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Integrated Hydrogeochemical Characterization and Drinking Water Quality Assessment of the Terminal Complex Aquifer in El Oued Region (Southeastern Algeria) Based on Multivariate Analysis and Water Quality Index

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Abstract
Groundwater from the Terminal Complex aquifer is a principal water resource in the El Oued region of southeastern Algeria, where the region relies heavily on deep aquifers for domestic supply. This study investigates the hydrochemical characteristics and drinking suitability of this groundwater using Pearson correlation analysis, Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), hydrochemical facies diagrams, and the Water Quality Index (WQI). A total of 36 groundwater wells and 15 physicochemical parameters were analyzed across the study area. The results show marked spatial variability in mineralization and distinguish two main groups of wells; one characterized by higher mineralization and the other by lower mineralization. Multivariate analysis grouped the chemical variables into three clusters associated with hardness-related ions, salinity and secondary anthropogenic indicators, and carbonate-buffered parameters. The Piper and Schoeller-Berkaloff diagrams indicate an evolution from calcium-magnesium sulfate waters toward sulfate-sodic facies, controlled mainly by evaporite dissolution and ion-exchange processes. Correlation analysis shows that salinity is closely linked to Na^+ and SO_4^{2-}, whereas total hardness is mainly governed by Mg^{2+}. The WQI values, ranging from 222.55 to 339.13, classify most samples as very poor to unsuitable for drinking. Overall, the groundwater is highly mineralized and hard, and it is not suitable for direct domestic use without treatment. These findings provide a useful basis for future softening and treatment strategies in the El Oued region.
Keywords: *Groundwater; El Oued; Multivariate analysis; WQI; Hydrochemical facies; Mineralization*

INTRODUCTION

Groundwater quality is a major concern for the management and protection of this precious resource in arid and semi-arid regions. In such regions, groundwater is often highly mineralized, which can limit its use for human and agricultural purposes. However, less mineralized water may also be present, offering opportunities for sustainable use of this resource. The region of Souf, also known as El Oued, located in the southeastern part of the Algerian Sahara, is entirely dependent on groundwater for drinking water supply and irrigation. This region hosts significant reserves of groundwater stored in various aquifers.This region is home to significant reserves of groundwater stored in various aquifers located at different depths within different geological formations. It includes three aquifers of the North Sahara Aquifer System, namely the shallow aquifer, the complex terminal aquifer, and the continental intercalary aquifer, which consists of multiple stacked water tables.

For over two decades, the exploitation of the shallow groundwater has experienced a significant decline, mainly due to its high mineral content and high levels of pollution, whether mineral or organic in origin [1]. New boreholes in the region have been drilled with the aim of tapping into the terminal complex aquifer, either to meet drinking water needs or for irrigation purposes. This approach has been favored due to its relatively affordable cost compared to other options.

In Algeria, research has highlighted the complex chemistry and quality of groundwater in the northern Algerian Sahara, as well as the issue of high mineralization [2–6]. High concentrations of major ions such as calcium, magnesium, sodium, chlorides and sulfates have been reported. In this context, this study addresses three primary objectives aiming to provide an integrated assessment of groundwater resources in the Complex Terminal aquifer of El-Oued. First, it seeks to characterize the spatial variability of groundwater quality using multivariate statistical techniques, specifically Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), to identify dominant hydrochemical facies and their distribution. Second, the suitability of water for human consumption is quantitatively assessed using the Water Quality Index (WQI) methodology to delineate potential health risks. Finally, based on these findings, the study offers management recommendations to ensure the sustainable exploitation of resources in this arid region. The synergy between dimensionality reduction (PCA), pattern recognition (HCA), and practical assessment (WQI) provides a comprehensive understanding of hydrochemical dynamics, which is essential for informing decision-making by local water management authorities.

MATERIALS AND METHODS

presentation and geographical localization of the study area

The El Oued region in Figure 1 is one of the main oases in the northern Algerian Sahara. It is located in the southeast of Algeria, at a distance of 650 km from the capital, northeast of the northern Sahara, and 350 km west of Gabes (Tunisia). It covers an area of approximately 44,586 km2, representing 1.87% of the national territory. It is bounded by the following geographical coordinates: Longitudes X1 = 05°30' and X2 = 07°00' East. Latitudes Y1 = 35°30' and Y2 = 37°00' North.

According to the National Agency for Investment Development of El Oued Province [7], this area is characterized by an arid desert Saharan climate. In winter, temperatures drop below 0°C, while in summer, they can reach over 50°C. The average annual rainfall varies between 80 and 100 mm. With its location in the sedimentary basin of the northern Sahara, which covers an area of 780,000 km2, this area represents a major topographic depression, featuring an asymmetric synclinal structural basin [2]. In terms of geology, the region is composed of sedimentary formations, mainly consisting of sandstones, conglomerates, and clays. These formations are often covered by sandy and eolian deposits [8, 9].

The El-Oued aquifer system consists of three superimposed aquifer layers, namely the Continental Intercalary Aquifer (CI), the Terminal Complex Aquifer (CT), and the shallow aquifer.

The Continental Intercalary Aquifer, which is located at a depth ranging from 500 to 700 meters, is considered one of the largest reserves of underground water in the world. This aquifer, often referred to as the "Albian Aquifer," constitutes the deepest and most extensive reservoir of the North-Western Sahara Aquifer System. It is hosted within continental detrital formations (sandstones, clayey sands, and gravels) of Lower Cretaceous age (Barremian-Albian), covering over 600,000 km^2 in Algeria [10]. This confined aquifer is characterized by strong artesian pressure and a high geothermal gradient, yielding hot waters (50-70°C) with significant mineralization, sealed by Cenomanian clays and marls acting as the upper confining layer [10- 11].

The Terminal Complex Aquifer is situated between 200 and 400 meters deep, this aquifer in the Algerian Sahara is a heterogeneous multilayer system ranging from Senonian to Mio-Pliocene age. It consists of alternating carbonate and sandy detrital formations, locally separated by marly-clay layers. In the Grand Erg Oriental, the presence of evaporites (gypsum, halite) within the sedimentary matrix results in high water mineralization and a dominant Ca–Mg–Cl–SO_4 hydro chemical facies [12]. while the shallow aquifer is located at a depth of less than 200 meters [10–12]. This aquifer is hosted within Quaternary and upper Mio-Pliocene sandy-gypsiferous formations. Characterized by a shallow water table (rising groundwater phenomenon), it is heavily influenced by irrigation return flows and urban wastewater, leading to excessive mineralization and critical nitrate contamination.

The parameters measured in situ included pH, temperature, and conductivity. Water analysis focused on determining the concentrations of major elements (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-}). Before commencing the study of chemical parameters and validating the analyses, it was deemed necessary to determine the quality of the analyses by calculating the ion balance (IB%) to assess the error rate. The ion balance is a ratio between the difference in concentrations of major cations and major anions and the sum of these concentrations [16]. It is calculated using the following formula:

$$IB(\%) = 100x \left| \sum (Cations) - \sum(Anions) \right| / \sum(Cations) + \sum(Anions) \qquad (1)$$

The concentrations of cations and anions are expressed in meq/l.

- 0 < IB < 5%: Excellent analysis results
- 5% < IB < 10%: Usable analysis results
- IB > 10%: Analysis results to be redone

sampling and measurements

A comprehensive sampling campaign, designated as the 2023 baseline survey, was executed by the Algerian Water Company (ADE) laboratory team. Comprising both in situ parameters and laboratory analyses, this dataset establishes a robust baseline for the hydrochemical characterization of the Complex Terminal Aquifer in El Oued Region.

Table 1 illustrates that the results of the analyzed water samples are satisfactory and can be used in terms of ion balance.

Table 1. Ion balance results (IB in %)

Drilling	IB (%)	Drilling	IB (%)
W1	5.376	W21	1.578
W2	5.860	W22	3.374
W3	2.353	W23	3.873
W4	5.541	W24	3.129
W5	1.459	W25	7.066
W6	6.935	W26	6.749
W7	6.566	W27	3.422
W9	5.941	W28	1.193
W10	2.583	W29	5.050
W11	7.086	W30	7.345
W12	4.661	W31	3.008
W13	7.059	W32	1.737
W14	2.137	W33	2.773
W16	8.669	W34	3.924
W17	7.561	W35	0.240
W18	1.084	W36	1.942
W19	1.259	W37	7.248
W20	-1.204	W39	7.868

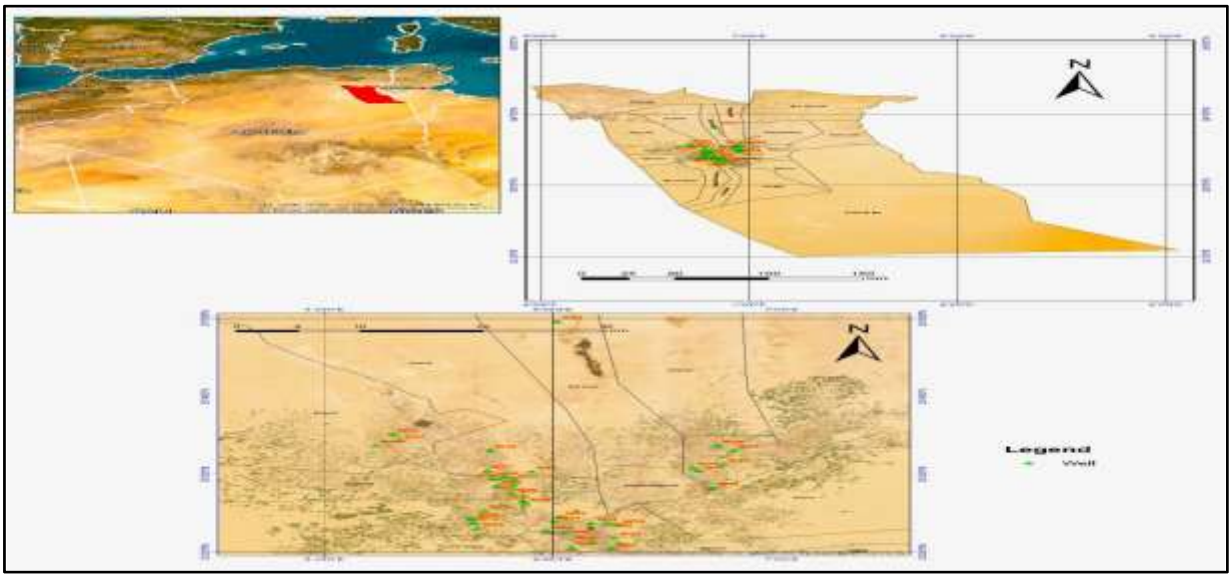

Figure 1. Geographic location of the study area

RESULTS AND DISCUSSION

physicochemical characteristics of the study area

Table 2 provides a summary of the physicochemical characteristics of the parameters analyzed from the groundwater samples taken and their compliance or not with Algerian standards [17] and the standards of the World Health Organization [18].

Table 2. Water classification standards according to Algerian and World Health Organization (WHO) (Official Journal of the Algerian Republic, 2011; World Health Organization, 2017)

Variables	Min	Max	Means	Standard deviation	Algerian Standards (2011)	WHO Standards (2017)
Ca^{2+} (mg/l)	260.52	420.84	323.809	33.82	200	75
Mg^{2+} (mg/l)	53.47	226.036	134.799	45.83	-	50
Na^{+} (mg/l)	241.3	647.5	455.39	105.54	200	200
K^{+} (mg/l)	16	45.21	33.112	7.26	12	12
NH_4^{+} (mg/l)	0	1.104	0.038	0.19	0.5	-
Cl- (mg/l)	560.157	1481.935	939.088	242.55	500	250
SO_4^{2-} (mg/l)	246.66	1325	925.988	295.06	400	250
HCO_3^{-} (mg/l)	46.36	146.4	117.0	14.2	-	120
NO_3^{-} (mg/l)	0.983	33.452	18.0	6.3	50	50
PO_4^{3-} (mg/l)	0	3.27	0.6	0.70	-	-
pH	7.12	7.74	7.4	0.10	6.5-9.5	6.5-8.5
T (°C)	12.2	25.6	20.7	4.8	25	-
Cond (μS/cm)	2330	4070	3561	291.1	2800	1000
TH (mg/l)	920	1800	1357	222.3	500	300
TAC (mg/l)	38	120	95.9	11.7	-	-

multivariate statistical analysis

principal component analysis

The principal component analysis (PCA) aims to reduce the dimensionality of data while finding the most important linear combinations of variables and to examine the characteristics of groundwater in the study area. Several previous studies have highlighted the importance of this method, such as those by [19], [20], [21], [22]. The principal component analysis (PCA) has also been used to synthesize information and compare the characteristics of groundwater, as reported in the studies by [3], [4], [5], [23], [24], [25], [26].

The Pearson correlations obtained in Table 3 for Terminal Complex (TC) groundwater in El Oued region reveal an evolved hydrochemical system dominated by sulfated-sodic mineralization, magnesium hardness, and anthropogenic influences. The strong correlation between Na^{+} and SO_4^{2-} (r=0.71) and between Na^{+} and electrical conductivity (r=0.53) indicates sodium's major contribution to total salinity, while the weak relationship between Ca^{2+} and SO_4^{2-} (r=0.24) suggests simple gypsum dissolution cannot fully explain water composition. This pattern reflects advanced cation exchange and evolution toward a sulfated-sodic facies, consistent with previous TC studies.

Total hardness is primarily magnesium-controlled, as evidenced by the very strong Mg^{2+}/TH correlation (r=0.93) versus the moderate Ca^{2+}/TH relationship (r=0.55). This confirms predominantly magnesian hardness, indicating complex geochemical evolution through magnesium mineral dissolution and rock-water interactions in the TC. Additionally, negative correlations between pH/conductivity (r=−0.73), pH/SO_4^{2-} (r=−0.57), and HCO_3^{-}/conductivity (r=−0.56) reflect declining alkalinity in highly mineralized waters, while NO_3^{-} and PO_4^{3-} relationships suggest agricultural anthropogenic inputs.

Overall, Terminal Complex aquifer (TC) in El Oued region hydrochemistry results from evaporite dissolution, ion exchange, saline concentration, and diffuse pollution superimposed on geogenic background. The use of principal component analysis (PCA) has revealed two distinct groups among the 36 wells studied in the F1-F2 plots, as illustrated in Figures 2a and 2b.

The first group is from wells W18, W19, W20, W21, W22,

W23, W27, W28, W29, W30, W31, W32, W33, W34, W35, W36, W37, and W39. The second group includes wells W1, W2, W3, W4, W5, W6, W7, W9, W10, W11, W12, W13, W14, W16, W17, W24, W25, W26.

Table 3. Correlation matrix of physicochemical parameters of water in the El Oued region

Variables	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	NH^{4+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}	PO_4^{3-}	pH	T	Cond	TH	TAC
Ca^{+2}															
Mg^{+2}	0.21	1.00													
Na^{+}	-0.04	0.08	1.00												
K^{+}	-0.31	-0.19	0.03	1.00											
$NH4^{+}$	0.07	-0.05	0.00	0.20	1.00										
Cl^{-}	0.46	0.30	-0.05	-0.42	0.03	1.00									
SO_4^{2-}	0.24	0.38	0.71	-0.28	-0.35	0.17	1.00								
HCO_3^{-}	-0.20	0.10	-0.39	0.07	0.07	0.04	-0.42	1.00							
NO_3^{-}	-0.07	0.04	0.43	0.04	-0.09	-0.24	0.41	-0.54	1.00						
PO_4^{3-}	0.06	-0.04	0.40	-0.17	-0.12	-0.20	0.40	-0.54	0.56	1.00					
pH	-0.32	-0.23	-0.49	0.28	0.05	-0.22	-0.57	0.55	-0.64	-0.47	1.00				
T	0.10	0.14	0.68	-0.18	0.16	0.16	0.62	-0.24	0.13	0.18	-0.39	1.00			
Cond	0.26	0.41	0.53	-0.20	-0.12	0.20	0.61	-0.56	0.59	0.43	-0.73	0.40	1.00		
TH	0.55	0.93	0.06	-0.28	-0.02	0.43	0.42	0.01	0.02	-0.01	-0C.32	0.16	0.45	1.00	
TAC	-0.20	0.10	-0.39	0.07	0.07	0.04	-0.42	1.00	-0.54	-0.54	0.55	-0.24	-0.56	0.01	1.00

The principal component analysis, summarized in Table 4, identified five significant components that together account for 54.38% of the total hydrochemical variability observed across the study area. The first axis (F1), which alone explains 35.40% of the variance, acts as the main driver of overall mineralization, while the second axis (F2), contributing 18.98%, helps distinguish between different ionic facies types. Taken together, the F1–F2 factorial plane captures more than half of the active geochemical processes at work in the aquifer, offering a meaningful window into the dominant hydrochemical dynamics. Broadly speaking, the PCA results point to salinization and hardness-related processes as the primary forces shaping groundwater chemistry in the region.

Looking more closely at each factor, Factor 1 emerges as a strong mineralization signal. It is positively associated with electrical conductivity (Cond), sulfates (SO_4^{2-}), sodium (Na^+), temperature, total hardness (TH), and nitrates (NO_3^-), while showing a negative relationship with pH, bicarbonates (HCO_3^-), and alkalinity. This pattern reflects intense mineral loading coupled with a reduced capacity of the water to buffer acidity, a hallmark of highly mineralized groundwater.

Factor 2 sheds light on the role of alkaline-earth ions, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}), alongside chlorides (Cl^-) and total hardness. This factor highlights how these elements contribute to water hardness and the development of saline hydrochemical facies.

Factor 3 points to a more advanced stage of hydrochemical evolution, driven by sodium enrichment and prolonged water-rock interaction, suggesting that some groundwater bodies have undergone significant geochemical transformation along their flow paths.

Factor 4, dominated by ammonium (NH_4^+), stands apart from the geogenic signals of the other factors. Its localized influence likely reflects anthropogenic contamination, possibly linked to agricultural practices or inadequate wastewater management in certain areas. Finally,

Factor 5 captures a minor but distinct contribution from potassium (K^+) and magnesium (Mg^{2+}), representing a secondary geochemical signature that, while limited in scope, adds nuance to the overall hydrochemical picture.

Table 4. Correlations between variables and factors

Parameters	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
Ca^{+2}	0.50	0.47	-0.41	0.30	-0.13	-0.05	-0.10	0.42	-0.20	0.13	0.08	0.01	-0.04	0.00
Mg^{+2}	0.41	0.66	0.10	-0.23	0.52	-0.02	-0.14	-0.15	0.11	-0.04	-0.06	-0.01	-0.04	-0.01
Na^+	0.65	-0.29	0.57	0.14	-0.05	-0.16	0.00	0.06	0.02	-0.01	-0.07	0.30	-0.11	0.00
K^+	-0.35	-0.39	0.13	0.28	0.58	-0.34	0.22	0.32	0.11	-0.08	-0.04	-0.10	0.02	0.00
$NH4^+$	-0.14	0.06	0.14	0.83	0.23	0.39	-0.12	-0.12	0.06	0.14	-0.02	0.05	0.08	0.00
Cl^-	0.24	0.68	0.03	0.13	-0.37	0.13	0.44	0.07	0.30	0.01	-0.13	-0.04	-0.03	0.00
SO_4^{2-}	0.80	-0.02	0.31	-0.24	-0.13	-0.26	-0.08	0.05	0.04	0.25	-0.10	-0.03	0.19	0.00
HCO_3^-	-0.69	0.34	0.53	-0.21	0.04	0.21	0.04	0.15	-0.12	0.02	0.03	0.01	0.02	0.00
NO_3^-	0.56	-0.56	-0.02	-0.18	0.27	0.29	0.24	-0.04	-0.13	0.28	-0.08	-0.10	-0.11	0.00
PO_4^{3-}	0.51	-0.48	0.01	-0.22	-0.05	0.45	-0.30	0.29	0.26	-0.12	-0.02	-0.05	0.00	0.00
pH	-0.84	-0.04	0.05	-0.07	-0.06	-0.19	-0.17	0.00	0.30	0.29	0.19	-0.01	-0.09	0.00
T	0.56	0.03	0.61	0.33	-0.25	-0.14	-0.14	-0.09	-0.07	-0.08	0.06	-0.27	-0.08	0.00
Cond	0.84	-0.02	0.09	-0.06	0.14	0.11	0.26	-0.04	0.06	-0.05	0.40	0.04	0.06	0.00
TH	0.54	0.73	-0.08	-0.08	0.38	-0.04	-0.15	0.03	0.02	0.02	-0.02	0.00	-0.04	0.01
TAC	-0.69	0.34	0.53	-0.21	0.04	0.21	0.04	0.15	-0.12	0.02	0.03	0.01	0.02	0.00

hierarchical cluster analysis

Hierarchical Cluster Analysis (HAC) is a commonly used statistical method for the analysis of hydro-chemical water data, aimed at determining natural statistical groups or structures in the data. This method is often used in conjunction with Principal Component Analysis (PCA) and is particularly useful for analyzing chemical water data due to the complexity of hydrochemical systems and the challenges associated with their interpretation. In this article focusing on the El Oued region, an analysis of Hierarchical Ascending Classification (HAC) was conducted to obtain a collection of distinct observation groups based on hydrochemical parameters. The objective of this study was to classify the data into specific

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groups for further statistical analysis. The results of this analysis could have important implications for water resource management and conservation in the region. Several previous studies have also used HAC in combination with other statistical methods for groundwater analysis in different regions worldwide, including Algeria [4], [5], [23], [27], [28].

In this study, we used fifteen hydrochemical parameters, namely Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-}, PO_4^{3-}, pH, T, Electrical Conductivity (Cond), Total Hardness (TH), and the complete alkalimetric titer (TAC).

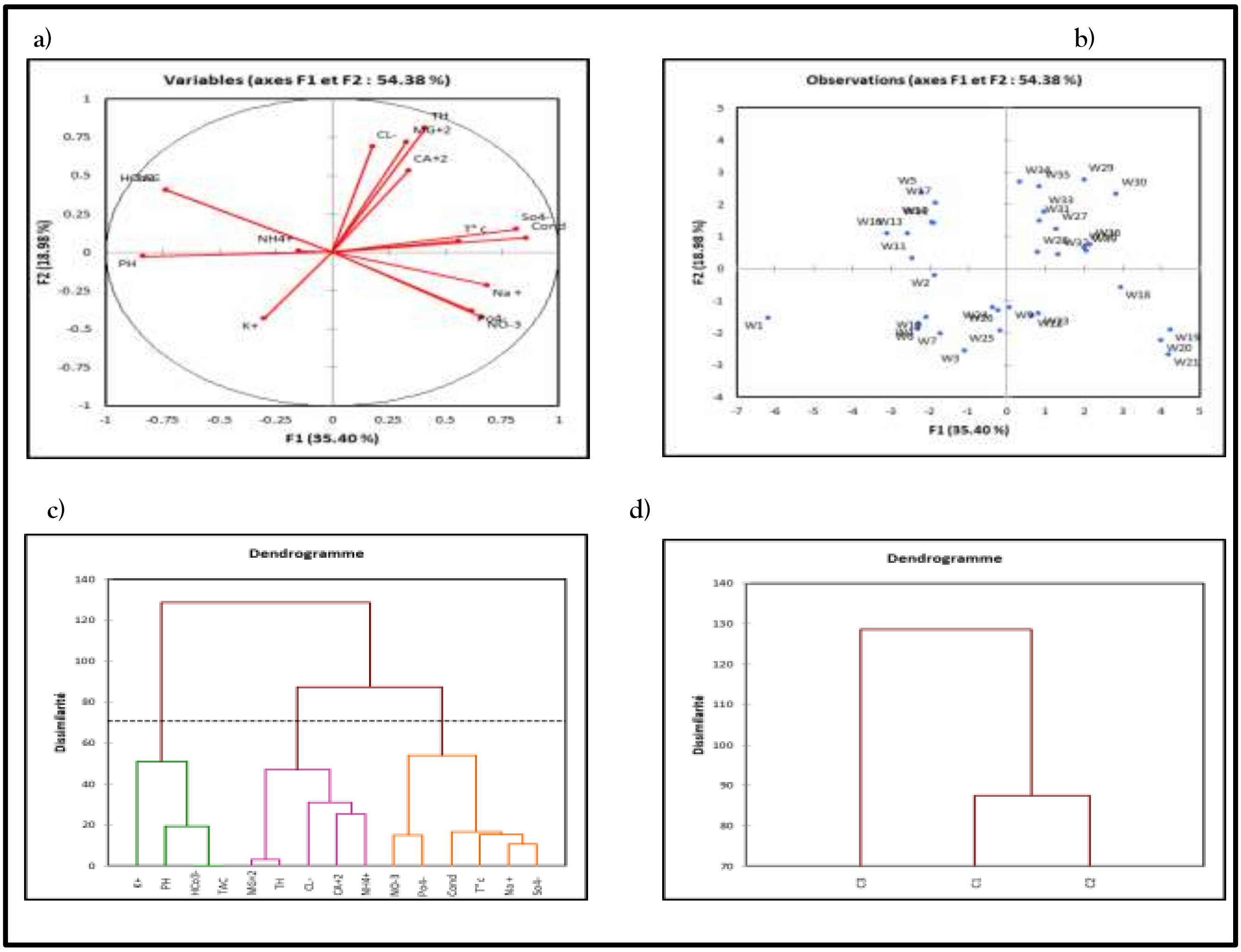
The classes were chosen based on their visual appearance in the dendrogram of Figures 1c and 1d. The fifteen parameters were classified into three groups, namely:

- Group 1 (C1): Ca^{2+}, Mg^{2+}, Cl^{-}, and TH
- Group 2 (C2): Cond (Conductivity), NO_3^{-}, PO_4^{3-}, T, SO_4^{2-}, and Na^{+}
- Group 3 (C3): NH_4^{+}, K^{+}, TAC, HCO_3^{-}, and pH

After grouping the hydrochemical parameters into three clusters, applying the same previous technique on the entire groundwater samples collected from the studied wells. The results of this grouped analysis are presented in details in Figures 2e, 2f which show the existence of three different well families (C1, C2, and C3), each exhibiting distinct chemical characteristics based on the degree of mineralization.

These groups include:

- Group 1 (C1): Wells W1, W2, W3, W4, W6, W7, W9, W10, W11, W12, W13, W14, W16, W17, W22, W23, W24, W25, W26
- Group 2 (C2): Wells W5, W18, W27, W28, W29, W30, W31, W32, W33, W34, W35, W36, W37, W39
- Group 3 (C3): Wells W19, W20, and W21



e) f)

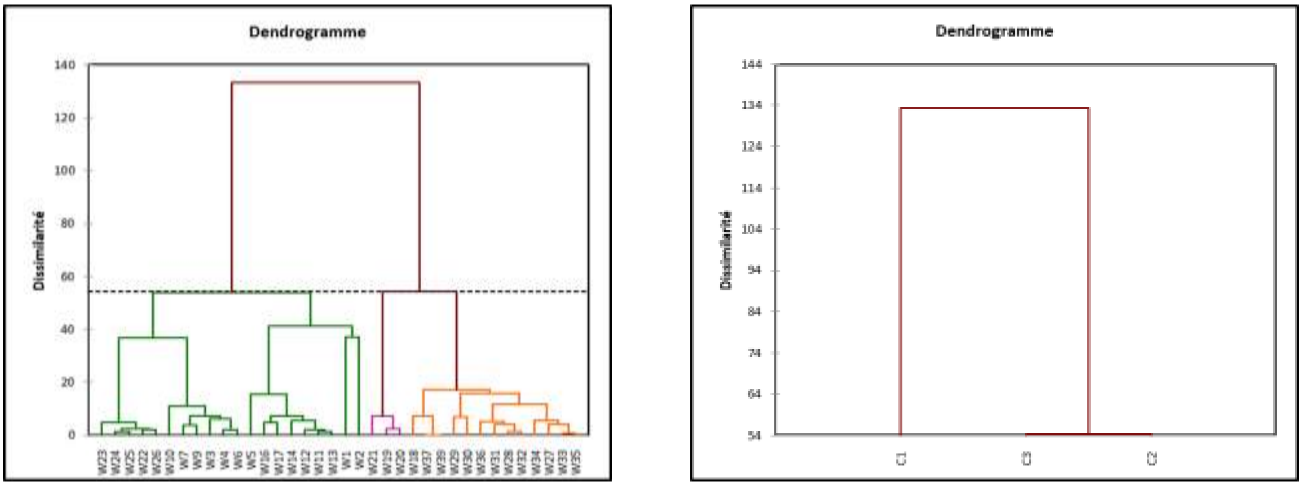


Figure 2. Correlations between variables and factors: a), b), Classification dendrogram for variables: in fifteen groups c) and in three groups d), Cluster dendrogram: in 39 groups e) and in three groups f)

Diagrams

piper diagram

The Piper diagram was used to represent the different chemical facies of a set of water samples. This type of diagram is often used to study the evolution of water with increasing mineralization, to identify the main types of anions and cations present in the water, and to classify samples into groups. Figure 3 presents the representation of the chemical analysis results of the water samples collected from the 39 water wells on the Piper diagram. It is known that calcium and magnesium are the main cations, and sulfates and chlorides are the main anions for all the samples studied. Figure 3 presents the hydrochemical facies of the water in the studies area.

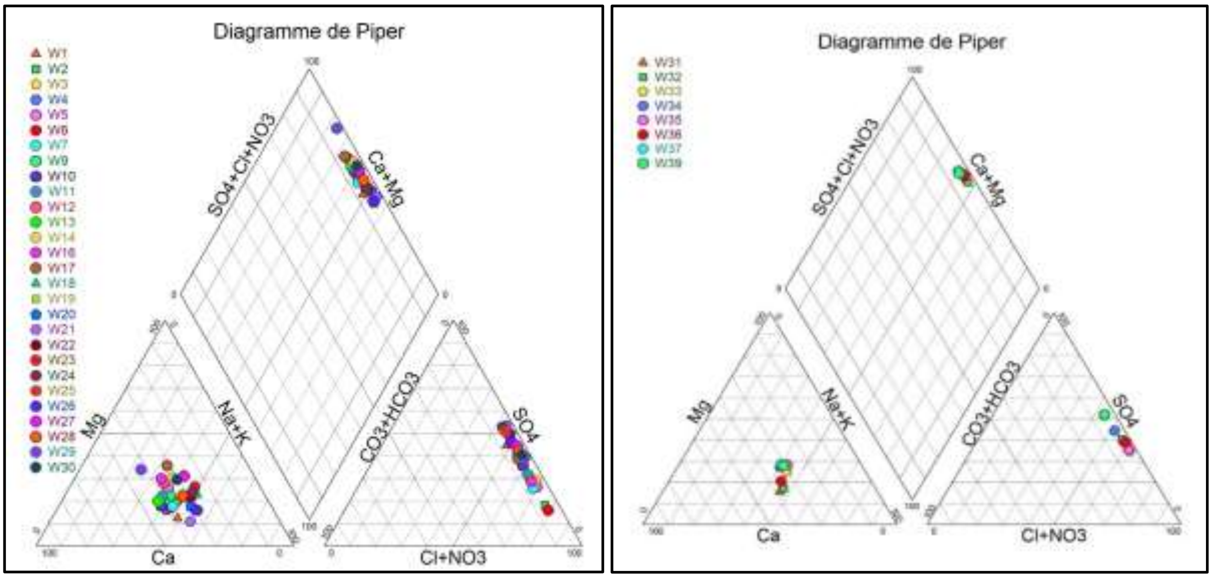


Figure 3. Classification of water wells in the Terminal Complex Aquifer (El Oued region) on the Piper diagram

The Piper diagrams reveal that the groundwater of the Terminal Complex in the Oued Souf region is dominated by a sulfate-rich hydrochemical facies, with a progressive tendency toward sodium enrichment in several samples. In the cationic triangle, most samples plot in the Ca–Mg domain, indicating that alkaline-earth cations remain predominant, whereas a number of samples show a shift toward the Na+K apex, which reflects hydrochemical evolution and cation-exchange reactions. In the anionic triangle, the samples are concentrated toward the SO4 pole, confirming the predominance of sulfate over bicarbonate and chloride-nitrate species. Taken together, these patterns indicate that the groundwater chemistry is mainly controlled by evaporite dissolution, especially gypsum-bearing formations, followed by ion-exchange processes that progressively increase Na^+ in solution while reducing the relative contribution of Ca^{2+} and Mg^{2+}.

The central diamond confirms an overall transition from a calcium-magnesium sulfate facies toward a sulphate-sodic facies. This evolution is typical of groundwater circulating through evaporitic sediments in arid environments and is consistent with prolonged water-rock interaction, high residence time, and geochemical concentration processes. The presence of a few samples displaced toward the Na+K and SO4 poles suggests local hydrochemical heterogeneity, probably related to differences in recharge conditions, circulation depth, and possible anthropogenic influence. These results are in agreement with previous studies conducted on the same aquifer system, which reported high mineralization and strong evaporitic control in the Oued Souf Terminal Complex.

From a practical point of view, this hydrochemical facies indicates hard and highly mineralized groundwater, which is unsuitable for direct domestic use without treatment.

The observed composition supports the need for softening and desalination-oriented treatment strategies, particularly in zones where sodium and sulfate enrichment is strongest.

schoeller-berkaloff diagram

The semi-logarithmic Schoeller-Berkaloff diagram is widely used in the field of hydrochemistry to graphically represent the chemical composition of groundwater. Numerous studies have demonstrated the effectiveness of this diagram in characterizing the chemical quality of groundwater in various contexts [29]. The Schoeller-Berkaloff diagram indicates a highly mineralized and broadly homogeneous groundwater composition in the Terminal Complex of the Oued Souf region, with nearly parallel sample profiles reflecting a common hadrochemical evolution. The dominance of Na+K, Cl, and SO4, together with the lower relative contribution of Ca, Mg, and HCO3+CO3, supports a sulfated-sodic facies with local chlorinated tendencies. This pattern is consistent with groundwater influenced mainly by evaporite dissolution and ion-exchange processes,
while the weak bicarbonate signal suggests limited carbonate buffering.

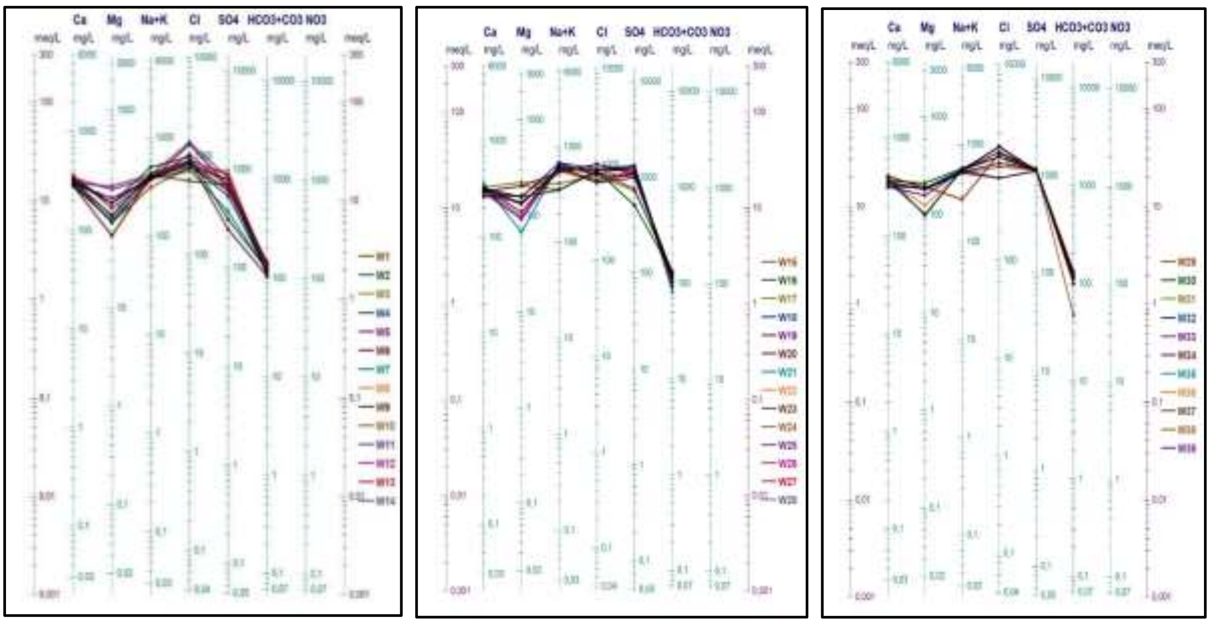


Figure 4. Classification of water wells in the Terminal Complex Aquifer (El Oued region) on the Schoeller-Berkaloff diagram

The small variations observed in Ca, Mg, and NO3 among the samples likely reflect differences in residence time, depth of circulation, and local anthropogenic inputs. Overall, the diagram confirms the presence of hard, chemically evolved groundwater, typical of Saharan aquifers developed in evaporitic environments, and it supports the need for treatment before domestic use.

Water Quality Index and drinking suitability

In addition to the hadrochemical facies and multivariate analysis, the Water Quality Index (WQI) was used to provide a practical measure of the overall drinking suitability of groundwater. (WQI) is a commonly used tool for assessing water quality [30]. It is widely accepted as one of the most effective tools for assessing and analysing water quality, particularly with regard to its potability.

Provided a comprehensive picture of the quality of groundwater for most domestic uses, the water quality index (WQI) is defined as a rating of that reflects the composite influence of different water quality parameters [31]. This method of calculation has been used for many decades by scientists and other actors to assess water quality on a global scale [32]. Its main objective is to assess the suitability of groundwater for human consumption.

In this study, we calculated the (WQI) for the groundwater of the CT aquifer in the Souf region with reference to who drinking water quality standards [18]. This calculation involves several methodological steps that make it possible to synthesize the chemical data and obtain an overall measure of water quality. As a first step, it is necessary to assign a weight (wi) to each chemical parameter, on a scale of 1 to 5, where higher values indicate a greater influence on water quality, based on their impact on human health and geochemistry (Table 5). Indeed EC, Cl^-, and SO_4^- have received maximum weight (5) due to their significant health impact once their concentrations exceed the recommended thresholds [33]; [34]; [35]. In contrast, pH and NO_3^- received the lowest weight (1) due to its lesser influence on water quality assessment.

Table 5. The weight and relative weight of each of the chemical parameters used For the WQI determination

Physicochemical Parameters	Unite	WHO Standard (2017)	wi	RWi
Ca^{2+}	mg/l	75	4	0.10
Mg^{2+}	mg/l	50	3	0.07
Na^+	mg/l	200	4	0.10
K^+	mg/l	12	3	0.07
NH_4^+	mg/l			
Cl^-	mg/l	250	5	0.12
So_4^{2-}	mg/l	250	5	0.12
HCo_3^-	mg/l	120	2	0.05
NO_{3-}	mg/l	50	1	0.02
Po_4^-	mg/l			
pH		8.5	1	0.02
Cond	µS/cm	1500	5	0.12
TH	mg/l	500	4	0.10
T° c	C°			
Sum			42	1

As a second step and in order to calculate the (WQI), we use specific formulas, such as those proposed by [34]. Relative weight (RWi) is calculated using the weighted arithmetic index method, as shown in equation (1).

$$RW_i = w_i / \sum_{i=1}^{n} w_i \quad (1)$$

To establish the quality rating scale in step three for each parameter, the concentration of the parameter in each water sample is divided by its respective standards, as defined by the World Health Organization (WHO) in 2017, [18]. The value obtained is then multiplied by 100 according to the equation:

$$q_i = \left(\frac{C_i}{s_i}\right) \times 100 \qquad (2)$$

Where -Ci represents the measured concentration of the parameters in mg/L, qi-corresponds to the quality score, and si- is the limit value established by the World Health Organization (WHO) in 2017, [18] in milligrams per liter [36];

To obtain the values of the water quality index (WQI), we first calculate the values of the sub-indices (SI) as shown equation (3) for each water quality parameter, taking into account the subsequent calculation of the WQI (equation (4).

$$SI_i = W_i \times q_i \qquad (3)$$

$$WQI = \sum_{i=1}^{n} SI_i \qquad (4)$$

The Water Quality Index (WQI) results are categorized into five distinct categories to assess drinking water quality as shown in Table 6.

Table 6. Water quality index classification of drinking water (Sahu and Sikdar, 2008; Yidana and Yidana, 2010)

WQI value for drinking purpose	Type of groundwater water
<50	Excellent water
50 - 100	Good water
100 - 200	Poor water
200 ÷ 300	Very poor water
>300	Water unsuitable for drinking

The (WQI) provides an integrated assessment of groundwater suitability by combining the effects of the main physicochemical parameters into a single quality indicator.

In the present study, the (WQI) values indicate that groundwater from the Terminal Complex aquifer is of poor to unsuitable quality for drinking purposes. The values, ranging from 222, 55 to 339, 13 (Table 7) clearly indicate that the groundwater in the study area is of very poor water quality unfit for domestic consumption.

These results are consistent with the high salinity, significant magnesium-related hardness, and sodium sulfate facies identified by correlation analysis, PCA, and hydrochemical diagrams. They confirm that the observed mineralization and hardness result in poor water quality, thus highlighting the need for appropriate treatment and a management strategy focused on water softening.

Table 7. WQI and classification of groundwater from Terminal Complex Aquifer (El Oued region)

Sample	WQI	Classification	Sample	WQI	Classification
W1	222.55	Very Poor Water	W21	275.54	Very Poor Water
W2	278.20	Very Poor Water	W22	276.51	Very Poor Water
W3	275.46	Very Poor Water	W23	275.26	Very Poor Water
W4	258.50	Very Poor Water	W24	266.45	Very Poor Water
W5	294.29	Very Poor Water	W25	254.58	Very Poor Water
W6	256.09	Very Poor Water	W26	271.37	Very Poor Water
W7	245.04	Very Poor Water	W27	292.66	Very Poor Water
W9	292.06	Very Poor Water	W28	275.83	Very Poor Water
W10	240.84	Very Poor Water	W29	298.31	Very Poor Water
W11	280.57	Very Poor Water	W30	314.21	Unsuitable Water
W12	307.51	Unsuitable Water	W31	287.32	Very Poor Water

W13	291.63	Very Poor Water	W32	279.63	Very Poor Water
W14	320.03	Unsuitable Water	W33	293.59	Very Poor Water
W16	279.04	Very Poor Water	W34	289.88	Very Poor Water
W17	305.85	Unsuitable Water	W35	300.19	Unsuitable Water
W18	339.13	Unsuitable Water	W36	280.65	Very Poor Water
W19	282.04	Very Poor Water	W37	277.60	Very Poor Water
W20	277.67	Very Poor Water	W39	280.15	Very Poor Water

CONCLUSION

This study provides an integrated hydrochemical assessment of groundwater from the Terminal Complex aquifer in Oued Souf region, southeastern Algeria. The combination of correlation analysis, multivariate statistics, hydrochemical diagrams, and the Water Quality Index reveals that the groundwater is strongly mineralized, hard, and chemically evolved.

The results show that sulfate-sodic mineralization, magnesium-dominated hardness, and limited bicarbonate buffering are the main features controlling water chemistry. The Piper and Schoeller-Berkaloff diagrams confirm the dominance of sulfate-rich facies, while the (WQI) indicates that most samples are of very poor quality or unsuitable for drinking.

These findings demonstrate that groundwater quality in the study area is not compatible with direct domestic use without treatment. In particular, the strong contribution of magnesium to total hardness highlights the need for a dedicated softening strategy rather than a simple partial treatment focused only on calcium removal.

Overall, the study not only characterizes the hydrochemical status of the Terminal Complex aquifer, but also provides a scientific basis for treatment-oriented management. The results support the next step of the research, which consists in modeling and optimizing an appropriate softening process for hard Algerian groundwater.

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