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Articles

Hydrogeochemical assessment of groundwater quality in the middle Seybouse sub-basin (North-Eastern Algeria)

Evaluación hidrogeoquímica de la calidad del agua subterránea en la subcuenca media del Seybouse (Noreste de Argelia)

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Abstract

This study evaluates groundwater potability in the Middle Seybouse sub-basin (northeastern Algeria) using the Groundwater Quality Index (GWQI) based on eleven key physicochemical parameters. A total of 17 groundwater samples were collected during the dry season of 2021 and analyzed for major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}), pH, electrical conductivity (EC), and total dissolved solids (TDS). The calculated GWQI values ranged from 23.33 to 81.18, with a mean of 46.03. Results indicate that 94.1% of groundwater samples are suitable for drinking purposes (excellent to permissible quality), while the remaining 5.9% fall into the doubtful quality category. The spatial distribution of water quality reveals significant mineralization in specific areas, particularly at sampling point F BS2, where elevated chloride

(398.2 mg/L), sodium (81 mg/L), and electrical conductivity (2090 μS/cm) reflect localized salinization. Hydrochemical analysis and Piper diagram classification indicate that groundwater chemistry is primarily controlled by water-rock interaction, particularly the dissolution of carbonate formations and evaporitic minerals. The temporal analysis (2017-2021) shows a steady increase in nitrate concentrations, suggesting an increasing anthropogenic influence from agricultural activities. This study provides an updated, spatially explicit evaluation of groundwater potability in the Middle Seybouse sub-basin, supporting evidence-based water resource management in one of Algeria's increasingly stressed basins.

Keywords: groundwater, water quality, water analysis, water pollution, water resources management, Seybouse sub-basin, Algeria.

Resumen

Este estudio evalúa la potabilidad de las aguas subterráneas en la subcuenca del Seybouse Medio (noreste de Argelia) utilizando el Índice de Calidad de las Aguas Subterráneas (GWQI), basado en once parámetros fisicoquímicos clave. Se recogieron un total de 17 muestras de aguas subterráneas durante la estación seca de 2021 y se analizaron para determinar los iones principales (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}), el pH, la conductividad eléctrica (CE) y los sólidos totales disueltos (TDS). Los valores calculados del GWQI oscilaron entre 23,33 y 81,18, con una media de 46,03. Los resultados indican que el 94,1 % de las muestras de aguas subterráneas son aptas para el consumo humano (calidad excelente o aceptable), mientras que el 5,9 % restante se clasifica en la categoría de calidad dudosa. La distribución espacial de la calidad del agua revela una mineralización significativa en áreas específicas, especialmente en el punto de muestreo F BS2, donde los elevados niveles de cloruro (398,2 mg/L), sodio (81 mg/L) y conductividad eléctrica (2090 µS/cm) reflejan una salinización localizada. El análisis hidroquímico y la clasificación según el diagrama de Piper indican que la química de las aguas subterráneas está controlada principalmente por la interacción agua-roca, en particular la disolución de formaciones carbonatadas y minerales evaporíticos. El análisis temporal (2017-2021) muestra un aumento constante de las concentraciones de nitratos, lo que sugiere una influencia antropogénica cada vez mayor derivada de las actividades agrícolas. Este estudio ofrece una evaluación actualizada y espacialmente explícita de la potabilidad de las aguas subterráneas en la subcuenca del Seybouse Medio, lo que respalda una gestión de los recursos hídricos basada en datos empíricos en una de las cuencas de Argelia que se encuentra sometida a una presión cada vez mayor.

Palabras clave: agua subterránea, calidad del agua, análisis del agua, contaminación del agua, gestión de los recursos hídricos, subcuenca Seybouse, Argelia.

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1. Introduction

Groundwater constitutes a vital freshwater resource for domestic supply, agricultural production, and industrial development, particularly in arid and semi-arid regions where surface water availability is inherently limited and climatic variability is pronounced. Across North Africa, and especially in Algeria, reliance on groundwater has intensified in recent decades in response to rapid population growth, expanding socio-economic activities, and the increasing impacts of climate change. These combined pressures have placed considerable stress on already constrained groundwater reserves, both in terms of quantity and quality (Hamed et al., 2018). Despite its strategic importance, groundwater quality in many Algerian basins has been progressively degraded by overexploitation, unplanned urban expansion, intensive agricultural practices, and inadequate wastewater treatment infrastructure, raising serious concerns regarding its long-term suitability for human consumption and sustainable use (Bouteraa et al., 2019; Derdour et al., 2020).

The Middle Seybouse sub-basin, encompassing the Guelma region in north-eastern Algeria, represents a strategically important hydrological system that supplies groundwater for domestic and industrial uses to an increasingly urbanised population. Previous research in this area has primarily focused on characterising the hydrogeological framework (Brahmia, 2016; Boudjebieur et al., 2021), water resources management strategies (Brahmia et al., 2016), and assessments of surface water quality (Belabed et al., 2017; Guettaf et al., 2017). Although several studies have reported increasing mineralisation, nitrate enrichment, and marked spatial heterogeneity in groundwater chemistry resulting from both natural hydrogeochemical processes and intensifying anthropogenic pressures (Djabri et al., 2003; Belabed et al., 2017), a comprehensive and systematic evaluation of groundwater quality—particularly with respect to drinking water suitability—remains insufficiently addressed at the sub-basin scale.

In particular, basin-wide assessments of groundwater suitability for drinking purposes are still scarce in the Middle Seybouse sub-basin, as most existing investigations have relied on limited datasets or have focused on individual wells and localised areas. Furthermore, relatively few studies have adopted integrative, index-based approaches capable of synthesising multiple physicochemical parameters into a single, interpretable metric suitable for decision-making. The absence of such holistic frameworks constrains the effective interpretation of groundwater quality patterns and limits their practical application in water resources planning and management. To overcome these limitations, the present study employs the Weighted Arithmetic Water Quality Index (WQI), a widely recognised and robust method for evaluating groundwater suitability for drinking purposes (Horton, 1965; Brown et al., 1970), thereby providing a systematic, basin-scale appraisal of groundwater potability across the Middle Seybouse sub-basin. Accordingly, this study assesses groundwater potability using eleven key physicochemical parameters—pH, electrical conductivity (EC), total dissolved solids (TDS), Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-} and NO_3^{-}—which collectively reflect the dominant geochemical processes and anthropogenic influences shaping groundwater quality in the study area (Wang et al., 2023; Sarfraz et al., 2020; Jing et al., 2019). The specific objectives of this research are to: (i) compute and spatially map the Groundwater Quality Index (GWQI) across the Middle Seybouse sub-basin; (ii) delineate areas where groundwater quality exceeds the World Health Organization (WHO) drinking-water guidelines (WHO, 2017); and (iii) elucidate the principal natural and human-induced processes controlling groundwater chemistry. By providing an updated and spatially explicit evaluation of groundwater potability in the Guelma region, this study contributes scientifically robust evidence to support informed groundwater management and sustainable water-resource planning in one of Algeria's increasingly stressed hydrological basins.

2. Materials and methods

2.1. Study Area

The Middle Seybouse sub-basin (sub-basin code 14-04) covers an area of approximately 822 km² and is entirely located within Guelma Wilaya in north-eastern Algeria (Brahmia et al., 2016; Boudjebieur et al., 2021). It is bounded to the north-east by sub-basin 14-06 (Oued Seybouse Maritime), to the east by sub-basin 14-05 (Oued Melah), to the south-west by sub-basin 14-02 (Oued Cherf Aval), to the south by sub-basin 14-01 (Oued Cherf Amont), and to the west by sub-basin 14-03 (Oued Bou Hamdane) (ABH-CSM, 2002). The basin extends approximately 40 km in the north–south direction and about 20 km east–west, with elevations ranging from nearly 200 m above sea level (a.s.l.) in the central plain to more than 1.200 m a.s.l. in the surrounding mountainous areas(Boudjebieur et al.,2021).

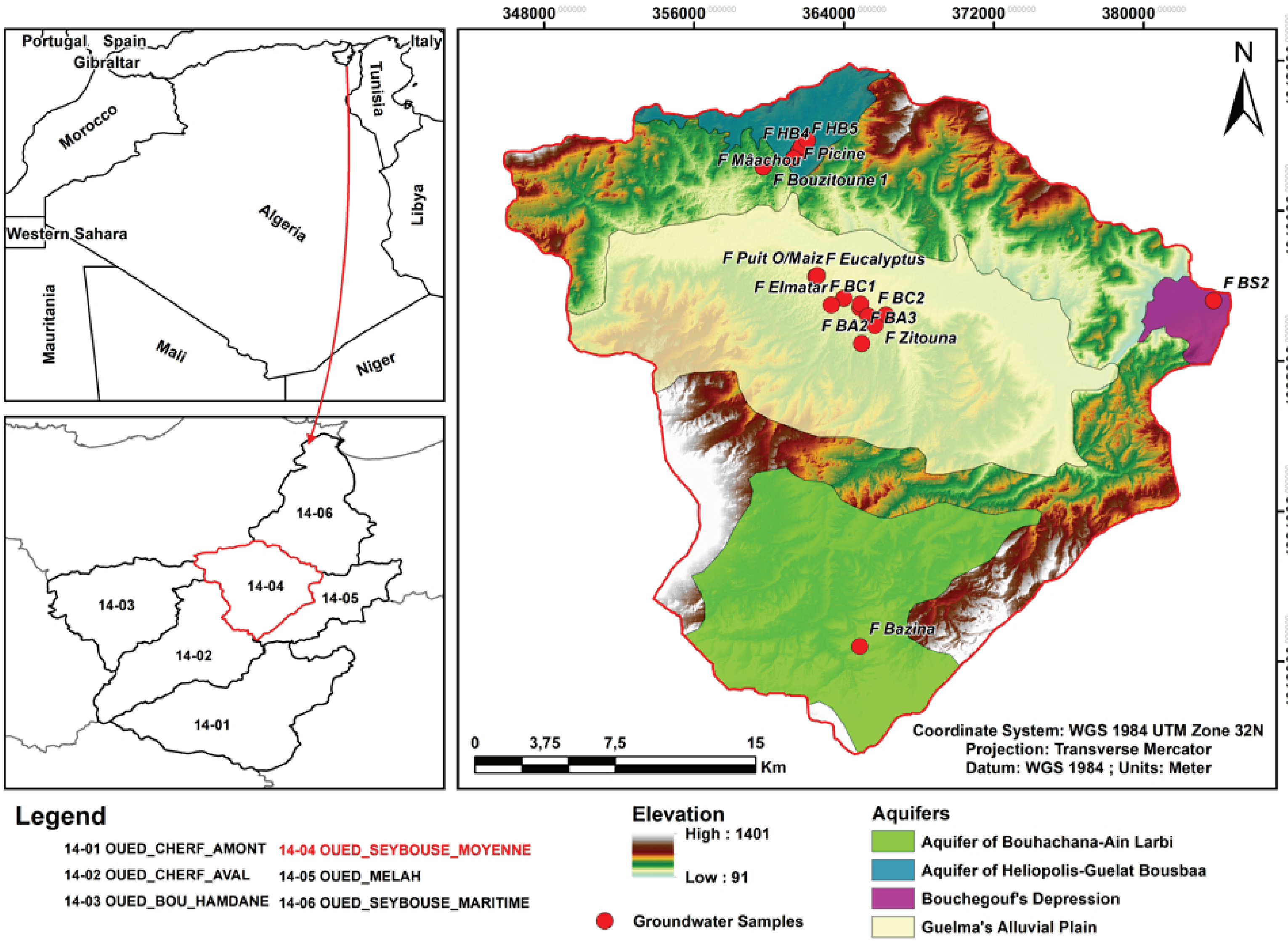

Figure 1. Location map of the study area.

The region is characterised by a Mediterranean climate with a transition from semi-arid to sub-humid conditions. Summers are typically hot and dry, whereas winters are mild and wet. Mean annual precipitation averages around 600 mm, while mean annual temperatures range between 17 and 19 °C. High potential evapotranspiration significantly limits effective groundwater recharge, which occurs predominantly during the October–April period and governs seasonal fluctuations in the water table (Brahmia, 2016).

From a geological perspective, the Middle Seybouse sub-basin is situated within the eastern Tell Atlas and exhibits a complex stratigraphic evolution from the Triassic to the Quaternary (Brahmia, 2016). The basin is mainly infilled with Quaternary alluvial deposits composed of gravels, sands, silts, and clays, forming three principal terrace levels (high, medium, and low) along the Seybouse River. These deposits overlie Miocene marls and sandstones that act as semi-permeable formations, while Cretaceous–Eocene carbonate rocks crop out extensively in the surrounding uplands, particularly in the Heliopolis and Bouhachana areas. At the outlet of the watershed, the Bouchegouf depression is underlain by Pliocene sandstones and conglomerates, bordered to the south by Triassic gypsum formations. In addition, locally developed fractured Ypresian limestones provide favourable conditions for groundwater storage and aquifer development. Structural features, including faults and lineaments predominantly oriented NE–SW, enhance secondary permeability and play a key role in facilitating groundwater circulation throughout the basin.

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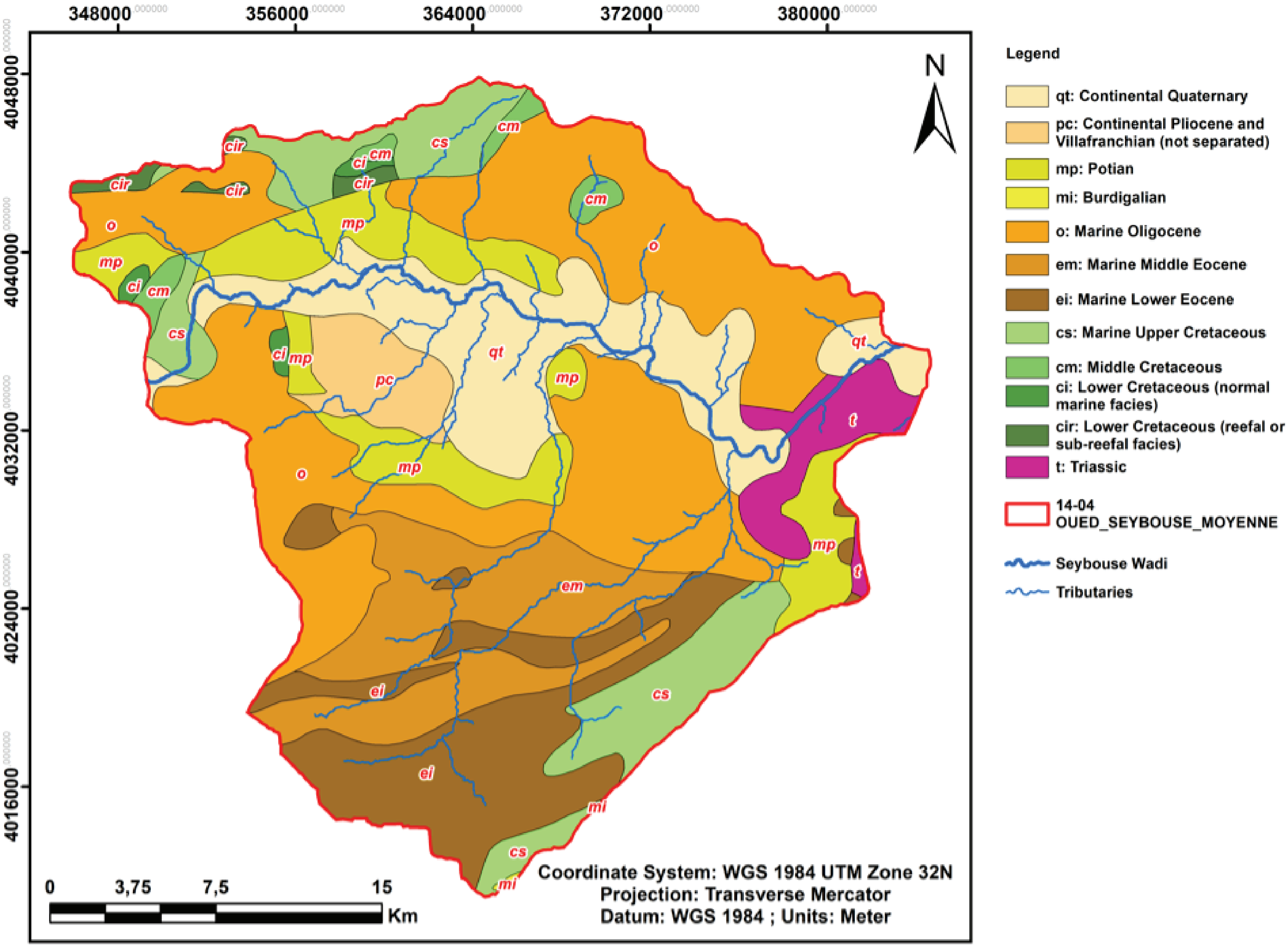

Figure 2. Geological map of the study area. Source: Vila, 1980.

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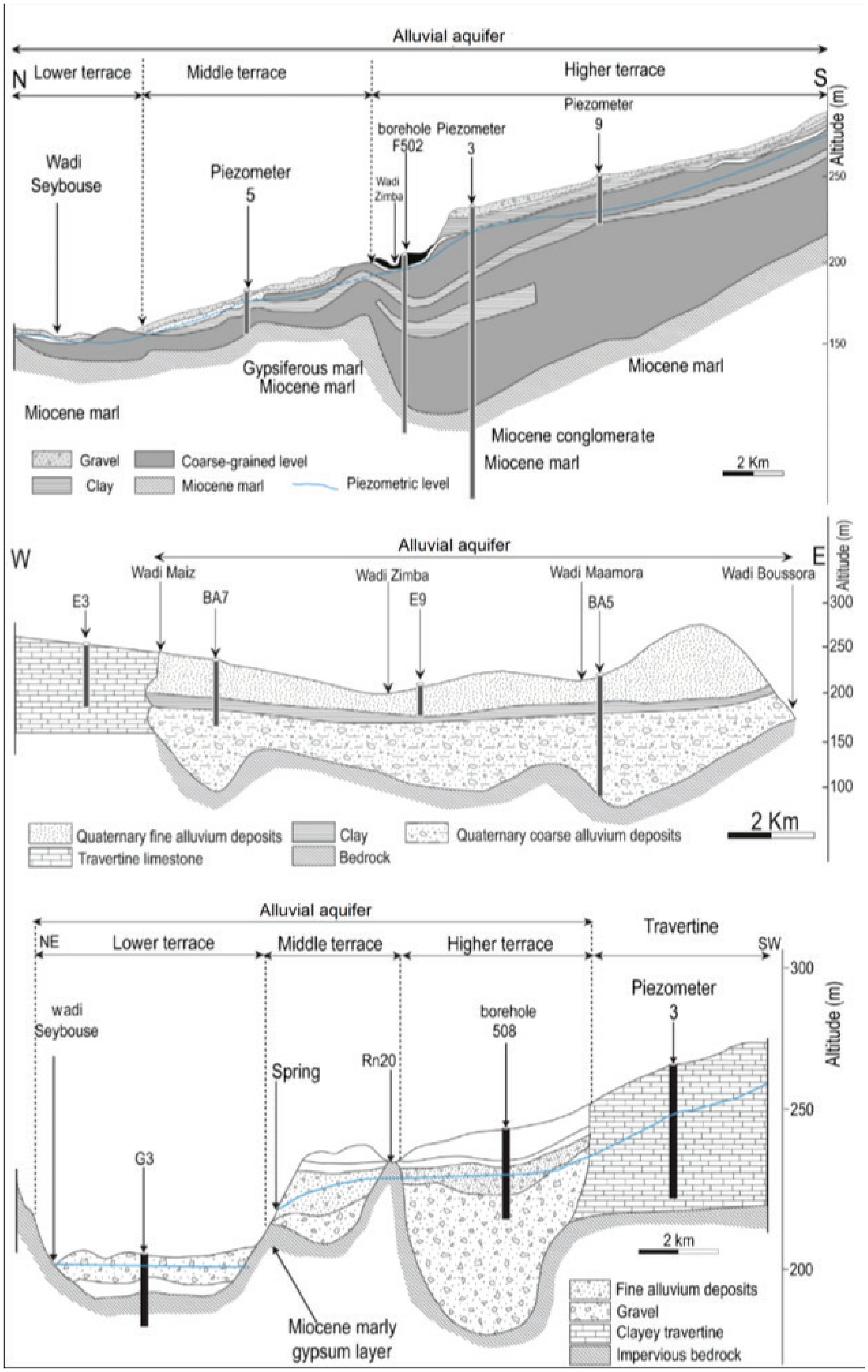

Figure 3. Geological cross-sections of the study area. Source: Gaud, 1974.

Hydrogeologically, groundwater resources within the Middle Seybouse sub-basin are sustained by four main aquifer systems. The Quaternary alluvial aquifer, which dominates the central plain, exhibits saturated thicknesses ranging from approximately 10 to 40 m and shallow water-table depths generally between less than 2 m and 15 m. This aquifer represents the principal source of water for agricultural and domestic uses (Brahmia, 2016; NWRA, 2017). The Pliocene sandstone–conglomerate aquifer is semi-confined and occurs mainly in the Bouchegouf area, while the Miocene detrital aquifer forms a transitional hydrogeological unit connecting shallow and deeper groundwater flow systems (Benmarce, 2015). The Cretaceous–Eocene carbonate aquifers, developed in the Bouhachana, Ani Larbi, and Khezarra sectors, locally provide high-yield groundwater through fractured and karstified zones and receive partial recharge from the Seybouse River (Boudjebieur et al., 2021; Brahmia, 2016). Groundwater recharge predominantly occurs through outcrops in the surrounding uplands, with a general west-to-east flow direction towards Oued Seybouse. However, intensive groundwater abstraction, combined with high evapotranspiration rates has led to localised declines in groundwater levels.

2.2. Data Collection and Preparation

Groundwater data were obtained from the regional laboratory of the Algerian Water Company (ADE) as part of its 2021 groundwater monitoring program. Sampling was conducted during the dry season (July–August), when limited recharge reduces dilution effects and allows groundwater chemistry to better reflect baseline aquifer conditions, particularly for dissolved solids and nitrate.

Seventeen groundwater samples were collected from boreholes and wells distributed across the Middle Seybouse sub-basin. The sampling network was designed according to a hydrogeologically stratified scheme rather than by random selection in order to represent the main aquifer units and their spatial heterogeneity. The geographic coordinates of all sampling locations are provided in Table 1, while the complete Euclidean distance matrix between sampling points is presented in Supplementary Table S1. The spatial distribution of the sampling network is illustrated in Figure 1, allowing the sampling design to be accurately identified and reproduced in future investigations.

Sampling and sample preservation followed the Algerian drinking-water regulations (JORA, 2011), ADE operational protocols, the WHO Guidelines for Drinking-water Quality (WHO, 2017), and the ISO 5667 series for groundwater sampling. Before sampling, well outlets were disinfected, and boreholes were purged for several minutes until the physicochemical parameters had stabilised. This procedure removed stagnant water and ensured that the collected samples were representative of groundwater within the aquifer.

Samples were transferred into pre-cleaned polyethylene bottles. Immediately after collection, the bottles were cooled, stored at temperatures below 5 °C, and transported under insulated conditions to the ADE regional laboratory. The time between sample collection and laboratory analysis was minimized to limit chemical alteration.

The most reactive physicochemical parameters, including pH, electrical conductivity, and temperature, were measured in situ using a calibrated multiparameter probe immediately after sampling. Laboratory analyses were performed using standard hydrochemical methods. Calcium, magnesium, bicarbonate, and chloride were analysed by titrimetry, sodium and potassium by flame photometry, sulfate by the turbidimetric method, nitrate by the cadmium reduction method, and iron, manganese, and phosphate by visible spectrophotometry.

The dataset used in this study consisted exclusively of the physicochemical analytical results provided by the regional laboratory of the Algerian Water Company (ADE). Detailed laboratory quality-control documentation, including information on field duplicate samples, analytical variability between duplicate measurements, and the reference standards used during routine quality-control procedures, was not available to the authors and is therefore not reported.

All concentrations were expressed in mg/L. The analytical results were interpreted by comparison with the *WHO Guidelines for Drinking-water Quality* (WHO, 2017) and the Algerian drinking-water standards (JORA, 2011) to assess groundwater suitability for drinking purposes.

Table 1. Geographic coordinates and description of the groundwater sampling locations in the Middle Seybouse Sub-basin.

ID	X (m)	Y (m)	Centre
F BA2	929500	358500	Guelma
F BA3	929300	360400	Guelma
F BC1	929300	360600	Guelma
F BC2	929750	360000	Guelma
F Oravie	930700	360100	Guelma
F SNTR	928400	360850	Guelma
F Eucalyptus	926825	361900	Guelma
F Bazina	930450	342400	Guelma
F Elmatar	927750	360450	Guelma
F Zitouna	930146	359513	Guelma
F Puit O/Maiz	926900	361950	Guelma
F Bouzitoune 1	923650	367550	Guelaat Bou Sbaa
F HB4	925500	368500	Guelaat Bou Sbaa
F HB5	925608	368777	Guelaat Bou Sbaa
F Mâachou	925900	369100	Guelaat Bou Sbaa
F Picine	925234	368098	Guelaat Bou Sbaa
F BS2	948100	362000	Bouchegouf

2.3. Groundwater Quality Index (GWQI) Calculation

The Groundwater Quality Index (GWQI) was calculated using the Weighted Arithmetic Index Method, a widely accepted approach for assessing water quality (Horton, 1965). This method involves the following sequential steps:

2.3.1. Assignment of Parameter Weights

Each water quality parameter was assigned a weight (w_i) reflecting its relative importance for drinking water suitability, on a scale from 1 (least important) to 5 (most important) (Table 2). Weights are not assigned randomly. They emerge from a hierarchy of health relevance embedded in drinking-water quality assessment frameworks. WHO (2017) guidelines and Algerian standards (JORA, 2011) define the reference boundary conditions, but the internal structure of the index reflects toxicity, exposure pathways, and cumulative risk potential.

High weights (4–5) concentrate on parameters with direct physiological impact. Nitrate (NO_3^-), with its link to methemoglobinemia. Sulfate (SO_4^{2-}), total dissolved solids (TDS), electrical conductivity (EC), sodium (Na^+), chloride (Cl^-). These are not only chemical indicators; they act as proxies for salinity stress and overall mineralization load in drinking water systems. When thresholds are exceeded, the response is not aesthetic—it is health-relevant.

A second layer exists beneath. Moderate weights (2–3). Calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), and pH. These parameters operate differently. They rarely trigger acute toxicity at natural groundwater concentrations. Their influence is indirect—organoleptic quality, buffering capacity, long-term exposure effects.

At the lower end, weight 1. Parameters with limited direct health impact under typical hydrogeochemical conditions. Their role is supportive rather than determinant within the risk structure.

The weighting logic is not detached from place. It is calibrated against the hydrogeochemical reality of the Moyen-Seybouse Basin, where agricultural inputs and anthropogenic pressure shape distributions and concentration patterns. Local conditions matter. They shift relevance.

Even so, the system is not absolute. It is comparative, not definitive. Alternative weighting structures exist and may slightly shift GWQI outcomes. Sensitivity remains inherent to the method. For this reason, the index functions as a decision-support tool, not a fixed measure of groundwater quality. The relative weight (W_i) of each parameter was then calculated by dividing its assigned weight by the sum of all parameter weights according to the formula:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

2.3.2. Computation of Quality Ratings

For each parameter, a quality rating (q_i) was calculated as the ratio of the measured concentration (C_i) to the corresponding World Health Organization (WHO) standard (C_i), multiplied by 100:

$$q_i = \frac{C_i}{S_i} * 100 \quad (2)$$

2.3.3. Calculation of the Sub-Index

The sub-index (SI_i) for each parameter was then computed by multiplying its relative weight by its quality rating:

$$SI_i = W_i * q_i \quad (3)$$

2.3.4. Derivation of the GWQI

Finally, the overall groundwater quality index was obtained by summing all sub-indices across the considered parameters:

$$GWQI = \sum_{i=1}^{n} SI_i \tag{4}$$

The calculated GWQI values were classified into five water quality categories, ranging from excellent to unsuitable for drinking, following the classification scheme proposed by Bouderbala and Hadj Mohamed (2020) Table 3.

Table 2. WHO Standards and parameter weights used for GWQI calculation.

Parameter	Units	WHO Standard (S_i)	Weight (w_i)	Relative Weight (W_i)
Ca^{2+}	mg/L	75	2	0.0476
Mg^{2+}	mg/L	50	4	0.0952
Na^{+}	mg/L	200	5	0.1190
K^{+}	mg/L	12	1	0.0238
Cl^{-}	mg/L	250	5	0.1190
SO_4^{2-}	mg/L	250	5	0.1190
HCO_3^{-}	mg/L	500	2	0.0476
NO_3^{-}	mg/L	50	5	0.1190
pH	-	6.5–8.5	3	0.0714
TDS	mg/L	1000	5	0.1190
EC	µS/cm	2000	5	0.1190
Sum			42	1.0000

Source: Elkhalki et al., 2023

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Table 3. Classification of groundwater quality based on GWQI values

Class	GWQI Range	Water Quality Classification
1	< 25	Excellent water quality
2	25.1 – 50	Good water quality
3	50.1 – 75	Permissible water quality
4	75.1 – 100	Doubtful quality
5	> 100	Water unsuitable for drinking uses

2.4. Spatial representation map

Groundwater quality mapping was carried out using the Inverse Distance Weighting (IDW) interpolation method implemented in ArcGIS. The selection is based on a simple but effective spatial principle: locations that are geographically closer tend to share more similar hydrochemical characteristics than those separated by greater distances. Distance, therefore, becomes the primary driver of prediction (Ohlert et al., 2023).

The interpolation process translates this principle into a mathematical framework. Each sampled point contributes to the estimation of an unknown location, yet its influence is not constant. It declines progressively as distance increases, allowing nearby observations to dominate the prediction while limiting the effect of more remote measurements. The resulting surface is not an abstract statistical construct but a continuous representation of local groundwater quality patterns derived directly from the measured data.

This mechanism distinguishes IDW from geostatistical approaches that depend on explicit spatial models. No semivariogram is required. No assumption of stationarity needs to be satisfied. Instead, the method relies on the spatial organization of observations, making it particularly appropriate when sampling density is moderate and the underlying correlation structure cannot be robustly characterized (Babak et Deutsch, 2009; Li et Heap, 2008).

The practical implications are significant. Local anomalies remain visible instead of being excessively generalized, while gradual transitions between sampling points are preserved through distance-based weighting. Such behavior is especially valuable in hydrogeochemical investigations, where groundwater composition is controlled by localized geological conditions, recharge processes, and human activities that rarely produce abrupt regional changes but instead generate spatially progressive variations (Ohlert et al., 2023).

Previous groundwater studies have reported the effectiveness of IDW for representing hydrochemical distributions and identifying areas of contrasting water quality. Its computational efficiency and transparent weighting scheme also facilitate interpretation, enabling the spatial pattern to be traced directly to the influence of surrounding observations rather than to a fitted statistical model.

From this perspective, IDW is more than a deterministic interpolation technique. It operates as a local spatial reasoning framework in which prediction reflects the cumulative influence of neighboring measurements. This emphasis on proximity allows the generated maps to capture the heterogeneous yet continuous nature of groundwater quality across the Middle Seybouse Sub-basin, revealing spatial gradients that are both hydrogeologically meaningful and straightforward to interpret.

3. Results and Interpretation

3.1. Descriptive Statistics of Hydrochemical Parameters

The statistical summary of the 11 hydro-chemical parameters measured in the 17 groundwater collection points during the dry season of 2021 is presented in Table 4. The results reveal significant spatial variability in water quality across the Middle Seybouse Plain, reflecting the complex interplay of natural and anthropogenic processes.

a) **The pH** values ranged from 7.39 to 7.74 (mean: 7.57), falling within the acceptable limits for drinking water set by both Algerian and WHO standards. The neutral to slightly alkaline conditions are typical for carbonate-rich aquifers and indicate a stable buffering system.

b) **Electrical Conductivity (EC)** values showed a wide range from 480 to 2090 µS/cm (mean: 1073.88 µS/cm), indicating moderate to high mineralization. The highest value at point F BS2 suggests significant localized salinization, coinciding with elevated Na^+ and Cl^- concentrations.

c) **Total Dissolved Solids (TDS)** concentrations ranged from 226 to 983 mg/L (mean: 501 mg/L). While the mean is below the WHO aesthetic guideline of 1000 mg/L, the maximum value approaches this limit, confirming that salinization is a key factor for increased mineralization in specific areas.

d) **Nitrate (NO_3^-)** concentrations showed significant variability, ranging from 1.34 to 36.00 mg/L (mean: 11.27 mg/L). Fortunately, all samples were well below the drinking water guideline of 50 mg/L, suggesting that agricultural contamination, while present, is not at a critical level.

e) **Calcium (Ca^{2+})** concentrations ranged from 96.12 to 152.19 mg/L with a mean of 124.94 mg/L. The mean concentration significantly exceeds the WHO guideline of 75 mg/L, indicating substantial water hardness. This is primarily attributed to the dissolution of carbonate formations (limestones and marls) prevalent in the region.

f) **Magnesium (Mg^{2+})** concentrations varied from 10.45 to 47.63 mg/L (mean: 29.00 mg/L). Most samples are within the WHO limit of 50 mg/L. The spatial distribution often mirrors that of calcium, suggesting co-dissolution from dolomitic and magnesian carbonate minerals.

g) **Sodium (Na^{+})** concentrations ranged from 11.00 to 81.00 mg/L (mean: 30.59 mg/L). All samples are well within the WHO guideline of 200 mg/L. Elevated concentrations in specific points like F BS2 are indicative of localized salinization processes.

h) **Potassium (K^{+})** concentrations were relatively low, ranging from 0.80 to 5.20 mg/L (mean: 2.20 mg/L), well within international and national guidelines. Its presence is generally neutral, with isolated peaks potentially linked to localized agricultural inputs.

i) **Chloride (Cl^{-})** concentrations varied from 28.40 to 398.20 mg/L (mean: 144.21 mg/L). While the mean is below the WHO guideline of 250 mg/L, the maximum value significantly exceeds it. The strong Na^{+}-Cl^{-} correlation in high-salinity samples points towards anthropogenic contamination or dissolution of evaporites.

j) **Sulfate ($SO_4{}^{2-}$)** concentrations ranged from 27.50 to 160.00 mg/L (mean: 76.74 mg/L), comfortably within the WHO guideline of 400 mg/L. Elevated levels are likely due to the dissolution of evaporitic minerals (gypsum) within the geological formations.

k) **Bicarbonate (HCO_3^-)** concentrations varied from 231.80 to 335.50 mg/L (mean: 298.68 mg/L), well below the WHO guideline of 500 mg/L. The consistently high concentrations are consistent with the predominance of carbonate formations and result from water-rock interaction, contributing to the water's alkalinity and buffering capacity.

Table 4. Descriptive statistics of hydrochemical parameters

Parameter	Mean	Minimum	Maximum	Standard Deviation	WHO Guideline Limit	Exceedance (%)
Ca^{2+} (mg/l)	124.945	91.310	152.190	20.909	75	100.0%
Mg^{2+} (mg/l)	28.997	10.450	47.630	8.514	50	0.0%
Na^{+} (mg/l)	30.588	6.000	81.000	18.361	200	0.0%
K^{+} (mg/l)	2.200	0.200	5.200	1.542	12	0.0%
Cl^{-} (mg/l)	144.212	28.400	398.200	101.691	250	11.8%
SO_4^{2-} (mg/l)	76.735	27.500	160.000	44.643	250	0.0%
HCO_3^- (mg/l)	298.682	231.800	335.500	32.766	500	0.0%
NO_3^- (mg/l)	11.269	1.335	36.000	10.554	50	0.0%
pH	7.572	7.390	7.740	0.116	6.5–8.5	0.0%
EC (µS/cm)	1073.882	480.000	2090.000	389.240	2000	5.9%
TDS (mg/l)	501.000	226.000	983.000	186.538	1000	0.0%

3.2. Correlation Matrix Analysis

The Pearson correlation matrix of the hydrochemical parameters measured during the dry season of 2021 (Figure 4) provides insight into the interrelationships among groundwater constituents and the dominant processes controlling groundwater chemistry in the Middle Seybouse sub-basin. The Pearson correlation coefficient was selected to examine linear relationships among continuous hydrochemical variables. Beyond quantifying statistical associations, it provides insight into the hydrogeochemical mechanisms governing groundwater composition, including shared geochemical sources, water–rock interactions, and salinization processes. Its widespread application in hydrogeochemical studies also enables meaningful comparison with previously published groundwater investigations.

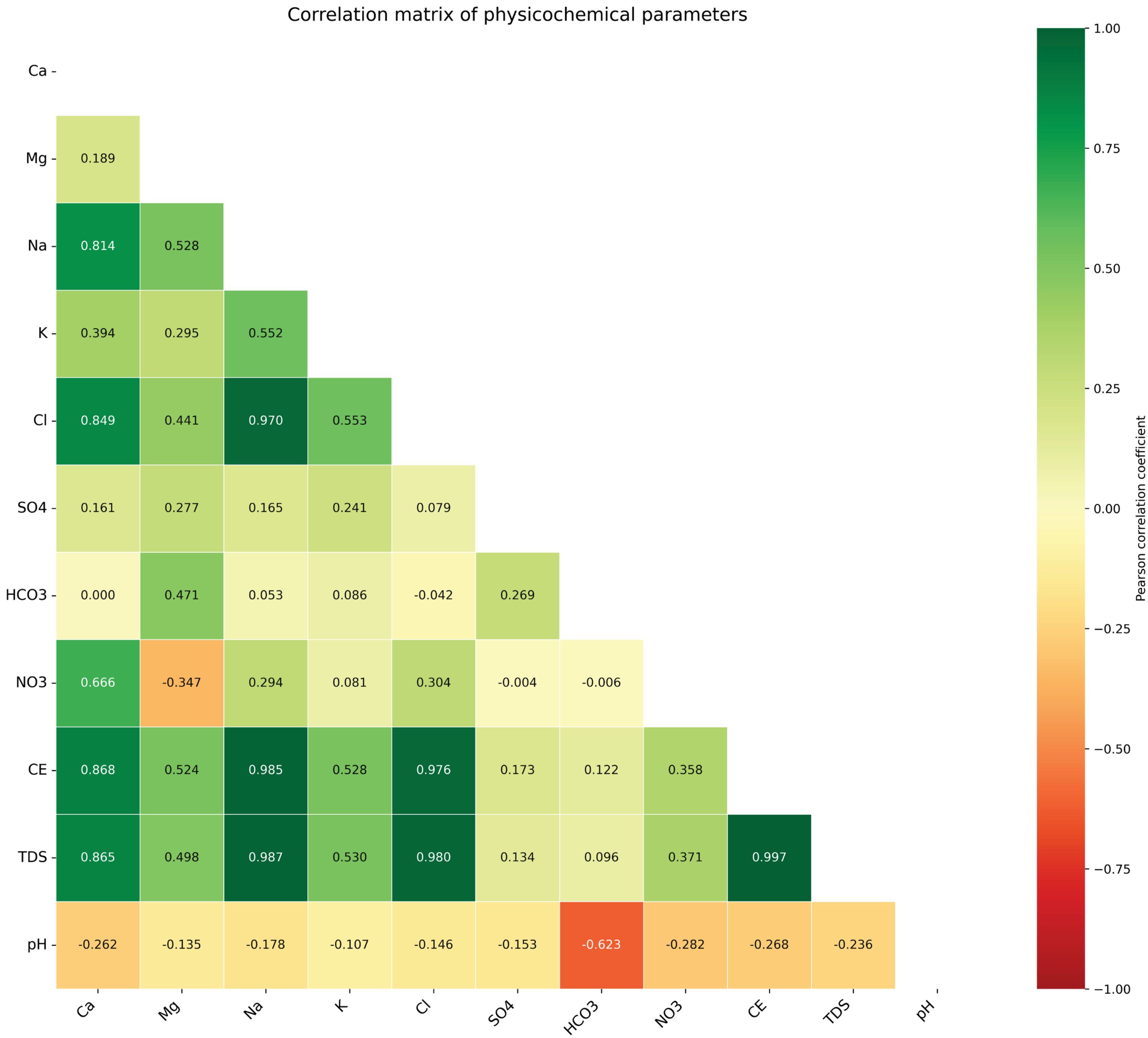

Figure 4. Correlation matrix of hydrochemical parameters during the dry season of 2021.

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Correlation strength was interpreted according to conventional thresholds commonly used in hydrogeochemical studies (Patil et al., 2020), where correlation coefficients (r) ≥ 0.70 indicate strong relationships, values between 0.40 and 0.70 indicate moderate relationships, and values below 0.40 indicate weak relationships. In the present study, these thresholds were used as a diagnostic framework to facilitate the interpretation of the dominant hydrogeochemical processes.

Strong positive correlations generally indicate that the correlated parameters are influenced by common geochemical sources or processes, whereas weak or negative correlations suggest distinct origins, independent geochemical reactions, or different transport mechanisms within the aquifer system.

One of the most prominent features of the correlation matrix is the near-perfect positive correlation between chloride (Cl^-) and total dissolved solids (TDS) (r = 0.997), indicating that groundwater mineralization is largely controlled by chloride enrichment. Electrical conductivity (EC) exhibits a similar pattern, showing very strong positive correlations with both Cl^- (r = 0.988) and TDS (r = 0.985). These relationships indicate that EC primarily reflects the overall ionic content of groundwater rather than acting as an independent hydrochemical parameter.

Sodium (Na^+) and chloride (Cl^-) also show a strong positive correlation (r = 0.891). This relationship likely reflects the combined influence of natural and anthropogenic processes. Natural contributions are mainly associated with the dissolution of evaporitic minerals, whereas anthropogenic inputs may originate from agricultural return flows and domestic wastewater. Consequently, the strong Na^+–Cl^- correlation represents the cumulative effect of these processes on groundwater salinization within the semi-arid aquifer.

A different hydrogeochemical pattern is observed for calcium (Ca^{2+}) and bicarbonate (HCO_3^-), which exhibit a moderate positive correlation (r = 0.653). This relationship is primarily controlled by lithological factors rather than anthropogenic contamination and reflects the dissolution of carbonate minerals, particularly calcite and dolomite. Accordingly, the Ca^{2+}–HCO_3^- association provides clear evidence of the importance of water–rock interactions in controlling groundwater chemistry throughout the study area.

The behaviour of pH differs from that of the other hydrochemical parameters, showing weak to negative correlations with most major ions. The only notable exception is its relationship with bicarbonate, highlighting the buffering capacity of the carbonate system. This buffering effect contributes to maintaining groundwater under near-neutral to slightly alkaline conditions despite variations in ionic composition.

Overall, the correlation matrix reveals a coherent hydrogeochemical framework rather than a random distribution of relationships. Geogenic processes, particularly carbonate weathering and evaporite dissolution, constitute the primary controls on groundwater chemistry, while anthropogenic activities further enhance groundwater salinization in some areas. Consequently, the correlation analysis not only describes statistical relationships among the measured variables but also provides valuable insight into the principal mechanisms governing groundwater composition in the Middle Seybouse sub-basin.

3.3. Piper Diagram Hydrochemical Facies Classification

The Piper diagram for the dry season of 2021 (Figure 5) provides a structural classification of the hydrochemical facies within the Middle Seybouse sub-basin. By integrating the relative proportions of major cations and anions into the central diamond field, the diagram facilitates the interpretation of groundwater types and the hydrogeochemical processes controlling groundwater composition. Rather than simply classifying water types, the Piper diagram highlights the influence of both geological and anthropogenic factors on groundwater chemistry.

Most groundwater samples are clustered within the Ca^{2+}–Mg^{2+}–HCO_3^- hydrochemical facies, indicating that groundwater chemistry is predominantly controlled by carbonate dissolution. The predominance of calcium, magnesium, and bicarbonate reflects the carbonate-rich lithology of the aquifer, where the dissolution of calcite and dolomite governs groundwater composition through water–rock interactions. This hydrochemical facies is characteristic of relatively fresh groundwater with low mineralization and indicates that natural geological processes remain the dominant control on groundwater chemistry in most parts of the study area.

A second hydrochemical trend is observed for samples such as F BS2, which shift towards the Ca^{2+}–Mg^{2+}–Cl^-–SO_4^{2-} facies. This change indicates the increasing influence of evaporitic mineral dissolution, particularly gypsum and halite, which contribute sulfate and chloride to groundwater. In addition, the enrichment of sodium and potassium suggests that ion-exchange processes and anthropogenic inputs, including agricultural activities and domestic wastewater, also contribute to the observed hydrochemical evolution. Consequently, the groundwater chemistry at these locations reflects the combined influence of natural hydrogeochemical processes and human activities.

The spatial distribution of the hydrochemical facies further supports this interpretation. Carbonate-dominated groundwater is mainly associated with the lithological units of Bouhachana, Ani Larbi, and Khezarra, where groundwater chemistry is primarily controlled by water–rock interactions. In contrast, groundwater in the Bouchegouf depression and in intensively cultivated areas exhibits more evolved hydrochemical signatures, characterized by higher mineralization and mixed facies. These characteristics indicate a progressive transition from groundwater chemistry controlled predominantly by lithology to groundwater influenced by salinization processes and anthropogenic pressures.

Overall, the Piper diagram illustrates the transition between the principal hydrogeochemical processes controlling groundwater composition in the Middle Seybouse sub-basin. Carbonate dissolution establishes the baseline hydrochemical framework, whereas evaporite weathering and anthropogenic inputs locally modify groundwater composition. Consequently, the observed hydrochemical facies reflect varying degrees of interaction between natural geological processes and human-induced influences across the aquifer system.

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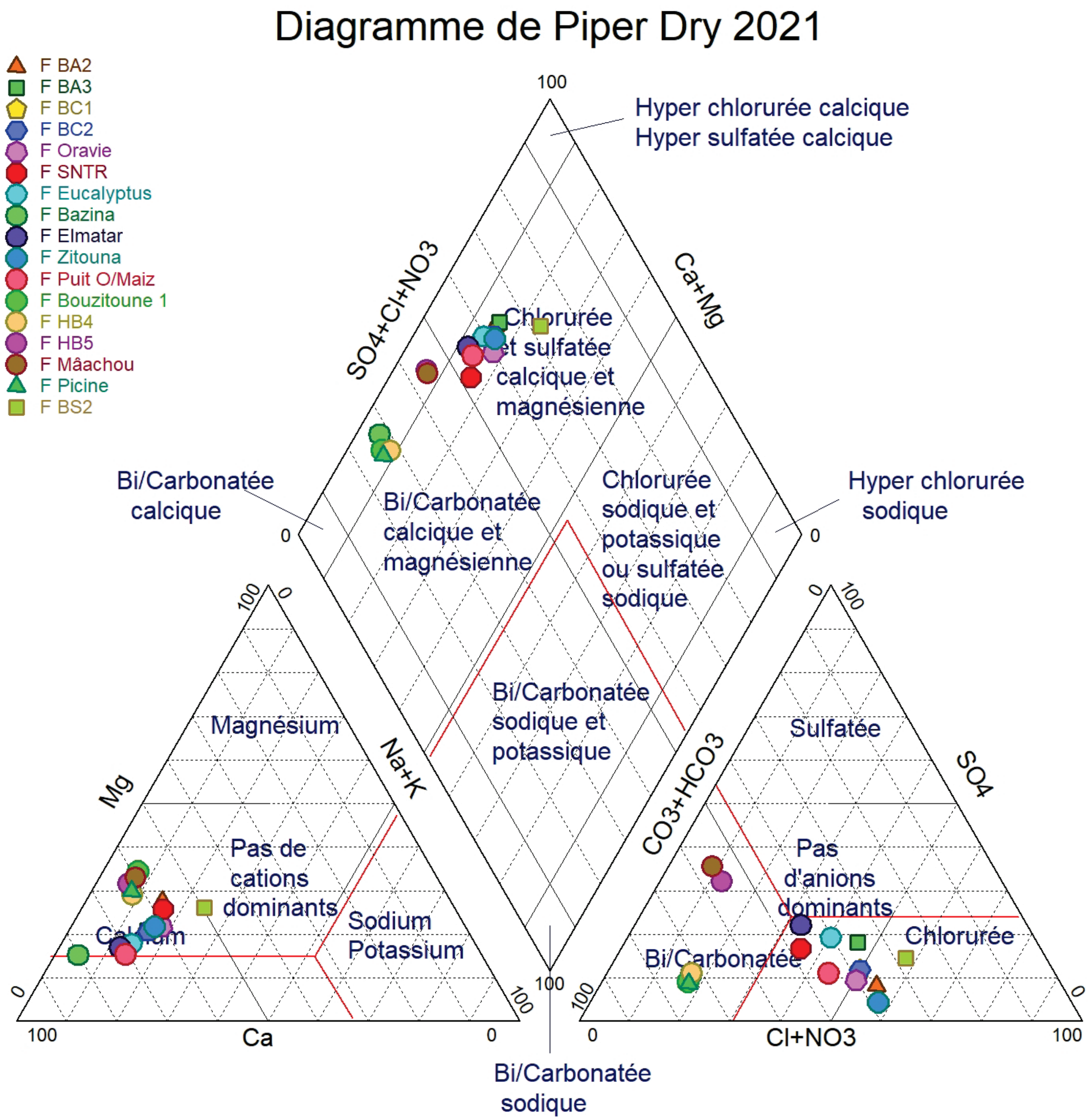

Figure 5. Piper diagram showing hydrochemical facies classification for the dry season of 2021.

3.4. Groundwater Quality Index Assessment

The calculated GWQI values for the dry season of 2021 ranged from 23.33 to 81.18 Table 5, with a mean of 46.03, the groundwater quality distribution for the 17 samples was as follows:

- Excellent water quality (GWQI < 25): 1 sample (5.9%)
- Good water quality level 1 (25.1 – 37.5): 4 samples (23.5%)
- Good water quality level 2 (37.6 – 50): 4 samples (23.5%)
- Permissible water quality (50.1 – 75): 7 samples (41.2%)
- Doubtful quality (75.1 – 100): 1 sample (5.9%)

These results indicate that 94.1% of the groundwater samples fall within the excellent to permissible categories, suggesting that groundwater is generally suitable for drinking purposes. Only 5.9% of the samples are classified as doubtful, indicating that some locations may require treatment prior to consumption. No samples were classified as unsuitable, confirming generally acceptable groundwater quality during the 2021 dry season.

The sample with doubtful GWQI value (F BS2, GWQI = 81.18) is characterized by high concentrations of several water quality parameters (Figure 6), particularly chlorides (398.2 mg/L), sodium (81 mg/L), and elevated electrical conductivity (2090 µS/cm). This location likely represents a point of significant salinization, potentially influenced by dissolution of evaporitic minerals.

The spatial distribution of GWQI values across the Middle Seybouse sub-basin was mapped to highlight groundwater quality patterns during the dry season of 2021 (Figure 6). Although the GWQI map generated using the Inverse Distance Weighting (IDW) interpolation method provides a useful representation of the spatial distribution of groundwater quality, its reliability is influenced by several sources of uncertainty. These include the spatial distribution and density of the 17 sampling points, the assumption that nearby observations exert a greater influence than more distant ones, and the inability of the IDW method to explicitly account for spatial autocorrelation. Consequently, the interpolated surface may not fully capture local-scale hydrochemical heterogeneity or abrupt spatial variations.

Therefore, the GWQI map should be interpreted as a tool for identifying general spatial trends and relative groundwater quality zones rather than as a precise representation of groundwater quality at individual sampling locations.

Table 5. Groundwater Quality Index (GWQI) values and drinking-water quality classification for groundwater samples from the Middle Seybouse sub-basin.

Samples	***Ca***	***Mg***	***Na***	***K***	***Cl***	***SO4***	***HCO3***	***NO3***	***CE***	***TDS***	***pH***	***GWQI***
F BA2	137.77	39.86	41	1.4	213	43.5	252.54	10.163	1289	604	7.7	54.27
F BA3	126.55	25.27	35	1.4	184.6	99	247.66	4.068	1105	519	7.63	47.78
F BC1	132.9	26.24	35	5	198.6	65.5	270.84	9.672	1166	550	7.65	50.53
F BC2	132.9	26.24	35	5	198.6	65.5	270.84	9.672	1166	550	7.65	50.53
F Oravie	140.17	30.621	47	1.4	198.8	53.5	292.8	24.639	1401	658	7.56	57.29
F SNTR	120.95	32.56	37	3.1	127.8	83.5	305	8.466	1059	498	7.61	46.8
F Eucalyptus	142.57	22.36	32	2.9	156.2	113.5	305	36	1183	556	7.43	55.8
F Bazina	91.31	10.45	6	0.2	28.4	27.5	231.8	5.511	480	226	7.72	23.33
F Elmatar	140.17	20.31	27	0.9	113.6	114	292.8	20.441	993	467	7.65	47.59
F Zitouna	152.19	32.56	46	0.8	269.8	28.5	322.08	13.806	1530	719	7.47	59.2
F Puit O/Maiz	147.38	19.44	32	2.5	165.2	62	319.64	30.71	1183	556	7.46	52.47
F Bouzitoune 1	96.12	34.02	12	1.4	42.6	32	326.96	2.566	678	319	7.74	32.2
F HB4	101.72	28.67	15	1.7	42.6	38.5	323.3	2.69	750	352	7.39	31.23
F HB5	112.94	34.99	13	1.6	42.6	151.5	335.5	1.456	799	315	7.42	38.2
F Mâachou	100.92	33.54	13	1.4	28.4	160	319.64	1.335	703	326	7.67	37.42
F Picine	96.92	28.19	13	1.5	42.6	30	325.7	3.492	681	319	7.49	30.16
F BS2	150.58	47.63	81	5.2	398.2	136.5	335.5	6.89	2090	983	7.48	81.18

Note: Samples F BC1 and F BC2 were collected from two different wells within the same hydrogeological unit during the same monitoring campaign. Their identical reported concentrations reflect local hydrochemical homogeneity together with laboratory reporting precision and rounding.

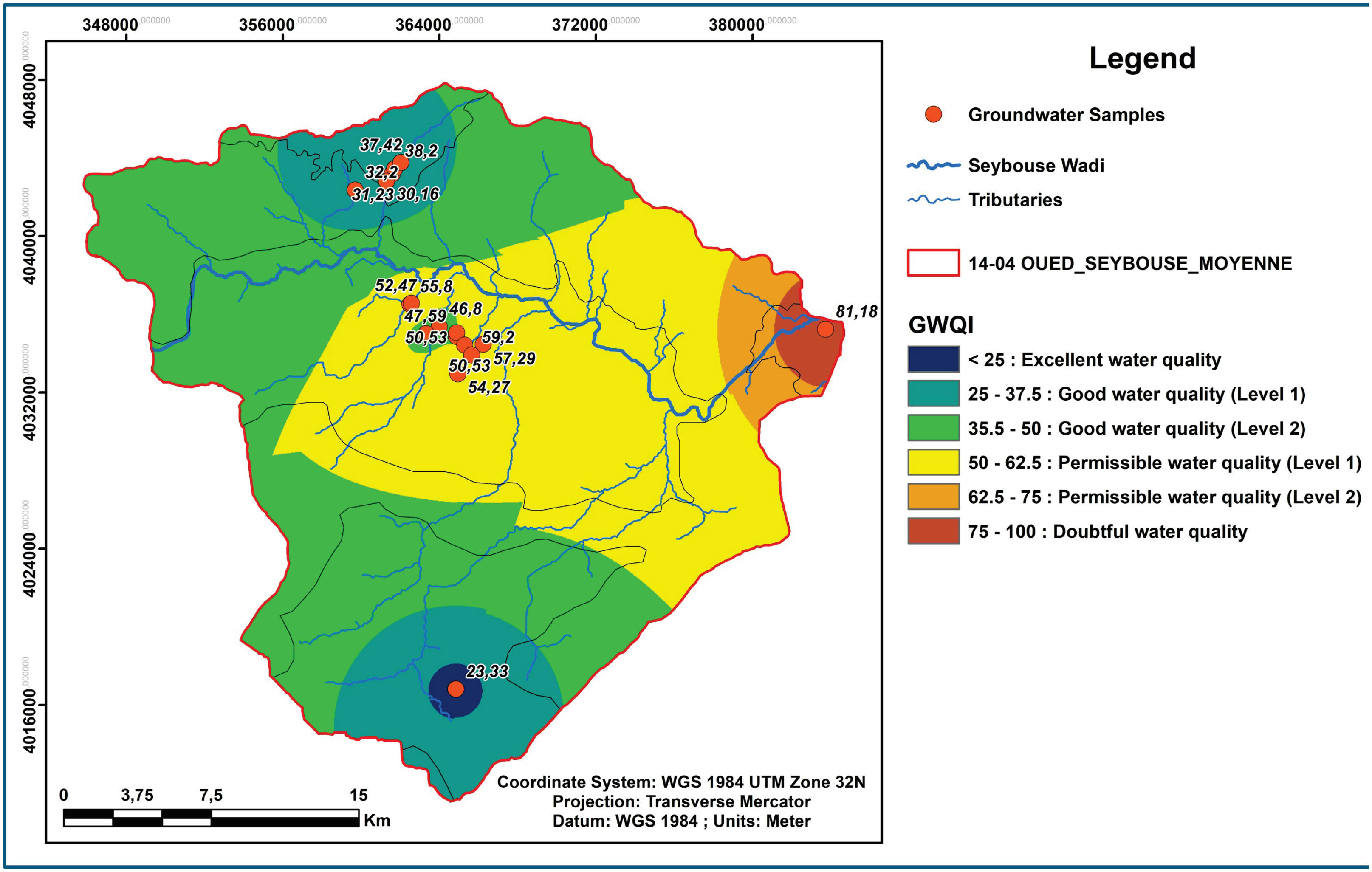

Figure 6. Spatial distribution of the Groundwater Quality Index (GWQI) during the dry season of 2021.

3.5. Spatiotemporal Evolution of Hydrochemical Characteristics

The analysis of multi-annual mean groundwater chemistry for the period 2017–2021, differentiated by wet and dry seasons (Table 6), reveals clear seasonal contrasts and temporal trends in the hydrochemical behaviour of the Middle Seybouse sub-basin. These variations reflect the combined influence of climatic conditions, recharge dynamics, water–rock interactions, and anthropogenic pressures.

Overall, groundwater during dry seasons systematically exhibits higher concentrations of major dissolved ions, particularly Ca^{2+}, Mg^{2+}, and Cl^{-}, compared to wet periods. This enrichment is mainly attributed to reduced recharge, enhanced evaporation, and longer groundwater residence times, which promote solute concentration. The corresponding increase in electrical conductivity (EC) and total dissolved solids (TDS) further confirms the role of evapoconcentration processes in controlling groundwater mineralisation.

In contrast, wet-period groundwater generally shows slightly diluted ionic concentrations due to recharge from precipitation and surface infiltration. However, bicarbonate (HCO_3^{-}) remains consistently high across both seasons, indicating a stable geochemical control dominated by carbonate mineral dissolution. This persistence confirms that water–rock interaction is the principal mechanism governing groundwater chemistry in the basin. This interpretation is further supported by the frequent exceedance of WHO guideline values for Ca^{2+} in both seasons.

A notable long-term trend is the progressive increase in nitrate (NO_3^{-}) concentrations from 2017 to 2021 in both wet and dry seasons. Although nitrate levels remain below drinking-water standards, this upward trend suggests increasing anthropogenic influence, likely associated with agricultural expansion, fertilizer application, and diffuse domestic wastewater inputs. As discussed in the methodological considerations, this temporal trend should be interpreted with caution because no formal statistical trend analysis was performed. Nevertheless, the limited seasonal variability of nitrate suggests relatively continuous rather than episodic contamination sources.

Other major ions, such as Na^+ and SO_4^{2-}, indicate moderate interannual variability without a clear temporal trend, suggesting combined control by lithology, evaporite dissolution, and ion-exchange processes. pH remains relatively stable, within neutral to slightly alkaline conditions, reflecting the buffering capacity of the carbonate aquifer system.

Overall, the results demonstrate that groundwater chemistry in the Middle Seybouse sub-basin is primarily controlled by natural geochemical processes, particularly carbonate weathering, while anthropogenic activities increasingly influence nutrient dynamics, especially nitrate. These findings highlight the need for continuous groundwater monitoring and improved land-use management to preserve water quality under evolving environmental pressures.

Table 6. Comparison of mean groundwater hydrochemical parameters during wet and dry seasons (2017–2021) in the Middle Seybouse sub-basin, with reference to Algerian (2011) and WHO (2017) drinking-water standards.

Year	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cl mg/l	SO4 mg/l	HCO3 mg/l	NO3 mg/l	CE µS/cm	TDS mg/l	pH
Wet period											
2017	119.26	30.84	27.83	1.62	111.23	87.06	321.50	3.20	979.67	489.89	7.53
2018	125.08	29.87	31.77	2.13	152.41	118.80	318.01	4.91	929.27	502.00	7.34
2019	123.98	30.76	25.36	1.87	116.64	95.05	322.69	5.40	812.21	450.43	7.52
2020	121.87	28.68	29.50	2.03	133.42	84.03	337.81	8.19	1087.60	486.40	7.40
2021	117.64	29.27	28.07	1.34	150.10	137.79	306.11	9.30	869.43	477.43	7.54
Dry season											
2017	130.26	28.64	31.53	2.05	167.56	110.07	319.00	5.45	1122.60	532.73	7.17
2018	135.21	26.08	30.57	2.18	160.22	104.61	278.55	7.22	1006.36	525.14	7.44
2019	124.27	29.61	31.31	1.83	152.89	96.10	293.00	8.50	1105.08	516.00	7.34
2020	121.28	28.06	24.55	1.57	130.64	90.13	320.45	7.74	1003.00	483.60	7.60
2021	124.94	29.00	30.59	2.20	144.21	76.74	298.68	11.27	1073.88	501.00	7.57
Standards											
Algerian 2011	200	150	200	12	500	400	/	50	2800	/	6.5-9.5
WHO 2017	75	50	200	12	250	400	500	50	2000	1000	6.5-8.5

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4. Discussion

4.1. Hydrochemical Processes and Geological Controls

The hydrochemical characteristics of groundwater in the Middle Seybouse sub-basin reflect a complex interaction between geological conditions and anthropogenic influences. The predominance of the Ca^{2+}–Mg^{2+}–HCO_3^- hydrochemical facies, as identified by the Piper diagram, is consistent with the carbonate-rich lithology of the region, particularly the Cretaceous–Eocene formations carbonate formations exposed in the uplands of Heliopolis and Bouhachana. Carbonate dissolution, facilitated by regional fracture systems and NE–SW oriented structural lineaments that enhance secondary permeability, represents a key mechanism controlling groundwater chemistry.

Elevated bicarbonate concentrations observed across the study area further support the dominance of carbonate weathering processes. Under slightly acidic to neutral pH conditions, the dissolution of calcite and dolomite can be expressed as follows:

- $\mathbf{CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-}$
- $\mathbf{CaMg(CO_3)_2 + 2CO_2 + 2H_2O \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-}$

The moderate positive correlation between Ca^{2+} and HCO_3^- ($r = 0.653$) supports this interpretation, although the relationship is not strong enough to suggest a single controlling process. This indicates that additional mechanisms, such as ion exchange reactions and the contribution of other mineral phases, may also influence groundwater chemistry. Similar hydrogeochemical behaviour has been reported in semi-arid carbonate aquifers, where deviations from ideal carbonate

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equilibrium are commonly linked to cation exchange processes affecting Na^+ and Ca^{2+} distributions (Madene et al., 2022).

Localized zones of elevated salinity, particularly at sampling point F BS2, can be explained by the hydrogeological context of the Bouchegouf depression. This area is characterized by Pliocene sandstones and conglomerates, structurally bounded by Triassic evaporitic formations containing gypsum and halite. The dissolution of these evaporites likely contributes to the enrichment of Na^+, Cl^-, and $SO_4{}^{2-}$ in groundwater at this site. This interpretation is supported by the very strong correlation between Cl^- and TDS ($r = 0.997$) and the strong relationship between Na^+ and Cl^- ($r = 0.891$), indicating a significant role of salinity-related processes in controlling groundwater composition.

Comparable hydrochemical patterns have been reported in other semi-arid Mediterranean aquifers, where interactions with evaporitic formations lead to the development of $Na–Cl–SO_4$ water types and progressive salinization under conditions of limited recharge and high evaporation (Bouderbala et Hadj Mohamed, 2020).

The spatial distribution of groundwater quality, illustrated by the GWQI map (Figure 6), generally reflects the hydrogeological framework of the study area. Areas underlain by Quaternary alluvial deposits generally exhibit better groundwater quality, most likely because of their higher recharge potential and the associated dilution effects. In contrast, lower groundwater quality is mainly observed near evaporitic formations and in areas affected by intensive agricultural activities and irrigation return flows. Nevertheless, these spatial patterns should be interpreted as general trends rather than precise boundaries because the IDW interpolation is influenced by the spatial distribution and density of the available sampling points.

Similar spatial patterns have been reported in other semi-arid basins across North Africa and the Mediterranean region, where alluvial aquifers generally contain relatively fresher groundwater, whereas aquifers influenced by evaporitic formations or intensive land use tend to exhibit higher mineralization and salinity (Madene et al., 2022).

4.2. Anthropogenic Influences on Groundwater Quality

Although natural processes primarily control the baseline hydrochemistry of the Middle Seybouse sub-basin, anthropogenic influences are increasingly evident, particularly in the temporal evolution of nitrate concentrations between 2017 and 2021. An apparent increase in NO_3^- concentrations observed during both wet and dry seasons suggests a possible increase in agricultural influence, most likely associated with the use of chemical fertilizers and manure in intensively cultivated areas of the central plain. However, this temporal pattern should be interpreted with caution because no formal statistical trend analysis was performed.

Spatially, nitrate concentrations remain generally below the WHO guideline value (50 mg/L), but relatively higher values are consistently observed in agricultural zones. This spatial pattern is consistent with a predominantly anthropogenic source of nitrate and agrees with findings reported in other agricultural regions of Algeria (Bouteraa et al., 2019; Derdour et al., 2020).

In addition to agricultural sources, localized anthropogenic impacts may also be linked to domestic wastewater from urban areas, particularly Guelma city, and, to a lesser extent, industrial activities. Although these influences are not dominant in the present dataset, some localized increases in electrical conductivity (EC) and total dissolved solids (TDS) could partially reflect mixed anthropogenic inputs.

The weak to moderate correlations between NO_3^- and most major ions further indicate that nitrate behaves independently from the main geogenic processes controlling groundwater chemistry, which supports the interpretation that its occurrence is primarily influenced by anthropogenic activities.

Overall, the results highlight the growing influence of human activities on groundwater quality, particularly through nitrate enrichment. This situation underscores the need for improved agricultural practices, including optimized fertilizer application and reduced leaching, as well as strengthened wastewater management strategies to prevent further deterioration of groundwater resources.

4.3. Methodological Considerations and Study Limitations

The Groundwater Quality Index (GWQI) approach applied in this study provides an integrated assessment of groundwater suitability for drinking purposes by combining multiple physicochemical parameters into a single interpretable metric. This approach is particularly useful for decision-makers and water resource managers. However, several methodological limitations should be acknowledged.

Firstly, the assignment of weights to individual parameters in the GWQI calculation introduces a certain degree of subjectivity. Although the weighting scheme adopted in this study is based on published literature (e.g., Elkhalki et al., 2023) and supported by WHO (2017) and Algerian drinking water standards (JORA, 2011), alternative weighting schemes could lead to variations in GWQI values and resulting water quality classifications. In addition, the relative importance of parameters may vary depending on local hydrogeological conditions and groundwater usage purposes. A preliminary sensitivity consideration indicates that parameters with higher weights, particularly NO_3^-, TDS, EC, and major ions, exert a stronger influence on the final GWQI values. Consequently, samples located near classification thresholds may be more sensitive to small changes in weighting. A comprehensive sensitivity analysis was not performed in this study but is recommended for future research in the Middle Seybouse basin.

Secondly, the spatial dataset is based on 17 sampling points, which, although selected to ensure hydrogeological representativeness, may not fully capture small-scale spatial heterogeneity in a structurally and lithologically complex aquifer system. Increasing sampling density, particularly in zones affected by salinization or intensive agricultural activity, would improve spatial resolution and strengthen the robustness of future spatial analyses.

Thirdly, the study mainly focuses on the dry season of 2021, complemented by interannual averages (2017–2021). While this provides meaningful insights into seasonal contrasts and long-term tendencies, higher temporal resolution (e.g., monthly or seasonal monitoring) would better capture short-term variability driven by recharge events and anthropogenic pressures.

Fourthly, the analysis is limited to major ions and basic physicochemical parameters. The inclusion of additional indicators such as trace elements, isotopic tracers, and microbiological parameters would provide a more comprehensive assessment of groundwater quality and associated health risks.

Finally, although the Piper diagram and correlation analysis provide useful insights into hydrochemical processes, the application of advanced multivariate statistical techniques (e.g., principal component analysis, hierarchical cluster analysis) and geochemical modelling tools (e.g., PHREEQC) would further improve the understanding of the interactions between natural and anthropogenic controls on groundwater chemistry.

4.4. Implications for Water Resource Management

The results of this study have important implications for groundwater resource management in the Middle Seybouse sub-basin. Overall, the GWQI assessment indicates generally good groundwater quality across most of the study area, suggesting that the aquifer system remains suitable for domestic and agricultural uses. However, the presence of localized degradation, particularly at site F BS2, highlights the need for targeted management strategies in vulnerable zones.

The apparent increase in nitrate concentrations observed over the study period suggests a growing agricultural influence. However, as no formal statistical trend analysis was performed, this temporal pattern should be interpreted with caution. If this pattern persists, it may contribute to the further deterioration of groundwater quality. This finding emphasizes the need to promote improved agricultural practices, including optimized fertilizer application, the establishment of buffer zones, and the adoption of efficient irrigation techniques to reduce contaminant leaching into groundwater systems.

In addition, the identification of salinization hotspots associated with evaporite dissolution underscores the importance of integrating geological and hydrogeological information into groundwater development planning. Areas influenced by evaporitic formations should be carefully considered in well siting, decisions, and where necessary, appropriate treatment measures should be applied prior to domestic use.

The spatial distribution of GWQI values provides a useful decision-support tool for water resource planning and zoning. Areas classified as having excellent to good water quality may be prioritized for drinking water supply, whereas zones with permissible or doubtful quality may be more suitable for agricultural or industrial uses, provided that adequate treatment is implemented when required. Nevertheless, because the groundwater quality map was generated using the Inverse Distance Weighting (IDW) interpolation method, these spatial patterns should be interpreted as general planning guidance rather than exact boundaries between groundwater quality classes.

Finally, the study highlights the importance of establishing a long-term groundwater quality monitoring network to detect potential contamination trends and support adaptive management strategies. Such a monitoring framework, combined with land-use and climate data, would enable more effective management of groundwater resources under increasing anthropogenic pressures and climate variability.

5. Conclusions

This study applied the GWQI framework to 17 groundwater samples collected during the 2021 dry season. The resulting GWQI values provide an integrated assessment of groundwater suitability for drinking purposes rather than a simple classification of water quality. Most samples were classified within the excellent to permissible categories, representing 94.1% of the observations. Only one sample (5.9%) was classified as doubtful, indicating that groundwater at this location may require treatment before domestic use.

The hydrochemical characteristics of the aquifer are primarily controlled by natural geochemical processes. The predominance of the Ca^{2+}–Mg^{2+}–HCO_3^- hydrochemical facies indicates that carbonate weathering constitutes the principal mechanism governing groundwater chemistry. The enrichment of calcium and bicarbonate reflects sustained water–rock interaction within the carbonate formations, demonstrating that the aquifer behaves as a geochemically active system.

This general hydrochemical pattern is locally modified at sampling point F BS2, where groundwater exhibits markedly higher salinity. This localized hydrochemical change is mainly associated with the influence of evaporitic formations in the Bouchegouf depression, which contribute additional dissolved ions to groundwater. Consequently, groundwater chemistry shifts locally from carbonate-dominated conditions towards greater evaporitic influence, highlighting the importance of lithological heterogeneity in controlling groundwater composition.

Anthropogenic activities introduce an additional influence on groundwater chemistry. A descriptive comparison with historical monitoring data (2017–2021) indicates that the annual mean nitrate concentrations recorded in 2021 are generally higher than those reported in the earlier monitoring years. This observation may reflect the cumulative influence of agricultural activities and fertilizer application within the basin. However, because the historical dataset consists of annual seasonal mean values presented for contextual comparison rather than a continuous temporal monitoring series, no statistically significant temporal trend is inferred in this study.

The spatial distribution of GWQI values reflects the hydrogeological framework of the Middle Seybouse sub-basin. Higher groundwater quality is generally associated with the Quaternary alluvial aquifer in the central plain, whereas lower groundwater quality is mainly observed in areas influenced by evaporitic formations and more intensive human activities. Accordingly, the GWQI provides a useful spatial indicator of both the geological setting and the distribution of anthropogenic pressures across the basin.

Overall, groundwater quality in the Middle Seybouse sub-basin is controlled by the combined influence of natural hydrogeochemical processes and anthropogenic activities. The GWQI successfully integrates these factors into a practical tool that can support groundwater management, including well siting, groundwater protection zoning, and land-use planning.

Future research should focus on expanding the groundwater monitoring network, incorporating additional indicators such as trace elements, isotopic tracers, and microbiological parameters, and applying advanced statistical and geochemical modelling approaches. Future investigations should also incorporate continuous long-term monitoring datasets with higher temporal resolution to enable rigorous statistical trend analyses, including methods such as the Mann–Kendall test or Spearman rank correlation. Such approaches would provide a more robust assessment of the temporal evolution of groundwater quality, particularly with respect to nitrate concentrations.

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8. Statement of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9. Statement on the use of IA

The authors used ChatGPT (OpenAI**)** solely to improve the linguistic quality of the manuscript, including grammar, spelling, and style. All scientific content, data analysis, interpretation of results, and conclusions were conceived, verified, and approved by the authors.

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