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Application of the Water Quality Index to Assess Groundwater Quality in the Bou Dhar Mining District in Beni Tajjit (High Atlas, Morocco)

Mohamed Abdellaoui[1*], Omar Abdellaoui[2], Abdellali Abdaoui[1], Ali Ait Boughrous[1]

[1] Research Team: Biology, Environment and Health, Faculty of Science and Technology of Errachidia, Moulay Ismail University of Meknes, Marjane 2, BP: 298, Meknes 50050, Morocco

[2] Laboratory of Applied Organic Chemistry, Faculty of Science and Technology, B.P. 2202, Fez, Morocco

* Corresponding author's e-mail: abdellaouimd@yahoo.fr

ABSTRACT

Water scarcity remains the main problem in Morocco, making water resource conservation paramount. The objective of this study is to shed light on how mining impacts the region of Beni Tajjit's groundwater resources, which are used for irrigation and watering, which includes the Bou Dhar mining district, known for its vast lead and zinc sulfide deposits. The oxidation of sulfide-rich mine tailings generates acid water loaded with sulfates, creating acid mine drainage (AMD), which hurts aquatic ecosystems and the environment through trace metals elements (TME). Hence the need to assess the possible contamination of aquifers by metallic pollutants. This work can help water managers make appropriate decisions for controlling the quality of the groundwater in the Beni Tajjit area. During this study, we adopted a method: the Water Quality Index (WQI), designed to indicate the overall level of water quality by aggregating various weighted measurements. Five samples representing water sources around the mine tailings were taken and analyzed. Their values of dissolved oxygen, electrical conductivity and pH were measured on-site. The results allow us to classify the water into good and bad categories. They showed that the TME values were practically lower than the maximum permitted level according to WHO norms and Moroccan irrigation standards. The main reason for this may be due to the carbonate geological context of the site, which buffers acidity and thus forms a chemical barrier against the transfer of TME to the aquifer. The high chlorine levels appear due to geochemical background or anthropogenies contaminations. The sulfate values recorded are related to the leaching of sulfide minerals from mine tailings.

Keywords: Bou Dhar Mine, High Oriental Atlas, TME, mining discharges, groundwater quality, WQI

INTRODUCTION

Despite its economic importance, mining is among the anthropogenic activities that hurt water resources (Bondu et al., 2023, Santana et al., 2020; Zhao et al., 2017). It can expose residues rich in sulfide minerals to oxidation (Sarker et al., 2023; Wang et al., 2023; Li et al., 2022), which are not economically exploitable and are the overall result of extraction and processing stages (Abdellaoui et al., 2023; Karacan et al., 2023; Araya et al., 2020). The oxidation of these sulfides in tailings under the effect of water and atmospheric oxygen leads to the generation of sulfate-laden acid waters (Bao et al., 2021; Stoica et al., 2022). The latter causes acid mine drainage to occur. (AMD) (Jiao et al., 2023; Ruiz-Sánchez et al., 2023), a source of nuisance for aquatic ecosystems and the environment (Munford et al., 2023; Zhou et al., 2022) through its negative impact on soil, sediment and water organisms (Simpson et al., 2023; Gu et al., 2022; Ottoni et al., 2020).

The degradation of aquatic ecosystems in the vicinity of mines as a result of mining activities has been demonstrated in several works (Yan et al., 2023; Beck et al., 2020; Little et al., 2020). As a result, natural processes and anthropogenic activity in the area tend to influence groundwater quality (Ahmed et al., 2022; Maria et al., 2022; Balamurugana et al., 2020 Zereg et al., 2018).

This phenomenon has gained widespread recognition in countries holding tailings from sulfide deposits: Qian'an and Qianxi Mine in China (Song et al., 2023), Anhui Mine in China (Zheng et al., 2019) and Paracatu Mine in Brazil (Veloso et al., 2019). In Morocco, DMA chemical processes of sulfide oxidation have been proven in several regions: Zaida Mine, High Moulouya in Morocco (El Alaoui et al., 2021), Kettara Mine in Morocco (El Amari et al., 2014).

Assessing the possible contamination of aquifers by metal pollutants is crucial, given the risks posed by mining activities to aquatic ecosystems and human health. Water quality assessment by scientists and researchers for various water bodies of countries and regions was carried out in the context of combating pollution and decline in the quality of the water (Peyman et al., 2017). Various approaches and models for objectively assessing water quality have been developed over the years, among them the traditional method of individually assessing groundwater quality parameters by comparing their concentrations in monitoring data with groundwater quality guidance values (Dede et al., 2013). Consequently, water samples with concentrations of parameters above established thresholds are of health significance. These parameters include water temperature, pH, turbidity, dissolved oxygen levels, nutrients (such as nitrates and phosphates), TME and organic pollutants (Batabyal and Chakraborty, 2015). Moreover, interpreting the results of this approach remains complicated. In most cases, different water quality parameters show levels within guidelines, while others exceed standards, making the overall water quality situation blurry. For this reason, the Water Quality Index (WQI) method have been adopted (Mohamad Najib Ibrahim, 2019).

The Water Quality Index (WQI) is a mathematical tool used to reduce large sets of water quality data into a single value and shared categorization that represents the overall level of water quality, assigning weights to each parameter according to its importance for human health and aquatic ecosystems (Uddin et al., 2023). The measured data are then normalized and combined to obtain a single value representing overall water quality, making it easier to compare different water sources and track changes over time (Kouadri et al., 2021). Since then, several authors and organizations have developed various methods of WQI determination to assess water quality for diverse uses (Chao et al., 2023; Uddin et al., 2023), which differ in the way their sub-indexes develop and the process by which these sub-indexes get aggregated to calculate the final index value (Ponsadailakshmi et al., 2018; Sutadian et al., 2017). So, worldwide, the water quality index is widely used to assess and monitor water quality by government agencies, researchers, and environmental organizations (Dutta et al., 2022; Varma et al., 2022). It is also used to assess water quality in the vicinity of pollution sources, such as mining activities, which generate a considerable volume of mining waste in nature (Zaghloul et al., 2023; Boum-Nkot et al., 2023; Effendi et al., 2015).

The Beni Tajjit region in Morocco's Eastern High Atlas is affected by the impact of mining activities. Indeed, the Jbel Boudher mining district can contaminate the region's groundwater with trace metal elements (TME) from its tailings. Thus, the DMA probably produced from these tailings wastes can impact groundwater quality located downstream, notably through sulfate ions, from the principal sources of TME contained in the Boudhar mine tailings, which are galena, calamine and chalcopyrite (Raddi et al., 2011). In this context, the groundwater quality in the Boudhar mining area is assessed using several physico-chemical variables.

This work aimed to assess groundwater quality using the water quality index (WQI) method and to evaluate the potential risk of groundwater contamination by trace metals (TME) due to nearby mining activities.

The present work presents the results of physicochemical analyses of groundwater in the Beni Tadjjit region. These results address concerns about the presence of mining in an area where groundwater is the principal source of irrigation and livestock, and thus enable water managers to take appropriate decisions and actions on groundwater quality management in this region.

MATERIALS AND METHODS

Study area, choice of stations and parameters

The research focuses on the quality of groundwater close to solid mining waste to assess the possible contamination of groundwater by mining waste left on site. As part of this study, physicochemical analyses of groundwater in wells around mine tailings were performed. Five sites were selected to collect groundwater samples from different aquifers. The sampling missions were carried out in 2022 in dry periods (June) and rainy periods (February). All sampling procedures, including sample preservation and parameter measurement, were completed following accepted practices for handling water and wastewater (APHA, 2005). Table 1 contains a list of the groundwater sampling stations. The water samples collected at each station were filtered immediately on filters mounted on a Nalgene unit. Filtrates were dispensed into polyethylene vials for analysis and stored in 5% HNO_3 at 4°C. During sampling, pH, EC and dissolved oxygen values were measured. Chemical analysis was carried out at the AFRILAB laboratory using ICP- OES for various elements such as Pb, Zn, Cu, Cr, Na, Fe, and SO_4. Generally, ICP-OES has been used to determine the concentrations of major, minor, and trace elements in groundwater samples (Espinoza-Quiñones et al., 2015). The geographic presentation was created using QGIS software. Groundwater contamination levels were assessed using WHO and Moroccan standards.

Diagnosis of the current state of the Boudhar mine

The J. Bou Dahar deposit is located in the southern part of the eastern High Atlas, immediately east of Beni Tajjite, a locality on the Rich to Bouanane road (Figure 1); J. Bou Dahar rises to 1300 m and consists of small multiple mines open in Pb-Zn mineralization in hydrothermal karsts and veins within Middle Lias reef carbonates (Raddi et al., 2011). It is an MVT district associated with a Jurassic platform in the eastern High Atlas (Rddad et al., 2016).

In the Boudhar mine, the landscape is cluttered by the waste in dykes with no vegetation and by slag heaps resulting from extraction, with a total volume of around 10,000 tons and a height of a few meters. They contain high levels of lead sulfide and zinc, as well as other chemical elements such as various concentrations of iron. Because of their unstabilized granulometry, they can be a source of nuisance for the water system, the aquifer, and the environment, once in the form of aerial fallout after being transported by the wind or run-off water. This solid waste overlies an impermeable clay-limestone substrate.

WQI calculation

In the present study, the groundwater WQI was calculated using the weighted arithmetic mean method (Krishan et al., 2023). Thus, the calculation methodology can be simplified into the five steps shown below (Kadam et al., 2021):

- Step 1: Parameter selection – The World Health Organization (WHO) claims that the main factors to considered when evaluating the quality of drinking water are those that have the most significant effects on health and usually detected in drinking water at substantial quantities. The WQI was calculated in this work for eleven parameters: pH, sulfates (SO_4^{-2}), chlorides (Cl^-), nitrates (NO_3^-), lead (Pb), chromium (Cr), sodium (Na^+), zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn).
- Step 2: Assigning a unit weight for each parameter – in the second step, we attributed a weighting (wi) to each of the eleven parameters according to their relative importance in the overall water quality intended for consumption, as shown in Table 2. Sulfate (SO_4^{-2}), Chloride (Cl^-), Nitrates (NO_3^-), Lead (Pb), and Chromium (Cr) are given the highest weight (5); parameters such as pH and Manganese (Mn) are given a weight of 4; Sodium (Na^+) and Iron (Fe) weight 3; Copper (Cu) and Zinc (Zn) have a weight of 2 based on their dominant influence on the overall quality of drinking water (Ma et al., 2020; Vasanthavigar et al., 2010).
- Step 3: calculating the relative weight (Wi) – the third stage involves calculating the relative weight (Wi) employing the weighted arithmetic index approach described below (Tiwari et al., 2017).

Table 1. Groundwater stations coordinates sampled in the Beni Tajjit region

ID	Stations	Geographic coordinates	Altitude	Aquifer depth
P1	Water well 1	X = 683101 Y = 588857	1112 m	24 m
P2	Water well 2	X = 683101 Y = 588857	1124 m	38 m
P3	Water well 3	X = 683101 Y = 588857	1116 m	120 m
P4	Water well 4	X = 683101 Y = 588857	1116 m	30 m
P5	Water well 5	X = 683101 Y = 588857	1122 m	140 m

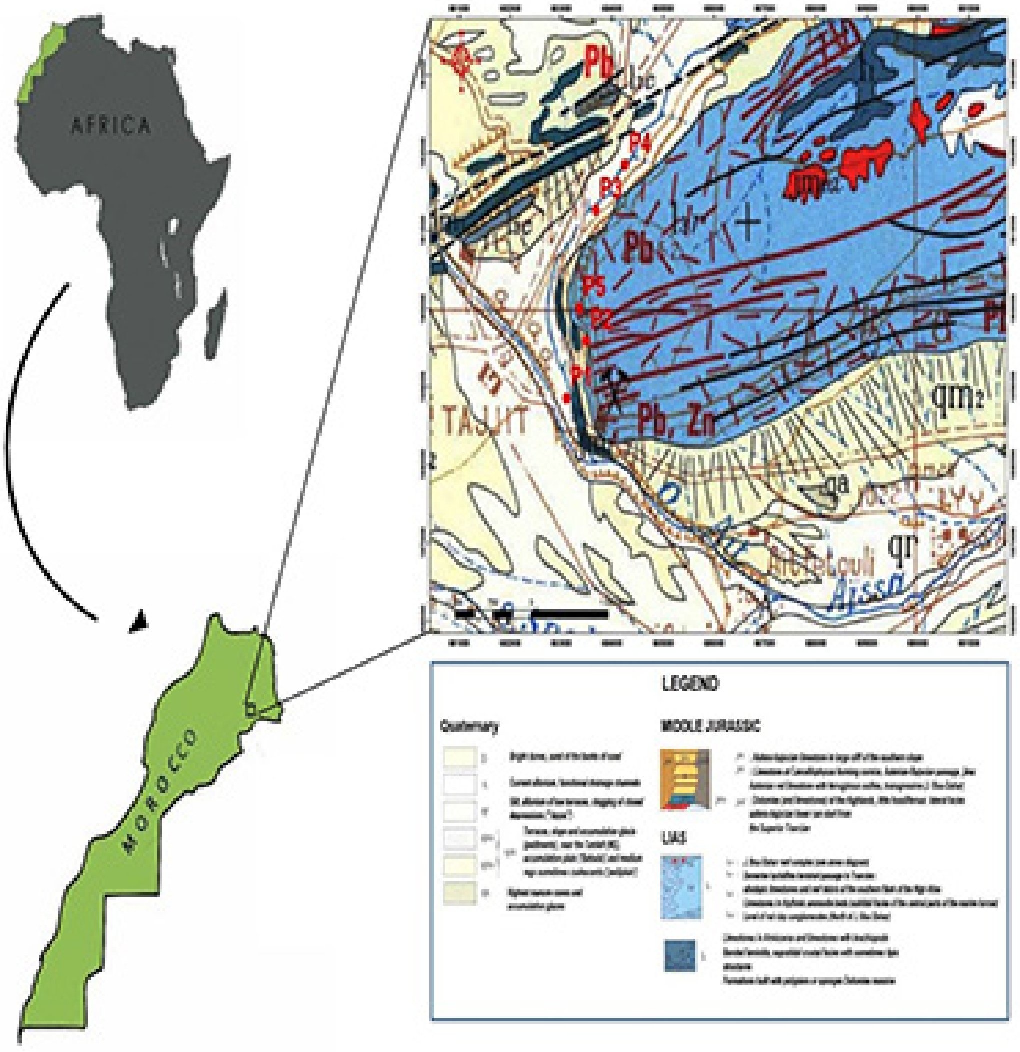

Figure 1. Geological map of the study region, with indications of nearby water wells

$$Wi = wi/\sum_{i=0}^{n} wi \tag{1}$$

where: *Wi* – the relative weight, *wi* – the weight assigned to each parameter, *n* is the number of parameters.

- Step 4: Calculate the rating scale for each parameter – in the fourth phase, each parameter is given a quality rating scale (*Qi*) by dividing its concentration in each water sample by its corresponding standard following APHA recommendations and then by 100:

$$Qi = (Ci/Si) \times 100 \tag{2}$$

where: *Ci* – indicates the level of each chemical characteristic in each sample of water, *Qi* – represents the quality score, *Si* – represents the drinking water standard for each chemical parameter as per APHA recommendations.

- Step 5: developing sub-index: the fifth step is to determine the SI value for each chemical parameter, which is then used to determine the WQI according to the following equation:

$$SIi = Wi \times Qi \tag{3}$$

where: *SIi* – the sub-index of the ith parameter, *Qi* – the score based on the concentration of the ith parameter.

Aggregation of sub-indices

The overall water quality index (WQI) was calculated by summing the values of each sub-index of the groundwater sample as follows:

$$WQI = \sum \mathrm{SIi} \tag{4}$$

The *WQI* values calculated are generally classified into five categories: excellent, good, poor,

Table 2. WHO standards, Moroccan standards, weight (wi), and calculated relative weight (Wi) for each parameter

No.	Parameters	Unit weight	Relative weight	WHO standards	Moroccan standards
1	pH	4	0.093023256	6.5–8. 5	8.5
2	Sulfates (SO_4^{-2}) mg/l	5	0.11627907	200	500
3	Chlorites (Cl^-) mg/l	5	0.11627907	200	750
4	Nitrates (NO_3^-) mg/l	5	0.11627907	45	50
5	Sodium (Na^+) mg/l	3	0.069767442	200	300
6	Copper (Cu) mg/l	2	0.046511628	1	2
7	Zinc (Zn) mg/l	2	0.046511628	5	4
8	Lead (Pb) mg/l	5	0.11627907	0.05	0.01
9	Iron (Fe) mg/l	3	0.069767442	0.3	1
10	Manganese (Mn) mg/l	4	0.093023256	0.1	0.4
11	Chrome (Cr) mg/l	5	0.11627907	0.05	0.05
		$\sum$ wi =43			

very poor and water unfit for consumption, according to Table 3.

RESULTS AND DISCUSSION

General quality characteristics of groundwater resources

Well water is used by local residents for irrigation and livestock watering. The flow regime of the wadis in the basin is intermittent, and drainage occurs only during rainy episodes. The average values of groundwater quality parameters measured at each sampling point in this study during the monitoring period are shown in Table 4 and Figure 2. The pH values ranged from 6.55 to 7.78 indicating the slightly alkaline nature of the groundwater at all the sites studied. According to Moroccan and WHO standards, all the values are within acceptable limits (6.5 to 8.5). The alkalinity of groundwater is mainly due to the concentration of bicarbonate in the aquifer (Beaume et al., 2018). The aquifers near the Boudhar mine are characterized by highly mineralized water, originating from minerals and salts dissolved in ion pairs, with conductivities varying between 6.5 ms/cm and 36,4 ms/cm. These values significantly exceed that set by the Moroccan and WHO standards at 2.7 ms/cm; these conductivity measurements (Table 4) are approximately 2.5 to 13 times higher than the limit value specified by the norms. That may reflect possible contamination of the aquifers or the geochemical background of the environment. High conductivity reflects the presence of large quantities of soluble and ionizable salts (Terzić et al., 2002).

Table 3. Water quality classification based on WQI

No.	WQI range	Water type
1	<50	Excellent
2	50.1–100	Good
3	100.1–200	Poor
4	200.1–300	Very poor
5	> 300.1	Unfit for consumption

One of the most important elements for measuring the quality of water is the amount of dissolved oxygen (O_2). It determines the state of several mineral salts and the life of aquatic animals through their participation in the majority of chemical and biological processes in the marine environment (Thanigaivel et al., 2022), as well as indicating the degree of water pollution (Mohan and Kumar, 2016). For all the samples taken, dissolved oxygen concentrations vary significantly

Table 4. Values for pH, dissolved oxygen and electrical conductivity in water well

Parameters	P1	P2	P3	P4	P5	Max	Min	Standard
pH	6.55	6.8	7.78	7.4	7.7	7.78	6.55	8.5
EC (ms/cm)	15.8	6.5	36.4	30.2	12.8	36.4	6.5	2.7
O_2 (mg/l)	0.2	0.2	0.73	2.11	1	2.11	0.2	10

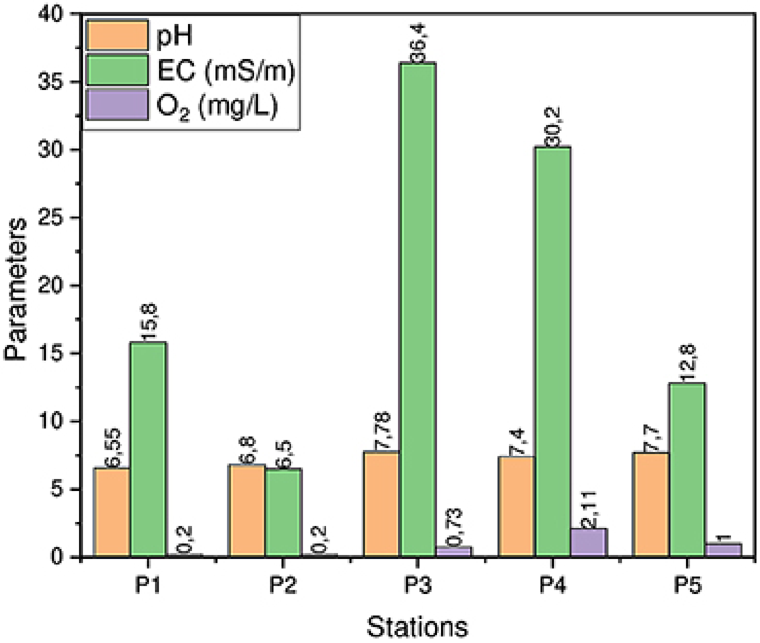

Figure 2. Variation in values of dissolved oxygen, electrical conductivity and pH in wells

from one point to another, ranging from 0,2 to 2,11 during the study period. These findings demonstrate the wells' significant under-oxygenation (Table 4). Low dissolved oxygen levels favor the development of pathogens (Tsai et al., 2020).

Sulfates

Sulfates (SO_4^{-2}) are chemical compounds widely present in nature and have various applications. They originate from the activity of certain bacteria that can oxidize hydrogen sulfide (H_2S) to sulfate (Linssen et al., 2023). They also result from runoff or infiltration into evaporite soils (Jiang et al., 2022; Prasad et al., 2019), as in the case of the oxidation of sulfide minerals in mine tailings, which is a direct source of groundwater contamination (Miao et al., 2013). Long-term groundwater consumption containing high sulfate concentrations could lead to dehydration and intestinal disorders (Qu et al., 2022). Sulfate concentrations in the water studied varied, ranging from 227 to 1,616 mg/l. These exceeded the maximum limit authorized by WHO and Moroccan standards (500 mg/l), except for sampling site S2, where the sulfate concentration was 227 mg/l. In addition, the sulfate value of the water studied is higher than 1000 mg/l. The high sulfate levels appear to be linked to potential contamination of the aquifer by polluted water resulting from the leaching of mining waste, which is extremely rich in lead and zinc sulfides and other metals. Studies have shown high values of this parameter in the aquifer near mining waste (Mao et al., 2023).

Chlorides

Significant levels of chlorides, primarily sodium chloride (NaCl) and potassium chloride (KCl), are present in natural streams. They come from lithological sources indicating an evaporitic environment or agricultural or industrial discharges (Sunkari et al., 2022). High chloride levels are considered pollution indicators and are potentially toxic for freshwater aquatic life (Kessasra et al., 2021). Chloride levels in the water samples analysed ranged from 43 mg/l to 694 mg/l (Figure 3). The water points studied, P1, P2 and P5, comply with standards, given that the chloride concentration in groundwater is lower than that limited by Moroccan and WHO norms, in the case of groundwater, which is around 200 mg/l. As a result, and with regard to this parameter, water quality at these stations is good. Stations P3 and P4 greatly exceeded the limit recommended by the standard, and this parameter indicates the degradation of groundwater.

Nitrates

The most oxidized form of nitrogen in water, nitrates represent the last stage of nitrogen oxidation. They generally come from the bacterial

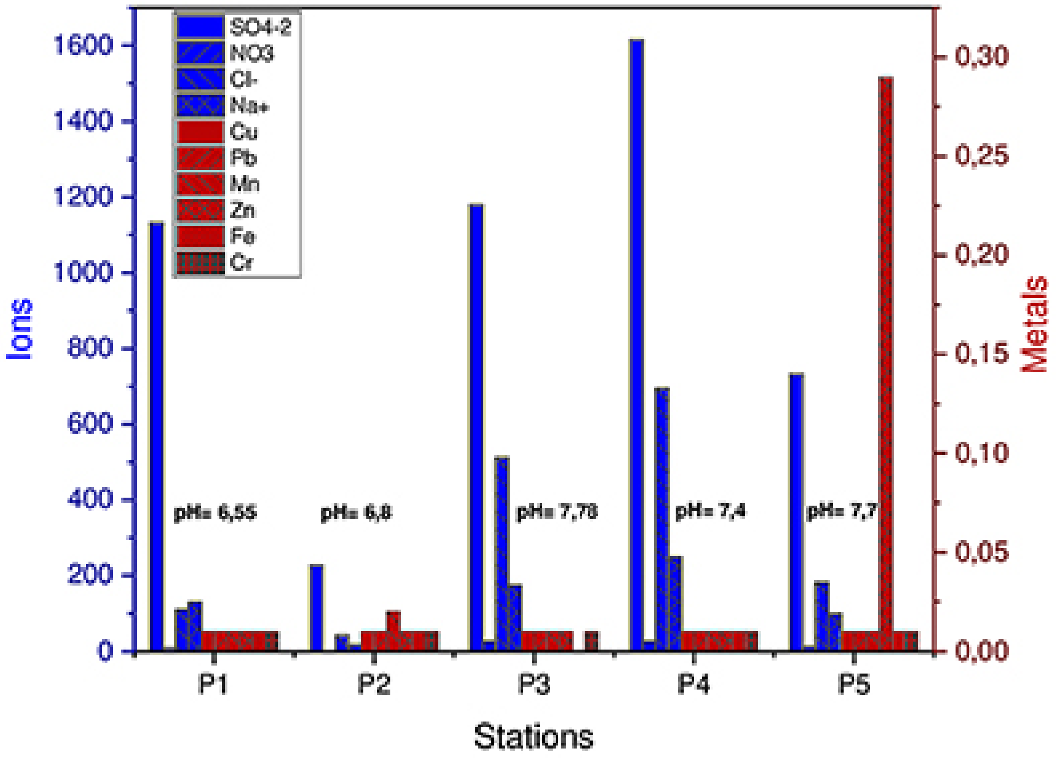

Figure 3. Variation in well-chemical factors

Table 5. Chemical analysis results for wells

Parameters	P1	P2	P3	P4	P5	Min	Max	OMS
SO_4^{-2}	1133	227	1180	1616	733	227	1616	200
Cl^-	110	43	512	694	182	43	694	200
NO_3	8.5	0.02	26.43	26.66	13.46	0.02	26.66	45
Na^+	130	18	175	249	99	18	249	200
Cu	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1
Zn	0.01	0.01	0.01	0.01	0.29	0.01	0.29	5
Pb	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05
Fe	0.01	0.01	0	0.01	0.01	0	0.01	0.3
Mn	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.1
Cr	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05

oxidative degradation of nitrite to break down organic matter, thus constituting the end product of nitrification. (Covatti and Grischek, 2021) or by leaching nitrogen products into the soil (Corré et al., 2014). However, human activity can contribute to nitrate contamination of groundwater through leaching and infiltration of nitrogen from industrial sources (Gutierrez et al., 2018), leading to serious environmental risk (Szymczycha et al., 2017) and human health concerns (Bahadoran et al., 2015). In the stations studied and as shown in Figure 3, nitrate levels varied between 0,02 mg/l and 26,66 mg/l. They did not exceed Moroccan standards (50 mg/l) or WHO standards. As a result, the waters studied are not subject to the risk of nitrate pollution.

Sodium

Sodium is a cation that occurs naturally in many soils and rocks, playing a crucial role in maintaining the water balance. It can enter aquifers through natural processes, such as the degradation of sodium-based mineral salts or by human agricultural or industrial activities. The concentration of sodium in groundwater can thus vary considerably depending on local geology and human practices (Sunkari et al., 2022). Data analysis showed that average sodium levels in the water at the points studied ranged between 18 mg/l and 249 mg/l (Figure 3). At the P4 station, only one value above 300 mg/l was observed, which would be related to the geochemical background. Concerning this parameter, most of the water analyzed during this study is acceptable for consumption and agriculture, except the water from station P4, and all the water does not exceed Moroccan or WHO standards.

MTE: Pb, Zn, Cu, Fe, Cr and Mn

Despite its many applications (industrial, medical, and agricultural) and economic importance (Tanya O'Garra, 2017), TME can have undesirable effects on aquatic ecosystems and the environment (Lozano-Bilbao et al., 2021). However, TME from human activities like mining and intensive agriculture can have a significant influence on human health, according to recent studies (Okewale et al., 2023). As a result, groundwater contamination by MTE is becoming a growing global concern due to its harmful impacts on human health through multiple and carcinogenic risks and on the aquatic ecosystem (Ayejoto et al., 2023). Thus, the presence of lead in water is considered a major health risk, as it can cause neurological disorders in children, such as developmental delays, learning disabilities and behavioral problems (Collin et al., 2022), as it can cause fertility problems, neurological disorders and cardiovascular disease in adults (Khatun et al., 2022). Also, excessive zinc consumption can have negative complications despite its essential role in human health, causing digestive problems such as nausea, vomiting, abdominal cramps, diarrhoea and reduced appetite, as well as nutritional deficiencies through interference with the absorption of other essential minerals such as copper, iron and magnesium (Li et al., 2014). Too much zinc can inappropriately stimulate the immune system, leading to inflammatory or autoimmune reactions (Kanwar et al., 2022). Furthermore, excessive levels of zinc in the body can damage the liver, leading to liver toxicity, or interfere with the functioning of hormones, particularly those related to growth and reproduction (Alkaladi et al., 2020). It should be emphasized that these negative effects often only happen with high zinc intake. The recommended daily dose of zinc for adults is around 11 mg for men and 8 mg for women (EFSA NDA Panel., 2014). Likewise, copper can have a harmful impact on human health, such as anemia, neurological diseases, gastrointestinal disorders and kidney toxicity (Jomova et al., 2022, Pajarillo et al., 2021). However, respecting recommended copper intake levels can help avoid health risks. Identically, iron is essential to human health, but too much of it can be dangerous, certain health risks are associated with excessive consumption of this element, such as iron poisoning known as "hemochromatosis" when the body absorbs and stores too much iron, which can damage vital organs like the liver, kidneys and heart (Kayaalti et al., 2015). Excess iron can also lead to oxidative stress: the free radicals produced during iron metabolism can damage cells and tissues, increasing the risk of cardiovascular disease and other chronic illnesses, or disrupt the absorption of other essential minerals such as zinc, copper and calcium, leading to nutritional deficiencies and associated health problems (Jomova et al., 2022). Research has also shown a link between excessive iron intake and an elevated risk of developing chronic conditions such type 2 diabetes, Alzheimer's disease, and certain malignancies (Fasae et al.,2021). In similar fashion, manganese is an essential element for human health, but it can also be harmful in excessive quantities, causing neurological disorders such as tremors, memory problems and sleep disorders, as well as behavioral changes and respiratory effects leading to the lung disease known as "manganism" which manifests itself with symptoms similar to those of Parkinson's disease (Miah et al., 2020). Chromium is a heavy metal that can have a negative impact on health when present in water. It is considered a human carcinogen by the International Agency for Research on Cancer (IARC) (Kim et al., 2018). Ingestion of chromium-contaminated water can cause respiratory illnesses such as asthma and chronic bronchitis, as well as digestive problems such as nausea, vomiting, abdominal pain and diarrhea, and it can damage the kidneys and liver, affecting their normal function. This can lead to kidney and liver failure (Braver-Sewradj et al., 2021). Chromium has also been shown to affect male fertility by reducing sperm production and motility, it can also cause birth defects in babies exposed during pregnancy (Badr et al., 2018). The level of toxicity and the undesirable impact depend on the species of the MTE. Chromium (Cr) and lead (Pb) are both

Table 6. Water quality index results for the groundwater sites studied

ID	WQI	Type of water
P1	93	Good water
P2	32	Excellent
P3	127	Poor water
P4	165	Poor water
P5	76	Good water

extremely poisonous to humans, even in small quantities, whereas metals like copper, manganese, iron, and zinc are necessary for humans, but an excess might create physiological difficulties (Qiao et al., 2020; Tchounwou et al., 2012).

In the localities studied (Figure 3), the concentrations of the MTE lead (Pb), zinc (Zn), chromium (Cr), copper (Cu), iron (Fe) and manganese (Mn) are less than 0.02 mg/l, except station P5, where the zinc content is 0.29 mg/l. According to Moroccan and WHO guidelines (Table 5), these MTE levels are below the highest permissible limits and do not endanger human health or the environment.

Assessment of groundwater quality based on the WQI

Table 6 lists the WQI results at the investigated sites. The WQI values that were calculated vary from 32 to 165. Therefore, the groundwater quality at the study sites is in the “Excellent” to “Poor” category. According to the results, of the five sites examined, two had “good water” (P1 and P5), while one classified as “excellent” (P2). The other two were classified as “poor water” with designations of P3 and P4. These results show a difference in water quality around the Bou Dhar mine site in the Beni Tajjit region.

On this site, station P3 corresponds to the shaft of a lead-zinc ore processing unit, with mine tailings estimated at several thousand tones. Unlike the other stations P1, P2 and P5, P4 station is near the active mine. This shaft is close to the mine but relatively far from the tailings.

Given the sodium and chlorine parameter values recorded at this station, the decline in water quality at station P4 was due to high salinity rather than MTE. The poor water quality at P3 station probably caused by the high chlorine content. This may be due to a layer of evaporation, which causes an increase in these ions by the dissolution of salts, or to human contamination by industrial or urban effluents. At all the points measured near the mine, sulphate showed extremely high values, which could be explained by the oxidation and leaching of sulfide minerals containing mining waste. With the exception of the high zinc content at station P5, heavy metal concentrations at all monitoring stations were below the minimum limit and almost non-existent. The zinc content at station P5 could be due to geochemical background or contamination of the water table by mines tailings. The water quality index indicates that the station’s water quality is still good.

CONCLUSION

This study estimates the physicochemical quality of water in the aquifer surrounding the Boudhar mine. The WQI was used to assess quality, calculated on the basis of physico-chemical data. Analysis of the physical and chemical results for MTE in the groundwater revealed that these parameters are almost below the maximum level permitted by Moroccan and WHO standards, which means that the water at the points monitored has not been affected by metal pollution, which may be a reflection of the mining activities in the Boudhar mining district. The water table was not affected, except at station P5, which may be due to the geochemical background.

The overall water quality at stations P3 and P4 is declining due to increased chlorine and sodium concentrations caused by salt deposits or anthropogenic pollution. The high sulfate values at all the stations seem intrinsically linked to the leaching of sulfide minerals, mainly galena, chalcopyrite and sphalerite.

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