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Mapping and Assessment of Groundwater Quality in Ghardaia Region, Northern Sahara, Algeria

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Abstract
This study assesses the quality of groundwater of the phreatic aquifer in Ghardaia, used locally for drinking water supply. Accomplished by mapping and analyzing physico-chemical parameters and their spatial distribution, as well as calculating a water quality index (WQI).
Ten groundwater wells were analyzed. Water samples collected in December 2023 were tested at the laboratory of Algerian water company (ADE) for eleven quality parameters. The Water Quality Index (WQI) was then calculated using ArcGIS mapping and WHO standards to assess overall water suitability.
The physicochemical analysis indicates that the groundwater is generally slightly alkaline and weakly mineralized, suggesting good quality freshwater. However, most samples exhibit high hardness due to natural mineralization, with the Berriane and Selama–Sebseb wells exceeding the WHO limits for total hardness, as well as for magnesium and potassium. Elevated nitrate levels at the Djafar well (83.92 mg/L) suggest agricultural contamination. Spatial mapping reveals natural mineralization in the northern areas (Berriane) and nitrate pollution in areas close to agriculture and urban development, such as Noumerate. Overall, eight of the ten wells are of excellent quality (WQI = 5.03–17.57), while the quality of Selama–Sebseb and Laadira is lower, being classified as "good" and "poor", respectively.
The study concludes that the groundwater in Ghardaia is generally of an excellent quality, with a WQI ranging from 5.03 to 17.57. Nevertheless, localized issues persist, including natural mineralization in the northern areas (Berriane) and nitrate pollution exceeding WHO limits near agricultural zones such as Noumerate.
Keywords: *Water quality, groundwater, World Health Organization, Nitrate, Algeria.*

INTRODUCTION

Globally, groundwater is a vital source of water (1). Compared to surface water, it offers several advantages, such as higher volumes and better quality. Groundwater is among the approximately 23% of the world's freshwater resources that need to be preserved and protected from misuse and pollution (2).
Yet population growth, agricultural development, industrialization and climate change are putting this invaluable resource at risk of depletion and degradation. These challenges become more severe in arid and semi-arid regions (3, 4).
In Algeria, water intended for human consumption is sourced either from underground or from surface water. The majority of Algerians use potable water supplied by public distribution systems, which are required to comply with quality standards established by national norms. National

initiatives to provide the population with drinking water have led to 93% of households being connected to the supply in 2008, compared to 78% in 1999 and 92% in 2007 (5).
In the center of the northern Sahara lies the region of Ghardaia. Due to the arid climate and the ease with which this subterranean resource can be accessed, groundwater is the main source of water for this area. Significant groundwater resources are found there, primarily in two layers: the Complex Terminal (CT) layer of the Northern Sahara and the Continental Intercalary (CI) layer. Groundwater is crucial for providing the population with drinking water (6).
This investigation focuses on mapping the quality of groundwater in the region of Ghardaia region, northern Algeria; where it is a vital resource for human consumption. It is important to note that the water sources under examination are not subject to regular monitoring by the relevant authorities. Mapping groundwater quality requires an understanding of the physicochemical characteristics of the phreatic aquifer and the potential contaminants affecting the water supply. The region's groundwater quality is primarily influenced by natural geological formations and human activities, both of which contribute to variations in quality. The main concern is nitrate contamination, which poses a significant risk to the health of the local population. To improve data management and control, this study uses the ArcGIS tool to analyze ten phreatic aquifer wells located in specific municipalities in the region of Ghardaia.

METHODS

Study area

This investigation was carried out in the region of Ghardaia (32°28'N, 3°42'E), one of the largest oases in the Algerian Sahara; located in the center of the northern Sahara, around 600 kilometers south of Algiers, the capital of Algeria. The state is divided into nine (09) provinces and thirteen (13) municipalities, and has an area of 84,660.12 km2 (Fig. 01). The climate in this area is marked by hot, dry summers and mild winters, with an average yearly temperature of 23.27°C and 80.10 mm of precipitation (7, 8).

Water sample collection and analysis

The method of collecting and analyzing data relating to water quality enables exploration of the site and assessment of water quality. In this context, ten water wells from the phreatic aquifer intended for irrigation and human consumption were examined in several municipalities in December 2023, namely: Berriane (Soudan well), Ghardaia (Oued Nimel well and Himoud well (Laâdara), Dayet Bendhahoua (Dejdra well), and Metlili Eljadida or Noumerat (Fouinice well, Djafar well and Tarach well), as well as Sebseb (El Ferd well, Cheaab Elaargoub well and Slama well) (Figure 1).

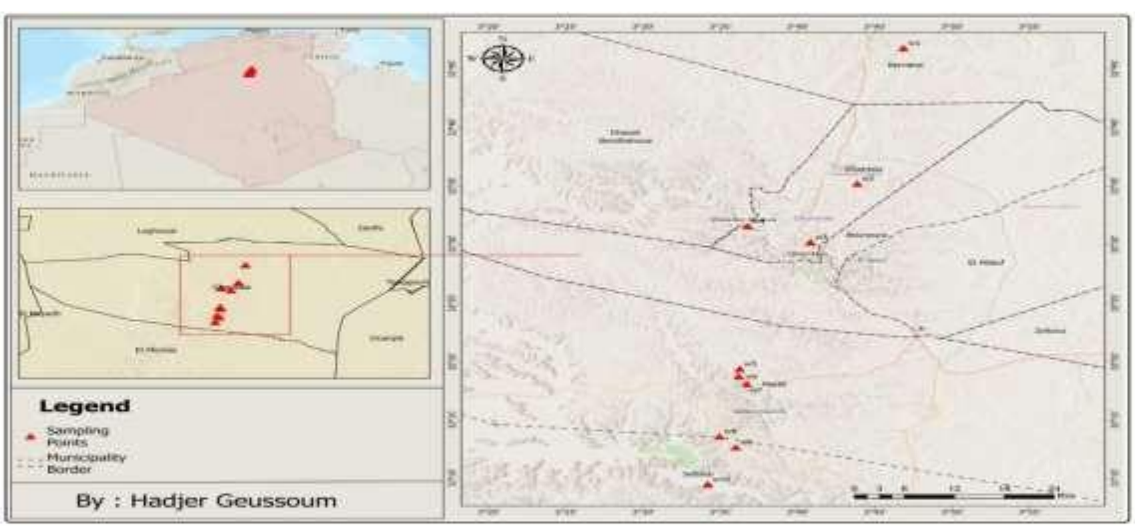

Figure 01: Geographic distribution of analyzed water samples.
Magellan GPS device with UTM metric was used to locate the sampling points (Figure 1). The sampling bottles were rinsed with water from the wells to be sampled and the wells were pumped for

five minutes prior to collection. Two distinct series of 500 ml plastic bottles were used for every sampling site: one for cation analysis and the other for anion analysis.

Following sample collection, physicochemical parameters including pH, electrical conductivity (EC) and total dissolved solids (TDS) were tested immediately using a portable, waterproof Hanna multi-parameter measuring instrument. The concentration of the principal cations (Na^+ and K^+) was determined using a flame photometer, while $Ca2^+$ and $Mg2^+$ were analyzed using EDTA titrimetric methods. Chloride content (Cl^-) was measured using argentometric titration. A UV spectrophotometer was also used to quantify the concentrations of iron ($Fe2^+$), nitrate (NO_3^-) and nitrite (NO_2^-) at 440 nm.

All analyses were performed at the laboratory of Algerian water company in Ghardaia (ADE).

The results were processed using ArcGIS 10.8 and displayed on maps, and statistical analysis was performed using MS Excel tools.

Water Quality Index

The Water Quality Index (WQI) is a direct method of analyzing overall water quality. It uses a set of factors to summarize large amounts of data into a single, typically dimensionless value that can easily be reproduced (9). This approach was first put forward by (10) and (11). (11) developed the first method of calculating the index that considers all the factors necessary for determining the quality of surface water and represents the combined influence of several significant factors in the management and assessment of water quality (12, 13). The WQI was initially employed to identify physicochemical changes anticipated during the year and their potential impact on drinking water quality (14, 15).

In this approach, a numerical value called the 'relative weight' (Wi), which is specific to each physicochemical parameter, is calculated according to the following formula:

$Wi = wi / \sum wi$ (1)

In this equation, Wi denotes proportional weighting; wi denotes the assigned weight for a specific parameter; and n indicates the total number of parameters involved.

To determine the quality rating scale (qi) for a given parameter, its measured concentration is divided by the corresponding WHO standard value and the result is multiplied by 100.

$qi = (Ci/Si) \times 100$ (2)

Where:

- qi: quality rating scale
- Ci: concentration of each parameter in mg/L
- Si: WHO standard of each parameter in mg/L

The Sub-Index (SIi) is the first index to be determined to calculate the Water Quality Index. The WQI of each sample is calculated by adding the Sub-Indices of each parameter:

$SIi = Wi \times qi$ (3)

$WQI = \sum SIi$ (4)

Water quality index data can be used to identify five quality classes (Table 1).

Table 1. Classification and possible water use according to WQI (Adapted from 16-17-18)

WQI Class	Water Type	Possible Use
0-25	Excellent quality	Drinking water, agricultural use, and industrial
>25-50	Good quality	Drinking water, agricultural use, and industrial
>50-75	Poor quality	agricultural use, and industrial
>75-100	Very poor quality	agricultural use
>100	Non potable water	Pre-use requires necessary purification steps.

RESULTS

Water physicochemical properties

Eleven water quality categories were analyzed for all groundwater samples in this study. Table 2 provides a detailed overview of these parameters, presenting the minimum and maximum values, averages, and instances in which limits were exceeded. Furthermore, the table incorporates the corresponding drinking water quality standards set by the World Health Organization (19).

Table 2. Results of analysis of water quality parameters for the phreatic aquifer in the study area

Parameters	WHO, 2017	Min	Max	Mean
pH	6.5-8.5	7.2	8.04	7.68
EC (µs/cm)	500-1500	566	1436	833.8
TDS (mg/L)	500-1000	288	802	438.6
Turbidity / NTU	5	0.187	1.620	0.55
TH	100-500	284	744	428.8
Ca^{+2} (mg/L)	75-200	62.52	110.62	84.25
Mg^{+2} (mg/L)	≤50 (Algerian Standard	29.160	114.210	53.43
Na^{+} (mg/L)	200	26.36	65.71	33.37
K^{+} (mg/L)	12	3.81	17	7.17
Cl^{-} (mg/L)	250-500	35.45	265.90	95.51
NO_3^{-} (mg/L)	45	3.16	83.92	24.23

Spatial distribution of groundwater quality parameters

The geographical spread of each water quality metric was visualized using kriging maps created with ArcGIS Pro.

Maps showing the spatial distribution of pH, conductivity, TDS and turbidity were created using geostatistical interpolation in a GIS environment. Figure 02 illustrates these maps of groundwater quality in the study area. The pH levels increase towards the southeast, indicating slightly alkaline groundwater. Both electrical conductivity and TDS concentrations rise in the south. Since the maximum allowable limits for conductivity and TDS in drinking water are 1500 µS/cm and 1000 mg/l respectively, the groundwater in this region is classified as suitable for consumption given that both measurements are below these limits. Figure 02 shows that all turbidity concentrations are within the WHO-established acceptable limit of 5 NTU. In contrast, the highest concentration is located in the west of the area. This indicates that these waters are potable in terms of turbidity.

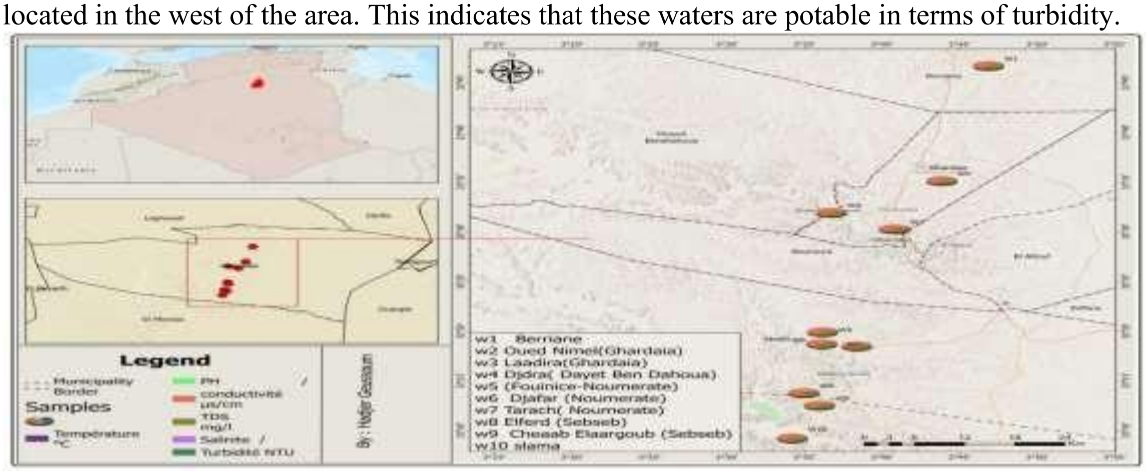

Figure 02: The map shows the spatial distribution of physical parameters of the phreatic aquifer in the study area.

The spatial distribution of each chemical characteristic of water quality was visually represented by Kriging maps created with ArcGIS Pro. As shown in Figure 03, the ionic group map indicates that the Berriane well in the northern part of the region of Ghardaia displays the highest concentrations of calcium ($Ca2^{+}$), magnesium ($Mg2^{+}$), potassium (K^{+}), chloride (Cl^{-}) and total hardness (TH). Moreover, the Slama well in Sebseb shows high levels of sodium (Na^{+}). The remaining wells are mainly characterised by low concentrations of ionic groups.

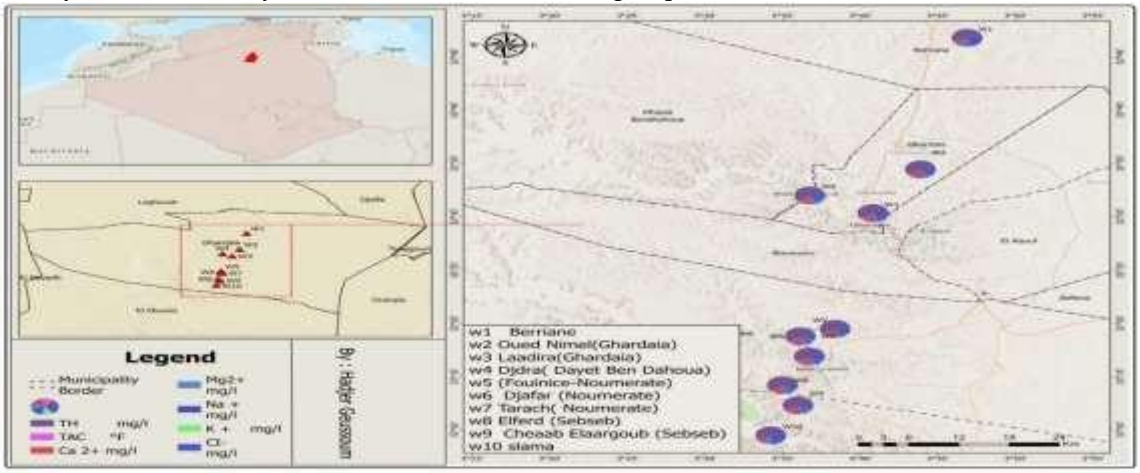

Figure 03: The map illustrates the spatial distribution of chemical parameters of the phreatic aquifer in the study area.

Figure 04 presents a map of the distribution of pollution indicators. It shows that the Fouinice well in Noumerate has the highest nitrate content (NO_3^{-}), while the Tarach well has the lowest. Additionally, the Berriane well exhibits a slight increase in iron content ($Fe2^{+}$). However, the concentration of phosphorus (P) is relatively insignificant in all wells.

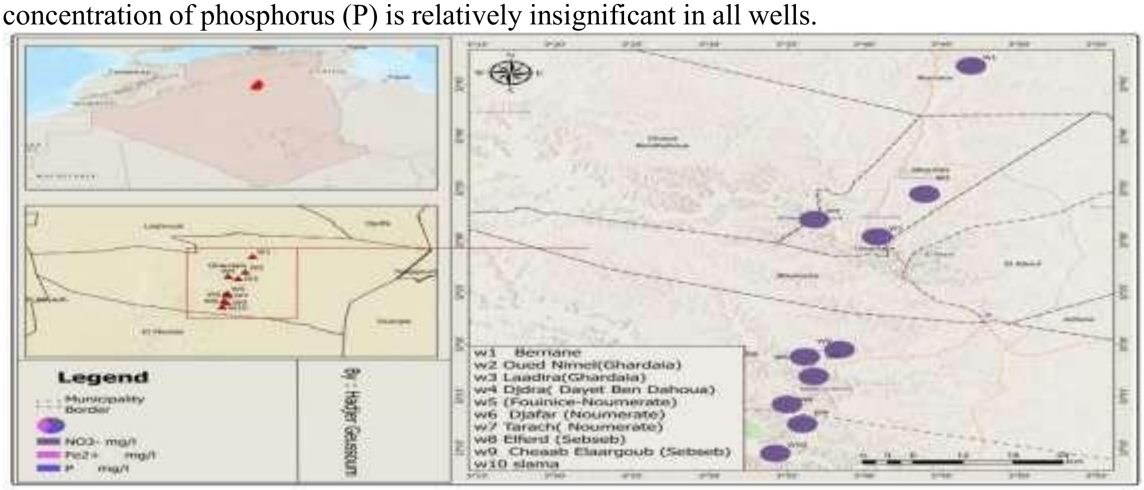

Figure 04: Map of the spatial distribution of pollution parameters in the phreatic aquifer in the study area.

Water Quality Assessment

Water Quality Index (WQI)

Table 3. Calculation of the Water Quality Index (WQI) and quality class of the phreatic aquifer water in the region of Ghardaia

The studied wells	**WQI**	**Water Type**
Berriane	**17,57**	Excellent Quality
Oued Nimel (Ghardaia)	**5,28**	Excellent Quality
Laadira (Ghardaia)	**52,39**	Poor Quality
Djdra (Dayet Ben Dahoua)	**8,36**	Excellent Quality
Founice (Noumerate-Metlili)	**5,03**	Excellent Quality
Djafar (Noumerate-Metlili)	**15,89**	Excellent Quality

Tarache (Noumerate-Metlili)	**7,92**	Excellent Quality
Elferd-Sebseb	**5,79**	Excellent Quality
Cheaab Elaargoub-Sebseb-	**5,49**	Excellent Quality
Slama-Sebseb-	**40,17**	Good Quality

Eight out of ten of the analyzed wells are classified as having 'Excellent Quality' (WQI ranging from 5.03 to 17.57), including wells in Berriane, Oued Nimel, Dayet Ben Dahoua, Noumerate and El Ferd/Cheaab Elaargoub. Two wells showed reduced quality: Slama-Sebseb was classified as 'good quality' (WQI of 40.17) and Laadira (Ghardaia) as 'poor quality' (WQI of 52.39). This indicates that there are localized areas that require attention regarding water potability.

DISCUSSION

Groundwater quality in the phreatic aquifer of Ghardaia shows that pH values range from 7.20 to 8.04, with an average of 7.68, indicating alkalinity. Note that groundwater in the Sahara is generally alkaline, although the lithological composition, including evaporitic rocks and clay, influences pH fluctuations and salinity levels. Electrical conductivity (EC) values range from 566 to 1436 µS/cm with an average of 833.8 µS/cm, suggesting slight mineralization. As the EC of the samples in this area is below the WHO guideline, the groundwater of the region is classified as freshwater (21).

The mean total dissolved solids (TDS) level in the water samples was 438.6 mg/L, with concentrations ranging from 288 to 802 mg/L. All of the samples examined complied with the standards set by WHO regulations. Turbidity values ranged from 0.187 to 1.620 NTU, averaging 0.55 NTU. All analyzed water wells contained clear water, which explains why the turbidity was below the maximum acceptable content according to the WHO standard. While turbidity itself does not pose a health risk, the potential presence of pollutants in the water could be a cause for concern from a health perspective.

Total hardness (TH) measurements in the groundwater samples ranged from 284 to 744 mg/L, with an average of 428.8 mg/L. Eight samples fell below the acceptable consumption level of 500 mg/L, while two samples (Berriane well and Slama well in Sebseb) exceeded this limit. Water is categorized as 'very hard' when its TH concentration is above 300 mg/L, and as 'hard' when the concentration is between 150 and 300 mg/L. According to (23), 99% of the samples were classified as very hard and only 1% as hard. Regular consumption of water with a high TH level can lead to kidney stones and cardiovascular issues and may aggravate eczema (22). Phreatic aquifer waters have an average calcium level of 84.25 mg/L, ranging from 62.52 to 110.62 mg/L, and all results are within the World Health Organization's acceptable limit.

The magnesium ion content is an indicator of water mineralization and hardness (TH is the total amount of $Ca2^{+}$ and $Mg2^{+}$). The magnesium concentration shows considerable variability, ranging from 29,160 mg/L to 114,210 mg/L with an average of 53,430 mg/L. When the results are compared to the Algerian standard of 50 mg/L, it is evident that two wells, Berriane (114,210 mg/L) and Selama-Sebseb (105,948 mg/L), significantly exceed the authorized threshold. These figures are indicative of the natural hyper-mineralization of deep or confined aquifers, which is a common occurrence in the Algerian Sahara (24). The circulation of groundwater is essential for dolomitisation, as it provides a continuous supply of $Mg2^{+}$ ions. Studies indicate that regional dolomitisation is primarily due to reflux infiltration mechanisms, which facilitate the exchange of large volumes of water and magnesium from evaporitic brines (25).

All of the samples had sodium concentrations below the WHO acceptable limit, with an average of 33.37 mg/L and a range of 26.36 to 65.71 mg/L. Excessive sodium intake can lead to cardiovascular and circulatory problems (26).

In all samples tested, the potassium level was below the recommended limit of 12 mg/L, except for the waters from the Berriane wells, which had a level of 17 mg/L and thus exceeded this limit. Potassium levels varied from 3.81 to 17 mg/L, with an average of 7.17 mg/L. According to reference 27, the CT aquifer is affected by the dissolution of evaporitic minerals, which leads to the release of potassium ions into the phreatic groundwater. Its presence may also be linked to wastewater contamination. Elevated potassium levels can increase the risk of gastrointestinal and neurological problems (28).

The chloride ion levels in the sampled well waters are below the WHO standard of 500 mg/L. They vary between 35.45 and 265.90 mg/L, with an average of 95.51 mg/L. According to WHO (19), the release of sodium chloride (NaCl) highlights the nutritional importance of chlorine, particularly with regard to chronic heart disease.

High nitrate levels in groundwater are primarily caused by excess agricultural fertilisers, animal and human waste, and plant debris. The highest concentration of nitrate that can be found in drinking water is 50 mg/L. In the studied area, however, nitrate concentrations at the Djafar well (Noumerat) range from 3.16 to 83.92 mg/L, with an average of 24.23 mg/L. The high nitrate concentration in the Djafar well is explained by pollution mainly resulting from agricultural activities, urbanization and the use of nitrogen fertilisers. These factors contribute to the deterioration of water quality in different aquifers (29, 30).

Spatial analysis reveals that natural geological processes and localized human activities significantly influence groundwater quality in this arid region, where groundwater constitutes a primary source of drinking water. Figure 2 visually illustrates the variability in mineralization indicators (EC and TDS) along the M'zab Valley.

The high mineralization observed in the northern sector at well W1 (Berriane) is reflected in the significant proportion of the pie chart dedicated to high EC and TDS. This is consistent with the hydrogeological properties of Saharan aquifers overall, where extended water-rock interaction pathways and restricted recharge in the shallow aquifer lead to high concentrations of dissolved solids (Figure 2). While the central area near Ghardaia appears less mineralized, wells to the south, particularly around Sebseb (W9 and W10), may also exhibit high electrical conductivity and salinity. These findings are generally attributed to the dissolution of evaporitic minerals (such as gypsum and anhydrite) within the arid environment (32). The water is generally near-neutral or slightly alkaline, which is typical of groundwater buffered by carbonate minerals. This confirms a relatively stable hydrochemical environment in terms of acidity/alkalinity (Figure 2).

The spatial distribution of the main physicochemical parameters, as shown on the hydrochemical map of the Ghardaia region (Northern Sahara, Algeria), reveals marked variability in groundwater quality across the studied wells (W1–W10). The dominant ions (including $Ca2^+$, $Mg2^+$, Na^+ and Cl^-) and parameters (such as total hardness (TH) and total alkalinity (TAC)) indicate that groundwater chemistry is primarily controlled by geogenic processes and, to a lesser extent, anthropogenic influences (Figure 3).

Groundwater in the northern part of the study area (wells W1–W3, in Berriane, Oued N'Imel and Laadira) shows relatively low salinity and hardness levels. This pattern suggests shorter durations of water-rock interaction or recharging from less mineralized sources.

The dissolution of halite and gypsum-bearing formations, which are characteristic of the Continental Intercalary aquifer system, is likely responsible for the elevated concentrations of Na^+ and Cl^- observed in samples from the southern and southwestern zones (W6–W10: Djafar, Elferd, Cheaab, Elaragoub and W10: Slama) (33) (Figure 3). While the high $Na^+/Ca2^+$ ratio in the southern wells may suggest cation exchange processes (Na–Ca exchange) in clay-rich layers, the dominance of $Ca2^+$ and $Mg2^+$ ions in several samples (most notably W4–W7) supports carbonate and dolomitic rock dissolution (34) (Figure 3).

The spatial distribution of nitrate (NO_3^-), ferrous iron ($Fe2^+$) and phosphorus (P) concentrations, as shown on the map of the Ghardaia region, reveals significant variability between sampling sites (W1–W10) (Fig. 4). The northern wells (W1–W3) in Berriane and Ghardaia exhibit elevated NO_3^- values, indicating the influence of anthropogenic sources such as home effluents, agricultural activities and nitrogen-based fertilisers. Comparable nitrate enrichments have been documented in other Saharan aquifers with intense irrigation and inadequate wastewater treatment (35, 36) (Figure 4).

Although their WQI is very low (ranging from 5.03 to 17.57), almost all analyzed wells show 'excellent quality' (Table 3). This suggests that groundwater in these regions is generally well preserved from

pollution or that its mineralization rate remains within acceptable limits for consumption. This is a promising result for the drinking water supply in this arid environment.
Two wells stand out as lower quality (Table 3): Slama-Sebseb: Classified as 'good quality' (WQI of 40.17), it could be affected by high natural mineralization. In the Algerian Sahara, deep aquifer water can be geologically ancient and highly saline due to its long residence time and interaction with evaporitic rocks. This contributes to an increase in the WQI. Laadira (Ghardaia): Rated as 'poor quality' (with a WQI of 52.39), this assessment is due to defects or failures in sanitation systems and septic tanks. These can cause the infiltration of untreated wastewater, introducing microbiological and chemical pollutants (such as nitrates and chlorides) into shallow groundwater (38).

CONCLUSION

This research aimed to evaluate the quality of groundwater in the phreatic aquifer in the Ghardaia region (Northern Sahara), Algeria. Ten wells were analyzed using physicochemical parameters, spatial distribution and the Water Quality Index (WQI).
The study confirms that groundwater is the main source of drinking water in the region of Ghardaia, an area with an arid climate.
According to the WQI index, eight of the ten analyzed wells show 'excellent quality' (ranging from 5.03 to 17.57), suggesting that groundwater in these regions is generally preserved from contamination. However, water quality shows significant disparity, highlighting two distinct non-compliance issues requiring specific management approaches.
The results reveal a complex issue in which pollution (nitrates) is the main factor contributing to the WQI in urban areas (Laadira). Conversely, mineralization ($Mg2^+$, TH) is the main non-compliance factor in other regions (Berriane and Selama), despite the latter showing little pollution.
Mapping shows apparent differences in water quality issues. In the north (Berriane), water contains high levels of natural minerals. In contrast, areas with human-made pollution problems, such as nitrates, are predominantly found in urban and agricultural regions, including Noumerate. These differences highlight the need for a location-specific approach to managing water resources effectively. This is crucial to ensuring a reliable supply of water that meets safety standards.

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Methodology: Hadjer Guessoum, Hadjira Benhedid, Hamza Negais
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Validation: Hadjer Guessoum
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