

Pre-mining baseline characterization of groundwater quality using integrated water quality indices around metalliferous deposits, northeastern Algeria

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ABSTRACT

Groundwater faces increasing pressure from mining and agricultural activities, raising major concerns about its quality. Yet, no pre-mining groundwater assessment has been conducted in the Bejaia district, despite the region's strong mineral and agricultural potential. This study employs a tripartite index-based approach including groundwater quality assessment (water quality index WQI and heavy metal evaluation index HEI), non-carcinogenic risk assessment (HQ and HI), and irrigation suitability assessment (SAR, RSC, %Na, MAR) in an agricultural area primarily influenced by significant Pb-Zn mineralization. Twenty-six groundwater samples were collected during the low-water period and analyzed for major ions and trace elements. ArcGIS software was used for the spatial distribution of the indices. WQI values ranged from 24.78 to 102.05 indicating poor to unsuitable groundwater quality in 54% of the samples. HEI values ranged from 0.01 to 147.83 with 27% of the samples showing high heavy metal pollution, with an extremely high value of 147.83 coinciding with Pb-Zn mineralized zones. Furthermore, a significant non-carcinogenic risk was identified in both children and adult groups, with greater vulnerability observed among children. Irrigation suitability indices confirmed the suitability of groundwater for agricultural use across the majority of samples. These findings provide an initial pre-mining seasonal groundwater quality reference for this region and are essential for identifying contaminated zones, mitigating health risks, and supporting sustainable management strategies to preserve the mineral and agricultural resources of the Bejaia district.

Keywords: groundwater quality, irrigation suitability, non-carcinogenic risk, pre-mining baseline, Bejaia.

INTRODUCTION

Although mining activities play a crucial role in economic development of countries, they can generate significant environmental impacts (Dehkordi et al., 2024). Mining can considerably affect groundwater levels and hydrochemistry (Qu et al., 2022). Despite the presence of possible

contamination pathways, low anthropogenic impact and health risk associated with groundwater have been reported (Egbueri et al., 2023). Seasonal monitoring of an open-pit copper mine in eastern Turkey demonstrates that groundwater is currently suitable for drinking and irrigation, despite serious contamination related to AMD affecting surface water and soil, and recommends

long-term protection planning for areas where groundwater contamination may develop (Yessilnacar and Kadiragagil, 2013). Similarly, long-term monitoring has shown that groundwater responds more slowly than surface water to acid mine drainage impacts (Liu et al., 2023). Furthermore, research in karst lead and zinc mining regions has shown that the groundwater contains more types of toxic elements than surface water (Zhou et al., 2024). These findings highlight the importance of establishing pre-mining baseline data. Heavy metal contamination of groundwater in mining districts worldwide remains a persistent issue (Hao et al., 2024; Sahoo et al., 2025). In Algeria, climate change has increased the vulnerability of water resources through demographic growth, reduced water runoff, water scarcity, degradation of hydraulic infrastructure, and threats to wetlands (Mohammed and Al-Amin, 2018). Moreover, several studies in the region have investigated groundwater quality, including a hydrochemical study revealing high concentrations of heavy metals, with considerable spatial and seasonal variations (Zaidi et al., 2025), as well as the identification of zones vulnerable to contamination in the alluvial aquifer along the Oued Soummam (Ouyahia et al., 2024). In addition, other studies have investigated water quality for drinking purposes in and around mining areas (Celebi et al., 2026; Diop et al., 2023). However, research on groundwater

in unexploited Pb-Zn mining sites in Algeria remains critically absent. Although Kissar and Khemmoudj (2025) assessed the carcinogenic and non-carcinogenic health risks in the Soummam Basin, no previous study has applied an index-based approach combining water quality (WQI, HEI), human health risk assessment related to heavy metal exposure through the hazard quotient (HQ) and the hazard index (HI) in addition to irrigation suitability indices (SAR, RSC, MAR, %Na) in this mineralized region to provide a pre-mining groundwater quality reference framework. The present study therefore aims to investigate groundwater quality by providing a pre-mining seasonal reference point through multiple indices (WQI, HEI, HI, SAR, RSC, %Na, MAR) covering water quality, non-carcinogenic health risk, and irrigation suitability from a pre-mining perspective in this polymetalliferous-rich region of northeastern Algeria.

STUDY AREA

The study area is situated in the Bejaia-Amizour region and is part of the Soummam watershed (Figure 1). It is characterized by sedimentary and volcano-plutonic rocks (Figure 2). The Oued Amizour magmatic complex is located 15 km west of Bejaia. The Miocene magmatic rocks traverse the Bouhatem metamorphic

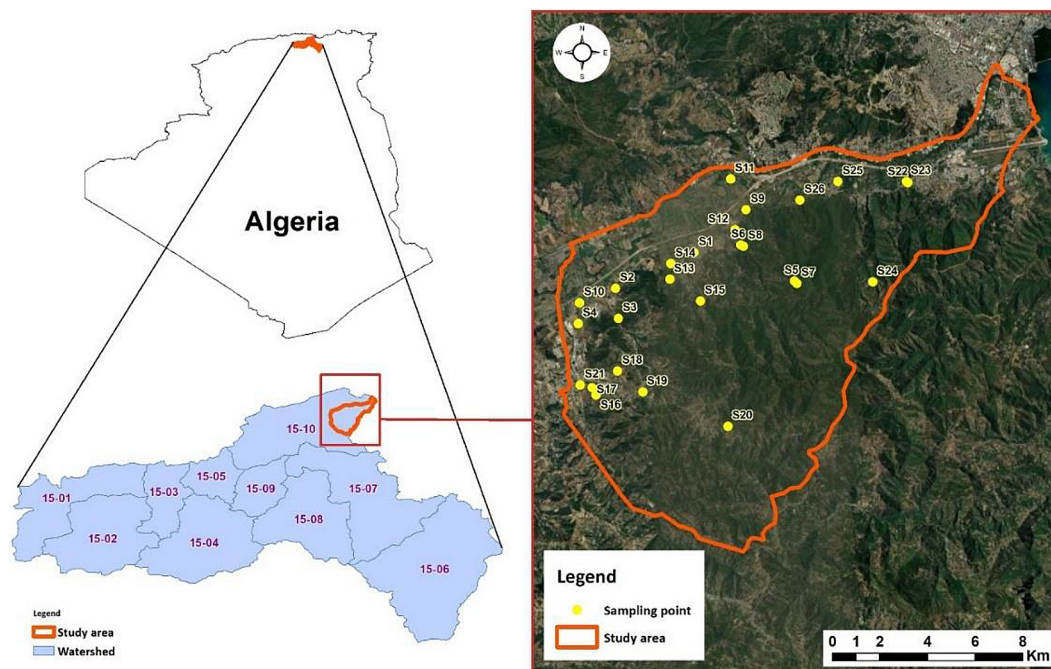


Figure 1. Study area and location of groundwater sampling points

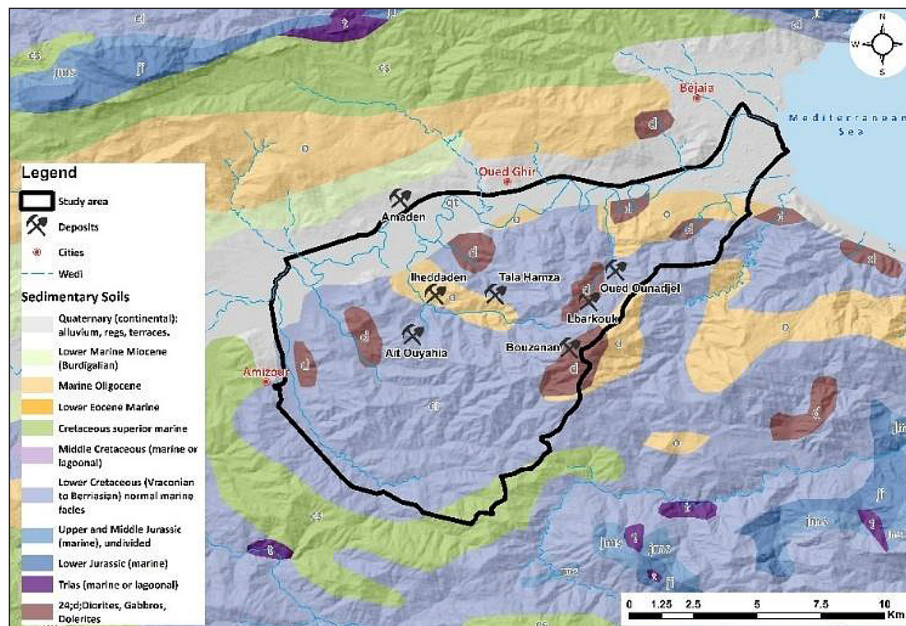


Figure 2. The geological map of the study area

basement, with the Baborian carbonate formation emplaced in the Cretaceous flysch, which is locally covered by Tertiary sediments and intruded by the Miocene Oued Amizour igneous rocks (Laouar et al., 2018). The rocks forming the volcanic complex of the Amizour region of Béjaïa date from the Miocene and cut across the Cretaceous, Mauretanian, and Massylian flyschs; this complex contains mainly andesites, rhyolitoids, and andesitic tuffs (Semroud, 1993). The Bejaia coastal region, part of the Tellian Atlas, has a semi-arid climate with rainy winters and dry summers, an average annual precipitation of 777 mm, and a mean temperature of 18 °C (Megherfi et al., 2020). The shallow aquifer, hosted within the alluvial Mio–Plio–Quaternary formations, has experienced considerable depletion of its reserves due to continuous groundwater withdrawal (Ghodbane et al., 2022). The most important mineral occurrences in the region are those of Ait Bouzid, Bouzenan, Iheddaden, Ait Dali and Amaden. Among these, the Tala Hamza deposit, located in the Ait Bouzid region at a depth of 400 to 500 m, this deposit consists of an oval ore body with a thickness of 20 to 30 m of yellowish sphalerite hosted in andesitic tuffs and breccias overlying metasomatized granodiorites (Laouar et al., 2018). This study therefore assesses the suitability of groundwater for both drinking and irrigation in order to understand the natural influence of the polymetallic deposits on groundwater composition and quality.

MATERIALS AND METHODS

Sampling and laboratory analysis

Twenty-six groundwater samples, including samples from wells, boreholes and natural springs were collected across the study area during a single low-water campaign conducted in September 2023, in accordance with ISO 5667 water-quality standards (ISO, 2009; ISO, 2020). For each sampling point, the source type (well, borehole or spring) and geographic coordinates were recorded (Figure 3). Prior to sampling, purging was carried out by pumping until temperature, pH and electrical conductivity stabilized within ± 2 °C, ± 0.1 pH unit and $\pm 3\%$ respectively.

Physicochemical parameters were measured in-situ using a portable multi-parameter device (HANNA HI 99300), and a pH-meter (Ohaus starter 300), the pH meter was calibrated using three solutions with pH 3, pH 7, and pH 10. An additional water sample was collected from each site for the analysis of major ions. Trace metal samples were collected in acid-washed polyethylene bottles, filtered through a 0.45 µm membrane filter and then acidified with nitric acid to pH 1–2; all samples were stored and handled in accordance with ISO 5667-3 (ISO, 2018), in a refrigerated container at 5 ± 3 °C, and immediately submitted for laboratory analysis to ensure data integrity and the reliability of the results. Sodium (Na^+) and potassium (K^+) concentrations



Figure 3. Representative groundwater sources sampled during the field campaign: (a) borehole, (b) well, and (c) spring

were measured using a flame photometer (Model S-931) whereas calcium (Ca^{2+}) and magnesium (Mg^{2+}) were analyzed by a complexometric titration with 0.05 mol/L EDTA. Nitrate (NO_3^-) and sulfate (SO_4^{2-}) were quantified via UV–visible spectrophotometry (DR 5000), while bicarbonate (HCO_3^-) and chloride (Cl^-) were quantified using ion chromatography (Dionex ICS 3000). Graphite furnace atomic absorption spectroscopy (GFAAS) was employed to quantify the trace elements Zn, Pb, Fe, Mn, Cu, and Co. To

guaranty the accuracy and reliability of the analytical results, quality assurance and control (QA/QC) techniques were used throughout the atomic absorption spectroscopy (AAS) analysis. A series of AAS standard solutions was prepared at concentrations of 0.00, 0.25, 0.5, 0.75 and 1.00 mg/L, with the 0.00 mg/L solution served as the analytical blank. Every absorbance of standard solutions was measured under identical experimental conditions at the selected analytical wavelength (Figure 4).

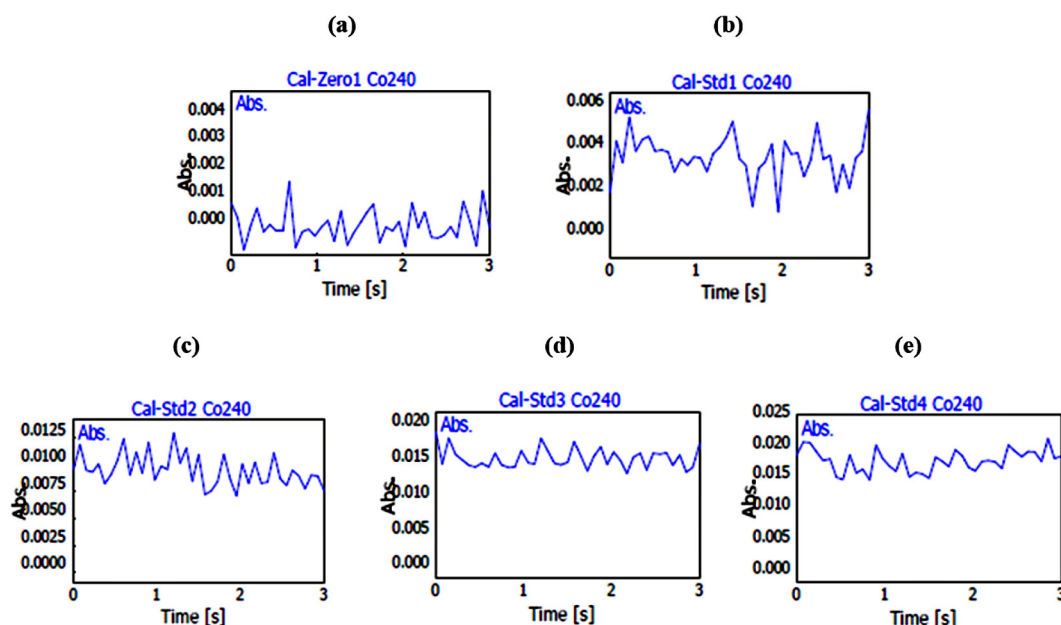


Figure 4. The absorbance of standard solutions for cobalt: (a) blank sample with 0 mg/l, (b) 1st standard 0.25 mg/l, (c) 2nd standard 0.5 mg/l, (d) 3rd standard 0.75 mg/l and (e) 4th standard

The measured absorbance values were plotted against the corresponding concentration of the standard solutions to generate the calibration curve. The calibration was considered acceptable based on the strong linear correlation between absorbance and concentration, subsequently, the concentrations of the twenty-six samples collected during the study were calculated based on the established calibration curve. Figure 5 presents the calibration curve obtained by plotting the absorbances versus the corresponding Cobalt (Co) standard concentrations (0.00 –1.00 mg/l). The curve exhibited good linearity, with $R=0.9964$ and a slope of 0.0198 Abs / (mg/l). The calibration equation was $Y = 0.000355 + 0.0167762 X$, where Y represents the absorbance and X is the cobalt concentration in mg/l.

The charge balance error (CBE) was used to assess the quality of the data. All the collected groundwater samples had CBE values within acceptability range of $\pm 5\%$ showing a suitable ionic balance, and the analytical data of the major ions present a satisfactory internal consistency (Figure 6).

Following the conservative methodology recommended for metals risk assessment (USEPA, 2007), the low water period was specifically

selected for this study. High water periods are responsible for geochemical disturbances, such as dilution, cation exchange, and pollutant mobilization from the surface into the aquifer (Manikandan et al., 2020). These disturbances may mask contamination signals that are more clearly detectable during the low-water period.

WATER QUALITY ASSESSMENT

To assess water quality for drinking purposes, WQI and heavy metal evaluation index (HEI) were calculated following the methodology proposed by Gaber et al. (2024). Previous index-based water-quality studies, including the combined use of the entropy-weighted WQI and the pollution index of groundwater in semi-arid Turkey, demonstrate the value of multi-parameter indices for translating hydrochemical data into management-relevant water-quality classes (Yazici-Karabulut et al., 2024).

Water quality index (WQI)

WQI serves as a crucial indicator of water contamination, enabling the assessment of water

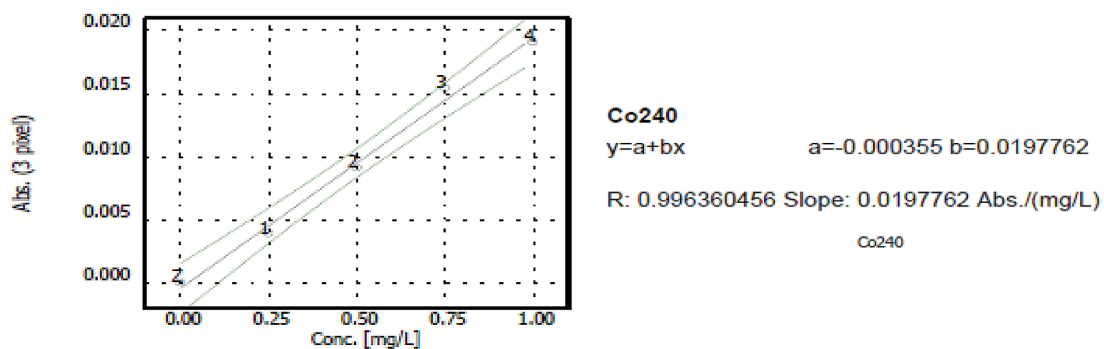


Figure 5. Calibration curve of cobalt used in the present study

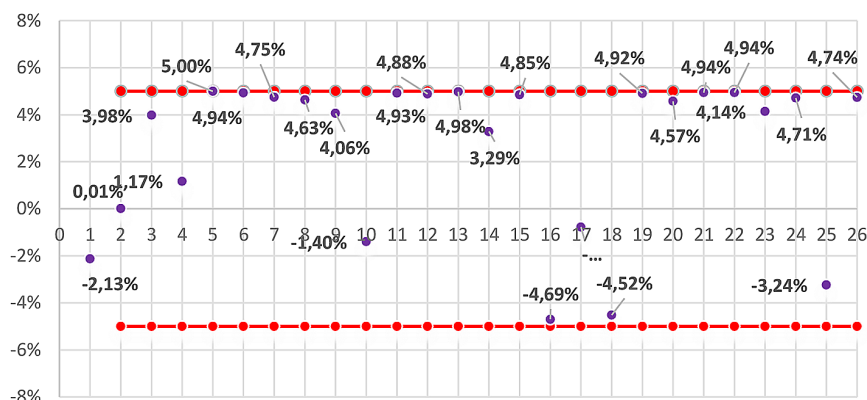


Figure 6. The charge balance error of the collected samples

quality and the preservation of this vital resource. Its calculation follows several steps, beginning with the determination of the following constants:

$$K = \frac{1}{\sum_{i=1}^n \frac{1}{S_i}} \quad (1)$$

The normalized weights (W_i) for each parameter were then calculated using the following equation:

$$W_i = \frac{K}{S_i} \quad (2)$$

where: S_i represents the standard permissible limit for the selected parameter according to WHO standards (WHO 2022).

The sub-index quality rating (Q_i) is calculated differently depending on the parameter. For pH, whose ideal value is 7:

$$Q_i = \frac{(V_{ac} - V_{id})}{(S_{st} - V_{id})} \times 100 \quad (3)$$

For all other parameters, for which the ideal value is zero, the sub-index of quality (Q_i) is given by the following equation:

$$Q_i = C_i \times \frac{100}{S_i} \quad (4)$$

where: V_{ac} is the value measured during laboratory analysis, V_{id} is the ideal Value, S_{st} is the standard permissible value for each parameter and C_i is the measured concentration.

Then, the WQI is obtained as follows:

$$WQI = \sum_{i=1}^n W_i Q_i / \sum_{i=1}^n W_i \quad (5)$$

The standard permissible values (S_i) for each physicochemical parameter, used in the calculation of the WQI are illustrated in (Table 1).

Heavy metal evaluation index (HEI)

HEI is used to evaluate the heavy metal concentrations in groundwater. An HEI value below

10 indicates low metal pollution, a value between 10 and 20 indicates medium metal pollution, whereas values exceeding 20 reflect high metal pollution (Dippong and Resz, 2024). The HEI is calculated using Equation (6), where H_c is the measured concentration of each parameter and H_{mac} represents the maximum admissible concentration. The H_{mac} used to calculate the HEI were considered for five heavy metals: Zn, Pb, Fe, Mn, and Cu (Table 2).

$$HEI = \sum_{n=1}^n \frac{H_c}{H_{mac}} \quad (6)$$

Human health risk assessment

The human health risk was assessed using hazard quotient (HQ), which was calculated according to Equation 7 proposed by Latif et al. (2025).

$$HQ = \frac{ADD}{R_f D} \quad (7)$$

The reference dose ($R_f D$) represents the reference level of daily oral exposure that is not expected to cause non-carcinogenic health risks over a lifetime. Equation 8 calculates the average daily dose (ADD). Following Preonty et al. (2025), the exposure frequency, EF (365 days/year); the exposure duration, ED (6 years for children and 30 years for adults); the average body weight, BW (16 kg for children and 70 kg for adults); and the averaging time, AT ($ED \times 365$) respectively. The average daily water consumption was assumed to be 2 L for adults and 1 L for children (USEPA, 2018).

$$ADD = \frac{C \times IR \times ED \times EF}{BW \times AT} \quad (8)$$

The hazard index (HI) is used to evaluate the potential non-carcinogenic health risks associated with water consumption and is calculated as the sum of the target hazard quotients (HQ) for individual metals (Uchendu and Edogbo, 2025). It represents the sum of all the HQ values of each assessed metal as expressed in the following equation:

Table 1. Standard values used for water quality index (WQI) calculation

Parameters	pH	EC μS/cm	TDS mg/L	TH mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Na ⁺ mg/L	K ⁺ mg/L	NO ₃ ⁻ mg/L	HCO ₃ ⁻ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L
Si (WHO, 2022)	8.5	1000	500	300	75	50	200	12	50	300	250	250

Table 2. The H_{mac} values of heavy metals used for HEI calculation

Metal	Zn	Pb	Fe	Mn	Cu
H_{mac} (WHO, 2022)	3	1×10^{-2}	3×10^{-1}	8×10^{-2}	2

$$HI = \sum HQ_i \quad (9)$$

An HI value below 1 indicates the absence of significant non-carcinogenic health risks, whereas an HI equal to or greater than 1 indicates a potential health risk. Accordingly, the risk level is considered negligible when $HI < 1$. Table 3 lists the oral reference doses (R_{fD}) for the metals assessed in the present study for both adults and children.

GROUNDWATER ASSESSMENT FOR IRRIGATION PURPOSES

Water quality for irrigation was assessed by several indices including SAR, %Na, RSC and MAR.

Sodium adsorption ratio (SAR)

The sodium adsorption ratio is one of the most important indicators of water quality for irrigation purposes. Irrigation suitability decreases as SAR values increase. When SAR is less than 10 the water is considered suitable for irrigation, when SAR is between 10 and 18 the water is doubtful, when SAR is higher than 18, the water is considered unfit for irrigation uses (Moharir et al., 2025). SAR is calculated using the equation proposed by Richards (1954):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}} \quad (10)$$

Irrigation water rich in Na^+ salts affects soil quality by increasing soil saturation with sodium and reducing calcium (Cucci and Lacolla, 2013), which eventually degrades the soil environment (Rengasamy, 1987).

Percent sodium (%Na)

Percent sodium is a frequently used index to determine whether groundwater is suitable for irrigation, representing the percentage of sodium ions (Mahammad et al., 2023). Water is considered excellent for irrigation when %Na varies from 0 to 20; good from 20 to 40; doubtful from 40 to 60, and unsuitable when %Na value exceeds 80 (Khodapanah et al., 2009). It is determined using the following equation (Wilcox, 1955):

$$\%Na = \frac{Na^+ + K^+}{Ca^{+2} + Mg^{+2} + Na^+ + K^+} \times 100 \quad (11)$$

Table 3. Oral reference doses of the metals used to assess the non-carcinogenic risk

Metals	R_{fD} (mg/kg/day)	Reference
Zn	3×10^{-1}	(USEPA, 2005)
Pb	1.4×10^{-3}	(Mohammadi et al., 2019)
Fe	7×10^{-1}	(USEPA, 2006)
Co	3×10^{-2}	(Finley et al., 2012)
Mn	1.4×10^{-1}	(USEPA, 1995)
Cu	4×10^{-2}	(Taylor et al., 2023)

Residual sodium carbonate (RSC)

Residual sodium carbonate (RSC) is a crucial parameter used for assessing irrigation suitability. High RSC levels can deteriorate soil structure by reducing water infiltration and limiting plant access to water and essential nutrients (Abbas et al., 2025). RSC is expressed by the following equation (Chaudhary and Satheeshkumar, 2018):

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{+2} + Mg^{+2}) \quad (12)$$

Magnesium adsorption ratio (MAR)

The magnesium adsorption ratio (MAR), also known as magnesium hazard (MH), is the magnesium content of irrigation water. MAR values exceeding the 50% threshold increase soil alkalinity, thereby negatively affecting crop growth (Gandla et al., 2024). The magnesium adsorption ratio is calculated using the following equation (Raghunath, 1987).

$$MAR = \frac{Mg^{+2}}{Ca^{+2} + Mg^{+2}} \times 100 \quad (13)$$

RESULTS AND DISCUSSION

Table 4 presents the physicochemical parameters of the groundwater from this study in comparison with those reported for Pb-Zn mining regions worldwide. The hydrochemical behavior of the Amizour groundwater is characterized by significant mineralization compared to other Pb-Zn districts across the world, highlighting the importance of establishing reference data for these mineralized deposits prior to any mining operations.

The pH in this study is lower than in other districts, indicating an acidic environment linked to geogenic mechanisms in the region. The EC and TDS values recorded in the study area are higher than those reported in Korea (Lee et al., 2005)

Table 4. Comparative analysis of groundwater quality characteristics in the worldwide and the selected area

The Region	pH	EC	TDS	Ca	Mg	K	Na	HCO ₃	Cl	NO ₃	SO ₄
Pakistan (Khafaga et al., 2025)	7.4–8.4	–	144–990	34–116	58–215	8–16	104–508	100–480	46–763	5–18	100–340
Korea (Lee et al., 2005)	6.4–7.1	116–648	–	5.2–86.9	2.3–20.9	0.7–2.4	5.1–9.6	9.8–70.8	2.1–4.3	0.1–0.3	16.2–382.5
Southwestern China (Qin et al., 2019)	7.2–8.3	20.7–757.0	–	1.0–92.3	0.9–40.9	0.1–12.7	0.3–17.4	6.1–381.8	0.7–12.2	0.8–54.9	1.6–46.9
Bejaia, Algeria (Zaidi et al., 2025)	5.7–7.8	556–2874	289–1495	44.1–364.7	12.1–98.4	2.0–16.0	27.0–184.0	176.9–497.3	55.8–395.0	4.6–48.9	39.4–421.9

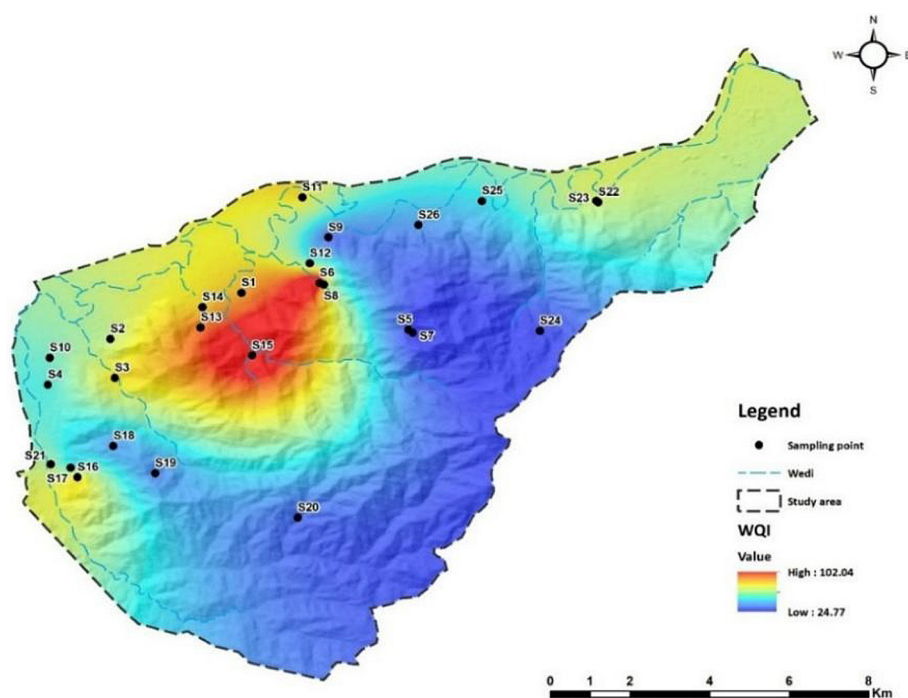
and China (Qin et al., 2019), while the HCO₃[–] values are higher than those in the other studies cited, indicating a carbonate neutralization process. The SO₄^{2–} values are almost equivalent to those reported for Pakistan (Khafaga et al., 2025), confirming the dissolution of sulfide minerals in both deposits.

WATER QUALITY ASSESSMENT

Water quality index

The results of the WQI range from 24.78 to 102.05 for the twenty-six (26) groundwater samples. The water quality is classified from excellent to extremely poor and unsuitable water quality for drinking purposes. Only one sample was classified as excellent, eleven (11) samples were classified as good. Thirteen (13) samples range

from poor to very poor waters, and only one sample is classified as unsuitable for drinking, though it may still be used for industrial and irrigation purposes. Water quality deterioration is likely related to water–rock interaction with metalliferous deposits, agricultural inputs through the use of nitrogenous fertilizers, and industrial discharges. The distribution map of the final WQI values was prepared using a geographic information system (GIS) and is presented in Figure 7, revealing a highly spatially variable hydrochemical distribution. The main WQI hotspot locations, classified as poor to very poor or unfit, are located in the central-western part of the study area (S13, S15, S14, S1, S2) spatially related to the metalliferous deposits Tala Hamza, Iheddaden and Ait Ouyahia extending with medium values to the Amaden deposit. Water quality is mainly good in the eastern and northern parts of the study area. The obtained results are consistent with the geological

**Figure 7.** Spatial distribution of the water quality index (WQI)

formations, far from mineralized zones, owing to the renewal of hydrological activity by the rivers such as the Oued Soummam, which crosses this area, ensuring continuous dilution processes that constrain the accumulation and precipitation of contaminants. Overall, 46 % of the groundwater samples were of excellent to good quality, while 54 % of the samples were considered unsuitable for drinking purposes, indicating localized deterioration of water quality within the study area.

Heavy metal evaluation index HEI

HEI values ranged between 0.01 and 147.83, with approximately 27% of samples classified as highly polluted and 23% as moderately polluted. The HEI distribution is heterogeneously spread across the study area (Figure 8). The highest HEI values were recorded at point S6 corresponding to the sample with the highest concentrations of Fe and Mn followed by Zn. High HEI values were primarily located in three zones: the first, in the southwest of the study area, comprised three samples with a mean HEI of 11.74; the second zone, in the northeast, included three other samples with a mean of 19.21; and the third and most affected zone consisted of seven samples (S1, S5, S6, S7, S11, S13, and S15) with a mean HEI of 41.68. This last zone is located around the Tala Hamza Pb-Zn deposit. The particularly high HEI values

recorded in this area suggest a potential significant contribution of heavy metals to the observed contamination. The high Fe and Mn concentrations could be attributed to the lithology and geology of the region, which is dominated by volcanic formations. Further studies, such as lead isotope analysis would be essential to confirm the geogenic origin of the contamination. Zinc concentrations were generally within the standards of the World Health Organization. Most NO_3^- values complied with the recommendations of the World Health Organization; however, several samples showed moderate to high values without exceeding the maximum admissible limit. The highest recorded nitrate concentration was 48.90 mg/L at S17, posing a potential risk to human health through oral and dermal exposure. Despite the absence of values exceeding the WHO recommendations, elevated nitrate concentrations in water have been associated with several health disorders, including methemoglobinemia, gastric cancer, birth malformation, and goitre (Majumdar and Gupta, 2000; Shaban et al., 2023), emphasizing the need to implement a monitoring system at sites approaching the limit value, especially S17. Sulfate concentrations exceeded 250 mg/L in 19.23% of samples, below the WHO notification threshold of 500 mg/L (WHO 2022), highlighting a potential risk to groundwater quality possibly associated to the geochemical hazards from the leaching of mineralized formations.

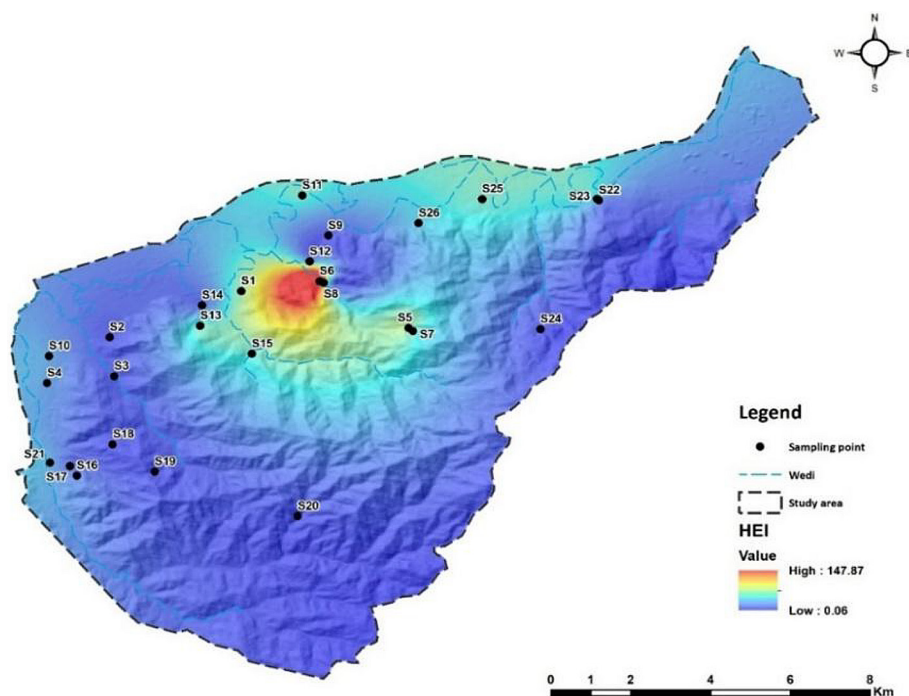


Figure 8. Spatial distribution of the heavy metal evaluation index (HEI)

These elevated concentrations are attributed to incipient or carbonate-buffered acid rock drainage processes, whereby carbonate host rocks neutralize acidic conditions; nevertheless, metal dissolution and mobility continue to release contaminants into the groundwater. According to WHO (2022) iron concentrations exceeded the aesthetic guideline value of 0.3 mg/L in 15.38% of samples, which may lead to discoloration of groundwater. Mn concentrations exceeded 0.08 mg/L in 38.46% of the samples, reflecting potential health risks while Pb concentrations exceeding the limit value of 0.01 mg/L in 34.61% of the samples consistent with the elevated HEI high observed.

HUMAN HEALTH RISK ASSESSMENT

To thoroughly evaluate the overall non-carcinogenic health risk, the Hazard Index (HI) was calculated for both children and adults in the study area. Children exhibited a higher mean HI value (mean = 2.31) compared to adults (mean = 1.05),

demonstrating greater vulnerability in this group, likely due to their higher ingestion rate relative to body weight (Hauptman and Woolf, 2017), a result consistent with the non-carcinogenic risk assessment of groundwater conducted in the urban coastal aquifers of the Bejaia district (Toumi and Khemmoudj, 2026). HI values enable the localization of priority zones requiring urgent water monitoring and assessment prior to any mining activities. Although S5 recorded the second highest HEI value and a low WQI, it shows the highest HI value among both children and adults, with 9.77 and 4.47, respectively, driven mainly by Pb with HQ equal to 9.24 for children and 4.22 for adults. At S23, HI is mainly driven by Pb (HQ = 4.12) followed by Mn (HQ = 2.89) and Fe (1.58), unlike most other samples where Pb is the only contributor (Table 5). HQ values remain below 1 for the most assessed metals; however HQ for Pb exceeds 1 in nine out of twenty-six samples, confirming that lead is the main driver of high HI values for both children and adult groups. Eleven

Table 5. HI and HQ for each metal separately for both categories children and adults

S number	Children							Adults						
	HQ Zn	HQ Pb	HQ Fe	HQ Co	HQ Mn	HQ Cu	Total HI	HQ Zn	HQ Pb	HQ Fe	HQ Co	HQ Mn	HQ Cu	Total HI
S1	0.00	0.00	0.47	0.05	0.28	0.04	0.84	0.00	0.00	0.22	0.02	0.13	0.02	0.38
S2	0.02	0.00	0.00	0.04	0.00	0.06	0.11	0.01	0.00	0.00	0.02	0.00	0.03	0.05
S3	0.04	0.00	0.00	0.03	0.01	0.03	0.11	0.02	0.00	0.00	0.01	0.01	0.02	0.05
S4	0.06	4.51	0.00	0.05	0.00	0.07	4.68	0.03	2.06	0.00	0.02	0.00	0.03	2.14
S5	0.01	9.24	0.00	0.03	0.44	0.05	9.77	0.01	4.22	0.00	0.01	0.20	0.02	4.47
S6	0.18	3.35	1.58	0.08	2.89	0.05	8.13	0.08	1.53	0.72	0.04	1.32	0.02	3.72
S7	0.00	3.79	0.00	0.04	0.38	0.06	4.27	0.00	1.73	0.00	0.02	0.17	0.03	1.95
S8	0.00	0.00	0.00	0.04	0.01	0.03	0.08	0.00	0.00	0.00	0.02	0.01	0.01	0.04
S9	0.10	0.00	0.00	0.04	0.00	0.05	0.19	0.04	0.00	0.00	0.02	0.00	0.02	0.09
S10	0.00	5.04	0.00	0.04	0.00	0.06	5.14	0.00	2.31	0.00	0.02	0.00	0.03	2.35
S11	0.99	0.00	0.00	0.04	0.74	0.05	1.83	0.45	0.00	0.00	0.02	0.34	0.02	0.84
S12	0.04	0.00	0.00	0.03	0.01	0.07	0.14	0.02	0.00	0.00	0.01	0.00	0.03	0.06
S13	0.02	0.00	0.06	0.05	0.78	0.03	0.94	0.01	0.00	0.03	0.02	0.36	0.01	0.43
S14	0.10	0.00	0.00	0.03	0.00	0.03	0.17	0.05	0.00	0.00	0.02	0.00	0.02	0.08
S15	0.33	2.01	0.04	0.04	0.48	0.03	2.92	0.15	0.92	0.02	0.02	0.22	0.01	1.33
S16	0.45	0.00	0.00	0.04	0.25	0.03	0.77	0.21	0.00	0.00	0.02	0.12	0.01	0.35
S17	0.00	0.00	0.00	0.03	0.01	0.10	0.14	0.00	0.00	0.00	0.01	0.01	0.05	0.07
S18	0.00	0.00	0.00	0.04	0.00	0.04	0.08	0.00	0.00	0.00	0.02	0.00	0.02	0.04
S19	0.13	0.00	0.00	0.06	0.00	0.05	0.24	0.06	0.00	0.00	0.03	0.00	0.03	0.11
S20	0.34	0.00	0.00	0.04	0.00	0.05	0.43	0.16	0.00	0.00	0.02	0.00	0.02	0.20
S21	0.00	6.07	0.00	0.05	0.00	0.02	6.15	0.00	2.78	0.00	0.02	0.00	0.01	2.81
S22	0.01	1.25	0.00	0.06	0.00	0.08	1.40	0.00	0.57	0.00	0.03	0.00	0.04	0.64
S23	0.05	9.02	0.00	0.04	0.00	0.37	9.48	0.02	4.12	0.00	0.02	0.00	0.17	4.33
S24	0.03	0.00	0.00	0.06	0.00	0.10	0.19	0.01	0.00	0.00	0.03	0.00	0.05	0.08
S25	0.00	0.00	0.00	0.06	0.79	0.19	1.04	0.00	0.00	0.00	0.03	0.36	0.09	0.48
S26	0.11	0.04	0.00	0.05	0.53	0.09	0.73	0.01	0.02	0.00	0.02	0.24	0.04	0.33

of twenty-six samples exhibited an HI exceeding 1 for children, and eight for adults, both mainly driven by Pb concentrations, further emphasizing the higher vulnerability of children compared to adults. Samples S4, S5, S6, S7, S10, S15, S21 and S23 are the same hotspots among both groups of children and adults, underlining elevated metal contamination at these locations and underscoring the necessity of establishing specific management measures, particularly for children, given their higher vulnerability.

IRRIGATION SUITABILITY

SAR values were below 10 across all samples (Figure 9), classifying all sites as suitable for irrigation with no sodium hazard. Meanwhile the highest SAR values were observed in S13 and S15 and S11 respectively, all located near the Tala Hamza deposits. Figure 10 shows the spatial distribution of the magnesium ratio, MAR values ranged from 9.07 to 56.21%; most samples fell below the critical threshold of 50%, however, four samples S5, S6, S7 and S8 exceeded this limit, classifying them as unsafe for irrigation purposes. The residual sodium carbonate (RSC) values are negative across the study area (Figure 11), indicating the absence of carbonate and bicarbonate alkalinity hazards and confirming the suitability of groundwater for irrigation across most soils.

Figure 12 presents the spatial distribution of % Na. The %Na ranged from 10.48 % to 40.28% across the study area, falling within the excellent to good classification, indicating that sodium does not adversely impact the agricultural activity in the region. Overall, the indices SAR, RSC, %Na and MAR confirm that groundwater in the study area is suitable for irrigation, with the exception of localized mineralization influences that warrant continuous monitoring and particular attention especially if mining activities start in the region.

Correlation analysis between indices

The correlation between the physicochemical parameters and the measured water quality indices in this study (Table 6) shows two main axes controlling water quality for both human consumption and irrigation in the selected study area.

The first axis is influenced by TDS and EC, which show a strong correlation of 0.85 with WQI and strong negative correlations with RSC of -0.85 and -0.86, respectively, emphasizing that water mineralization is related to drinking water quality deterioration. Na^+ and K^+ showed strong correlation with WQI of 0.88 and 0.87, respectively, and near-perfect correlations with SAR of 0.96 and 0.97, illustrating their interdependence aligned with their geochemical origin. SO_4^{2-} showed a strong negative correlation with RSC (-0.89), explaining that these waters rich in

Table 6. Correlation matrix between physicochemical parameters and water quality indices

Elements	SAR	% Na	RSC	MAR	WQI	HI children	HI adult	HEI
TDS	0.749***	0.483*	-0.855***	-0.466*	0.854***	0.062	0.062	0.342
EC	0.745***	0.479*	-0.861***	-0.466*	0.853***	0.069	0.068	0.341
Ca ²⁺	0.417*	0.113	-0.811***	-0.701***	0.576**	-0.016	-0.016	0.072
Mg ²⁺	0.117	0.012	-0.383	0.618***	0.398*	0.202	0.202	0.561**
Na ⁺	0.964***	0.817***	-0.688***	-0.299	0.877***	0.123	0.123	0.382
K ⁺	0.970***	0.851***	-0.630***	-0.320	0.871***	0.119	0.118	0.350
NO ₃ ⁻	0.067	0.051	0.001	-0.330	0.008	-0.145	-0.144	-0.269
HCO ₃ ⁻	0.126	-0.133	-0.383	-0.391*	0.396*	0.072	0.072	0.150
Cl ⁻	0.782***	0.641***	-0.690***	-0.200	0.756***	-0.039	-0.040	0.235
SO ₄	0.506**	0.233	-0.888***	-0.406*	0.696***	0.131	0.131	0.395*
Th	0.431*	0.108	-0.903***	-0.387	0.693***	0.069	0.069	0.299
Zn	0.294	0.220	-0.201	-0.112	0.287	-0.059	-0.059	0.114
Pb	-0.009	0.014	0.056	0.170	-0.041	0.955***	0.954***	0.307
Fe	0.318	0.252	-0.314	0.301	0.588**	0.345	0.345	0.930***
Co	-0.003	-0.018	0.006	0.049	0.183	0.236	0.236	0.580**
Mn	0.354	0.238	-0.343	0.187	0.594**	0.370	0.371	0.954***
Cu	-0.034	0.013	0.206	-0.291	-0.132	0.352	0.352	0.004

Note: *p < 0.05 ; ** p < 0.01 ; *** p < 0.001.

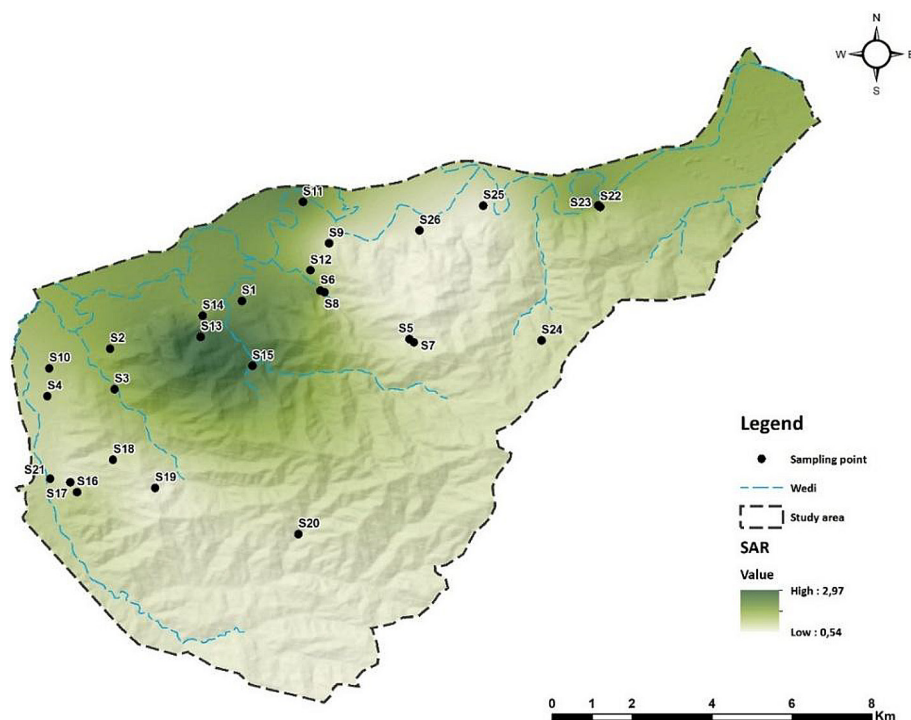


Figure 9. Spatial distribution of the sodium adsorption ratio (SAR)

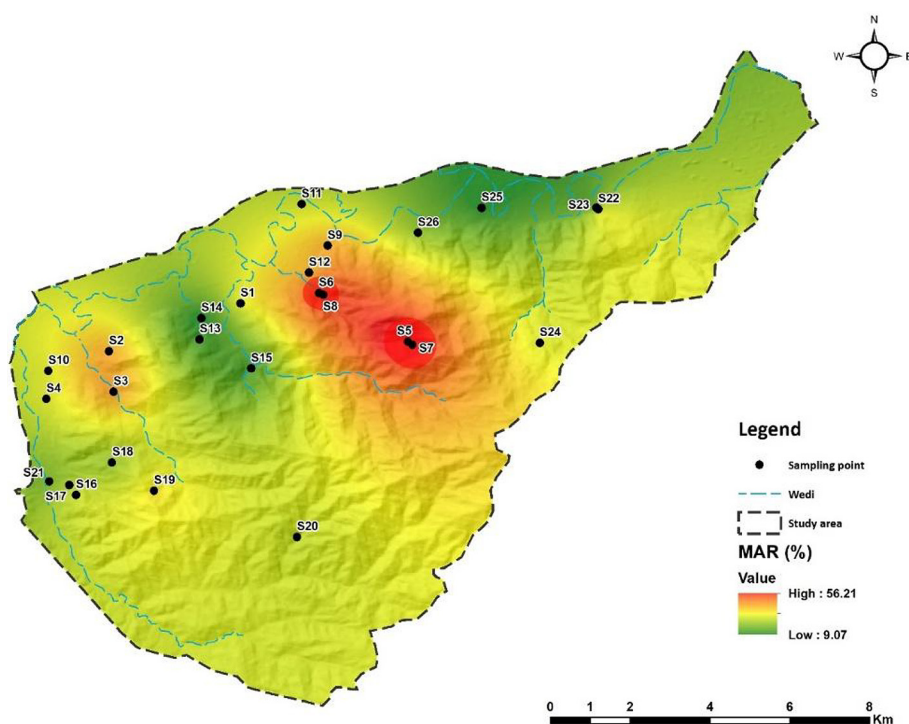


Figure 10. Spatial distribution of the magnesium adsorption ratio (MAR)

Sulfate are associated with geochemical processes in this highly mineralized region. Ca^{2+} showed a strong negative correlation with RSC (-0.81) and a moderate positive correlation with WQI (0.58). RSC thus exhibited strong negative correlations with the physicochemical parameters, confirming

groundwater irrigation suitability. Na^+ and K^+ dominate the sodium percentage, while MAR is weakly to moderately correlated with most parameters, particularly negatively with Ca^{2+} (-0.70) and positively with Mg^{2+} (+0.62), suggesting that soil permeability in this region may be threatened

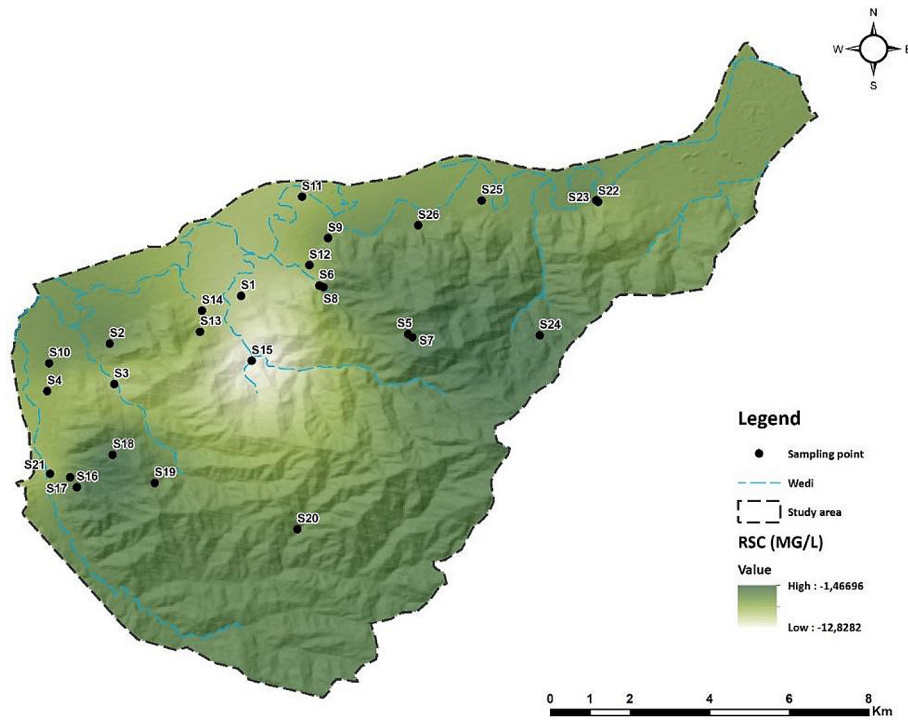


Figure 11. Spatial distribution of the residual sodium carbonate (RSC)

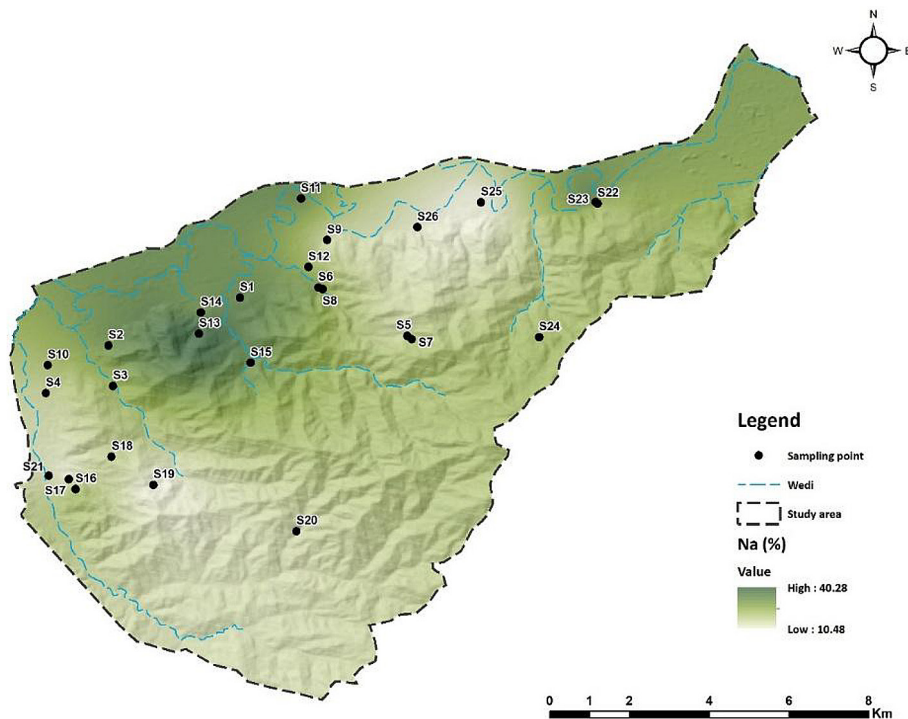


Figure 12. Spatial distribution of the sodium percentage (%Na)

by magnesium hazard as confirmed previously in S5, S6, S7 and S8. The correlation matrix confirms a strong positive correlation between HI and Pb ($r=0.95$, $p<0.001$), which demonstrates that Pb is the main driver of HI. Correspondingly, HEI has a strong correlation with Fe and

Mn ($r=0.93$ and 0.95 , respectively $p<0.001$) indicating their significant contribution to the global metal pollution. HEI and HI has a moderate correlation ($r=0.57$, $p=0.0025$), in agreement with 62% of samples with $HEI>10$ showing high HI values in adults and 77% showing high HI values

in children suggesting a link between metal pollution and the potential health risk. Collectively, these results confirm that the groundwater quality in the selected area is mainly controlled by mineralization, affecting both drinking and agricultural water quality, with a possible spatial association with Pb-Zn mineralized zone. These findings are essential for developing management and remediation strategies before, during, and after mining activities, with priority given to iron, manganese and lead removal techniques, to prevent non-carcinogenic health risks in both population groups. Therefore, it should be noted that the correlations discussed do not constitute independent evidence of a common source or a cause-and-effect relationship, since they are partly linked to the mathematical structure of these indices.

CONCLUSIONS

The present study provides an initial reference point for groundwater quality evaluation for both human consumption and agricultural use in a pre-mining area in the Bejaia region. Multiple indices were applied, including the WQI for groundwater quality, the HEI and HI for human health risk assessment, the SAR, RSC, %Na, and MAR for irrigation suitability. The results reveal that water quality in the study area is deteriorated, with 54% of the samples ranging from poor to unsuitable, underlining the necessity of implementing a proactive remediation and prevention plan. The HEI indicates that 27% of the samples are highly contaminated by heavy metals, predominantly driven by Fe and Mn showing a spatial association with to Pb-Zn mineralization. The non-carcinogenic health risk assessment revealed significant spatial heterogeneity in HI values, with 42% of children's samples and 31% of adult samples exceeding an HI of 1, with a notable vulnerability observed among children. Pb was the main contributor to the non-carcinogenic risk across all samples. Water quality management and control measures must be implemented in these areas to minimize long-term risks. Irrigation suitability indices (SAR, RSC, %Na and MAR) indicate generally suitable groundwater quality for irrigation, with only minor influences likely associated with the dominant mineralization controlling groundwater quality in the region. This study serves as a seasonal reference for assessing the potential long-term environmental impacts in this region rich in

both mining and agricultural resources, supporting the development of surveillance, monitoring, and sustainable groundwater management plans. Particular emphasis should be placed on the high-risk areas identified in this study prior to any mining activity.

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