EREM 81/3
Journal of Environmental Research, Engineering and Management
Vol. 81 / No. 3 / 2025
pp. 134–146
10.5755/j01.erem.81.3.40964

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Received 2025/05 | Accepted after revisions 2025/08

https://doi.org/10.5755/j01.erem.81.3.40964

The Study of Groundwater Salinization Mechanisms: A Case study of the Remila Basin, Northeastern Algeria

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This study provides a thorough hydrogeochemical analysis of the Remila basin in northeastern Algeria, addressing critical water resource issues. The groundwater exhibits diverse chemical facies, mainly calcium-sulfate (Ca-SO_4) and calcium-bicarbonate (Ca-HCO_3) types, reflecting complex geology and water-rock interactions. Groundwater mineralization is primarily driven by evaporitic mineral dissolution, such as gypsum and halite, with strong correlations between electrical conductivity and major ions. Ion exchange processes, indicated by Na^+/Cl^- ratios and relationships between calcium, magnesium, and sodium, significantly influence groundwater chemistry. Elevated strontium levels, especially in rapid runoff areas, suggest an influence of evaporitic formations and celestite dissolution, supported by Sr^{2+}/Ca^{2+} ratios exceeding 1%. Lithium concentrations indicate prolonged water-rock interactions and deep aquifer systems. Principal component analysis (PCA) reveals that natural salinization processes primarily driven by the dissolution of evaporitic minerals account for 44.65% of the total variance (PC1), while anthropogenic pollution, particularly nitrate contamination from agricultural sources, contributes 13.73% (PC2). Groundwater is generally undersaturated with major minerals, indicating ongoing dissolution processes, and spatial variations in water quality parameters emphasize the combined influence of geological factors and anthropogenic activities on the aquifer system.

Keywords: Northeastern Algeria, Remila, hydrogeochemistry, mineralization, water.

Introduction

Water scarcity is becoming an increasingly critical global challenge particularly in developing countries, where the quantity and quality of available water resources pose increasingly complex challenges (Fletcher et al., 2013). As highlighted by the United Nations, water scarcity affects more than 40% of the global population, with projections indicating that this number will continue to rise due to climate change and unsustainable water management practices (Berkani et al., 2023). Groundwater, a vital resource worldwide, is threatened by various point and non-point sources of contamination, presenting significant environmental and public health risks (Rina et al., 2013). In semi-arid regions, the sustainability of groundwater resources is further compromised by a complex interplay of climatic and anthropogenic factors. Population growth, the expansion of irrigated agriculture, and climate change collectively contribute to a substantial increase in water demand, placing unprecedented pressure on already limited water resources (Masoud et al., 2018).

Researchers such as Gleeson et al., 2012; Aouidane et al., 2017 have demonstrated that groundwater depletion is becoming a critical global issue, with many regions experiencing unsustainable extraction rates that exceed natural recharge. Declining groundwater quality in semi-arid regions presents a significant future challenge for effective water resource management (Berkani et al., 2023). Studies by Stigter et al., 2006; Houha et al., 2008 have shown that these regions are especially vulnerable to environmental changes, with groundwater systems experiencing significant alterations in chemical composition and recharge patterns. Climate change exacerbates these challenges, leading to more frequent and severe droughts that further stress these fragile water resources (Rosen and Jones, 1998). This study aims to address the critical challenges of groundwater quality degradation in the Rémila basin, a semi-arid region located in northeastern Algeria that is increasingly vulnerable to water scarcity and salinization. By focusing specifically on this basin, which plays a key role in supporting local agricultural and domestic needs, the research conducts a detailed hydrogeochemical assessment to identify the main factors driving groundwater mineralization. Through the integration of chemical analyses and multivariate statistical techniques, the study seeks to disentangle the natural and anthropogenic processes such as water rock interaction, ion exchange, and agricultural return flows—that influence groundwater composition in the Remila basin. The findings aim to inform more targeted and effective water management strategies tailored to the specific hydrogeological and socio-environmental conditions of the basin, thereby contributing to sustainable resource planning in similar semi-arid contexts.

Material and methods

Study a rea

The study area, situated in the northeastern region of Algeria, is a subwatershed of Garaat Et Tarf basin located between the Tell Atlas and the Saharan Atlas (Aures massif), spanning approximately 250 square kilometers of relatively flat terrain between 35°25’-35°40’N and 06°30’-07°05’E, with elevations ranging from 800 to 1000 meters above sea level. This Rémila basin features an endoreic depression known as the Sebkha of Garâat-Et-Tarf, covering 200 km², and is bounded by Djebel Bou-Arif (1450m) and Djebel Amrane (1000m) to the west, Djebel Fedjoudj (1248m) to the north, the salt depression of Garâat-Et-Tarf to the east, and the Cretaceous reliefs of the Aurès to the south, including Djebels Aidel (1300m), Aures (1600 m), and Chelia (2308 m), while experiencing a semi-arid climate characterized by average annual rainfall of 400 mm/year and an average annual temperature of 16°C.

Geology

The study area’s geology (*Fig. 2*) is characterized by diverse formations across different periods. Triassic outcrops appear in Khenchela, specifically at Djebel Aidel in Hammam Essalihine and Djebel Elkrouma in Hammam El-Knif. The Lower Cretaceous is represented by marly and compact limestones that are cracked and karstified, while the Albian stage, present in the Aurès anticlines, exhibits sandy, marly, and dolomitic facies. In the southern basin, Albian outcrops at Djebel-Aidel consist of thick dolomitic limestones, sourcing the Ain El-Kerma spring.

These carbonate formations are overlain by gypseous red clay, which unconformably rests on the Lower Cretaceous (Laffitte 1939; C.G.G. 1969). The recent Quaternary deposits form a multi-layered aquifer system, comprising alternating layers of conglomerates, sand, gravel, and clay, which hosts two distinct aquifers: a deep conglomerate layer and a superficial sand and gravel layer (Houha et al., 2008).

Sample collection

During a sampling campaign conducted in May 2018, 54 water samples (*Fig. 3*) were collected from the Rémila basin.

Fig. 1. *Location of study area (Remila plain)*

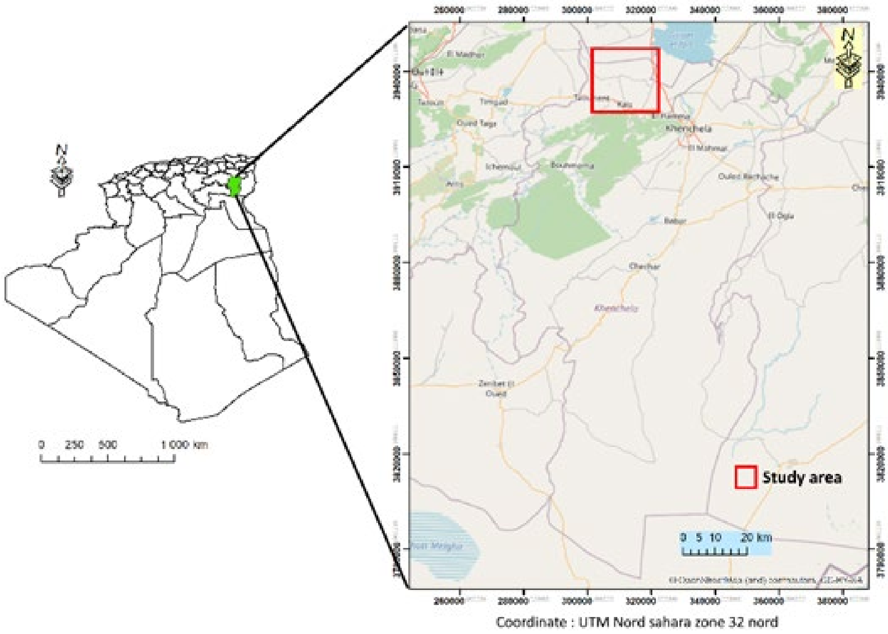


Fig. 2. *Geological map of Remila plain (adapted from Villa 1977)*

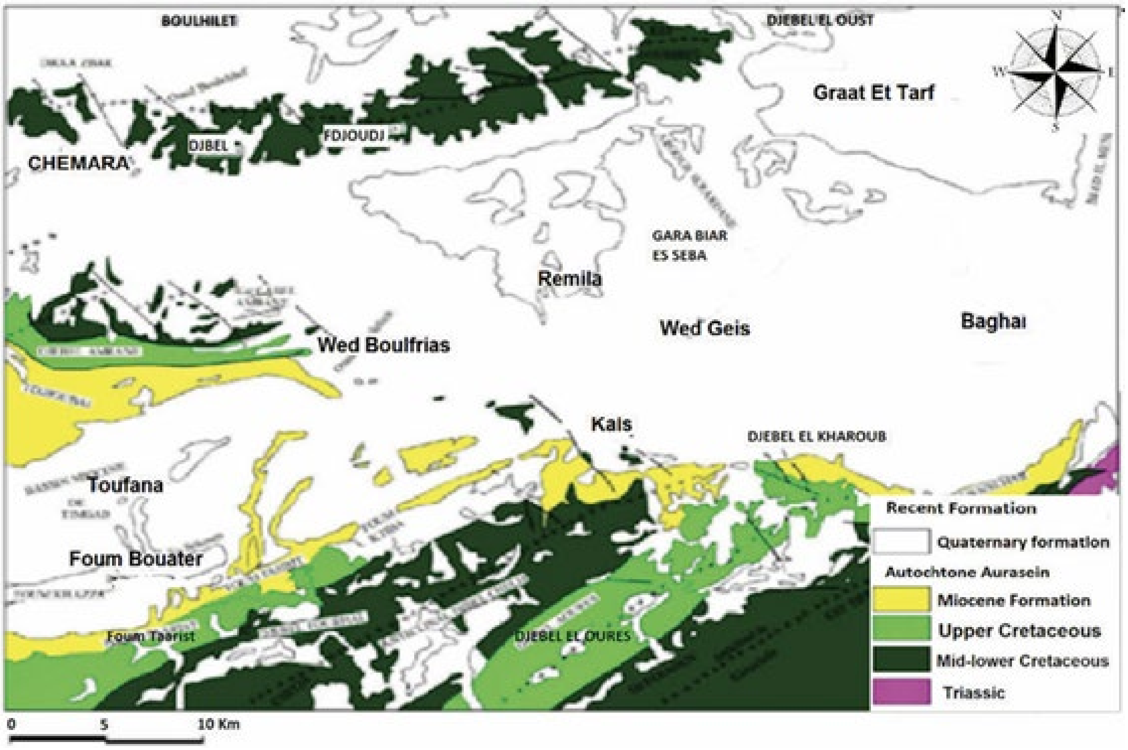
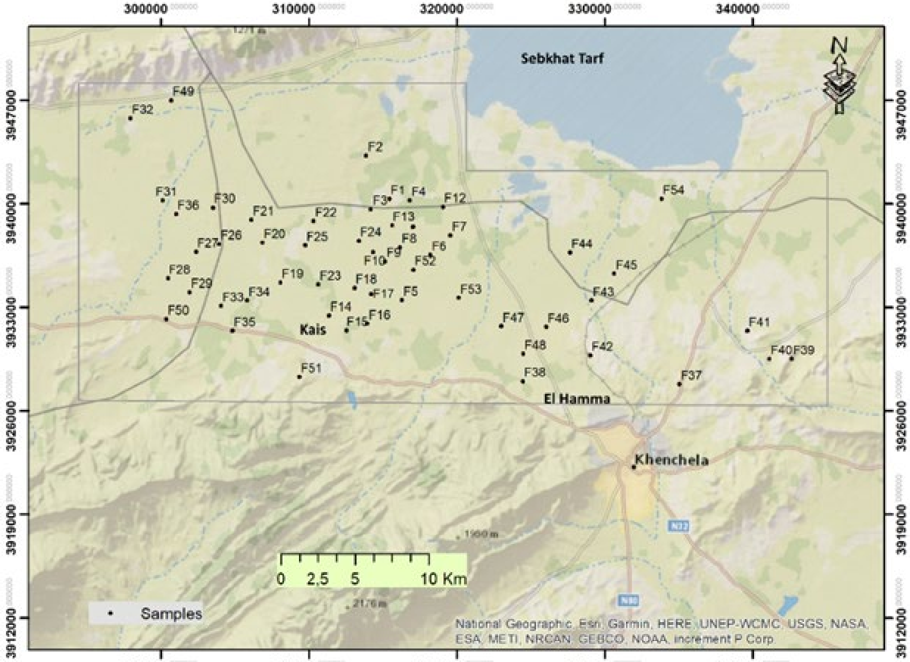


Fig. 3. *Water point distribution map of the Remila plain*



National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

The study employed a Consort C931 multi-parameter analyzer (version 2.4) for in situ measurements of temperature, electrical conductivity, and pH. This instrument is a versatile benchtop/portable device capable of measuring multiple parameters simultaneously. For the analysis of major elements and trace elements (Sr^{2+} and Li^{+}), flame spectrophotometry was utilized. This technique, also known as flame photometry, is particularly well-suited for measuring alkali and alkaline earth metals.

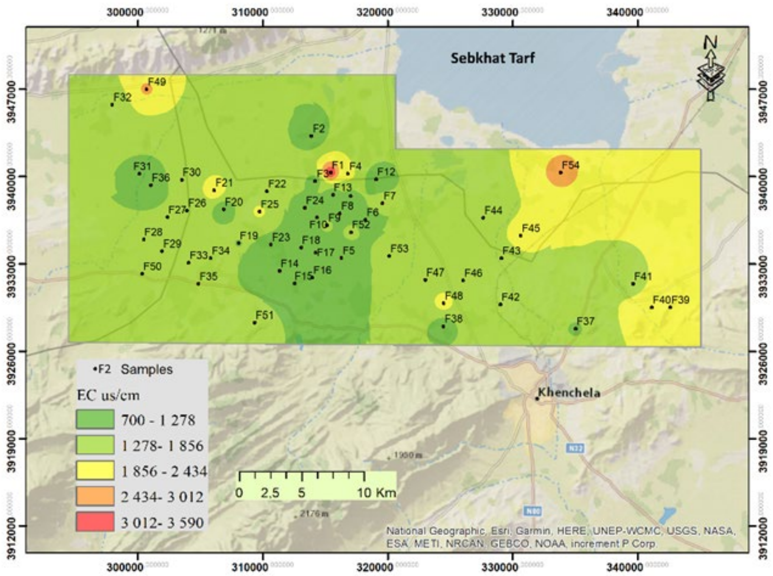
Results and Discussion

Physical parameters

The temperature of groundwater in the study area ranges from 17°C to 24°C, with an average temperature of 19.76°C. The highest temperatures are associated with waters from the Cretaceous aquifer, indicating the influence of geothermal gradients in these deeper geological formations. Shallow wells, with depths less than 5 meters, are more susceptible to external climatic conditions, showing greater temperature variability due to seasonal changes and surface temperature fluctuations (Bouguerra and Douaoui, 2021; Mebarki and Hamzaoui, 2018).

Electrical conductivity (EC) of groundwater in the region varies significantly, from 700 µS/cm to 3591 µS/cm, with an average value of 1461 µS/cm (*Fig. 4*). This wide range of EC values reflects the diverse mineralization levels and ionic concentrations in the groundwater. The spatial variation of EC across the Remila plain aligns closely with both lithological and anthropogenic patterns. Zones of elevated EC correspond to geological sectors dominated by evaporitic formations, particularly Triassic and Quaternary units rich in gypsum and halite (Djezzar and Laid, 2015). Simultaneously, areas under intensive agriculture show elevated EC values, suggesting an additive role of irrigation return flows in increasing salinity. The pH of groundwater in the study area exhibits a range from 6.5 to 7.91, with an average value of 6.94. This variation in pH indicates that the groundwater is generally slightly acidic to near-neutral. Such pH levels can be influenced by various factors, including the geological composition of the aquifers, the presence of dissolved gases and minerals, and potential contamination sources (Mebarki and Hamzaoui, 2018).

Fig. 4. *Electric conductivity spatial distribution in Remila plain (IDW interpolation)*



Descriptive analysis

Performing a descriptive statistical analysis of data is crucial in any statistical evaluation (see *Table 1*) (Hosseini et al., 2014; Yang et al., 2011; Aouidane et al., 2021). The most critical metric for describing the variability of water parameter values is the variance coefficient (VC). This statistical measure quantifies the extent of variation in relation to the mean of the data set, making it particularly useful for comparing variability across different parameters with diverse units and scales. High VC values indicate significant variability, suggesting that certain water quality parameters fluctuate considerably, potentially due to natural processes or anthropogenic influences.

Table 1. *Descriptive statistics of physicochemical parameters*

Parameters	EC	pH	T	Ca	Mg	Na	K	HCO_3^-	Cl	SO_4	NO_3^-	Sr	Li
Mean	1456.9	6.94	19.8	150.97	51.87	85.66	1.54	264.95	165.89	309.17	11.91	7.12	0.43
Median	1412	6.92	20	140.28	38.16	85.44	1.01	262.30	134.90	285	4.10	6.69	0.41
Min	700	6.50	17	48.10	6.96	29.67	0.089	180.50	35.50	120	0.20	3.19	0.124
Max	3591	7.91	24	308.62	239.64	217.58	4.65	390.80	340.15	1250	58	17.6	0.908
CV %	37.8	7.2	7.4	37.2	89.4	47.3	71.8	18.2	63.7	57.9	129.6	41.7	44.2

T: temperature (°C), EC: electrical conductivity (μS/cm). Ionic concentrations in mg/l.

A low coefficient of variation (CV) for pH and temperature, both less than 10%, suggests minimal spatial variability in these parameters across the study area. This indicates a relatively uniform distribution, likely influenced by stable environmental conditions. In contrast, bicarbonate (HCO_3^-), EC, calcium (Ca^{2+}), sodium (Na^+), strontium (Sr), and lithium (Li) exhibit moderate CVs ranging from 20% to 50%. This indicates a moderate spatial distribution, which may be attributed to variations in geological formations and localized sources of these elements.

On the other hand, magnesium (Mg^{2+}), potassium (K^+), sulfate (SO_4^{2-}), and nitrate (NO_3^-) demonstrate high CVs, indicating significant spatial variability within the study area. The elevated variability in these parameters suggests that both natural factors, such as mineral dissolution and geological heterogeneity, and anthropogenic influences. Agricultural practices and human activities have a clear impact on groundwater quality. In farming areas, fertilizers and irrigation water seep into the ground, raising nitrate, magnesium, and potassium levels. Wastewater from homes or small industries can also add pollutants like nitrate and sulfate. These human-driven sources, combined with natural factors, create noticeable differences in water quality across the region.

Chemical facies

The analysis of Piper diagram (*Fig. 6*) reveals several distinct hydrochemical facies, primarily dominated by calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) ions. The major water type identified is the Ca-SO_4 facies (61.4 %), which is particularly evident in samples with higher EC values, suggesting significant interaction with gypsum or anhydrite-bearing formations. A secondary but important facies is the Ca-HCO_3 type (24.56 %), typically found in samples with lower mineralization, indicating influence from carbonate rock dissolution processes.

Some samples exhibit a mixed Ca-Mg-SO_4 character (5.26 %), particularly noticeable in the central portion of your dataset, pointing to the influence of both carbonate and evaporite mineral dissolution. The presence of elevated sodium (Na^+) in certain samples suggests a minor but notable Na-mixed facies, possibly resulting from ion exchange processes or the weathering of sodium-bearing minerals. The generally moderate to high sulfate concentrations across many samples indicate significant influence from evaporitic formations in the aquifer system.

The bicarbonate (HCO_3^-) concentrations show moderate to high values throughout the dataset, suggesting active carbonate weathering processes. The chloride (Cl^-) concentrations are relatively variable, with some samples showing elevated values, possibly indicating localized sources of chloride or mixing with more saline water types. The overall ionic distribution pattern suggests a complex hydrogeochemical evolution, likely influenced by multiple geological formations and various water-rock interaction processes.

Fig.5. *Chemical facies of groundwater (Piper diagram)*

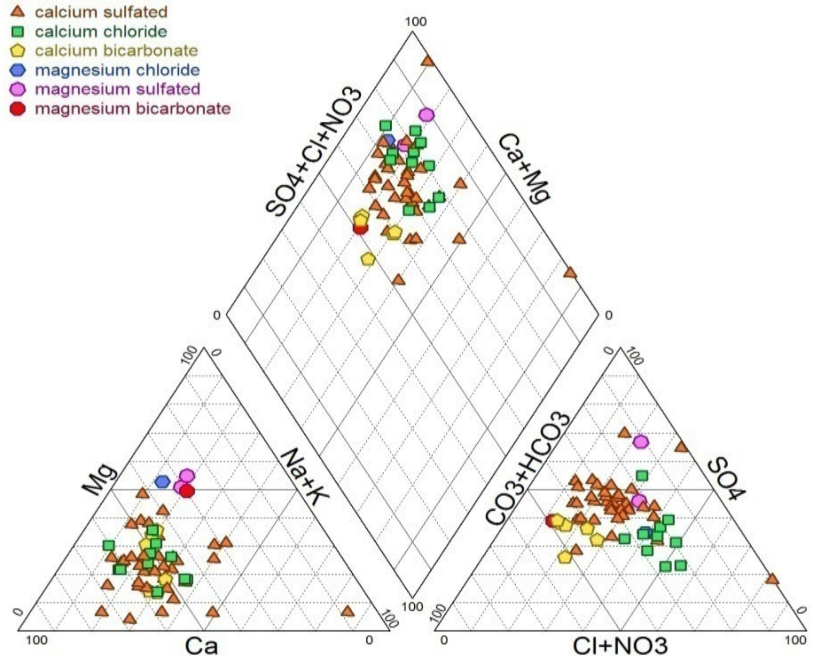
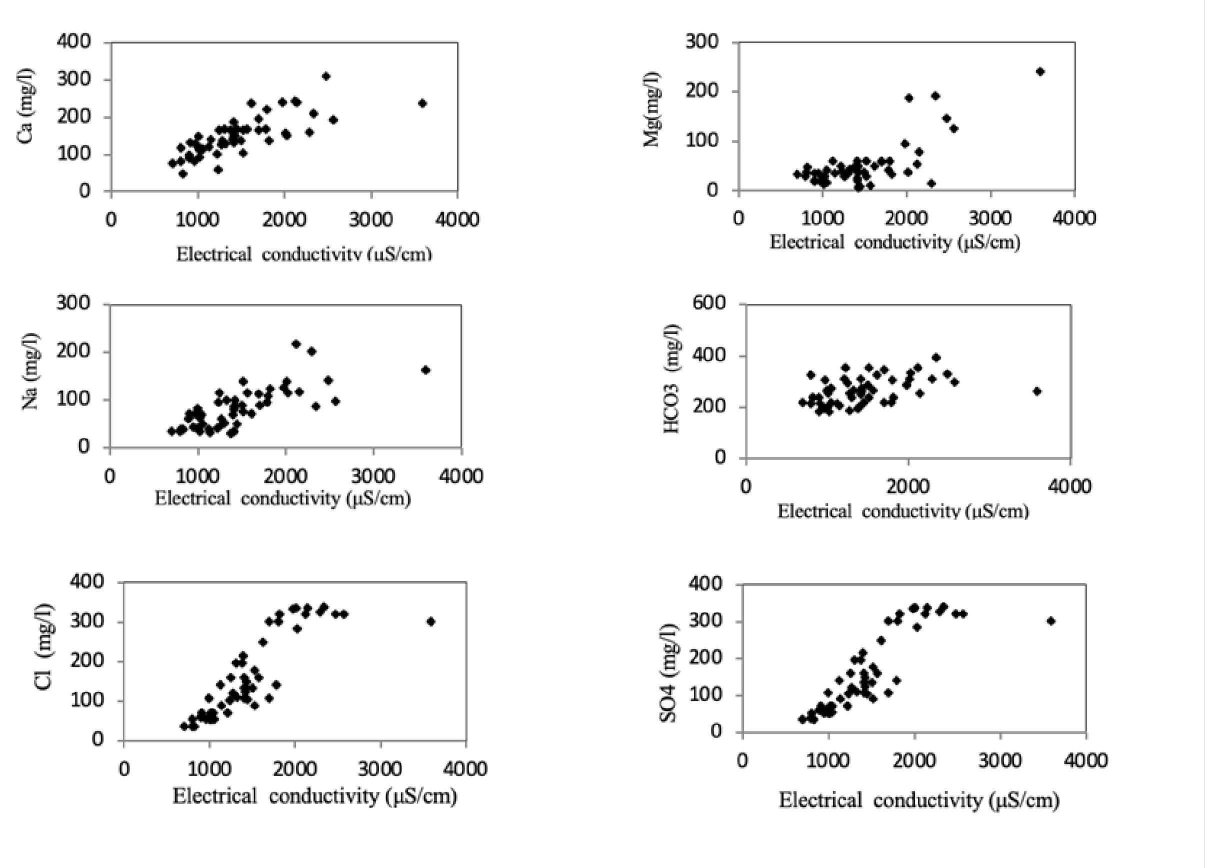


Fig. 6. *Relationship between the major elements and the electrical conductivity of Remila plain groundwater*

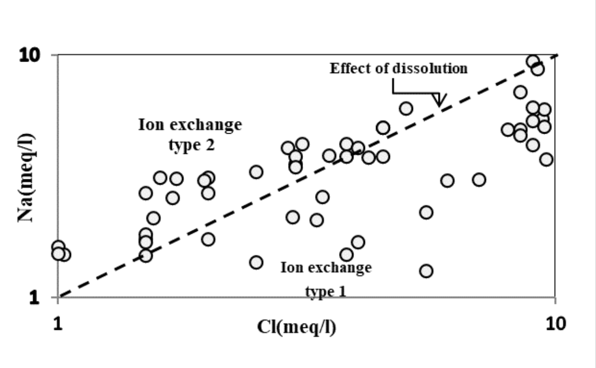


Origin of chemical elements and mechanisms of saline load acquisition

To trace the origin of mineralization in the Remila basin groundwater, a primary approach involves examining the relationships between major elements (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}) and EC (*Fig. 6*). The patterns indicate a positive correlation between these ions (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}, Cl^{-}, $SO4^{2-}$) and EC, highlighting their contribution to water mineralization. The coefficient of determination (R^2) between EC and Cl^{-} is 0.72, followed by $SO4^{2-}$, Na^{+}, and Mg^{2+} ions, respectively, confirming their significant roles in influencing the groundwater›s mineral content.

The study of the sodium-chloride (*Fig. 7*) (Na-Cl) relationship is an effective method to trace the origin of groundwater mineralization. Chloride (Cl^{-}), being a conserved ion that does not participate in water-rock interactions, is a key indicator of water salinity and acts as a mixing tracer (Hosseini et al., 2014; Yang et al., 2011).

Fig. 7. *Relation between Cl^{-} and Na^{+} of the Remila plain water*



The correlation between Na^{+} and Cl^{-} identifies three distinct groups. The first group, where data points align with a slope of 1, indicates halite dissolution as a primary influence. The second group, showing Na^{+}/Cl^{-} molar ratios less than 1, suggests base exchange reactions with clay minerals, where Ca^{2+} and/or Mg^{2+} ions are released in exchange for Na^+ fixation (Appelo and Postma, 2005). This process is clearly illustrated by the observed pattern in which the deficiency of Na^+ is offset by an enrichment in Ca^{2+} and Mg^{2+}. The third group of samples, positioned above the slope line of 1, indicates an excess of Na^+ relative to Cl^-. This suggests the occurrence of a secondary ion exchange, where Na^+ is released from exchange sites and replaced by Ca^{2+} and Mg^{2+} ions (Appelo and Willemsen, 1987). This detailed analysis helps elucidate the geochemical processes influencing groundwater mineralization in the study area.

To further understand groundwater mineralization, we analyzed major elements based on chlorides (*Fig. 8*). The positioning of various water samples along the freshwater-saltwater mixing line (rainwater-seawater) is valuable for identifying additional factors influencing saline load. Generally, groundwater in the study area shows enrichment in Ca^{2+} and SO_4^{2-} and a depletion in magnesium (Mg^{2+}). The key reactions responsible for these changes include Ca^{2+} and Mg^{2+} exchange due to interactions between water and carbonate rocks, Na^+ and Ca^{2+} or Na^+ and Mg^{2+} base exchange, and the reduction or dissolution of evaporitic sulfate. The graphical representation of calcium (Ca^{2+}) relative to sulfate (SO_4^{2-}) (*Fig. 9*) helps classify water samples into distinct groups. One group, where the Ca^{2+}/SO_4^{2-} ratios are close to 1, indicates that these ions are influenced by the dissolution of gypsum and/or anhydrite. Another group, displaying an excess of Ca^{2+}, suggests the presence of cation exchange processes.

Relationship between major chemical elements and origin of mineralization

To clarify the mechanisms of mineralization, we utilized the "Diagram" software to calculate the saturation indices of specific minerals. This analysis provides insights into the chemical equilibrium between groundwater and the minerals in the aquifer matrix during water-rock interactions. The groundwater analysis in the Remila basin indicates that the water is undersaturated with calcite, aragonite, dolomite, gypsum, anhydrite, and halite (*Fig. 10*). Consequently, the water's mineralization primarily results from the dissolution of these minerals during water-rock interactions.

Trace elements

The use of trace elements is a highly effective method for determining the causes of high salinity in groundwater (Chuanqiang et al., 2018; Mei et al, 2024) Trace elements, which are present in minor concentrations, can provide crucial insights into the geochemical processes and sources of contamination affecting water quality.

Fig. 8. *Relation between [(Ca + Mg)/ (HCO_3 + SO_4)] and [Na/Cl]*

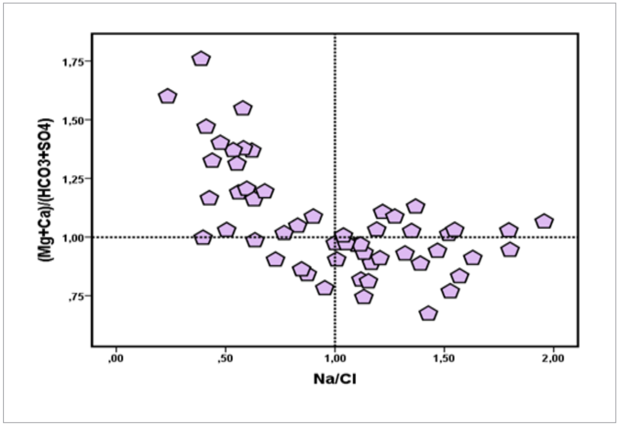
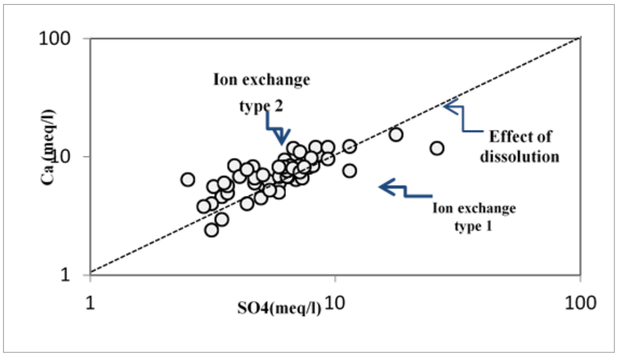


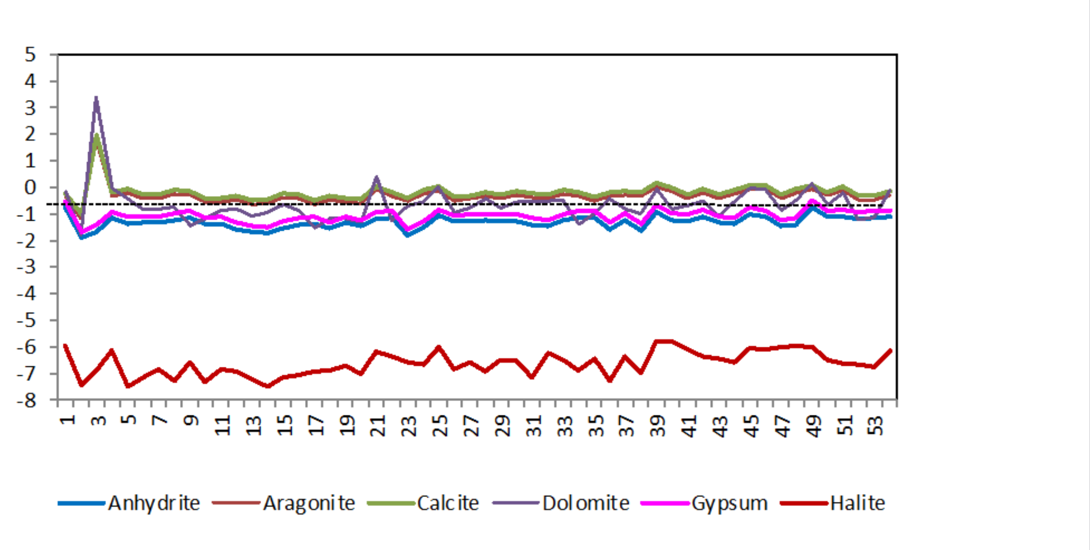
Fig. 9. *Relation between SO_4^{2-} and Ca^{2+} of groundwater*



Strontium Sr^{2+}

Strontium is an alkaline earth metal that naturally occurs in the form of $SrCO_3$ and $SrSO_4$ (celestite). Celestite is typically associated with evaporitic formations (Houha et al., 2008). The low concentration of Sr^{2+} (less than 7 mg/L) is observed in the southern zone, where runoff occurs exclusively in detrital materials at a relatively slow rate. This slow movement indicates a prolonged residence time of water in the medium. Conversely, high Sr^{2+} concentrations, reaching up to 17 mg/L, are found in areas located in the northwest, northeast, and center of the plain, where runoff is relatively rapid. This reflects a shorter residence time of water in these zones. The elevated strontium levels coincide with the outcrops of

Fig. 10. *Saturation index with respect to the main minerals*

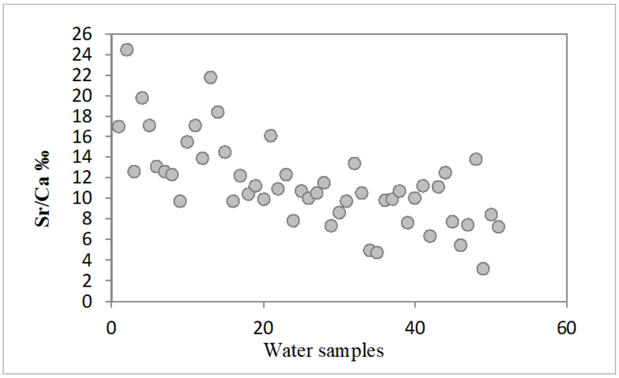


evaporitic formations, suggesting that the presence of this element is linked to saliferous formations through the dissolution of celestite ($SrSO_4$).

Sr^{2+}/Ca^{2+} typical ratio

The Sr^{2+}/Ca^{2+} ratio is an effective indicator of the evaporite origin of high sulfate levels in water (Fidelibus et al., 1996; Houha, 2007; Hamed et al., 2014; Mokadem et al., 2016). Sr^{2+}/Ca^{2+} molar ratios greater than 1‰ are typically indicative of gypsiferous water (Meybeck, 1986). The analysis of the Sr^{2+}/Ca^{2+} ratio revealed that the majority of water samples have values greater than 1‰, reflecting the influence of gypsiferous formations on the presence of strontium. This finding aligns with the observed facies types, where wells with bicarbonate facies are predominantly located in the southern part of the plain and represent a small percentage, while wells with sulfate or chloride facies occupy the majority of the plain.

Fig. 11. *Sr^{2+}/Ca^{2+} ratio of Remila plain groundwater*



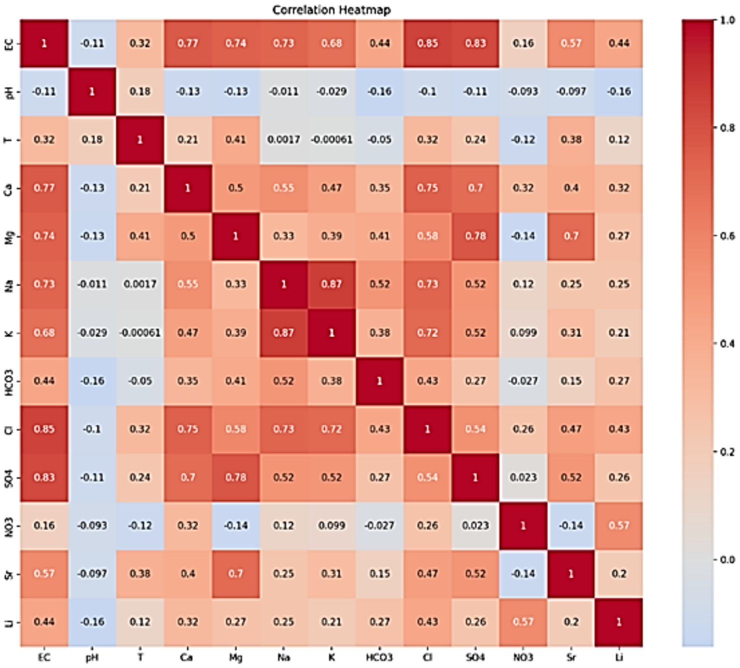
Lithium

A slight increase in temperature can significantly elevate the Li^+ content in groundwater, ranging from 100 to 10,000 times the original concentration (Fidelibus et al., 1996; Barbieri et al., 1998; Fehdi et al., 2009; Hamed, 2009). In the Remila plain, the Li^+ concentration in groundwater varies between 0.12 and 0.91 mg/L, with an average of 0.43 mg/L. This elevated level of lithium suggests prolonged water-rock interaction, indicating that the groundwater is likely of considerable depth. Such prolonged contact allows for more extensive dissolution of lithium-bearing minerals, contributing to the observed concentrations.

Principal component analysis

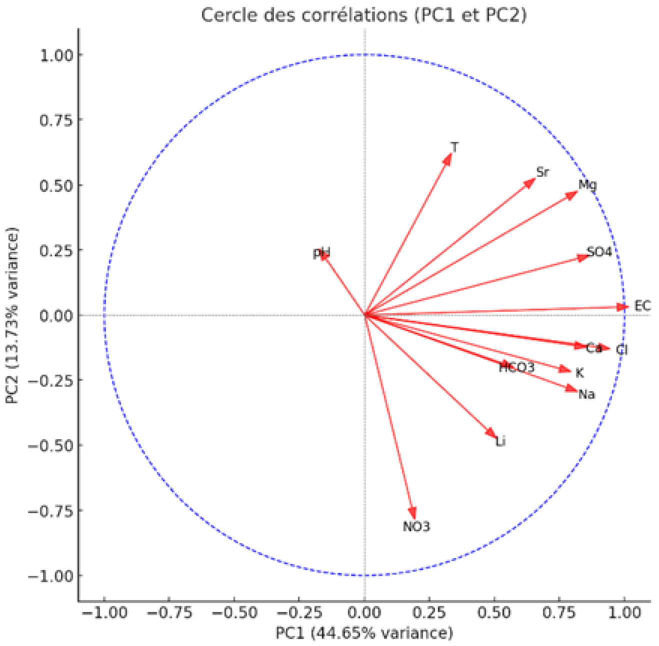
Principal component analysis (PCA) of groundwater chemical variables is a valuable method for understanding the relationships between variables and the processes influencing water quality (Travi and Mudry, 1997; Baali, 2007; Subba Rao, 2007). The correlation matrix for major ions (*Fig. 12*) reveals key interactions among chemical parameters. EC shows strong positive correlations with chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+), indicating these ions' significant

Fig. 12. *The correlation matrix for major ions*



	EC	pH	T	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3	Sr	Li
EC	1	-0.11	0.32	0.77	0.74	0.73	0.68	0.44	0.85	0.83	0.16	0.57	0.44
pH	-0.11	1	0.18	-0.13	-0.13	-0.011	-0.029	-0.16	-0.1	-0.11	-0.093	-0.097	-0.16
T	0.32	0.18	1	0.21	0.41	0.0017	-0.00061	-0.05	0.32	0.24	-0.12	0.38	0.12
Ca	0.77	-0.13	0.21	1	0.5	0.55	0.47	0.35	0.75	0.7	0.32	0.4	0.32
Mg	0.74	-0.13	0.41	0.5	1	0.33	0.39	0.41	0.58	0.78	-0.14	0.7	0.27
Na	0.73	-0.011	0.0017	0.55	0.33	1	0.87	0.52	0.73	0.52	0.12	0.25	0.25
K	0.68	-0.029	-0.00061	0.47	0.39	0.87	1	0.38	0.72	0.52	0.099	0.31	0.21
HCO3	0.44	-0.16	-0.05	0.35	0.41	0.52	0.38	1	0.43	0.27	-0.027	0.15	0.27
Cl	0.85	-0.1	0.32	0.75	0.58	0.73	0.72	0.43	1	0.54	0.26	0.47	0.43
SO4	0.83	-0.11	0.24	0.7	0.78	0.52	0.52	0.27	0.54	1	0.023	0.52	0.26
NO3	0.16	-0.093	-0.12	0.32	-0.14	0.12	0.099	-0.027	0.26	0.023	1	-0.14	0.57
Sr	0.57	-0.097	0.38	0.4	0.7	0.25	0.31	0.15	0.47	0.52	-0.14	1	0.2
Li	0.44	-0.16	0.12	0.32	0.27	0.25	0.21	0.27	0.43	0.26	0.57	0.2	1

Fig. 13. *Factorial plan of the principal component analysis (PCA): F1 – F2*



role in groundwater mineralization and salinity (Hem, 1985; Hounslow, 1995). Conversely, pH demonstrates weak correlations with most ions, reflecting its stability despite varying ion concentrations.

Temperature moderately correlates with EC, calcium, magnesium, and sodium, likely due to geothermal influences and increased mineral solubility at higher temperatures (Langmuir, 1997). Strong correlations among calcium, magnesium, sodium, chloride, and sulfate point to common sources, such as mineral dissolution (Appelo and Postma, 2005; Freeze and Cherry, 1979). Additionally, potassium's high correlation with sodium suggests shared geochemical behaviors, potentially from cation exchange processes (Fetter, 2001). Bicarbonate's moderate correlations reflect the groundwater's buffering capacity and interactions with carbonate minerals (Stumm and Morgan, 1996).

The PCA conducted on the physicochemical data of groundwater from the aquifer reveals hydrogeochemical processes driven by both natural and anthropogenic influences. The first principal component (PC1) (*Fig. 13*), which explains 44.65% of the total variance, highlights the predominant role of natural processes such as mineral dissolution within the aquifer. Major ions like Cl, Na, and SO4 are strongly correlated with this component, indicating their likely geological origin from the dissolution of evaporitic deposits in marl and clay formations. The intense evaporation characteristic of the region's semi-arid climate exacerbates these processes by increasing the concentration of these ions in the groundwater, thereby contributing to salinization. Additionally, water-rock interactions in the fractured limestone formations enrich the water with Ca and HCO3, also influencing pH, which tends toward alkaline values.

The second principal component (PC2), explaining 13.73% of the variance, reflects anthropogenic influences, primarily stemming from the agricultural activities dominating the region. Elevated NO_3 concentrations, correlated with this component, indicate contamination from chemical fertilizers and irrigation water. These nitrates rapidly infiltrate the aquifer, particularly in sandy zones with high permeability or in fractured limestone areas. The independent correlation between NO_3^- and major ions suggests a distinct source, confirming the anthropogenic impact on groundwater quality. Nitrate contamination of groundwater is a serious issue in semi-arid regions, primarily due to agricultural practices and wastewater discharge (Ramalingam et al. ,2022). In these areas, groundwater is a vital water source, and nitrate contamination can pose significant health risks (Khader et al., 2021; Bencheihk et al., 2025).

Samples located in the quadrant corresponding to Cl^-, Na_2^+, and SO_4^{2-} indicate dominance by evaporation processes and the dissolution processes of salts within geological strata. In contrast, those oriented toward NO_3^- and HCO_3^- signify zones influenced by agricultural inputs or recent recharge. This analysis highlights a clear dichotomy between highly mineralized waters of geological and climatic origin and those affected by human activities. An integrated water resource management approach, considering these two types of influences, is essential to preserve the quality of the aquifer in this semi-arid context.

Conclusion

The hydrogeochemical analysis of the Remila basin in northeastern Algeria reveals diverse chemical facies in groundwater, primarily characterized by calcium-sulfate ($Ca-SO_4$) and calcium-bicarbonate ($Ca-HCO_3$) types, reflecting complex geological compositions and water-rock interactions. Groundwater mineralization is mainly driven by the dissolution of evaporitic minerals like gypsum and halite, with strong correlations between electrical conductivity and ions such as chloride, sulfate, calcium, and sodium. Ion exchange processes, indicated by variations in Na^+/Cl^- ratios and relationships between calcium, magnesium, and sodium, significantly influence groundwater chemistry. Elevated strontium levels, especially in areas with rapid runoff, point to the impact of evaporitic formations and celestite dissolution, supported by Sr^{2+}/Ca^{2+} ratios exceeding 1%. Lithium concentrations suggest prolonged water-rock interactions, indicating deep aquifer systems. Principal Component Analysis (PCA) identifies natural mineralization and anthropogenic pollution, particularly nitrate contamination, as key factors affecting groundwater chemistry.

The groundwater is generally undersaturated with major minerals, indicating ongoing dissolution processes, while spatial variability in water quality parameters highlights both geological and anthropogenic influences on the aquifer system.

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