Water Supply

Water Supply Vol 24 No 4, 1267 doi: 10.2166/ws.2024.059

Spatial assessment of groundwater quality for drinking In Souk El Arbaa, Morocco

Elhassan Ghachoui[a,*], Hamid Taouil[a], Ramzy S. M. Naser[b] and Ibn Ahmed Said[a]
[a] Organic Chemistry, Catalysis and Environment, Department of Chemistry, Ibn Tofail University, B.P. 133, Kenitra 14000, Morocco
[b] Experience Club for Environmental and Water Consulting Services, Department of Studies and Research, Sana'a Yemen
*Corresponding author. E-mail: elhassan.ghachoui@uit.ac.ma

EG, 0000-0002-7379-6957

ABSTRACT

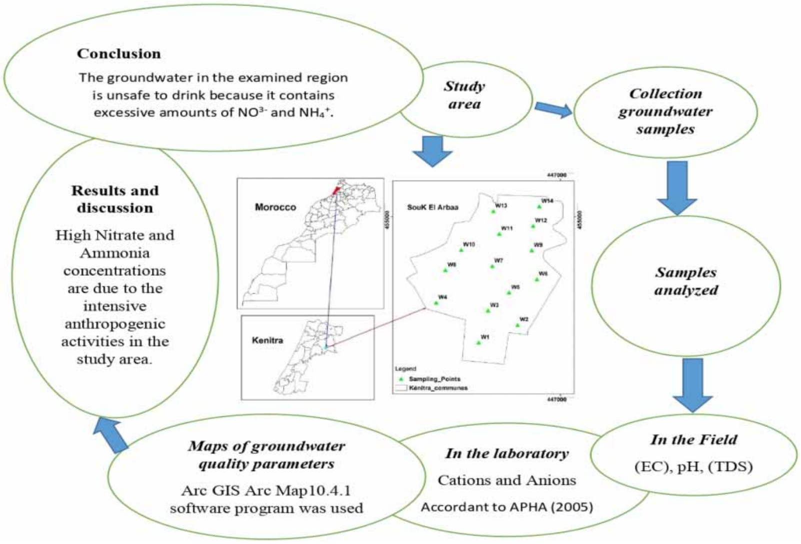
Morocco is facing challenges with its water resources due to population growth, industrial expansion, agriculture, urban development, tourism, climate change, overuse of underground water sources, and pollution from inadequate sanitation and chemical fertilizers. The Gharb aquifer is significant for supplying drinking water and irrigation in the country. Souk El Arbaa is a Moroccan city located in the northwestern part of the Kingdom of Morocco in the Kenitra Province. Its economic activities depend mainly on agriculture and livestock raising. This study aims to assess the groundwater status of a basin in a semi-arid climate in the Souk El Arbaa for drinking purposes by collecting 14 samples in 2022 from different locations and analyzing their physicochemical characteristics. The quality assessment was made by estimating electrical conductivity, pH, total dissolved solids, total hardness, calcium, magnesium, sodium, potassium, bicarbonates, chloride, sulfate, nitrate, and ammonium. The results showed that most of the groundwater in the study area is very hard, and all groundwater in the study area, according to the Moroccan Standards for drinking purposes, exceeds the permissible limits for nitrate and ammonium.

Key words: drinking water quality, GIS, groundwater, Morocco, Souk El Arbaa

HIGHLIGHTS

- Determine the hydrochemical and geochemical characteristics of groundwater in the region.
- Assess the suitability of groundwater in the study area for portability.
- High concentration of NO_3^- mg/L and NH_4^+ that exceed the maximum allowed.

GRAPHICAL ABSTRACT



INTRODUCTION

There is a higher demand for fresh water in Morocco's semi-arid regions due to less rainfall, population growth, and increased industrial and agricultural activities. It is important to use groundwater resources efficiently and take steps to prevent contamination (Mohammed *et al.* 2020; El Mountassir *et al.* 2021; Ez-Zaouy *et al.* 2022; Hilal *et al.* 2024). The best way to address groundwater pollution is to implement strategies to mitigate it early on. Protecting and managing groundwater requires specific plans and guidelines that focus on certain areas to prevent contamination. To safely use and develop groundwater, it is necessary to have a thorough understanding of the aquifer system and hydrological conditions in the area, which can be used to create a map that shows vulnerability to groundwater pollution (Marques *et al.* 2019).

Understanding the quality of groundwater is as important as its quantity because it is the main factor determining its suitability for drinking, domestic, agricultural, and industrial purposes (Darwesh *et al.* 2019; Darwesh *et al.* 2020). It relies heavily on groundwater in the water supply to the population, whether in urban or rural areas, and whether it is in humid areas or arid and semi-arid areas, and therefore must be protected from pollution. Natural and anthropogenic effects, including local climate, geology, and irrigation practices, influence water quality (Alhumairia & Rahalb 2023).

Groundwater vulnerability is crucial for understanding how the physical environment can protect groundwater from pollutants and assessing the sensitivity of different zones to prevent contamination (Bera *et al.* 2021). Addressing groundwater pollution is challenging due to the risk of contamination from human activities and land use, with varying levels of susceptibility across different areas (Olojoku *et al.* 2017). Assessments of groundwater vulnerability are essential for sustainable development and preserving groundwater resources (Majandang & Sarapirome 2013).

The chemical character of any groundwater determines its quality and utilization. The quality is a function of the physical, chemical, and biological parameters and could be subjective since it depends on a particular intended use.

Groundwater plays a key role in providing water for drinking, agriculture, and industry. Groundwater is used in the production of around 40% of the world's food, and it is dependent on one-third of the world's population. An already constrained water supply is in danger due to the growing global economy, population, and infrastructure (Bhat *et al.* 2018; Kumar *et al.* 2022). Water quality assessment is more crucial than water quantity assessment and provides crucial data for water management planning, especially in relation to drinking water (Naser *et al.* 2017; Li *et al.* 2018).

Nitrates, commonly used in agriculture as fertilizers, are a major source of groundwater pollution (Al-Aizari *et al.* 2020). They do not naturally occur in groundwater and can indicate the movement of contaminants. Evaluating the vulnerability of groundwater to pollution is crucial for ensuring clean water supplies and reducing negative impacts. Many models and techniques have been created and used worldwide to assess and map groundwater threats (Ekwere & Edet 2017; Shah *et al.* 2021; Mkumbo *et al.* 2022).

Morocco has an arid and semi-arid climate, with vastly different precipitation patterns depending on the season and location.

Although groundwater in Morocco is a significant component of the nation's hydrological legacy, it is contaminated by urban, industrial, and agricultural activities. Water supplies in Morocco are scarce. The annual amount of renewable water in Morocco is predicted to be 29 billion m^3; in 1998, it was 1,044 m^3 per person, but by 2020, it only be 786 m^3 per person/year.

After 2025, Morocco is predicted to have a water scarcity (less than 500 m^3/inhabitant/year), as it is already under water stress (less than 1,000 m^3/inhabitant/year) (Bzioui 2004; El Khodrani *et al.* 2016).

The Gharb region's coastal water resources are becoming more and more polluted because of artisanal, industrial, agricultural, and urban growth. Recent growth in the area has led to a rise in water consumption as well as the creation of various contaminated sites. Morocco's western area is crucial to the agricultural output of the nation HCP (2013).

In the Souk El Arbaa area in northwest Morocco, traditional methods are used for well digging; when water is at a depth of less than 10 m, manual drilling is employed with axes and shovels. At 30 m minimum depth, a drilling rig is widely used by local farmers. The depths of the wells in the area ranged between 3 and 42 m. In addition to the use of natural fertilizers to fertilize soil (animal waste residues), farmers also use synthetic fertilizers.

In addition to the use of natural fertilizers to fertilize soil (animal waste residues), farmers also use synthetic fertilizers.

The most widely used wastewater disposal method in the region is the public sewer system (43.3%), followed by septic pits (31.5%), and 5.2% of the population uses abandoned wells or public sewer systems. The present study found that 70.2% of urban areas had public sewer systems compared to 1.1% of rural areas. Septic pits are used by 48.1% of rural residences, but only 20.9% of urban households. It is also noted that wells are formed in rural areas (10%), but only 2.1% are used in urban regions (Maroc 2019). There are several types of irrigation systems used in agriculture, including drip irrigation, sprinkler irrigation, and surface irrigation. Drip irrigation is the most widely used system because it is efficient and allows precise control of water use. Sprinkler irrigation is also very popular, especially in large agricultural operations. Surface irrigation, which involves flooding fields, is used less frequently because of water conservation concerns. In this area are grown wheat, legumes, fodder, beetroot, sugar cane, and olives.

The objective of this study is to determine the suitability of the groundwater in the study area for drinking purposes.

Description of the study area

Souk El Arbaa is a Moroccan city located in the northwestern part of the Kingdom, in the Kenitra Province of the Rabat-Salé-Kenitra region at an altitude of approximately 37 m. It is about 110 km from the capital, Rabat, and 70 km from the city of Kenitra. It is located between Latitude: 34.68 and 34° 40′ 48″ North, Longitude: −5.98 and 5° 58′ 48″ East (Figure 1). The population is 69,265 inhabitants according to the 2014 General Population and Housing Moroccan census RGPH (2014). The climate influenced by the Atlantic is temperate to warm. Rain (around 600 mm of water per year) falls almost exclusively during the winter months.

MATERIALS AND METHODS

Collection and analytical procedure of groundwater samples

To assess the groundwater quality for drinking, 14 groundwater samples have been collected. The samples analyzed in the field for electrical conductivity (EC), pH, total dissolved solids (TDS), and were analyzed for major cations and anions in the laboratory according to the standard methods given by the American Public Health Association APHA (2005).

Production of the maps of groundwater quality parameters

The IDW tool in the Geostatistical Analyst of the ArcGIS Arc Map10.4.1 software program was used to produce the spatial distribution maps for groundwater quality based on the values of various quality parameters for drinking water.

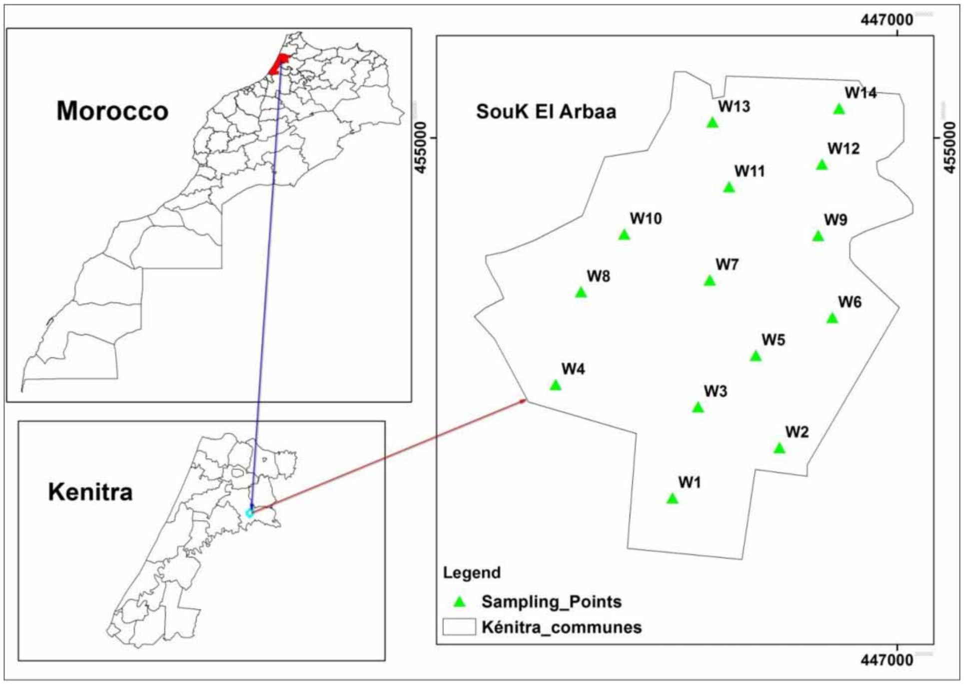


Figure 1 | Location of study area and sampling points.

Geostatistical Analyst Tools > Interpolation > IDW uses the measured values surrounding the prediction location to predict a value for any un-sampled location, based on the assumption that things that are close to one another are more alike than those that are farther apart.

Total hardness calculation

The total hardness of the groundwater was calculated using the following formula (Subramani *et al.* 2005):

$$TH(as\ CaCO_3)mg/l = (Ca^{+2} + Mg^{+2})meq/l \times 50 \tag{1}$$

Diagrams of hydrochemical facies

Software of hydrochemistry (Roland SIMLER Laboratory of Hydrogeology of Avignon) was used to obtain hydrochemical facies of groundwater in the study area.

RESULTS AND DISCUSSION

Groundwater chemistry

The pH values of groundwater range from 6.59 to 8.5 with an average value of 7.29 this shows that the groundwater of the study area is mainly alkaline in nature. The EC values range from 1,070 to 17,487 μS/cm with an average value of 4,050 μS/cm. TDS values range from 716,9 to 11,716 mg/l with an average value of 2,714 mg/l. Statistical summary of physical and chemical parameters of groundwater is reported in Table 1.

Correlation of physicochemical parameters of groundwater

The correlation coefficient is a commonly used measure to establish the relationship between two variables. It is simply a measure to exhibit how well one variable predicts the other (Subramani *et al.* 2005).

The correlation matrices for 12 variables were prepared (Table 2) and illustrate that EC and TDS show a high positive correlation with Cl^-, Na^+, total hardness, Mg^{2+}, and Ca^{2+}. Also, a good positive correlation is shown with K^+ and SO_4^{2-}. Total hardness shows a high positive correlation with Ca^{2+}, Na^+, K^+, Mg^{2+}, SO_4^{2-}, and Cl^-. Mg^{2+} shows high positive correlation with Na, K^+, and Cl^-. Na shows a high positive correlation with Cl^-, SO_4^{2-}, and K^+. K^+ shows a high positive correlation with Cl^- and shows a good positive correlation with SO_4^{2-}. Cl shows a high positive correlation with SO_4^{2-}. pH exhibits positive correlation with TDS, T.H, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-}, and the pH exhibits negative correlation with HCO_3^-, NO_3^-, and NH_4^+.

Table 1 | Descriptive statistics of physical and chemical parameters of groundwater

Water quality parameters	Units	Mini	Max	Average
EC	μs/cm	1,070	17,487	4,050
pH	mg/l	6.59	8.50	7.29
TDS	mg/l	716.9	11,716	2,714
T.H	mg/l	185	2,184	617
Ca^{2+}	mg/l	46.0	607.6	166.4
Mg^{2+}	mg/l	11.3	161.8	49.0
Na^+	mg/l	25	3,453	529
K^+	mg/l	2.34	89.69	14.60
Cl^-	mg/l	69	6,303	954
SO_4^{2-}	mg/l	27.4	729.6	198.1
HCO_3^-	mg/l	115.9	551.6	318.2
NO_3^-	mg/l	126	1,327	473
NH_4^+	mg/l	5.556	16.380	11.535

Table 2 | Correlation of physiochemical parameters of groundwater

	EC (μs/cm)	pH	TDS	T.H	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-
pH	0.769											
TDS	1	0.769										
T.H	0.904	0.717	0.904									
Ca^{2+}	0.85	0.632	0.85	0.973								
Mg^{2+}	0.859	0.767	0.859	0.883	0.751							
Na^+	0.978	0.765	0.978	0.96	0.913	0.889						
K^+	0.797	0.75	0.797	0.933	0.918	0.804	0.884					
Cl^-	0.973	0.774	0.973	0.966	0.923	0.887	0.999	0.905				
SO_4^{2-}	0.791	0.387	0.791	0.872	0.93	0.604	0.83	0.736	0.829			
HCO_3^-	−0.151	−0.236	−0.151	−0.052	−0.058	−0.03	−0.15	−0.156	−0.162	0.056		
NO_3^-	−0.249	−0.655	−0.249	−0.22	−0.074	−0.478	−0.269	−0.338	−0.274	0.237	0.144	
NH_4^+	−0.477	−0.581	−0.477	−0.495	−0.438	−0.525	−0.477	−0.468	−0.48	−0.351	−0.465	0.343

Hydrogeochemical facies—trilinear diagram (Piper diagram)

The geochemical evolution of groundwater can be understood by plotting the concentrations of major cations and anions in the Piper (1944) trilinear diagram (Piper 1944). The knowledge of hydrochemistry is essential to determine the origin of the chemical composition of groundwater (Zaporozec 1972).

The plot (Figure 2) shows that six of the groundwater samples fall in the field of Na-Cl water type, six of the groundwater samples fall in the field of mixed Ca-Mg-Cl water type, and two of the groundwater samples fall in the field of Ca-HCO_3 water type (Figure 3).

The Piper diagram (Figure 2) shows that the alkaline earth cations (Ca^{2+} and Mg^{2+}) exceed the alkalis cations (Na^+ and K^+) and the weak acids anions [(HCO_3^-) as the 'alkaline' constituents] exceed strong acids anions [($Cl^-$and SO_4^{2-}) as the 'saline' constituents].

The dominance of alkaline earth cations (Ca^{2+} and Mg^{2+}) and weak acids anions [(HCO_3^-) as the 'alkaline' constituents] on the chemical properties of groundwater is reported in Souk El Arbaa. This means that most of the groundwater in the study

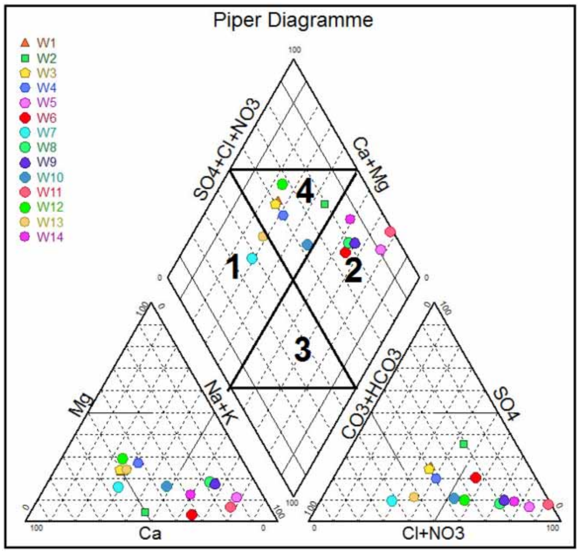


Figure 2 | Chemical facies of groundwater in Piper diagram.

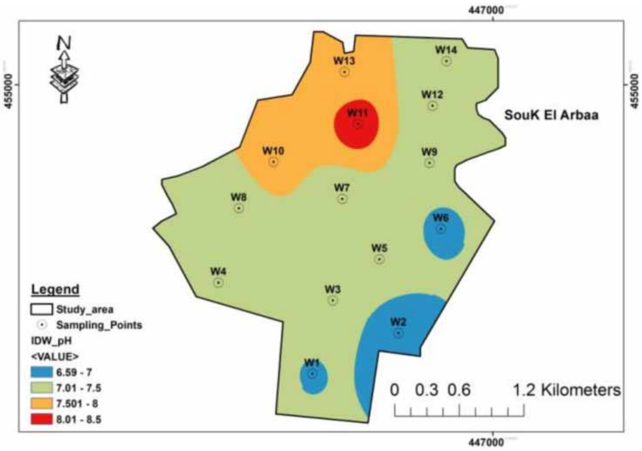


Figure 3 | Spatial distribution of pH.

area is considered as secondary saline water (indicating the impact of anthropogenic activities), and the rest of the groundwater is considered as primary saline water (indicating the impact of the geochemical processes natural) since the study area is considered a drainage area.

Drinking water quality

The analytical results of physical and chemical parameters of groundwater were compared with the standard guideline values as recommended by the Moroccan Standards for drinking water. The number and percentage of samples exceeding the allowable limits set by Moroccan Standards are presented in Table 3.

Electrical conductivity

Classification of groundwater in the study area according to their values of EC is presented in Table 4, and Table 4 shows that 21.43% of the samples is within the permissible limit and 28.57% of the samples fall is not permissible limit, and 50% of the sample locations can be classified as hazardous according to the WHO Standard. As shown in Table 2, the elements that have

Table 3 | The number and percentage of samples exceeding the allowable limits set by Moroccan Standards

Parameters	**Moroccan Standards**	**No. of wells**	**No. of wells exceeding permissible limits**	**Override %**	**Undesirable effect**
pH	6.5–9.5	14	0	0	Taste
EC (μs/cm)	350–2,700	14	7	50	
TDS (mg/L)	650–1,500	14	8	57	Gastrointestinal irritation
T.H (mg/L)	500	14	8	57	Scale formation
Ca^{2+} (mg/L)	100	14	9	64.28	—————————
Mg^{2+} (mg/L)	100	14	1	7.14	—————————
Na^+ (mg/L)	150	14	8	57	Increases blood pressure
K^+ (mg/L)	0–12	14	2	14.29	Increases blood pressure
Cl^- (mg/L)	750	14	6	42.86	Salty taste[a]
SO_4^{2-} (mg/L)	250	14	3	21.43	Laxative effect
HCO_3^- (mg/L)	500	14	1	7.14	——————
NO_3^- (mg/L)	50	14	14	100	Blue baby syndrome
NH_4^+	2	14	14	100	

[a] High concentrations of sulfate, in association with cations, such as magnesium, may have a laxative effect on people not accustomed to the water.

Table 4 | Groundwater classification according to electrical conductivity values

Electrical conductivity (μS/cm)	Classification	Sample numbers	Number of samples	Percentage of samples
< 1,500	Permissible	1, 7, 13	3	21.43
1,500–3,000	Not permissible	3, 4, 10, 12	4	28.57
> 3,000	Hazardous	2, 5, 6, 8, 9, 11, 14	7	50

a significant effect on EC and soluble solids are sodium, chloride, T.H, magnesium, Ca^{2+}, K^{+}, and SO_4^2. Spatial distribution of EC is shown in Figure 4.

Total dissolved solids

A spatial distribution map for the concentration of dissolved solids in groundwater of the study area based on the Moroccan Standards is shown in Figure 5. The classifications of groundwater in the study area depending on its nature based on their TDS for assessment of their suitability for any purposes (Davis & De Wiest 1966; Freeze & Cherry 1979) are presented in Tables 5 and 6.

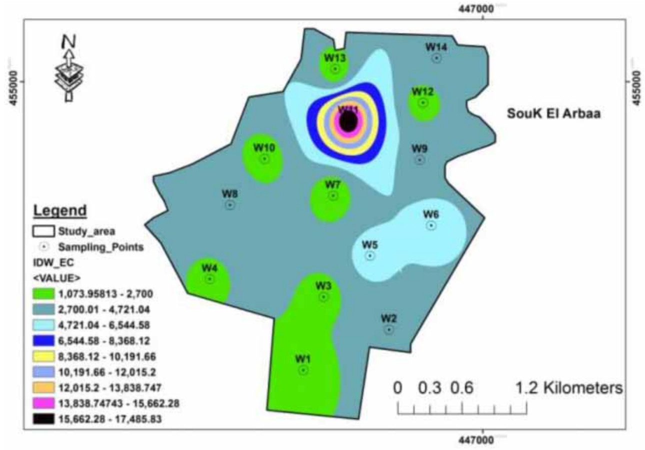


Figure 4 | Spatial distribution of EC.

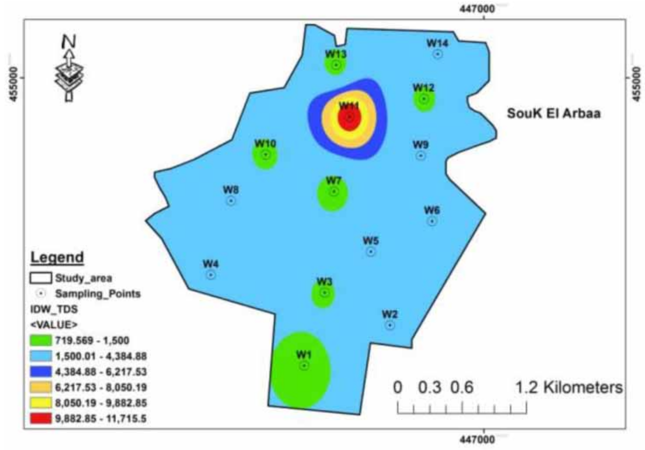


Figure 5 | Spatial distribution of TDS values.

Table 5 | Groundwater quality classification according to Davis & De Wiest (1966)

TDS (mg/l)	Classification	Sample numbers	Number of samples	Percentage of samples
< 500	Desirable for drinking		0	0
500–1.000	Permissible for drinking	1, 7, 13	3	21.43
1.000–3.000	Useful for irrigation	2, 3, 4, 8, 9, 10, 12	7	50
> 3.000	Unfit for drinking and irrigation	5, 6, 11, 14	4	28.57

Table 6 | Groundwater quality classification according to Freeze & Cherry (1979)

TDS (mg/l)	Classification	Sample numbers	Number of samples	Percentage of samples
<1.000	Fresh water type	1, 7, 13	3	21.43
1.000–10.000	Brackish water type	2, 3, 4, 5, 6, 8, 9, 10, 12, 14	10	71.42
10.000–100.000	Saline water type	11	1	7.15
>100.000	Brine water type	–	–	–

With regard of groundwater quality classification in the study area according to Davis & De Wiest (1966), we found that 21.43% of groundwater samples is permissible for drinking (TDS from 500 to 1.000 mg/l), 50% of groundwater samples is useful for irrigation (TDS from 1.000 to 3.000 mg/l), and 28.57% of groundwater samples is unfit for drinking and irrigation (TDS > 3.000 mg/l).

With regard to groundwater quality classification in the study area according to Freeze & Cherry (1979), we found that 21.43% of groundwater samples is fresh water (TDS < 1.000 mg/ l), 71.42% of groundwater samples is brackish water (TDS from 1.000 to 10.000 mg/l), and 7.15% of groundwater samples is saline water (TDS from 10.000 to 100.000 mg/l).

Total hardness

The principal natural sources of hardness in water are calcium and magnesium ions from sedimentary rocks, seepage, and runoff from soils (Yesilnacar & Gulluoglu 2008). The hardness values range from 184.9 to 2.183.6 mg/l with an average value of 617.44 mg/l. According to the Moroccan Standards for total hardness, 57% of groundwater samples is not suitable for drinking. Spatial distribution for the suitability of groundwater for drinking based on total hardness according to the Moroccan Standards is shown in Figure 6.

According to Freeze & Cherry (1979) for total hardness, the most desirable limit is 80–100 mg/l. Groundwater exceeding the limit of 300 mg/l is considered as very hard Sawyer (2003). The classification of groundwater based on total hardness

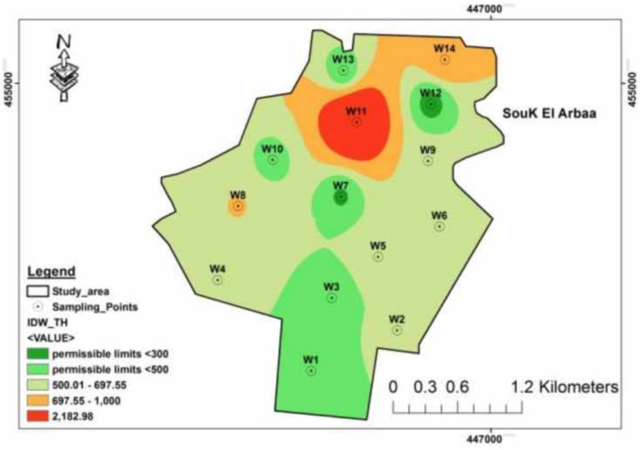


Figure 6 | Spatial distribution of total hardness.

Table 7 | Classification groundwater in study area based on total hardness (mg/l) (Yesilnacar & Gulluoglu 2008)

Total hardness as $CaCO_3$ (mg/l)	Type of water	Sample numbers	Number of wells	% of wells
<75	Soft	_	Nil	
75–150	Moderately hard	_	Nil	
150–300	Hard	12 and 7	2	14.3
>300	Very hard	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, and 14	12	85.7

(Table 7) shows that a majority of the ground water samples (12 samples out of 14 samples) in the study area fall in the very hard water category according to Yesilnacar & Gulluoglu (2008) (Figure 7).

Calcium (Ca^{2+})

Calcium (Ca^{2+}) is present in sedimentary rocks and crystalline rocks. It is very soluble and is widely present in most waters (Perkel 1979). Calcium concentrations in groundwater in the study area ranged from 46.0 to 607.6 mg/l, with an average of 166.4 mg/l. A total of 64.28% of the samples had high calcium concentrations compared to the Moroccan Standards (Figure 8).

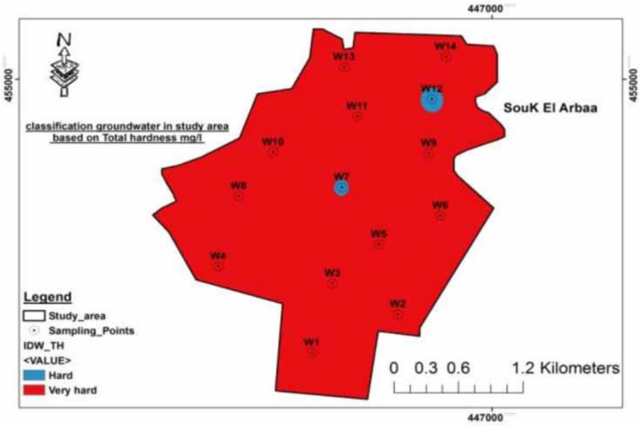


Figure 7 | Spatial distribution of total hardness.

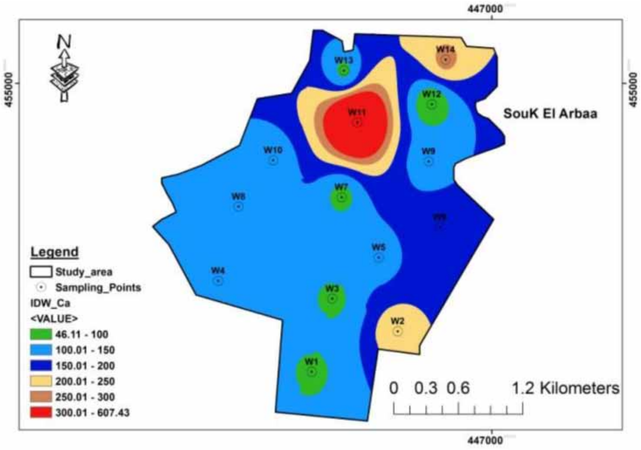


Figure 8 | Spatial distribution of Ca^{2+}.

Magnesium (Mg^{2+})

Magnesium was between 11.3 and 161.8 mg/L, with an average of 49.0 mg/L (Table 1). These results comply with the Moroccan Standards. The quality of water collected according to the concentration of Mg^{2+} can be divided into 57% excellent quality, 21.43% good quality, 14.28% average quality, and 7.14% (only 1 of the 14 samples) poor quality compared to the Moroccan Drinking Water Standards (Figure 9).

Chloride

Chloride at levels higher than 250 mg/l causes odor and salty taste apart from aggravating heart problems and contributing to high blood pressure (Saleh *et al.* 1999). Chloride concentrations in groundwater of the study area ranging from 69.38 to 6,302.6 mg/l with an average of 953.5 mg/l. The high concentrations of chloride have been found in the wells 6, 9, 8, 14, 5, and 11. The chloride concentration in groundwater of the study area exceeds the maximum allowable limit of 750 mg/l in six wells (6, 9, 8, 14, 5, and 11). The spatial distribution of chloride concentration in groundwater of the study area is illustrated in Figure 10.

Sodium

The concentration of sodium in the groundwater of the study area ranges from 24.55 to 3,452.76 mg/l with an average of 529.32 mg/l. The spatial distribution of sodium concentration in groundwater of the study area is illustrated in Figure 11.

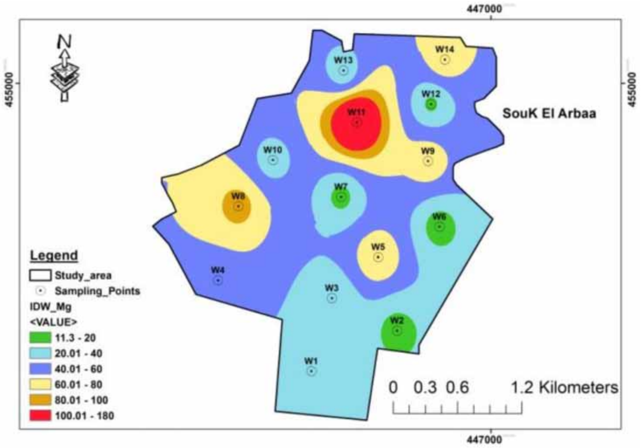


Figure 9 | Spatial distribution of Mg^{2+}.

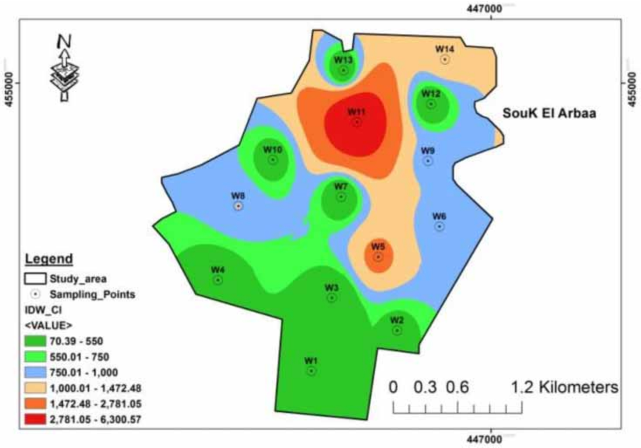


Figure 10 | The spatial distribution of Cl.

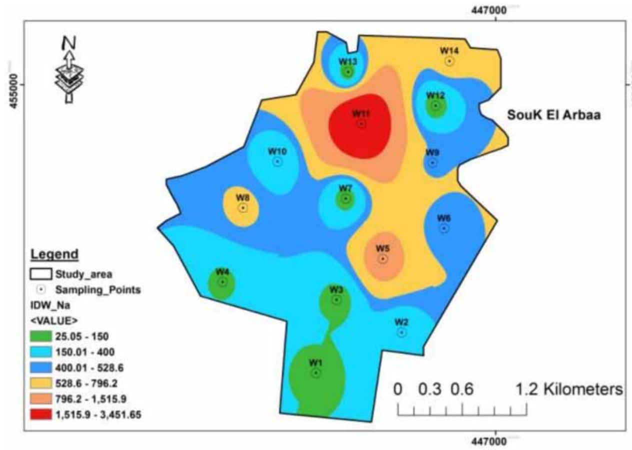


Figure 11 | Spatial distribution of Na^+.

According to the Moroccan Standards, 57% of groundwater samples exceed the maximum permissible of sodium, and therefore, they are not suitable for drinking.

Nitrate

The nitrate's concentration in groundwater of the study area varies from 125.75 to 1,326.78 mg/l with an average value of 473.11 mg/l. Table 3 shows that all groundwater samples in the study area exceed the maximum allowable limit of 50 mg/l. The high concentration of nitrate in drinking water is toxic and causes blue baby disease/methaemoglobinemia in children and gastric carcinomas (Subramani *et al.* 2005). The high nitrate concentration is due to the intensive anthropogenic activates in the study area. The spatial variation of nitrate in groundwater of the study area is illustrated in Figure 12. The study confirmed that the Gharb aquifer's vulnerability to pollution is reflected in the nitrate concentrations found in wells in the area. This aligns with previous studies conducted by Batchi *et al.* (2017) and Darwesh *et al.* (2020).

Ammonium (NH_4^+)

Ammonia is a water-soluble gas; groundwater is generally low in ammonia nitrogen. The presence of relatively large quantities of ammonium may be an indication of pollution from artificial or industrial emissions (chemical industries, nitrogen fertilizers, coking plants, ice plants, and textiles). The concentration of ammonium in water samples ranged from 5.5 to

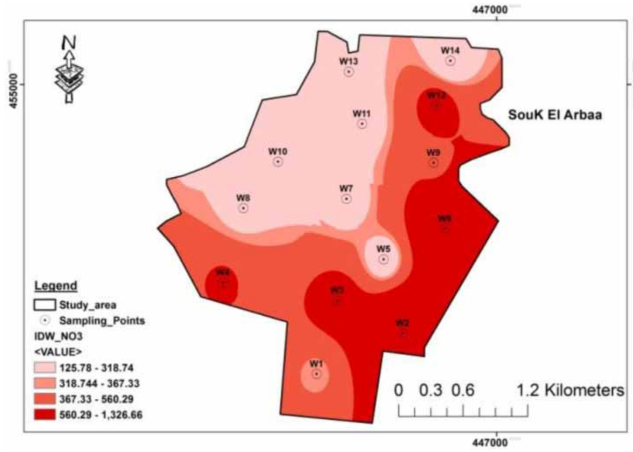


Figure 12 | The spatial distribution of nitrate.

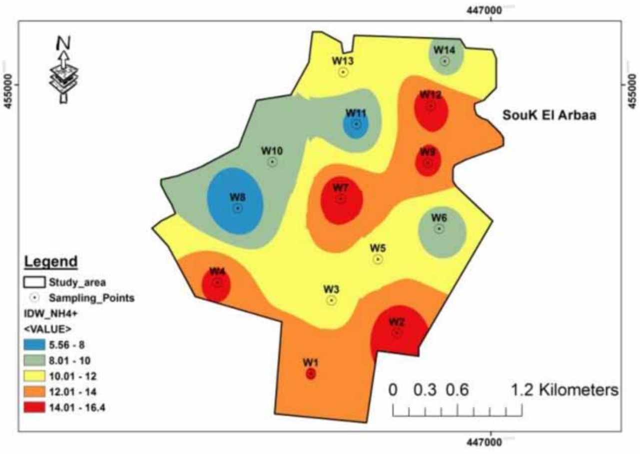


Figure 13 | The spatial distribution of ammonium.

16.3 mg/l with an average of 11.5 (Table 1 and Figure 13). According to the Moroccan Standards, not all samples collected are qualified as drinking water.

Bicarbonate

The presence of bicarbonates in groundwater is due to dissolving carbonate-containing metals by carbon dioxide (Lower 1999). According to the Moroccan Standards, 7.14% of s groundwater samples are not suitable for drinking.

Potassium

As per the Moroccan Standards, two samples of 14 groundwater samples exceed the maximum permissible of potassium, and these samples are distributed in agricultural areas, indicating that the increase in the concentration of potassium in the groundwater of the study area may be due to agricultural activity in those areas. The spatial distribution of potassium concentration in groundwater is shown in Figure 14.

Sulfate

Sulfate occurs naturally and is present in water at low concentrations (mainly in contact with gypsum or other common minerals) discharge of industrial wastes and domestic sewage tends to increase its concentration Joshi *et al.* (2009). High concentrations of sulfate in drinking water in combination with other ions (especially magnesium and sodium) can cause odors and a bitter taste in water, and a concentration over 600 mg/l has a laxative effect. Sulfate in combination with calcium

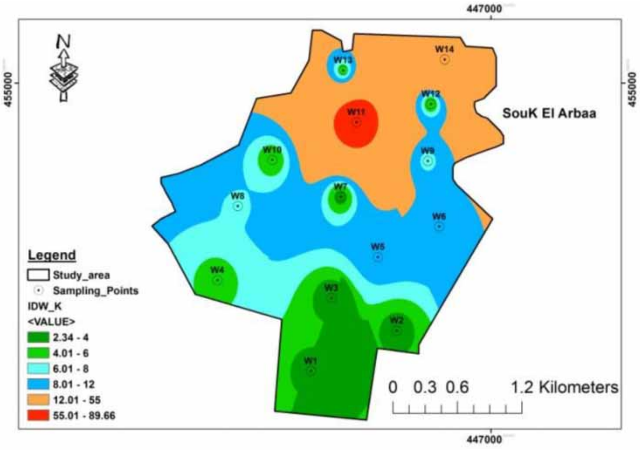


Figure 14 | Spatial distribution of K^+.

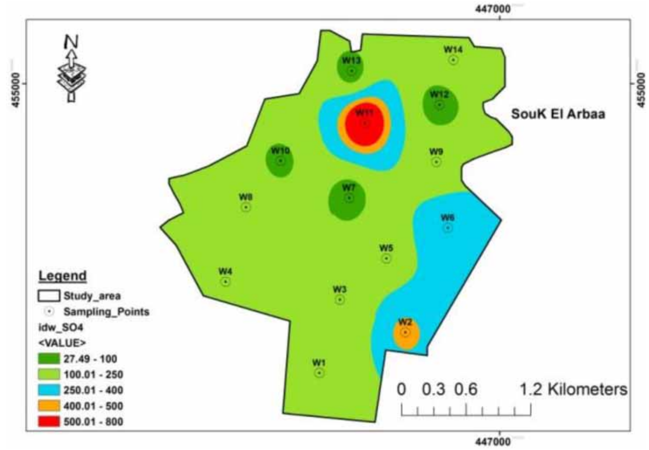


Figure 15 | Spatial distribution of SO_4.

in water forms hard scale in steam boilers. Only three samples exceed the maximum limits (250 mg/L) according to the Moroccan Standards. The spatial distribution for groundwater contamination by sulfate in the study area is presented in Figure 15.

CONCLUSION

From the overall analysis, it was observed that there is a significant fluctuation in the physical and chemical parameters of the groundwater samples studied. By comparing the results obtained with the standard specifications of Moroccan, it became clear that the groundwater in the study area is unfit for drinking purposes because high amount of NO_3^- mg/L and NH_4^+ is found, which exceeds the maximum quantity allowed. The high concentration of contamination at the Souk El Arbaa Basin is because the distribution of major ions largely depends on the type of geological formations in contact with the groundwater flowing through, irrigation return flow, and disposal of domestic and industrial wastewater.

Water pollution is becoming a bigger problem in Morocco because of population growth, industrialization, and increased use of agricultural chemicals. Efforts are being made to address this issue, but progress is slow. However, the study has some limitations, such as limited sampling and no consideration of seasonal variations. It is important to regularly evaluate groundwater quality to prevent further pollution and protect water quality.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

ACKNOWLEDGEMENTS

The authors extend their sincere thanks and gratitude to the Experience Club Office for Environmental and Water Consulting Services, Sana'a – Yemen, for its scientific and technical support in completing this research project.

REFERENCES

Al-Aizari, H., Fegrouche, R., Al-Aizari, A., Darwsh, N., Al-Kadasi, F. & Chaouch, A. 2020 Assessment of treated wastewater quality and impact of using it on the soil in Wadi Al-Mawaheb-Dhamar, Republic of Yemen. *Egyptian Journal of Aquatic Biology and Fisheries* **24** (2), 535–547.

Alhumairia, B. A. J. & Rahalb, N. S. 2023 Assessing drainage water quality for irrigation using the water quality index and DataFit Software. *Water Supply* **23** (6), 2349–2358.

APHA; AWWA and WEF 2005 *Standard Methods for the Examination of Water and Wastewater. 20th Edition, Part 2130*. American Public Health Association. American Water Works Association/Water Environment Federation, Washington, DC, USA.

Batchi, M., Al Karkouri, J., Fenjiro, I. & Maaqili, M. E. 2017 Étude Comparative de Deux Modèles (DRASTIC et SI) Pour l'évaluation de La Sensibilité de La Nappe Phréatique de Mnasra (Maroc Nord-Occidental) à La Pollution d'origine Agricole. *Physio-Géo. Géographie physique et environnement* **11**, 43–64.

Bera, A., Mukhopadhyay, B. P., Chowdhury, P., Ghosh, A. & Biswas, S. 2021 Groundwater vulnerability assessment using GIS-based DRASTIC model in Nangasai River Basin, India with special emphasis on agricultural contamination. *Ecotoxicology and Environmental Safety* **214**, 112085.

Bhat, M. A., Wani, S. A., Singh, V. K., Sahoo, J., Tomar, D. & Sanswal, R. 2018 An overview of the assessment of groundwater quality for irrigation. *Journal of Agricultural Science and Food Research* **9** (1), 209.

Bzioui, M. 2004 Rapport national 2004 sur les ressources en eau au Maroc. *Water-Africa Rapport National 2004 Sur Les Ressources En Eau Au Maroc 1–94*. http://doc.abhatoo.net.ma/doc/IMG/pdf/Rappt_national_eau_maroc.pdf.

Darwesh, N., Allam, M., Meng, Q., Helfdhallah, A. A., Ramzy SM, N., El Kharrim, K. & Belghyti, D. 2019 Using Piper trilinear diagrams and principal component analysis to determine variation in hydrochemical faces and understand the evolution of groundwater in Sidi Slimane Region, Morocco. *Egyptian Journal of Aquatic Biology and Fisheries* **23** (5 (Special Issue)), 17–30. doi: 10.21608/ejabf.2019.63248.

Darwesh, N., Naser, R. S. M., Al-Qawati, M., Raweh, S., El Kharrim, K. & Belghyti, D. 2020 Groundwater quality in Sidi Slimane, Morocco. *Journal of Health and Pollution* **10** (25), 1–10. doi: 10.5696/2156-9614-10.25.200305.

Davis, S. N. & De Wiest, R. J. M. 1966 *Hydrogeology*. Wiley, New York, p. 463.

Ekwere, A. S. & Edet, A. E. 2017 A comparative assessment of vulnerability of the Oban Massif aquifer system, SE-Nigeria, using DRASTIC, GOD and AVI models. *International Journal of Science and Engineering Investigations* **6** (9), 39–45.

El Khodrani, N., Zouahri, A., Arfaoui, A., Iaaich, H., El Oumlouki, K., Yahyaoui, A. & Fekhaoui, M. 2016 Study of physico-chemical quality of groundwater in the rural commune of SFAFAA (Sidi Slimane Gharb, Morocco). *Journal of Materials and Environmental Science* **7** (8), 2852–2860.

El Mountassir, O., Ouazar, D., Bahir, M., Chehbouni, A. & Carreira, P. M. 2021 GIS-Based Assessment of aquifer vulnerability using DRASTIC model and stable isotope: A case study on Essaouira Basin. *Arabian Journal of Geosciences* **14**, 1–21.

Ez-Zaouy, Y., Bouchaou, L., Saad, A., Hssaisoune, M., Brouziyne, Y., Dhiba, D. & Chehbouni, A. 2022 Morocco's coastal aquifers: Recent observations, evolution and perspectives towards sustainability. *Environmental Pollution* **293**, 118498.

Freeze, R. A. & Cherry, J. A. 1979 *Groundwater*. Prentice-Hall. Inc., Englewood Cliffs, NJ.

HCP 2013 Monographie regionale de la Région Du Gharb: p. 118.

Hilal, I., Oubeid, A. M., Qurtobi, M., Aqnouy, M., Amenzou, N., Saadi, R., Raibi, F., Bellarbi, M., Mhamdi, H. S., Sadiki, M., Hasnaoui, M. D. & Benmansour, M. 2024 Groundwater vulnerability mapping using the susceptibility index (SI) method and tritium isotopes: A case study of the Gharb aquifer in Northwestern Morocco. *E3S Web of Conferences* **489**, 07001. http://doi.org/10.1051/e3sconf/202448907001.

Joshi, N., Kumar, D. M. & & Agrawal, A. 2009 Assessment of the irrigation water quality of river Ganga in Haridwar district. *Rasayan Journal of Chemistry* **2** (2), 285–292.

Kumar, S., Kumar, A., Prashant, Jha, V. N., Sahoo, S. K. & Ranjan, R. K. 2022 Groundwater quality and its suitability for drinking and irrigational purpose in Bhojpur District: Middle Gangetic Plain of Bihar, India. *Water Supply* **22** (9), 7072–7084.

Li, P., He, S., Yang, N. & Xiang, G. 2018 Groundwater quality assessment for domestic and agricultural purposes in Yan'an City, northwest China: Implications to sustainable groundwater quality management on the Loess Plateau. *Environmental Earth Sciences* **77** (23), 0. doi: 10.1007/s12665-018-7968-3.

Lower, S. K. 1999 *Carbonate Equilibria in Natural Waters*. Simon Fraser University, **544**, 1–26. http://www.chem1.com/acad//webtext/pdf/c3carb.pdf.

Majandang, J. & Sarapirome, S. 2013 Groundwater vulnerability assessment and sensitivity analysis in Nong Rua, Khon Kaen, Thailand, using a GIS-based SINTACS model. *Environmental Earth Sciences* **68**, 2025–2039.

Maroc, R. 2019 Monographie Regionale sur le Secteur de l'Habitat Region de Rabat-Sale-Kenitra Année 2019 Table des matières.

Marques, J. M., Carreira, P. M., Neves, O., Marques, J. E. & Teixeira, J. 2019 Revision of the hydrogeological conceptual models of two Portuguese thermomineral water systems: Similarities and differences. *Sustainable Water Resources Management* **5**, 117–133.

Mkumbo, N. J., Mussa, K. R., Mariki, E. E. & Mjemah, I. C. 2022 The use of the DRASTIC-LU/LC model for assessing groundwater vulnerability to nitrate contamination in Morogoro Municipality, Tanzania. *Earth* **3** (4), 1161–1184.

Mohammed, B., Salah, O., Driss, O. & Abdelghani, C. 2020 Global warming and groundwater from semi-arid areas: Essaouira region (Morocco) as an example. *SN Applied Sciences* **2** (7), 1245.

Naser, R., Bakkali, M. E., Nahmi, F. A., Darwesh, N., El Kharrim, K. & Belghyti, D. 2017 Environmental contaminants and their impact on groundwater quality, in three area of Taiz, Yemen. *Revue De L'entrepreneuriat Et De L'innovation* **1** (4), 1–6.

Olojoku, I. K., Modreck, G., Adeyinka, O. S. & Adebayo, Y. M. 2017 Vulnerability assessment of shallow aquifer hand-dug wells in rural parts of northcentral Nigeria using AVI and GOD methods. *The Pacific Journal of Science and Technology* **18** (1), 325–333.

Perkel, D. H. 1979 Neural modeling: Electrical signal processing in the nervous system. *Mathematical Biosciences* **44** (3–4), 293–297. doi:10.1016/0025-5564(79)90087-7.

Piper, A. M. 1944 A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union* **25** (6), 914–928.

RGPH 2014 I. N. de la Statistique, Recensement Général de la Population et de l'Habitat 2014.

Saleh, A., Al-Ruwaih, F. & Shehata, M. 1999 Hydrogeochemical processes operating within the main aquifers of Kuwait. *Journal of Arid Environments* **42** (3), 195–209. doi: 10.1006/JARE.1999.0511.

Sawyer, C. N., McCarty, P. L. & Parkin, G. F. 2003 *Chemistry for Environmental Engineering and Science*. 5th Edn. McGraw-Hill Inc. New York, pp. 1–752. http://dspace.agu.edu.vn/handle/agu_library/4151.

Shah, S. H. I. A., Yan, J., Ullah, I., Aslam, B., Tariq, A., Zhang, L. & Mumtaz, F. 2021 Classification of aquifer vulnerability by using the DRASTIC index and geo-electrical techniques. *Water* **13** (16), 2144.

Subramani, T., Elango, L. & Damodarasamy, S. R. 2005 Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India. *Environmental Geology* **47** (8), 1099–1110. doi: 10.1007/s00254-005-1243-0.

Yesilnacar, M. I. & Gulluoglu, M. S. 2008 Hydrochemical characteristics and the effects of irrigation on groundwater quality in Harran Plain, GAP Project, Turkey. *Environmental Geology* **54** (1), 183–196. doi: 10.1007/s00254-007-0804-9.

Zaporozec, A. 1972 Graphical interpretation of water-quality data. *Ground Water* **10** (2), 32–43. doi: 10.1111/j.1745-6584.1972.tb02912.x.

First received 19 November 2023; accepted in revised form 15 March 2024. Available online 26 March 2024