 0.2 ng L^{-1} for Cd, and 0.3 ng L^{-1} for Pb. Hg was analyzed by atomic absorption spectrometry using a flow-injection cold vapor module (AAS-PerkinElmer FIMS-400), with a method detection limit below 5 ng L^{-1} under routine operating conditions. This analytical workflow provides robust results and enables the resolution of seasonal variations in groundwater quality within the study area.

All the reagents used in this study were of analytical grade or higher. Nitric acid (70% HNO_3, Merck) was used for sample preservation and digestion. Calibration standards for Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were prepared from certified multielement ICP stock solutions in 10% HNO_3 using ultrapure water (18.2 MΩ·cm, Milli-Q system). Calibration standards for As and Hg were prepared from certified As and Hg standard solutions (1,000 mg L^{-1}, Merck).

3) Pollution assessment indices

The contamination factor (CFi) is a widely used quantitative measure that assesses the degree of heavy metal contamination in groundwater. It is calculated as the ratio of the measured concentration of a specific heavy metal to its corresponding background or baseline value, as illustrated in Eq.1:

$$\mathrm{CF_i} = \mathrm{C_i}/\mathrm{B_i} \quad \text{(Eq.1)}$$

where C_i (mg L^{-1}) represents the concentration of the heavy metal in the sample and Bi (mg L^{-1}) represents the background or reference content of the heavy metal, which represents natural levels without anthropogenic influence. In this study, background values were determined on the basis of QCVN 01-1:2018/BYT (QCVN 01-1:2018/BYT, 2018). On the basis of the CFi values, the contamination levels were classified as follows: low ($CF_i < 1$), moderate ($1 \le CF_i < 3$), high ($3 \le CF_i < 6$), and very high ($CF_i \ge 6$) (Nlemolisa et al., 2025; Rakib et al., 2022).

The HPI (heavy metal pollution index) is a widely used metric for assessing water quality in relation to heavy metal contamination (Appiah-Opong et al., 2021; Pan et al., 2023). It consolidates measurements of multiple metals into a single score, providing an overall indication of pollution. In this study, the HPIs were determined in accordance with the methodology proposed by Pan et al. (2023). The resulting HPIs were interpreted using the guideline ranges defined by Pan et al. (2023), with values < 15 indicating low contamination, 15–30 representing moderate contamination, and > 30 reflecting high contamination levels. Notably, HPIs exceeding 100 indicate severe heavy metal pollution and pose significant potential risks to human health (Kumar et al., 2019; Shahmirnoori et al., 2023). The formulas for calculating the HPI and other equivalent indices are presented in Eqs. 2–4.

$$\mathrm{HPI} = \left(\sum_{i=1}^{n} \mathrm{W_i Q_i}\right) / \sum_{i=1}^{n} \mathrm{W_i} \quad \text{(Eq.2)}$$

$$\mathrm{Q_i} = (\mathrm{C_i}/\mathrm{B_i}) \times 100 \quad \text{(Eq.3)}$$

$$\mathrm{W_i} = \mathrm{k}/\mathrm{B_i} \quad \text{(Eq.4)}$$

where n denotes the number of heavy metals considered, W_i is the weight assigned to the i^{th} metal, Q_i is its corresponding subindex, and k is the proportionality constant, which was set to 1 in this study (Wu et al., 2024).

4) Assessment of human health risk

In this study, a human health risk assessment was performed in accordance with the guidelines established by the United States Environmental Protection Agency (USEPA, 1989). These guidelines were used to calculate noncarcinogenic risks associated with all investigated heavy metals, including Mn, Hg, Fe, Se, Cu, Ni, Zn, Cd, Pb, and As, as well as carcinogenic risks for selected metals, specifically Cd, Pb, and As. The formula for calculating chronic daily intake (CDI, mg kg^{-1} day^{-1}), which is used to assess the potential long-term health impacts of heavy metal exposure, is presented in Eq.5 (Latif et al., 2024; Qiao et al., 2020; USEPA, 1989).

$$\mathrm{CDI} = \mathrm{C_i} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}/\mathrm{BW} \times \mathrm{AT} \qquad \text{(Eq.5)}$$

where Ci (mg L^{-1}) is the concentration of heavy metal; IR (L day^{-1}) is the ingestion rate; EF (days $year^{-1}$) is the exposure frequency; ED (years) is the duration of exposure; BW (kg) is the average weight of the body; and AT (days) is the average exposure time. Detailed values for these parameters can be found in Table 1.

The noncarcinogenic risks are computed with Eqs. 6 and 7.

$$\mathrm{HQ_i} = \mathrm{CDI}/\mathrm{RfD} \qquad \text{(Eq.6)}$$

$$\mathrm{HI} = \sum \mathrm{HQ_i} \qquad \text{(Eq.7)}$$

where HQi represents the hazard quotient for ingestion and RfD represents the reference dose for ingestion (mg kg^{-1} day^{-1}). The reference dose values for the heavy metals examined in this research are provided in Table 2. The hazard index (HI) is used to evaluate noncarcinogenic risks from heavy metal exposure (Rakib et al., 2022). Values of HI > 1 imply a potential for adverse health effects, whereas HI ≤ 1 indicates no appreciable concern (Kumar et al., 2019; Rakib et al., 2022).

Table 1 Healthy risk calculation parameters (Karim et al., 2011; Rakib et al., 2022)

Parameters	**Adults (>18 years)**	**Children (0–17 years)**
IR	2.2	1
EF	365	365
ED	70	10
BW	70	25
AT	25,550	3,650

Table 2 RfD and SF values for As and heavy metals (Qiao et al., 2020; Rakib et al., 2022; USEPA, 2004; Wu et al., 2024)

Non carcinogen	**RfD (mg kg^{-1} day^{-1})**	**Carcinogen**	**SF (mg kg^{-1} day^{-1})$^{-1}$**
Mn	0.02	As	1.5
Fe	0.3	Cd	6.1
Ni	0.02	Pb	8.5
Se	0.005		
Hg	0.0003		
Cu	0.04		
Zn	0.3		
Cd	0.0005		
Pb	0.0014		
As	0.0003		

In this study, the potential cancer risk (CR) resulting from exposure to As, Cd, and Pb was assessed for both adults and children. In accordance with the identification of carcinogenic hazards to humans published by the World Health Organization, As and Cd are classified as Group 1 carcinogens (carcinogenic to humans), whereas Pb is classified as a Group 2B carcinogen (possibly carcinogenic to humans). CR values were calculated as shown in Eq.8.

$$\mathrm{CR} = \mathrm{CDI} \times \mathrm{SF} \qquad \text{(Eq.8)}$$

where SF is the slope factor (mg kg^{-1} day^{-1}) $^{-1}$, and the SF values for As, Cd, and Pb are given in Table 2. According to the United States Environmental Protection Agency (USEPA) risk classification, a CR exceeding 1×10^{-4} indicates a potentially unacceptable carcinogenic threat to human health, whereas a CR below 1×10^{-6} is generally considered negligible. CR values between 1×10^{-6} and 1×10^{-4} are deemed to fall within an acceptable risk range (USEPA, 2004).

Results and discussion

1) Groundwater quality status in Ha Trung, Quang Ninh Province, Vietnam

The groundwater quality in Ha Trung was comprehensively evaluated through the analysis of 16 different physicochemical parameters, including pH, EC, ORP, DO, TDS, salinity, and various heavy metals, such as Mn, Hg, Fe, Se, Cu, Ni, Zn, Cd, Pb, and As. The results of the analysis revealed that the groundwater sample pH levels in the wet and dry seasons ranged from 4.73 to 7.40 and from 4.39 to 7.27, respectively. The lowest pH values recorded in both seasons indicated a mildly acidic environment, which is likely influenced by the area's closeness to ongoing coal mining operations. Notably, the average pH during the dry season was 5.65, which was below the acceptable level set by QCVN 01-1:2018/BYT, which requires a range between 6.0 and 8.5. According to Zhu et al. (2022), the pH values ranged from 2.72 to 7.83 in mine water from abandoned sites in southwestern China. They reported that the lower pH values observed in some water bodies may be attributed to the influence of mine water discharge, which has the potential to acidify the local groundwater environment (Zhu et al., 2022). As reported by Monterroso and Macías (1998), the low pH values observed in water samples near coal mine dumps are primarily caused by acid mine drainage resulting from the oxidation of pyrite (FeS_2) exposed during mining. This process releases sulfate and hydrogen ions, directly lowering the pH, while subsequent iron oxidation reactions further increase the acidity. The average concentration of DO in the samples during the wet season was 3.70 mg L^{-1}, which was lower than that during the dry season (5.83 mg L^{-1}). This decrease in DO coincided with increases in the TDS, EC, and salinity during the wet season. This pattern can be reasonably explained by increased oxygen consumption resulting from elevated inputs of organic matter and reduced compounds, which enhance microbial respiration and oxidation processes. Moreover, these inputs increase the dissolved ion concentration, leading to an inverse relationship between the DO concentration and the TDS/EC. As shown in Table 3, most heavy metal concentrations were lower in the wet season than in the dry season. For instance, the concentrations of Mn, Fe, Ni, Se, and Pb during the wet season were 0.088, 0.391, 0.023, 0.011, and 0.018 mg L^{-1}, respectively. In contrast, the corresponding concentrations during the dry season slightly increased to 0.098, 0.415, 0.026, 0.013, and 0.019 mg L^{-1}, respectively. These seasonal variations reflect the influence of hydrological and environmental factors on groundwater quality in the study area. Similarly, a study by Sankoh et al. (2023) conducted at dumpsites in Sierra Leone reported clear seasonal variations in heavy metal concentrations in groundwater. The concentrations of Cu, Cr, Fe, Mn, As, and Pb were lower during the wet season than during the dry season, which was attributed to the dilution effect of rainfall and enhanced surface water runoff, which facilitated the transport and dispersion of contaminants.

The CF_i values of heavy metals in groundwater during both the wet and dry seasons are shown in Figure 2. Overall, the CF_i values were consistently higher in the dry season, reflecting the elevated concentrations of heavy metals observed during this period. Among the ten investigated metals, Pb presented the highest CF_i in both seasons, indicating the most severe level of contamination, followed by Fe and Se, which also presented elevated CF_i values and significant contributions to overall groundwater contamination. These findings are consistent with those of previous studies reporting groundwater contamination by Fe, Mn, Pb, and As in coal mining regions, such as coal mines in China (Wang et., 2022) and India (Srivastava et al., 2025). These studies indicated that elevated heavy metal concentrations in groundwater are governed mainly by mining activities and geogenic processes. For example, high Fe concentrations are attributed primarily to the reductive dissolution of Fe-bearing minerals, including goethite, hematite, magnetite, and pyrite (Srivastava et al., 2025; Wang et., 2022).

Table 3 Descriptive analysis of the physicochemical properties of groundwater

Parameters	**Wet season**				**Dry season**				**QCVN 01-1: 2018/BYT**
	Min	**Max**	**Average**	**SD**	**Min**	**Max**	**Average**	**SD**	
Mn (mg L^{-1})	0.015	0.285	0.088	0.080	0.010	0.366	0.098	0.110	0.1
Fe (mg L^{-1})	0.100	0.941	0.391	0.268	0.092	1.074	0.415	0.306	0.3
Ni (mg L^{-1})	0.002	0.062	0.023	0.021	0.003	0.075	0.026	0.024	0.07
Se (mg L^{-1})	0.005	0.018	0.011	0.003	0.010	0.020	0.013	0.003	0.01
Hg (mg L^{-1})	0.000	0.002	0.001	0.000	0.000	0.002	0.001	0.001	0.001
Cu (mg L^{-1})	0.010	0.185	0.070	0.059	0.008	0.202	0.069	0.062	1
Zn (mg L^{-1})	0.020	0.725	0.306	0.214	0.018	0.638	0.250	0.170	2
Cd (mg L^{-1})	0.000	0.001	0.0005	0.000	0.000	0.001	0.0005	0.000	0.003
Pb (mg L^{-1})	0.008	0.035	0.018	0.007	0.007	0.046	0.019	0.012	0.01
As (mg L^{-1})	0.002	0.008	0.005	0.002	0.003	0.008	0.005	0.002	0.01
pH	4.730	7.400	6.046	0.889	4.390	7.270	5.651	1.000	6.0-8.5
ORP	255.0	380.0	312.2	40.12	181.0	336.0	265.5	56.19	-
EC	0.263	2.580	0.714	0.694	0.179	0.774	0.443	0.195	-
DO (mg L^{-1})	2.310	5.690	3.702	1.181	4.770	8.090	5.828	1.233	-
TDS (mg L^{-1})	0.171	1.650	0.459	0.443	0.116	0.496	0.285	0.124	1,000
Salinity	0.012	0.133	0.035	0.036	0.008	0.038	0.021	0.010	-

Notably, although the mean CF_i values for Mn and Hg were less than 1, their maximum concentrations exceeded the background levels (Figure 2). In the wet season, the peak CF_i values were 2.85 (Mn) and 1.5 (Hg), increasing to 3.66 (Mn) and 2.0 (Hg), respecttively, in the dry season. These site-specific values indicate localized contamination of Mn and Hg in certain wells.

The quality rating (Qi) values of the ten heavy metals or subindexes by season are shown in Figure 3. Overall, the Qi values for all the metals were higher in the dry season than in the wet season, underscoring the pronounced seasonal variability in the heavy metal concentration in the groundwater. Across both seasons, the Qi values of the investigated metals decreased in the following order: Pb > Fe > Se > Hg > Mn > As > Ni > Zn > Cu > Cd. Notably, the highest Q_i values were observed for Pb, Fe, and Se, with wet-season values of 130.2, 114.0, and 176.0, respectively, which increased to 138.4, 130.0, and 189.0, respectively, during the dry season. Similarly, the Q_i values for Mn, Hg, As, Ni, Cu, Zn, and Cd during the wet season were 87.9, 80.0, 49.0, 33.4, 6.98, 12.5, and 8.67, respectively, and increased to 97.9, 100.0, 53.0, 37.1, 6.99, 15.3, and 12.5, respectively, during the dry season. These results indicate a general enrichment of heavy metals in groundwater during the dry period. These findings also align with those of previous studies that identified mining activities as major contributors to heavy metal pollution in groundwater (Haakonde et al., 2020). Such contamination poses serious environmental and public health risks (Haakonde et al., 2020; Siame et al., 2025).

The HPI values at the ten groundwater sampling sites during the wet and dry seasons are shown in Figure 4. The HPI values at most sampling sites exceeded 30, indicating high levels of heavy metal contamination, with the exception of sites S5 (HPI = 20.77) and S9 (HPI = 15.33) during the dry season, which exhibited moderate contamination levels. Notably, several sites recorded exceptionally high HPIs, exceeding the critical pollution threshold of 100. Specifically, sites S1, S2, and S3 in the dry season, as well as sites S1 and S4 in the wet season, exhibited severe heavy metal contamination. These elevated HPI values indicate serious groundwater pollution at these locations. The observed contamination is likely attributable to the close proximity of sampling sites S1, S2, S3, and S4 to active mining areas, which may significantly increase heavy metal loading in the surrounding groundwater. In contrast, the relatively low HPI values observed at sites S5 and S9 can be attributed to their greater distance from the mining zone (Figures 1 and 4).

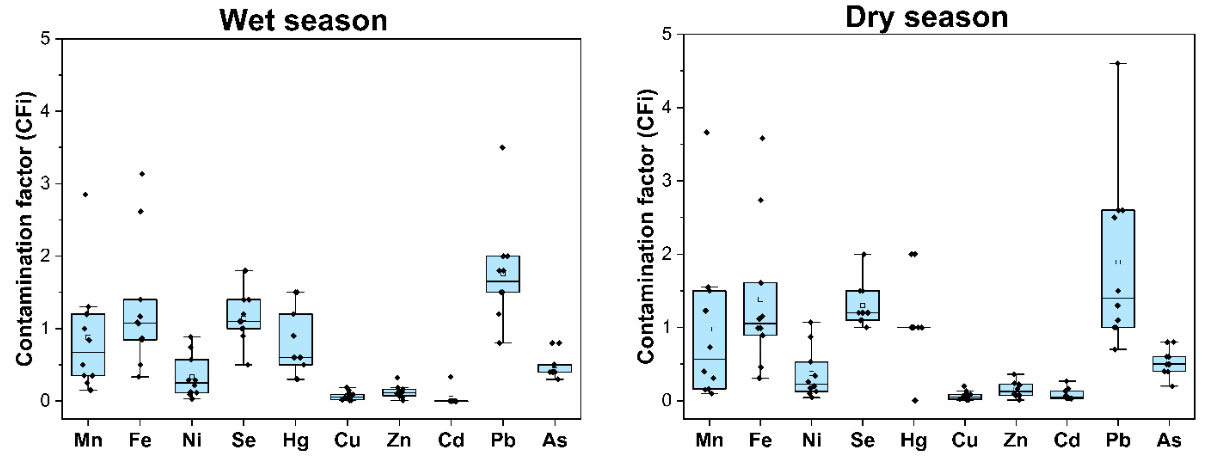

Figure 2 Contamination factor of heavy metals in groundwater during the wet and dry seasons.

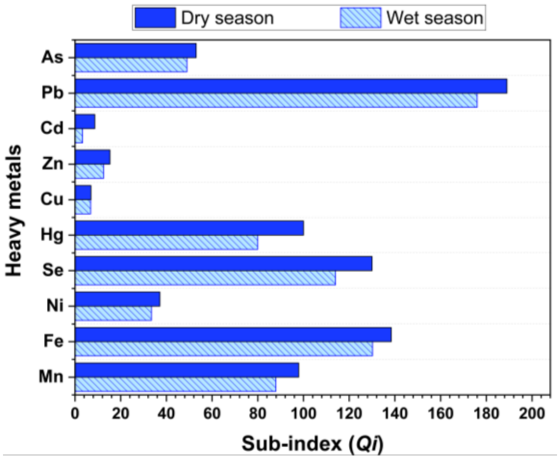

Figure 3 Quality rating of heavy metals in groundwater during both the wet and dry seasons.

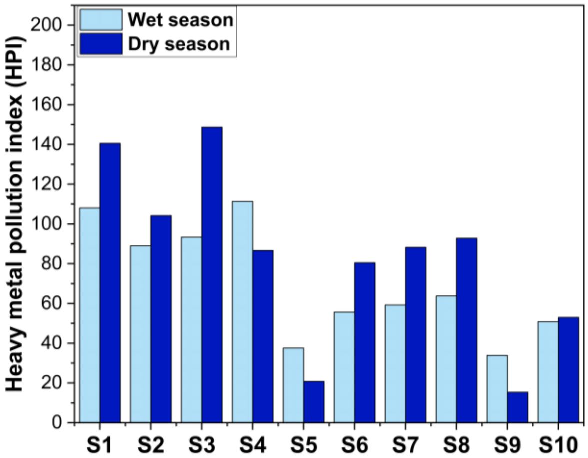

Figure 4 Heavy metal pollution index of the study area during both the wet and dry seasons.

2) Health risk assessment

2.1) Assessment of noncarcinogenic risks

The average HQ_i values for adults decreased in the following order: As > Pb > Mn > Hg > Se > Cu > Fe > Ni > Zn > Cd. A similar ranking pattern was observed for children in both seasons. These results indicate that As, Pb, and Mn are the primary contributors to noncarcinogenic health risks (Table 4). Among these elements, As contributed the most, accounting for 37.55% in the wet season and 36.86% in the dry season. These findings highlight its dominant role in noncarcinogenic health risks associated with groundwater in Ha Long city, Quang Ninh Province, and underscore the need for targeted monitoring and control measures. The subsequent contributions of Pb and Mn were 28.90% and 10.10% in the wet season and 28.17% and 10.21% in the dry season, respectively, indicating that these metals constitute a substantial proportion of the overall health risk and have a notable impact on human health.

This study provides a comprehensive risk appraisal for adults and children. The noncarcinogenic results are summarized in Table 5. For adults, the HI values ranged from 0.77 to 2.54 in the wet season and from 0.70 to 2.76 in the dry season. For children, the HI values in the wet and dry seasons ranged from 0.97 to 3.23 and from 0.89 to 3.52, respectively. The mean HI values (1.40–1.99) for both age groups exceeded 1 in each season, indicating appreciable health risks from exposure. As presented in Table 5, among the 10 groundwater sites, nine sample sites (accounting for 90%) exhibited HIs greater than 1 for both the adult and children's groups. These results underscore the significant health risks posed by groundwater quality in the study area (Haakonde et al., 2020; Latif et al., 2024). Only at sampling site S9 were the HI values during the wet season 0.77 for adults and 0.97 for children, whereas the corresponding values during the dry season were 0.70 and 0.89, respectively. All HI values were less than 1, indicating that the noncarcinogenic health risks at this sampling site (S9) are negligible.

Moreover, on the basis of the calculated average HI values given in Table 5, it is evident that the noncarcinogenic risks from heavy metal exposure are greater in children than in adults. These findings indicate that children are the most vulnerable group to these contaminants. This increased vulnerability is due mainly to children's lower body weight, higher exposure dose per unit mass, and immature immune and detoxification systems, which make them less capable of coping with heavy metal toxicity than adults are (Pan et al., 2023; Peek et al., 2018). These findings are consistent with the results of Wang et al. (2024) and Chen et al. (2023), who reported similar risk patterns across different demographic groups.

2.2) Assessment of carcinogenic risks

The CR for As, Cd, and Pb is shown in Figure 5. For both adults and children, the CR values for As and Pb exceeded the US EPA's upper acceptable threshold (1×10^{-4}) in both the wet and dry seasons. In contrast, only approximately 10% of the wells exceed the limit of 1×10^{-4} for Cd, while approximately 90% fall within the acceptable range of 1×10^{-6} to 1×10^{-4}. The average CR values for Cd were 0.24×10^{-4} and 0.63×0^{-4} in the wet and dry seasons, respectively, suggesting a nonnegligible carcinogenic risk of Cd for the local population. These results indicate that long-term consumption of groundwater in the study area may pose a potential carcinogenic risk, particularly because of exposure to As and Pb (Latif et al., 2024; Medgyesi et al., 2024; Siame et al., 2025). In other words, As and Pb constitute the primary contributors to the carcinogenic risk in the study area.

Among the analyzed heavy metals, the CR values were ranked in decreasing order as follows: Pb > As > Cd across both the investigated age groups and the seasonal conditions. In terms of individual heavy metals, the CR values for As in children were consistently greater than those in adults regardless of season. This trend was similar for Pb and Cd. Specifically, the average CR values for Pb in children were 59.8×10^{-4} during the wet season and 64.3×10^{-4} during the dry season, whereas the corresponding values for adults were 47.0×10^{-4} and 50.5×10^{-4}, respectively. These findings are consistent with those reported by Raheja et al. (2024), who investigated groundwater quality in coastal and floodplain regions of Bangladesh.

In terms of seasonal variation, the CR values for As, Cd, and Pb were greater during the dry season than during the wet season. These findings are in agreement with the higher groundwater concentrations of Pb, As, and Cd observed during the dry season than during the wet season as described above. For instance, the average CR values of As, Pb, and Cd for adults in the wet season were 2.30×10^{-4}, 47.0×10^{-4}, and 0.19×10^{-4}, respectively. In contrast, these values during the dry season were 2.50×10^{-4} for As, 50.5×10^{-4} for Pb, and 0.50×10^{-4} for Cd. In children, the average CR values for As, Pb, and Cd during the wet season (2.90×10^{-4}, 59.8×10^{-4}, and 0.24×10^{-4}, respectively) were consistently lower than those observed during the dry season (3.20×10^{-4}, 64.3×10^{-4}, and 0.63×10^{-4}, respectively). Thus, to protect public health, the groundwater in the study area requires appropriate treatment before it can be deemed safe for human consumption.

Table 4 Total HQ_i values in both seasons for adults and children

Heavy metals	Adult		Children		Contribution rate (%)	
	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season
Mn	0.14	0.15	0.18	0.20	10.10	10.21
Fe	0.04	0.04	0.05	0.06	2.99	2.89
Ni	0.04	0.04	0.05	0.05	2.69	2.71
Se	0.07	0.08	0.09	0.10	5.24	5.42
Hg	0.08	0.10	0.11	0.13	6.13	6.95
Cu	0.05	0.05	0.07	0.07	4.01	3.57
Zn	0.03	0.03	0.03	0.04	1.92	2.13
Cd	0.01	0.02	0.01	0.02	0.46	1.08
Pb	0.40	0.42	0.50	0.54	28.90	28.17
As	0.51	0.56	0.65	0.71	37.55	36.86
Average HQ_i	0.14	0.15	0.17	0.19	100	100

Table 5 HI values in both seasons for adults and children

Sample sites	Adult		Children	
	Wet season	Dry season	Wet season	Dry season
S1	1.22	1.38	1.55	1.75
S2	2.54	2.76	3.23	3.52
S3	1.33	1.97	1.69	2.50
S4	1.28	1.46	1.63	1.86
S5	1.18	1.19	1.51	1.51
S6	1.14	1.15	1.46	1.46
S7	1.76	1.72	2.24	2.19
S8	1.42	1.71	1.81	2.18
S9	0.77	0.70	0.97	0.89
S10	1.04	1.02	1.32	1.30
HI max	2.54	2.76	3.23	3.52
HI Min	0.77	0.70	0.97	0.89
HI average	1.40	1.56	1.79	1.99

Conclusions

In this study, the levels of heavy metal pollution in groundwater near a mining site in Ha Trung, Ha Long, Quang Ninh Province, Vietnam, were evaluated. The results indicated that the concentrations of Pb, Fe, and Se consistently exceeded national technical regulations for domestic water quality (QCVN 01-1:2018/BYT) during both the wet and dry seasons, with significantly higher levels observed during the dry season. Noncarcinogenic risk assessments revealed that most groundwater samples posed health risks to both adults and children, with children facing greater risks, as indicated by average HI values greater than 1. The average CR values for As and Pb adults were 2.30×10^{-4} and 47.0×10^{-4}, respectively, during the wet season and 2.50×10^{-4} and 50.5×10^{-4}, respectively, during the dry season. These values are significantly higher than the USEPA acceptable risk range of 10^{-6}–10^{-4}. These CR values indicate considerable long-term cancer risk for the local population. Without effective intervention, prolonged consumption of contaminated groundwater may lead to serious adverse health effects, including cancer and other systemic diseases. Given the current groundwater quality and the evident noncarcinogenic and carcinogenic risks associated with heavy metal exposure in the study area, there is an urgent need for continuous and long-term groundwater quality monitoring with an expanded range of monitoring parameters. In addition, the implementation of effective water treatment technologies, such as sand filtration, ultrafiltration, and reverse osmosis systems, is strongly recommended. Comprehensive public health strategies should also be developed, including raising awareness among local residents and organizing training workshops, with particular attention given to vulnerable groups such as children. Future studies should focus on investigating regional geochemical characteristics and local anthropogenic activities to better explain the sources and mechanisms of groundwater contamination in this area. Moreover, subsequent research should aim to address the limitations of the present study, including the relatively small sample size, the lack of control sites, and the absence of long-term monitoring data.

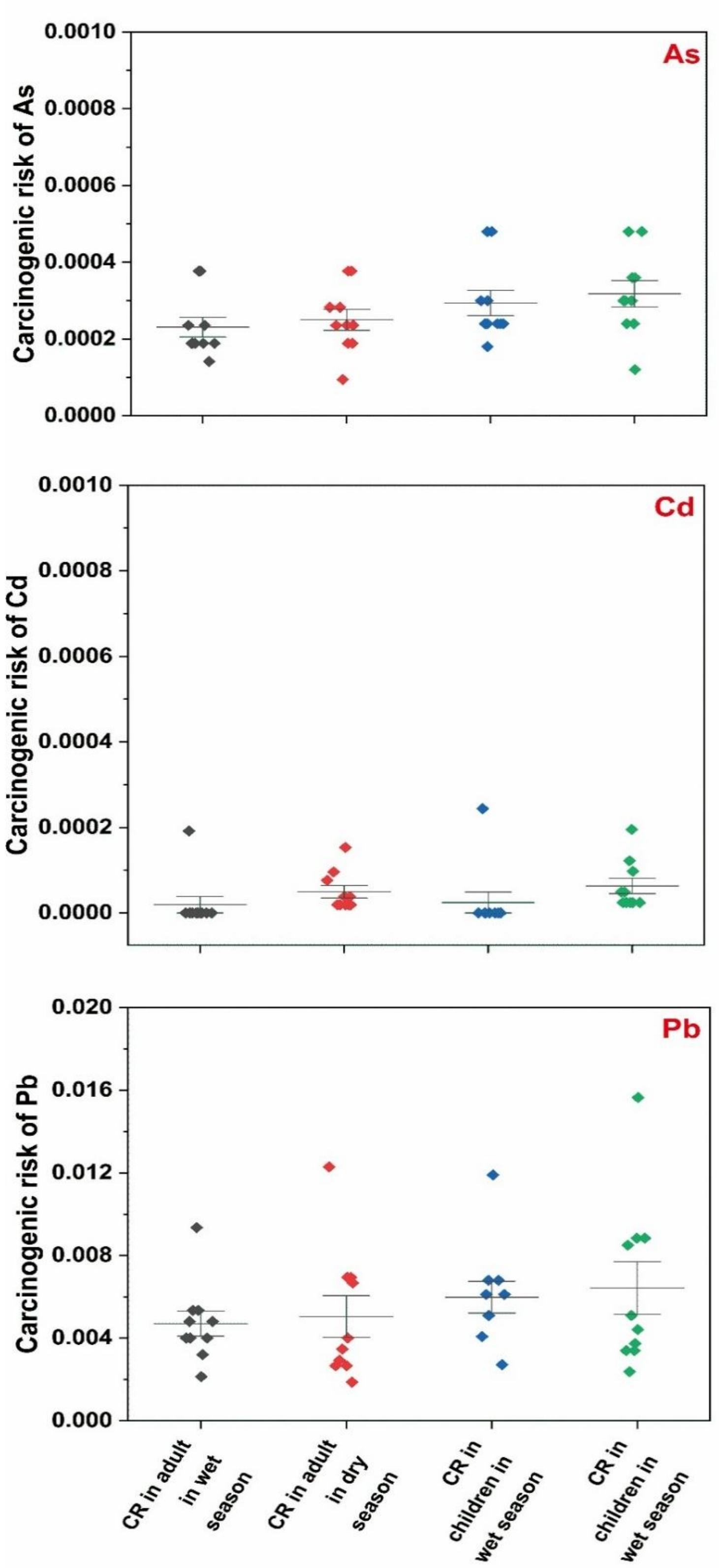

Figure 5 Carcinogenic risk of As, Cd, and Pb for different age groups during the wet and dry seasons.

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Data availability statement

Information and data used in the study will be disclosed upon request.

Author ORCID

Nguyen Quoc Tuan: 0000-0002-9496-9941
Ta Thi Hoai: 0009-0002-8232-8212
Nguyen Thi Hai: 0009-0003-9203-491X

Author contributions

Nguyen Quoc Tuan: Conceptualization, Software, Investigation, Writing – original draft, Visualization
Ta Thi Hoai: Methodology, Formal analysis
Nguyen Thi Hai: Validation, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition

Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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