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Origin and Evolution of Groundwater Salinization in the Ouargla Region, South-Eastern Algeria

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Abstract

This study presents a hydrogeochemical investigation based on the analysis of 24 groundwater samples collected mainly from boreholes within the Ouargla basin (south-eastern Algeria). Particular attention is given to the vulnerability of the Terminal Complex (TC) aquifer to chemical pollution of both mineral and organic origin. Hydrochemical analyses were interpreted using Wilcox and Riverside diagrams, allowing groundwater quality to be classified into three main categories: acceptable quality (Mekhadma and Sokra areas), moderate quality (Said Otba area), and poor quality (Beni Thour area). Spatial mapping of the contamination index was carried out using Surfer 12 software, highlighting the Chott area as the most vulnerable zone to mineral pollution, while the Beni Thour area shows the highest vulnerability to organic pollution. Geochemical modeling and statistical analysis using PHREEQC and STATISTICA software indicate that anhydrite and gypsum dissolution constitutes the main source of calcium and sulfate in the groundwater of the Terminal Complex aquifer. The results provide valuable insights for groundwater management and pollution mitigation in arid environments.

Keywords: Groundwater pollution; hydrogeochemistry; arid zone; Terminal Complex; Ouargla; Algeria.

1. Introduction

Groundwater constitutes the primary source of freshwater and plays a crucial role in sustainable development. For a long time, this resource was considered nearly inexhaustible and renewable. However, increasing water demand combined with climate change has led to significant depletion of groundwater reserves in several Mediterranean basin countries. The suitability of groundwater for drinking purposes and for other uses, such as industrial and agricultural activities, is strongly dependent on its quality (Walter et al., 2017; Alabjah et al., 2018; Hamidi et al., 2022; Sarkar et al., 2022; Ilyes et al., 2024). Among the various factors responsible for groundwater quality degradation, salinization is considered one of the most critical (Ahmed et al., 2013; Foster et al., 2013; Argamasilla et al., 2017; Mirzavand et al., 2020).

Salinization refers to the increase in dissolved salt concentrations in water and may result from natural processes or anthropogenic activities (Williams, 1999). It represents a major global environmental issue, particularly in regions characterized by limited water resources, such as arid and semi-arid zones where groundwater serves as the primary water supply (Dao et al., 2024). The growing reliance on groundwater has placed considerable pressure on aquifer systems, leading simultaneously to rising salinity levels and declining groundwater tables.

Groundwater salinization is a global phenomenon that affects aquifers in a wide range of climatic and geological environments, including coastal and inland systems across Australia, Asia, Europe, Africa, the Middle East, North America, and China (Mehta et al., 2000; de Montety et al., 2008; Tweed et al., 2011; Wang and Jiao, 2012; Argamasilla et al., 2017; Gurmessa et al., 2022). This problem is particularly severe in arid and semi-arid regions, where groundwater constitutes the primary water resource and natural recharge is limited.

Salinity in groundwater results from a combination of natural processes and anthropogenic influences, with human activities often accelerating natural salinization mechanisms. Excessive groundwater abstraction may induce seawater intrusion in coastal aquifers or promote the upward and downward migration of saline water from adjacent geological formations (Ahmed et al., 2013; Cary et al., 2015). Additional contributors include groundwater extraction exceeding recharge rates, irrigation return flows enriched with salts and agrochemicals, industrial and wastewater discharges, leakage from disposal structures, hydrocarbon exploitation activities, and geothermal processes that allow mineralized deep waters to contaminate freshwater aquifers through faults and fractures (Sarikhani et al., 2015; Dirks et al., 2018; Saeed et al., 2021).

Identifying the sources and spatial distribution of groundwater salinity is essential for sustainable groundwater management. Hydrochemical and isotopic analyses, coupled with statistical evaluations and ionic relationship studies, are commonly applied to trace salinity origins; however, their use is often limited by high costs and operational constraints, especially at regional scales (Gopinath et al., 2019; Ben Ammar et al., 2020; Mirzavand and Ghazban, 2022). Consequently, geophysical methods such as electrical resistivity tomography (ERT) and vertical electrical sounding (VES) have become increasingly popular due to their non-destructive nature, rapid implementation, and cost-effectiveness (Mhamdi et al., 2006; Alabjah et al., 2018). These techniques are frequently integrated with hydrochemical data to enhance the understanding of groundwater salinization processes and aquifer vulnerability (Kouzana et al., 2010; Najib et al., 2017; Kumar et al., 2021a, 2021b; Hibbs, 2024).

Understanding the quality of water, both surface and groundwater, begins with hydrochemical analysis of collected samples, which serves as a fundamental step. Additionally, various techniques can help track changes in water quality over time and across different locations, including Geographic Information Systems (GIS), geostatistical approaches, remote sensing mapping, and geophysical methods such as electrical and electromagnetic surveys (Aju et al., 2021; Kadam et al., 2022; Jesiya and Gopinath, 2018).

This research paper focuses on a hydrogeochemical study of groundwater in south-eastern Algeria. Special attention was given to assessing the extent of chemical contamination, both mineral and organic, in the Terminal Complex aquifer through the analysis of samples collected from boreholes. Additionally, the evolution of the contamination index was mapped using Surfer 12 software to identify the areas most affected by pollution. The results indicated that the region most susceptible to mineral contamination corresponds to the groundwater within the studied aquifer.

2. Study Area

2.1. Geographic Location

The Ouargla region is located in the north-eastern part of the Algerian Sahara, approximately 850 km south of Algiers. It is bounded to the north by the wilayas of Djelfa, El Oued, and Biskra; to the east by Tunisia; to the west by Ghardaïa; and to the south by Tamanrasset and Illizi. The Ouargla basin is defined by the following UTM coordinates (Clarke 1880):
Xmin = 710,000; Ymin = 3,530,000
Xmax = 730,000; Ymax = 3,600,000
The city of Ouargla is located at the bottom of a closed depression surrounded by palm groves. This geomorphological setting, combined with extreme aridity and shallow groundwater levels, favors water stagnation and progressive salinization.

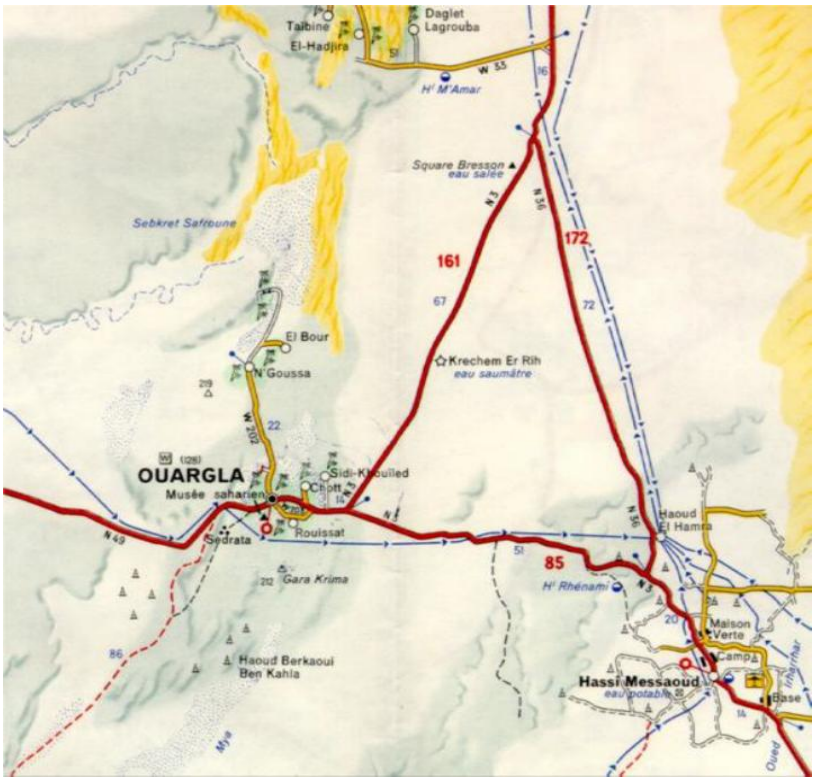


Fig. 1. Location map of the Ouargla region.

2.2. Climate Data

The climate of Ouargla is typically Saharan, characterized by extremely hot summers, mild winters, very low rainfall, and intense evaporation. These climatic conditions strongly influence soil processes, groundwater recharge, and hydrochemical

evolution.

Table 1. Climate data of Ouargla between 2004 and 2014 (Hamidi et al., 2022).

months	T min (°C)	T max (°C)	T med (°C)	H (%)	V (km/h)	Insolation (h)	P (mm)	E (mm)
January	5,11	18.77	11.94	61.07	55.60	244.77	9.10	90.70
February	6.83	21.08	13.96	51.21	60.73	241.84	0.64	129.15
March	10.99	25.81	18.40	45.67	60.95	259.09	4.30	204.51
April	16.26	30.38	22.82	39.34	72.29	280.90	2.11	254.53
May	19.75	34.89	27.32	33.90	66.13	301.03	1.47	327.61
June	24.81	40.28	32.54	29.50	57.45	253.20	0.74	399.75
July	28.21	43.71	35.96	25.79	64.53	327.18	0.32	464.44
August	27.54	42.84	35.19	28.84	56.11	330.68	1.70	419.87
September	23.51	37.75	30.63	37.90	55.78	269.05	3.56	299.57
October	17.61	32.18	24.89	44.42	48.73	265.28	5.72	230.60
November	10.46	24.16	17.31	54.85	47.64	249.68	6.56	124.89
December	6.02	19.23	12.62	60.54	45.02	223.28	4.18	88.80
Average	16.34	30.92	23.63	42.75	57.58	270.50	3.37	252.87
						Cumulative	43.76	3287.29

2.3. Hydrogeological Setting

The Ouargla basin belongs to the Lower Sahara sedimentary basin, characterized by a large synclinal structure with alternating permeable and impermeable layers. This geological configuration favors the development of several superimposed aquifer systems, including the Continental Intercalaire (CI) aquifer (Albian), the Senonian aquifer, the Terminal Complex (TC) aquifer (Mio-Pliocene and Eocene), and shallow Quaternary phreatic aquifers.

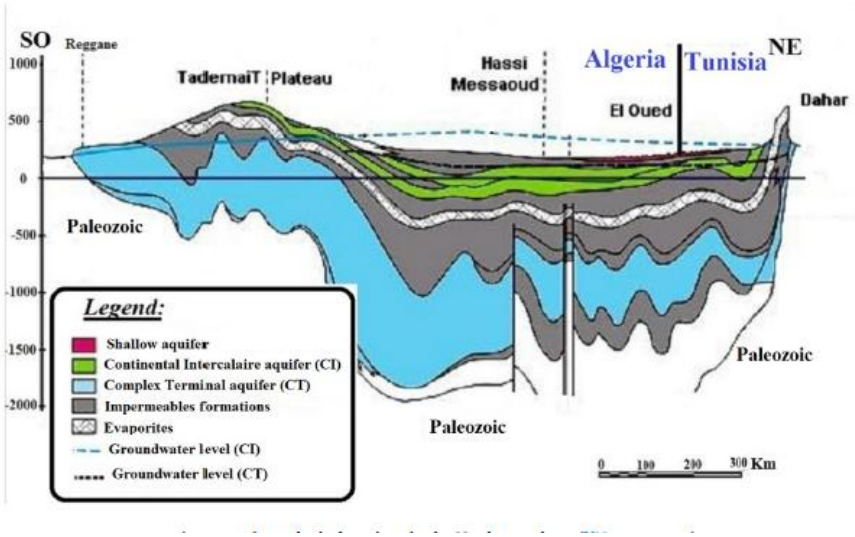


Fig. 2. Hydrogeological sections in the Northern Sahara (UNESCO, 1972).

2.3.1. Terminal Complex Aquifer

The Terminal Complex aquifer extends over an area of approximately 350,000 km², with depths ranging from 100 to 500 m. It consists mainly of two aquifer units: sandy Mio-Pliocene formations and carbonate Eocene formations. Hydraulic connections may exist between these units due to the absence of a continuous impermeable barrier.

2.3.2. Senonian Aquifer

The Senonian aquifer is artesian and characterized by groundwater salinity ranging from 1.8 to 4.4 g/L, with temperatures around 30°C. Depths vary between 180 and 350 m.

2.3.3. Continental Intercalaire Aquifer

The CI aquifer covers nearly 800,000 km² and represents one of the largest fossil groundwater reserves in the Sahara. Groundwater temperatures range from 51°C to 66°C, with total dissolved solids between 1.5 and 2.4 g/L.

2.3.4. Phreatic Aquifer

The shallow phreatic aquifer is hosted in Quaternary sandy-gypsiferous formations. Groundwater levels are very shallow, ranging from less than 0.5 m in sebkha areas to about 8-10 m in elevated zones. Drainage water from palm groves and wastewater discharge significantly contribute to groundwater level rise.

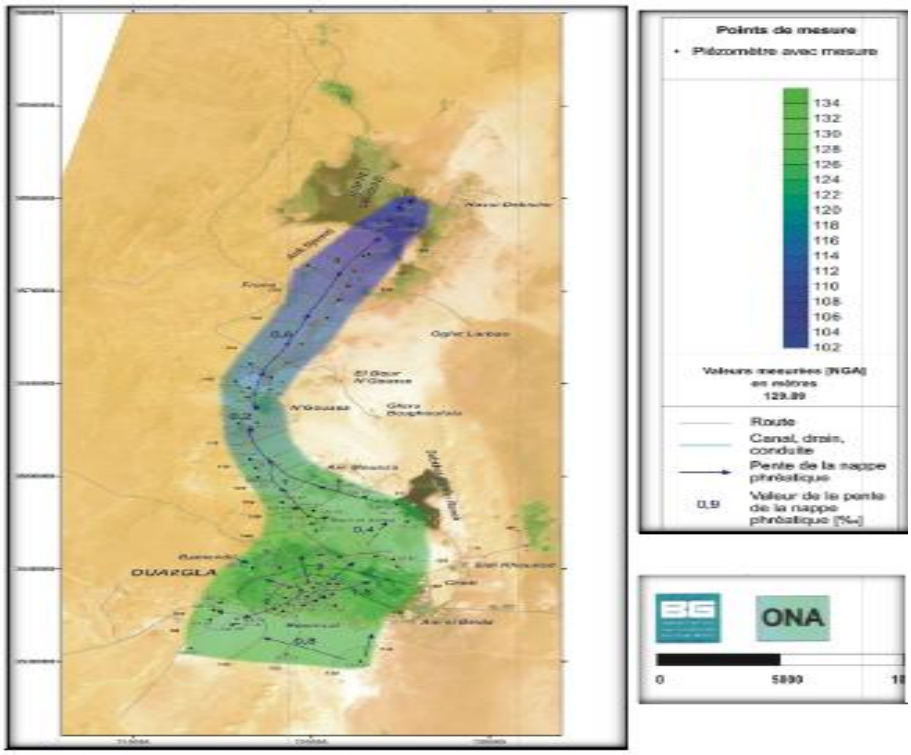


Fig. 3. Piezometric map of the Ouargla basin.

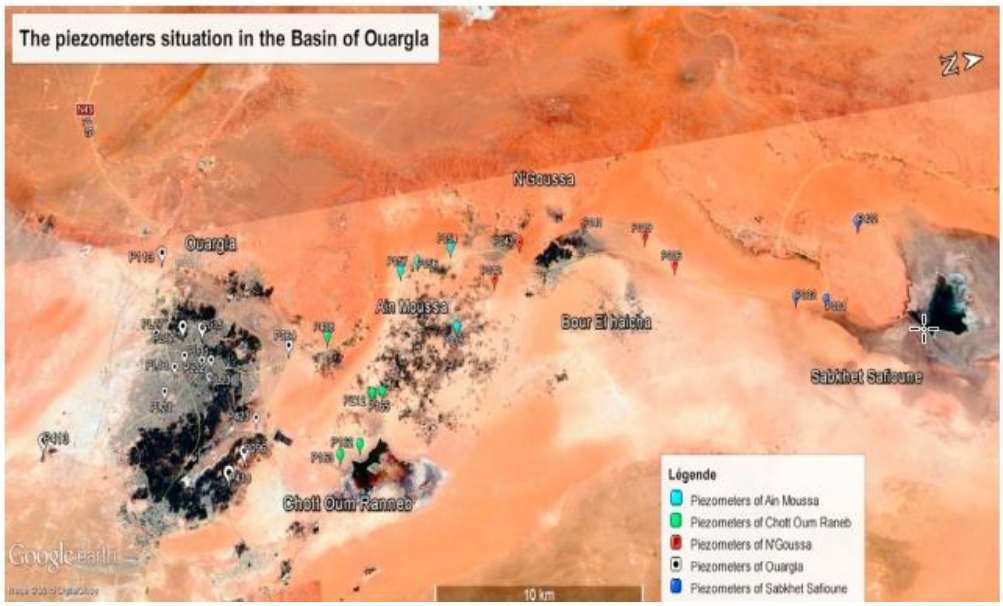


Fig. 4. Satellite view of the study site (Google Earth, modified).



Fig. 5. (a) Water-table rise; (b) Soil salinity in the Ouargla basin (Photographs by the authors, 08/03/2015).

3. Materials And Methods

3.1. Sampling

A total of 24 groundwater samples were collected from boreholes distributed across the Ouargla basin. The sampling network includes drinking-water supply wells (AEP) and irrigation wells (AEI) located in Mekhadma, Beni Thour, Said Otba, Sokra, Rouissat, Ouargla city, and Chott areas.

Table 2. Inventory of the boreholes studied.

No.	Location	No.	Location
F1	Mekhadma	F13	Mekhadma
F2	Mekhadma	F14	Said Otba
F3	Mekhadma	F15	Ouargla
F4	Mekhadma	F16	Ouargla
F5	Mekhadma	F17	Ouargla
F6	Mekhadma	F18	Mekhadma
F7	Mekhadma	F19	Rouissat
F8	Beni-Thour	F20	Sokra
F9	Beni-Thour	F21	Sokra
F10	Ouargla	F22	Rouissat
F11	Ouargla	F23	Rouissat
F12	Ouargla	F24	Chott

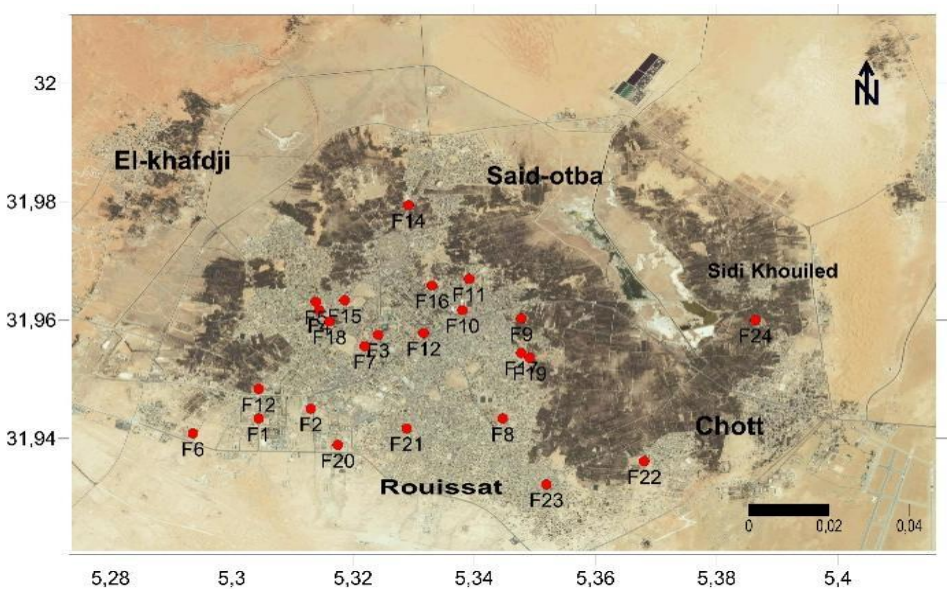


Fig. 6. Map of the water-point inventory.

3.2. Hydrochemical Analysis

Physicochemical parameters and major ion concentrations were analyzed using standard methods. The results were interpreted using hydrochemical diagrams (Wilcox and Riverside) to assess water suitability for irrigation and to identify salinization processes.

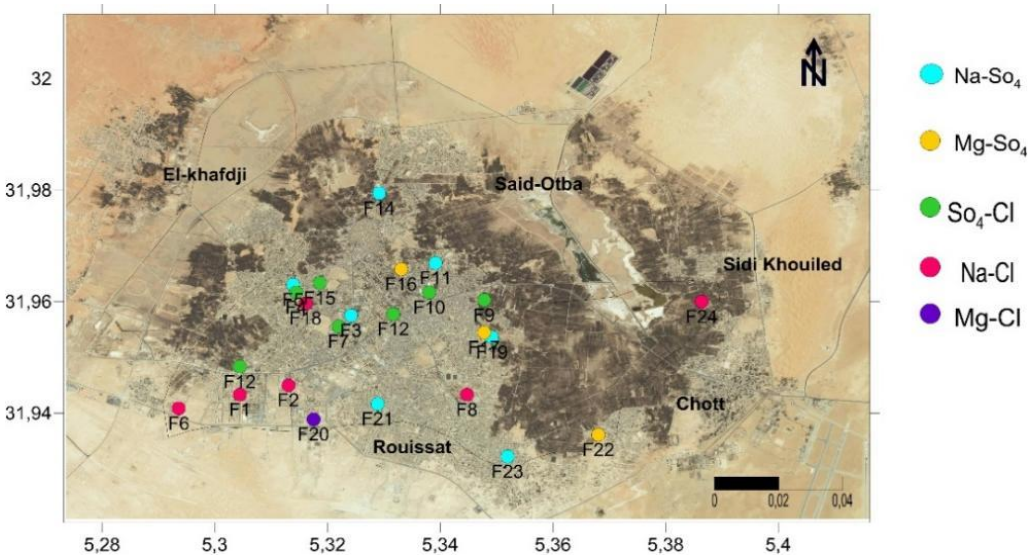


Fig. 7. Spatial evolution of the hydrochemical facies of groundwater in the Ouargla basin.

3.3. Geochemical Modeling

Geochemical modeling was performed using PHREEQC software under standard conditions (25°C) to calculate saturation indices and ion activities. Statistical analyses and correlation modeling were conducted using STATISTICA software to determine the origin of major ions.

4. Results

4.1. Hydrochemical Facies

The hydrochemical facies analysis reveals spatial variability in groundwater composition across the Ouargla basin. Two types of water points were sampled (AEP and AEI); the dominant facies are Na-Cl and SO4-Cl, with Na-SO4 and Mg-SO4 facies recorded at several boreholes (F14, F16, F11, F22).

4.2. Wilcox Diagram

The Wilcox diagram indicates that groundwater from the Terminal Complex aquifer falls into three categories:

- Acceptable quality: Na% between 20.68 and 50.68, corresponding to the Mekhadma and Sokra areas.
- Moderate quality: Na% between 37.08 and 85.24, corresponding to the Said Otba area.

• Poor quality: Na% between 33.81 and 39.30, corresponding to the Beni Thour area.

$$Na(\%) = 100 \times \frac{Na+K}{Ca+Mg+Na+K}$$

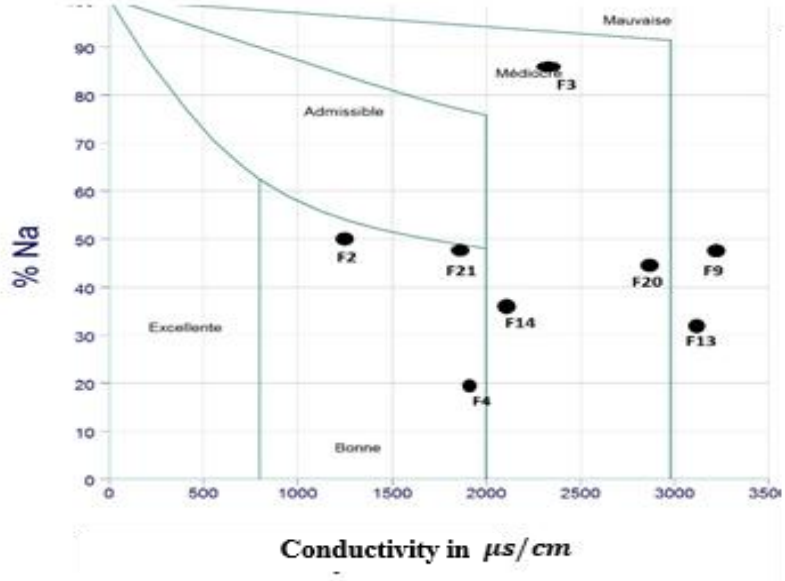


Fig. 8. Wilcox diagram of groundwater samples from the Terminal Complex aquifer.

4.3. Riverside Diagram

The Riverside classification, based on the Sodium Adsorption Ratio (SAR), shows varying degrees of alkalinization risk, ranging from low (SAR < 10) to moderate (10 < SAR < 18).

$$SAR = \frac{Na}{\sqrt{\frac{Ca+mg}{2}}}$$

4.4. Geochemical Modeling Results

Saturation indices calculated with PHREEQC and correlation analysis performed with STATISTICA reveal strong statistical relationships between dissolved calcium, sulfate, and the saturation indices of evaporitic mineral phases. Correlation coefficients of r ≈ 0.88 (log Ca^{2+} vs. IS_Gypsum/IS_Anhydrite, p < 0.0001) and r ≈ 0.69 (log $SO4^{2-}$ vs. IS_Gypsum/IS_Anhydrite, p = 0.0002) were obtained, while correlations with calcite, aragonite, dolomite, and halite saturation indices were weak and not statistically significant.

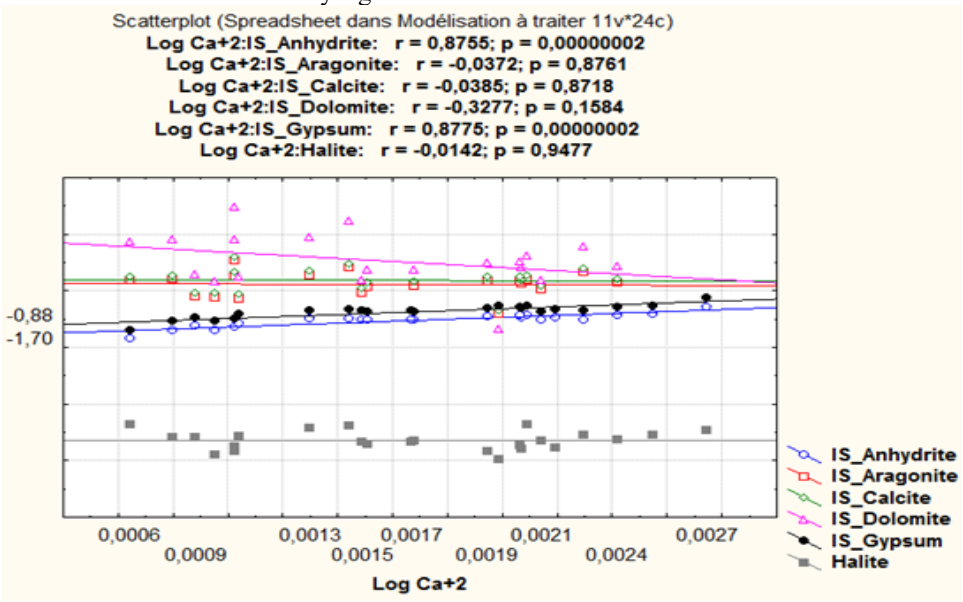


Fig. 9. Scatterplot of log[Ca^{2+}] versus saturation indices of evaporitic and carbonate minerals.

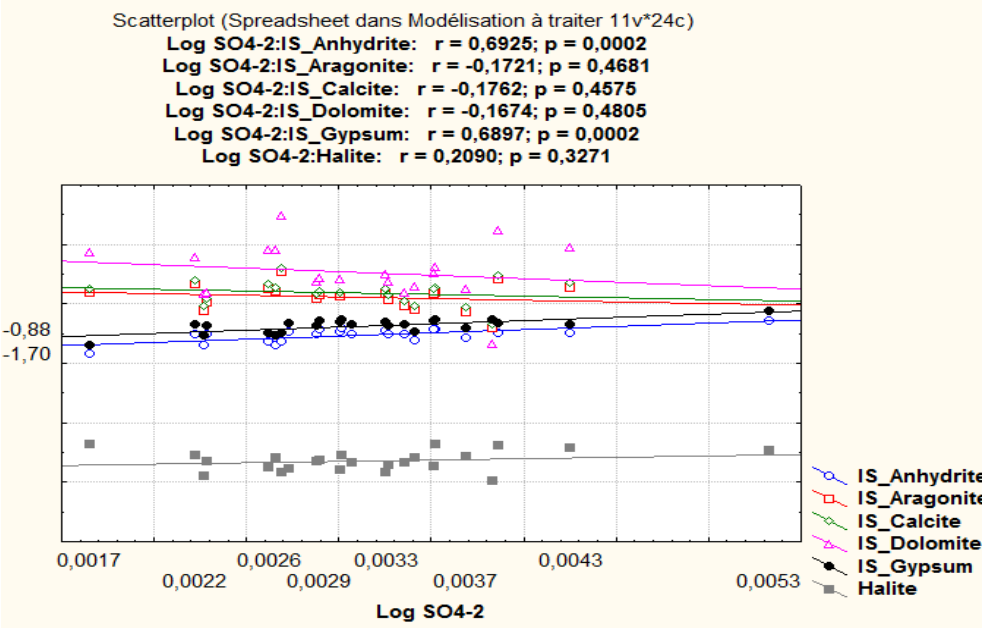


Fig. 10. Scatterplot of log[SO_4^{2-}] versus saturation indices of evaporitic and carbonate minerals.

5. Discussion

The spatial variability observed in groundwater quality across the Ouargla basin reflects the combined influence of evaporitic formations and anthropogenic inputs on hydrochemical facies. The classification of groundwater into acceptable, moderate, and poor quality categories through the Wilcox diagram is consistent with the region's Saharan hydrogeological setting, in which shallow water tables, intense evaporation, and limited natural recharge favor progressive salt accumulation (Sarikhani et al., 2015; Dirks et al., 2018).

The predominance of Na-Cl and SO4-Cl facies, together with the moderate-to-poor irrigation quality identified in the Beni Thour and Said Otba areas, suggests that both the dissolution of evaporitic minerals and the return flow of irrigation and drainage water contribute to salinization, in agreement with observations reported for other arid basins (Ahmed et al., 2013; Foster et al., 2013; Mirzavand et al., 2020). The low-to-moderate alkalinization risk indicated by the Riverside (SAR) classification further supports the conclusion that sodium-driven irrigation hazards, while present, remain moderate across most of the studied boreholes.

The strong correlations obtained between calcium, sulfate, and the saturation indices of gypsum and anhydrite, contrasted with the weak correlations with carbonate phases (calcite, aragonite, dolomite) and halite, indicate that the dissolution of evaporitic sulfate minerals — rather than carbonate dissolution or halite dissolution — constitutes the principal geochemical control on calcium and sulfate concentrations in the Terminal Complex aquifer. This finding is consistent with the widespread occurrence of gypsiferous and anhydritic formations reported in the Lower Sahara sedimentary basin (Kouzana et al., 2010; Najib et al., 2017) and supports the geophysical and hydrochemical approaches increasingly combined in similar arid-zone studies (Kumar et al., 2021a, 2021b; Hibbs, 2024).

Overall, these results confirm that groundwater salinization in the Ouargla basin results from the interaction of natural evaporitic dissolution processes with anthropogenic pressures linked to irrigation, drainage, and shallow water-table dynamics, underscoring the need for spatially targeted groundwater management strategies.

6. Conclusion

Groundwater pollution and salinization in the Ouargla basin represent a major environmental challenge for both local populations and public authorities. Hydrochemical analysis of 24 groundwater samples from the Terminal Complex aquifer shows significant spatial variability in water quality. According to WHO guidelines and Algerian standards, groundwater can be classified into acceptable, moderate, and poor quality categories, with the most degraded waters observed in the Beni Thour area. Geochemical and statistical analyses using PHREEQC and STATISTICA software demonstrate that the dissolution of anhydrite and gypsum constitutes the primary source of calcium and sulfate in groundwater. Identifying these processes is essential for developing effective groundwater protection and management strategies in arid regions such as Ouargla.

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