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Hydrochemical and geoelectrical investigation to determine the origin and spatial distribution of the salinization of the unconfined Plio-Quaternary aquifer of Tabeditt, Southern Tunisia

Indagine idrochimica e geoelettrica per determinare l'origine a la distribuzione spaziale della salinizzazione dell'acquifero non confinato del Plio-Quaternario di Tabeditt, Sud Tunisia

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Riassunto

L'espansione dell'agricoltura irrigua ed il sovrasfruttamento delle acque sotterranee nella regione del Tabeditt ha provocato un serio deterioramento della qualità chimica delle acque. La raccolta di studi a carettere idrogeologico e geofisico è essenziale per valutare la qualità delle acque nel Plio-Quaternario e per determinarne l'origine e la salinizzazione. In questo studio sono state condotte analisi idrochimiche su campioni di acque sotterranee della regione di Tabeditt. I dati idrochimici hanno mostrato che la salinità in quest'area può eccedere i 6 g/L. L'interpretazione delle analisi sugli ioni principali dimostra che la mineralizzazione è controllata da processi naturali. Il processo di mineralizzazione consiste nella dissoluzione di minerali evaporitici, vale a dire gesso, anidrite e halite. L'indagine geoelettrica è stata condotta per ottenere informazioni sulla distribuzione e la qualità delle acque nel Plio-Quaternario. L'interpretazione dei modelli di resistività mostra la presenza di due aree principali: la prima, vicina Tabeditt Wadi, è caratterizzata da bassi valori, che indicano l'influenza di acque saline nell'acquifero e la seconda, localizzata sulla riva destra del Wadi Jmal, è contraddistinta da valori variabili di resistività, in genere alti, collegati a variazioni laterali delle facise litologiche ed alla presenza di acque dolci. In una regione così arida che soffre di scarsità e di deterioramento (o esaurimento) delle risorse idriche, è fondamentale mettere a punto un piano generale che tenga sotto controllo il numero dei pozzi, sia noti che non, che captano questi acquiferi.

Abstract

The expansion of irrigated agriculture and the overexploitation of groundwater in the Tabeditt region lead to a serious deterioration of the chemical quality of water. The compilation of hydrogeological and geophysical studies is essential in order to assess the quality of the Plio-Quaternary waters and to determine the origin of the salinization of these waters. In this study, hydrochemical analyses were carried out on groundwater samples in the Tabeditt region. Hydrochemical data have shown that the salinity in this area could exceed 6 g/L. The interpretation of major ion analyses demonstrates that mineralization is controlled by natural processes. The mineralization process consists of the dissolu-tion of evaporite minerals, namely gypsum, anhydrite, and halite. The geoelectrical study is carried out to obtain information about the distribution and quality of water in the Plio-Quaternary. Interpreta-tion of the resistivity models show the presence of two main zones: the first, near Tabeditt Wadi, is characterized by low values, indicating the influence of salt water in the groundwater and the second, located on the right bank of Wadi Jmal, is characterized by variable resistivity values, generally high, indicating the lateral changes in lithological facies, and the presence of fresh water. In such an arid region suffering from scarcity and degradation (or depletion) of water resources, it is important to implement a master plan that keeps under control the number of wells both known and unknown ones taping these aquifers.

Introduction

Agricultural production depends heavily on water quantity and quality. In fact, high quality water in-creases agricultural productivity and economic growth (Egbueri and Unigwe, 2019). In addition, good quality water helps to improve the productivity of the industrial sector (Sajil Kumar and James, 2019; Egbueri, 2020b). Economic growth has become threatened by water scarcity, especially in the Medi-terranean countries where renewable water resources are becoming scarce e (Nicolas et al., 2018). The factors driving water scarcity are complex as being controlled by many factors. Therefore, it is useful to adopt appropriate methodologies that increase access to safe and high quality water and address the impacts of water scarcity by using various methodologies, including hydrochemistry and geo-physics (Pilla and Torrese, 2022; Marwa et al., 2023), and field investigations (Burbery, 2018; Jones et al., 2020).

In Tunisia, rainfall is generally insufficient and very irregular, making irrigation necessary for agricul-ture. There seems to be a technical need for the regulation and increase of agricultural production in regions where rainfall is insufficient, such as the Gafsa region, located in the center-west of Tunisia. This region is considered a relatively arid region (Salhi, 2017). In recent years, this region has been faced with many problems related to insufficient watershortages both in quality and quantity. The sali-nization of shallow unconfined aquifers has become a widespread challenge.

The mechanisms responsible for the salinity of a hydrogeological system are diverse and complex. They depend on the geographical, geological, and climatic contexts. For this reason, the investiga-tion/ determination of the saline load of the aquifers has been the subject of several studies. In some cases, dissolution or alteration of evaporates and carbonates (Mhamdi et al., 20015; Rajmohan et al., 2021; Tarki et al., 2020) or the return of concentrated surface irrigation water by evaporation also plays a major role. Evapotranspiration, overexploitation (Micol and Nicolo, 2021; Olusegun et al., 2021; Frol-lini et al., 2022), a long residence time of the water in the aquifer (Vetrimurugan et al., 2019), the intake of brines from Sebkhas could in some cases explain the salinization of the aquifers (Lotfi et al., 2018).

The region of Tabeditt (Fig. 1) has an arid climate, with evaporation (1600 mm/year) greater than rainfall (120 mm/year) on average (Regional Commissary for Agricultural Development Gafsa, 2018). It is the site of an increase in agricultural activities, resulting in increased demand for water resources and a gradual deterioration in the chemical composition of these waters.

The Tabeddit region, part of the Moularès-Redayef basin, is characterised by the presence of two main aquifers: a shallow one, (sandy clay sediments of Plio-Quaternary) and a deep, Miocene sand aquifer. A clay layer separates these aquifers.

In this study, hydrogeological information from the Plio-Quaternary and hydrochemical groundwater analyses are used in conjunction with resistivity data to identify possible factors and processes that control groundwater quality. The main objectives of this study are: chemical characterization of groundwater; identification of processes controlling water quality; assessment of groundwater quality; delineation of the extent of salinization; and identification of the origin of salinization.

Study area

Location and climate

Tabeditt covers an area of approximately 75 km². It is located 7 km from the Moulares region (Fig. 1). The region of Tabeditt, which belongs to the mining basin of Moulares-Redeyef, is located in the southwest of Tunisia (Ben Salem and Chouachi, 1985), in the northwest of the governorate of Gafsa. The climate in this basin is arid to semi-arid (Salhi, 2017). Rainfall is low and irregular. The average annual rainfall is in the range of 130 to 200 mm (Abdelkader et al., 2022). Temperatures are moderate, averaging 21°C annually.

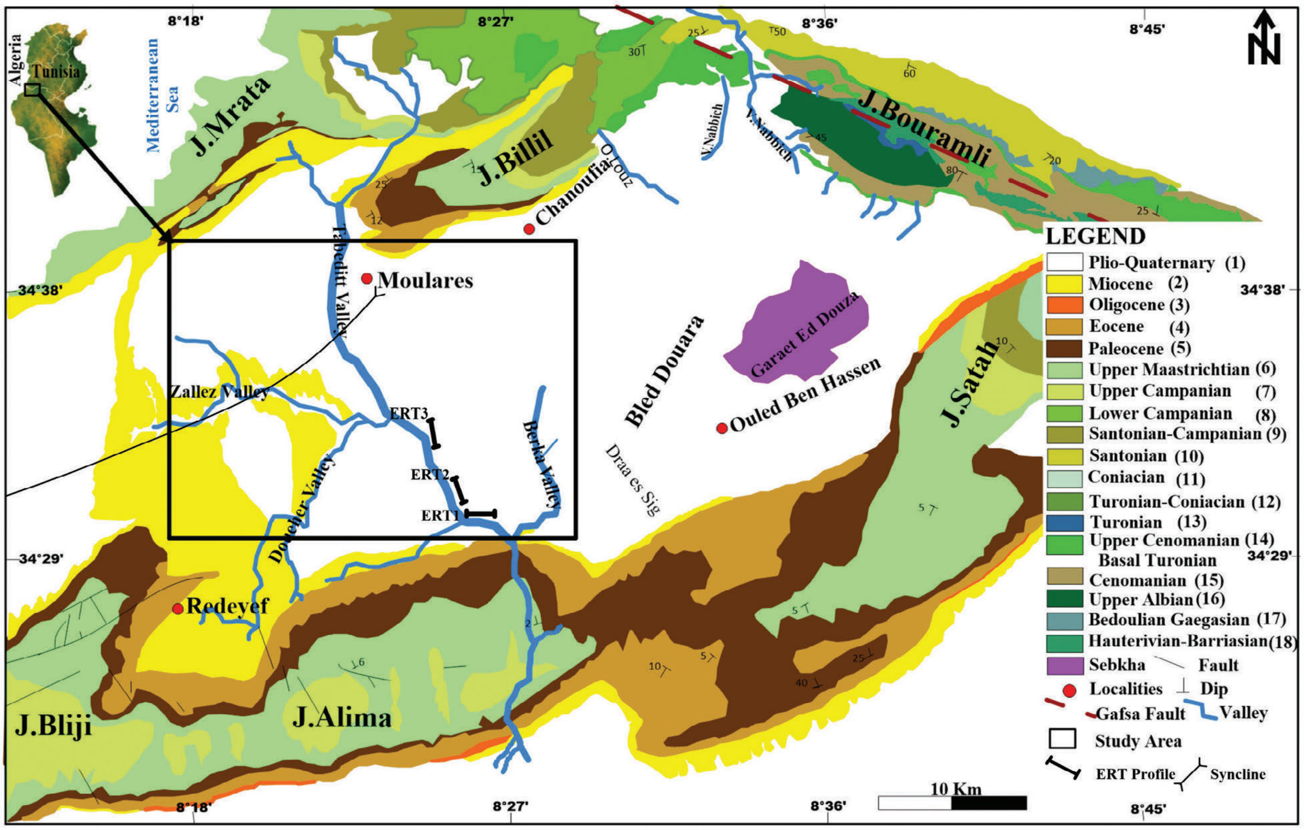
Geology

Tabeditt Region corresponds to the southern western domain of the Tunisian Atlas and integrates the western front of the Moulares-Rédayef mining basin (Amamria et al., 2017; Burollet, 1956). The strati-graphic series of the Moulares-Redayef basin extends from the Lower Cretaceous to the Quaternary (Fig. 1).

The geological formations were described from outcrops, lithological sections of the Moularès boreholes, and geological mapping. Their ages range from Cretaceous to Quaternary (Bédir, 1995; Bouaziz, 1995; Soumaya et al., 2020). The Lower Cretaceous is made up of clays, gypsum, limestones and dolomites. The Upper Cretaceous is represented by Cenomanian-Turonian dolomite and clay-stone thick units, with local gypsum intercalations. On these units deposited the Turonian-Campanian marly and calcareous claystone. The Campanian-Maastrichtian is made up of carbonate deposits. The Paleocene consists of limestone and clay. The Upper Paleocene is made up of dolomite and gypsum fossiliferous clay. The Lower Ypresian is composed of phosphate and phosphate limestone. The Upper Ypresian is made up of fossiliferous limestone. The Lutetian series consists of white dolomite at the base and massive gypsum. The Oligocene is composed of silt and clay sandstone with locally thick conglomerates at the base. This latter is covered by the oldest continental Neogene clay and silty conglomerate deposits of the Oligocene. These are overlain by the sandstone of the Middle and Late Miocene which consists of sands. The Pliocene-Quaternar is represented by heterogeneous deposits composed of clays, silts, sands and evaporites.

The entire Southern Atlas is located between two major tectonic structures (Zouari, 1992), the Gafsa Fault and the corridor south of Chebika (Zargouni, 1985).

The Moularès-Rédayef basin is characterized by a relatively dense hydrographic network that consists of several non perennial valleys, the main ones being Tabeditt Valley, Jemel Valley, Thelja Valley, El Berka Valley,Redayef Valley, and



1 : clays, silts, sands, gravels, gypsum and conglomerate ; 2 : sands ; 3 : silty claystone ; 4 : gypsum, limestones, phosphate, claystone and marl ; 5 : claystone and marl ; 6 : limestones ; 7 : limestones, claystone and marl ; 8 : limestones and claystone ; 9 : claystone ; 10 : claystone and marl ; 11 : limestones and marl ; 12 : limestones ; 13 : dolomitic limestones, claystone ; 14 : limestones, claystone and gypsum levels ; 15 :Clay with dolomitic and gypsum levels ; 16 : limestones and dolomites ; 17 : alternation of limestones, clays and gypsum levels ; 18 : sands, clays, gypsum, limestones with dolomitic levels

Fig. 1 - Simplified geological map of the study area.

Fig. 1 - Carta geologica semplificata dell'area di studio.

Moularès Valley (Fig. 2). These valleys collect rainwater from the surrounding Mountains areas towards the center of the basin. The region's water resources are there-fore essentially underground and in the form of deep groundwater. West of Gafsa, the chains of re-liefs of the Bliji-Alima-Satah jebels in the south and Mrata-Billil in the north are separated by a large NE-SO syncline: the Moularès-Redayef basin (Hamed et al., 2014). Within this Great Basin, there are two main hydrogeological watersheds separated by the Miocene Aquifer divide (Farhat, 1984) the Ta-merza basin and the Moularès-Redayef basin. This basin has two aquifers: the clay sand aquifer of Plio-Quaternary and the sandy aquifer of Miocene epoch. Surface water flows into Chott Gharsa and Garâat Douza through a river system divided into two sub-watersheds: the Tabeditt valley basin in the center of the Moularès-Redayef basin and the Garâat Douza basin east of the Moularès-Redayef ba-sin (Farhat, 1984).

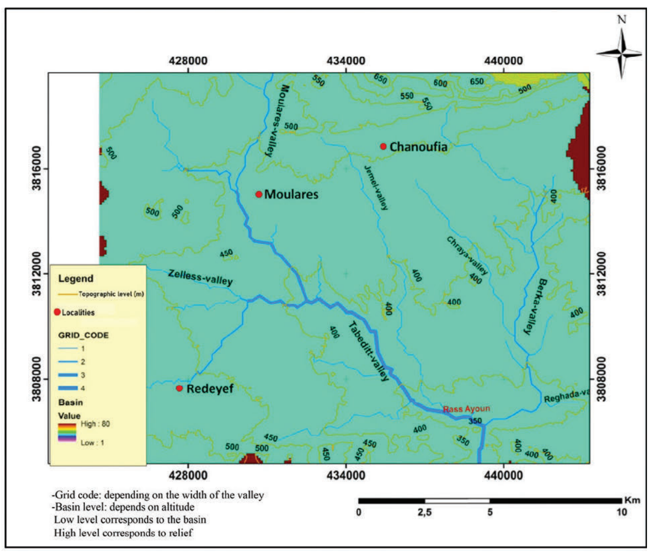


Fig. 2 - Hydrographical network of the study area.

Fig. 2 - Reticolo idrografico dell'area di studio.

Hydrogeology

The natural recharge of the unconfined Plio-Quaternary aquifer is achieved not only by direct infiltra-tion of rainwater but also by the flooding of the Tabeditt valley, Jemel valley an El Berka valley. How-ever, the natural recharge has become very limited due to the lack of rainfall in recent years. In addi-tion, the study area is located to the west of Garaat Douza Sebkha, which represents the natural dis-charge area. Consequently, Garaat Douza Sebkha presents the area of evaporation (Abdelkader et al., 2022). This situation could influence the chemical quality of the Tabeditt waters (the salts deposited in the sebkha will be transported and deposited in the recharge zones of the water table. Part of these salts will leach again into the groundwater). Another source of salinization is the lithological nature of the aquifer itself or the hydraulic exchanges through the evaporite layers that are part of the aquifer (Najib et al., 2017; Mirzavand and Fereydoun, 2022).

The 2020 (in September) piezometric map of the unconfined Plio-Quaternary aquifer shows that the piezometric values vary from north-west to south-east from 385 m a.s.l. to 305 m (Fig. 3). According to this map, the general direction of groundwater flow, is from basin borders towards its center (the axis of the syncline). Over-exploitation of the Plio-Quaternary groundwater reserves has led to a signi-ficant decrease in water levels (i.e. 0.2 m/year over the last decade). This situation would un-doubtedly increase the risk of saltwater intrusion.

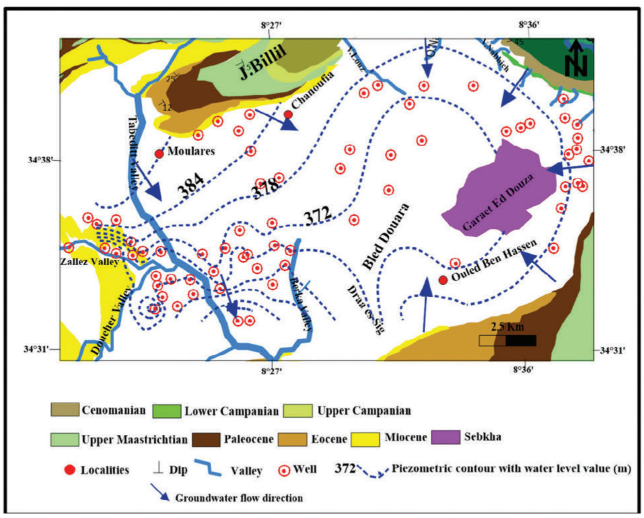


Fig. 3 - Piezometric map of the unconfined Plio-Quaternary aquifer (September 2020).
Fig. 3 - Carta delle isopieze dell'acquifero non confinato del Plio-Quaternario (Settembre 2020).

Geological cross-section

In order to investigate the geometry of the groundwater, a northwest-southeast lithostratigraphic cross section (Fig. 4) based on borehole data was established. It shows that the unconfined Plio-Quaternary aquifer is essentially composed of sand, clayey sand and sandy clay, while the clay forms an impermeable layer that separates the Plio-Quaternary aquifer from the deep one (Fig. 5). The thikness of the Plio-Quaternary aquifer exceeds 150 m in the Moulares borehole (Fig. 5), which is practically located on the axis of the Moulares-Rédayef basin syncline. Towards the west, the thick-ness of the Plio-Quaternary aquifer decreases.

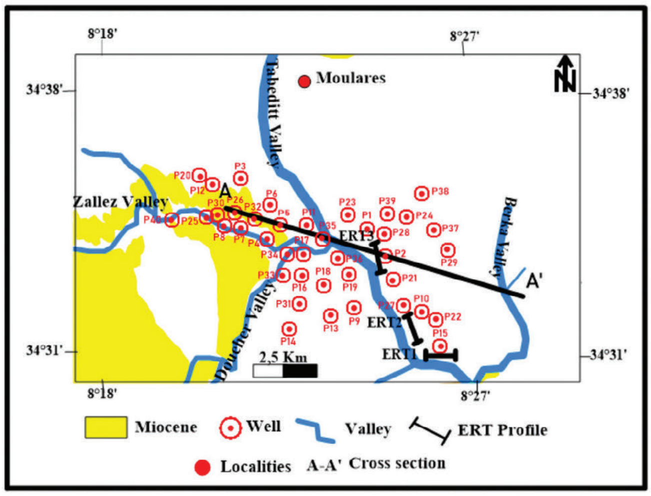


Fig. 4 - Location and sampling map showing the emplacement of the ERT profiles.
Fig. 4 - Ubicazione dei campionamenti e del profilo ERT .

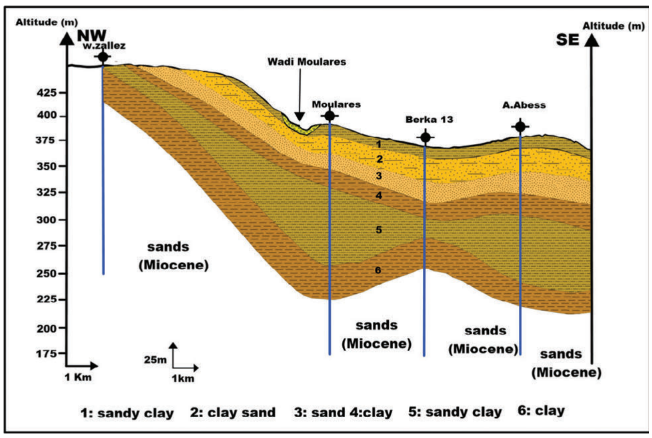


Fig. 5 - Cross section (AA') between Boreholes.
Fig. 5 - Sezione geologica (AA').

Materials and methods

Sampling and hydrochemical analysis

In the study area there are two types of wells: dug wells and tube wells. Generally, the depth of these wells does not exceed 50 m (between 10 and 50 m). A sampling campaign was conducted in Sep-tember 2020 and consisted in collecting fourty representative water samples from private wells dug into the shallow aquifers made of sand (Fig. 4). The samples were collected after well purging, filter-ing using 0.45 μm filters, and placed in acid-rinsed 100-ml polyethylene bottles for major ion anal-yses. These bottles are conserved at a temperature of 5°C.

In situ measurements including water temperature (T), Electrical Conductivity (EC), pH, and Total Dis-solved Solids (TDS), using a multi-parameter water analyzer. Chemical analysis of the major elements was conducted at the Regional Commissary for Agricultural Development laboratory in Kasserine (Table 1), using Ion Chromatography coupled with conductivity detection whereas the bicarbonate was measured by the titration method. Three standard methods were adopted for the chemical analyses: (1) the EPA Method

300.7 for Inorganic cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), (2) the EPA Method 300.1 for major anions (Cl^-, SO_4^{2-}) and (3) the 2320 B standard for HCO_3^-.

The ionic measurement accuracy is determined by calculating the absolute error in the ionic equili-brium. This error must not exceed the standard limit (± 5%) for all samples. The TDS of the water samples are estimated experimentally by integrating the conductivities and the summation of major ion concentrations. The saturation index (SI) of groundwater with respect to halite, gypsum and anhydrite are considered important indicators of the dissolution of these evaporate minerals. The satura-tion index values have been computed using the Phreeq interface in the Diagramm software (version 6.48, distributed by the Hydrogeology Laboratory of Avignon).

Electrical Resistivity Tomography (ERT)

ERT is a non-destructive subsurface exploration technique that has been widely applied, also for solving hydrogeological problems (Ling et al., 2016; Alshehri and Kamal, 2021; González et al., 2021).This technique has been applied on the surface to obtain a comprehensive image of the sub-surface in order to characterize the path of groundwater and to interpret salinization in the groundwater (Braham et al., 2022; Rochdane et al., 2022; Marwa et al., 2023).

Three resistivity profiles were conducted, where ERT 1 is oriented in E-W direction while ERT 2 and ERT 3 follow the NNW-SSE direction (Fig. 4). These profiles were made using a compact SYSCAL Pro stand-alone resistivity meter with 48 electrodes, spaced 5 m apart. The Wenner electrode configu-ration is the simplest type of array, in which the four electrodes - A, M, N and B - are arranged in a line, equidistant from each other. The two outer electrodes, A and B, are current electrodes and the two inner electrodes, M and N, are potential electrodes. With the Wenner configuration, the resistivity of the subsurface layers is found by increasing the distance between the electrodes while maintaining the position of the centre of the array. Wenner configuration was used to investigate the resistivity characteristics of up to 40 m deep section to follow the lateral variation in facies and to highlight and delineate the freshwater-saltwater interface. The acquired apparent resistivity data were inverted using the Res2Dinv software (Loke, 2010). The analysis is made on the assumption of 2 D structure. The 2-D model used by the inversion program consists of a large number of rectangular grids. The distribution and size of the grids are automatically generated by the program based on the minimum spacing be-tween the electrodes. The depth of the model space is set to be approximately equal to the median depth of investigation (Edwards, 1977) of the data points with the largest electrode spacing.

A finite-difference or finite-element modeling subroutine is used to calculate the theoretical apparent resistivity values, and a non-linear smoothness-constrained least-squares optimization technique is used to modify model parameters (de Groot-Hedlin and Constable, 1990). The result of the inversion is represented by a resistivity section showing the distribution of the true resistivity values in the model domain.

Results

ERT

The established resistivity tomography profiles (ERT) were calibrated with the logging data of wells P2 and P15.

ERT 2 and ERT 3 (Fig. 6 b, c) show that the unconfined Plio-Quaternary aquifer is characterized by low resistivity rangng from 1 to 8 Ohm.m. The lithology of the aquifer corresponds to a hetero-geneous unit composed of sands, clays and evaporate deposits. The water in this aquifer is salty. However, ERT 1 (Fig. 6 a) shows that the Plio-Quaternary aquifer is characterized by variable resistivi-ty, ranging from 1 to 35 Ohm.m .The aquifer is made up of unit composed of sand, gravel and pebbles. It is possible to distinguish two different qualities of water contained in the aquifer. Low values of (1- 8 Ohm.m) that indicate indicate the presence of salt-water, while resistivity values above 8 ohm.m, indicate the presence of moderately salt-water saturated sediments.

Interpretation of hydrochemical properties

In order to assess groundwater quality characteristics in relation to drinking and irrigation requirements (Wagh et al., 2017; Vinay et al., 2023), certain parameters are interpreted. The results of the physico-chemical analyses of well water from the Tabeditt region are shown in Table 1. The pH values revealed that all the groundwater samples were neutral to slightly alkaline. This result is within the safe limits specified in the WHO standard (WHO standards, 2011). The slightly alkaline nature of the groundwater is probably due to the presence of carbonate soils in the area. Groundwater well-head temperatures vary between 18°C and 24°C. The variations of the temperature of the groundwater could be explained by the return of variable amounts of irrigation water. The TDS map (Fig. 7) shows three zones: An area west of Tabeditt valley with relatively low TDS of 288 mg/L to 3288 mg/L, an intermediate zone cha-racterized values rangining between 3288 mg/L and 6288 mg/L, and an area East of Tabeddit valley were TDS is greater than 6288 mg/L.

Groundwater geochemistry was initially characterized by the identification of water types using the Piper diagram (Kelly, 2006), with the central left and right corners of the diamond occupied by the freshwater and salt water poles, respectively. However, the regions between these poles correspond to conserved mixed regions (Najib et al., 2017).

Groundwater samples monitored in this area were affected by mixing without ion exchange reactions (Fig. 8). The pooling of groundwater samples from the Tabeddit aquifer in the Piper diagram shows that SO_4–Cl/Na–Ca is the dominant aqueous phase. In general, anion abundance shows the evolution of $SO_4^{2-}>Cl^->HCO_3^-$. While cation abundance showed the evolution of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. The study of the correlations between anion/∑anions and cation/∑cations can provide information on the pro-cesses of acquiring the

Tab. 1 - In situ measurements geochemical data and saturation Indexes of groundwaters.
Tab. 1 - Dati idrochimici dei campioni di acque sotterranee relative all'acquifero del Plio-Quaternario.

	In situ measurements			Elemental composition					
Well N°	T (°c)	PH	Ec (mS/cm)	TDS (mg/L)	Ca2+ (meq/L)	Mg^{2+} (meq/L)	Na^{+} (meq/L)	K^{+} (meq/L)	Cl^{-}(meq/L)
P1	21	7,56	2,12	1574	21,93	12,41	22,86	1,19	28,68
P2	23	7,48	0,49	376	22,09	11,73	19,07	1,19	26,88
P3	23	7,34	0,65	488	24	13,43	23,98	1,19	29,14
P4	24	7,3	5,94	3602	25,54	13,25	24,55	1,19	30,53
P5	19	7,55	6,1	3267	24,37	12,08	19,89	1,19	25,96
P6	20	7,27	1,01	542	25,04	14,34	24,13	1,19	29,15
P7	22	7,68	1,43	1378	25,66	12,93	22,48	1,19	26,19
P8	24	7,48	0,52	529	23,32	11,98	24,36	1,19	27,22
P9	21	7,33	1,48	1294	25,42	14,65	24,15	1,19	29,33
P10	20	7,39	3,34	3349	22,61	11,6	18,85	1,19	27,36
P11	24	7,22	0,35	570	19,97	10,09	15,88	1,19	21,25
P12	22	7,45	0,26	433	18,47	10,01	14,55	1,19	20,95
P13	21	7,35	0,32	380	18,52	10,05	14,66	1,19	19,83
P14	19	7,57	2,06	1538	23,03	12,08	19,85	1,19	26,69
P15	21	7,11	5,47	6119	24,56	11,2	22,87	1,19	27,45
P16	21	7,61	0,74	366	18,52	10,02	12,92	1,19	20,81
P17	19	7,53	2,29	1872	20,52	10,9	16,12	1,19	23,75
P18	22	7,39	3,91	3160	23,32	12,16	21,03	1,19	25,99
P19	22	7,23	0,25	528	25,31	11,5	22,79	1,19	27,28
P20	22	7,27	4,7	4540	25,67	10,69	24,45	1,19	28,97
P21	20	7,38	2,45	2080	25,94	9,91	24,67	1,19	26,94
P22	21	7,46	1,75	1336	25,944	14,98	23,91	1,19	28,95
P23	23	7,34	1,39	1136	25,94	13,53	25,49	1,19	30,81
P24	22	7,2	3,47	2870	25,94	12,85	18,56	1,19	25,38
P25	21	7,25	3,23	2720	25,94	12,06	20,6	1,19	22,74
P26	21	7,32	4,26	3512	25,94	11,2	23,27	1,19	26,99
P27	18	7,27	0,74	612	25,94	10,95	22,31	1,19	27,03
P28	23	7,56	0,91	752	25,94	12,68	22,84	1,19	26,27
P29	20	7,26	0,38	288	25,94	10,26	19,08	1,19	24,48
P30	22	7,57	3,55	3013	25,94	14,9	25	1,19	26,97
P31	22	7,38	0,12	319	25,94	12,69	21,86	1,19	28,49
P32	21	7,32	0,38	554	25,94	13,14	24,6	1,19	29,06
P33	21	7,41	0,49	562	25,94	13,16	23,65	1,19	27,97
P34	22	7,51	0,49	3153	25,94	13,58	25,05	1,19	30,68
P35	22	7,46	0,49	468	25,94	11,06	23,22	1,19	26,81
P36	19	7,37	0,49	4063	25,94	12,25	22,08	1,19	28,85
P37	20	7,62	0,49	7702	25,94	13,13	22,52	1,19	28,61
P38	24	7,32	0,49	6387	25,94	12,95	23,48	1,19	28,32
P39	19	7,73	0,49	1550	25,94	13,97	25,28	1,19	31,49
P40	21	7,32	0,49	9479	25,94	14,49	24,31	1,19	31,46

Tab. 1 - In situ measurements geochemical data and saturation Indexes of groundwaters.
Tab. 1 - Dati idrochimici dei campioni di acque sotterranee relative all'acquifero del Plio-Quaternario.

	Elemental composition		Saturation Indexes (SI)					
Well N°	HCO_3^-(meq/L)	SO_4^{2-}(meq/L)	Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Halite
P1	3,17	27,5	-0,52	0,43	0,58	0,98	-0,29	-4,96
P2	3,56	27,03	-0,51	0,44	0,58	0,99	-0,28	-5,07
P3	2,17	28,63	-0,48	0,11	0,25	0,36	-0,25	-4,94
P4	4,45	29,13	-0,46	0,41	0,56	0,94	-0,23	-4,91
P5	4,55	27,42	-0,48	0,59	0,74	1,23	-0,24	-5,06
P6	4,27	28,71	-0,47	0,3	0,45	0,73	-0,24	-4,93
P7	4,43	27,78	-0,46	0,77	0,91	1,62	-0,24	-5,01
P8	3,71	26,6	-0,51	0,49	0,63	1,09	-0,28	-4,96
P9	4,81	27,14	-0,49	0,44	0,59	1,01	-0,26	-4,93
P10	3,87	25,79	-0,52	0,36	0,51	0,79	-0,28	-5,06
P11	2,45	21,81	-0,59	0,03	0,17	0,16	-0,37	-5,24
P12	2,16	20,71	-0,63	0,15	0,3	0,42	-0,4	-5,28
P13	2,64	21,19	-0,62	0,12	0,27	0,35	-0,39	-5,29
P14	2,95	26,1	-0,51	0,41	0,56	0,89	-0,27	-5,04
P15	3,16	26	-0,49	0,04	0,19	0,11	-0,26	-4,98
P16	2,41	19,48	-0,65	0,35	0,5	0,8	-0,42	-5,33
P17	2,5	22,9	-0,58	0,27	0,42	0,63	-0,34	-5,18
P18	4,97	24,89	-0,53	0,51	0,65	1,12	-0,3	-5,04
P19	2,94	26,4	-0,48	0,15	0,3	0,35	-0,25	-4,98
P20	2,88	27,94	-0,45	0,18	0,33	0,36	-0,22	-4,93
P21	4,69	25,55	-0,48	0,48	0,63	0,91	-0,24	-4,95
P22	4,03	27,58	-0,48	0,5	0,64	1,13	-0,25	-4,94
P23	4,78	28,74	-0,47	0,47	0,61	1,05	-0,24	-4,89
P24	2,53	25,14	-0,54	0,01	0,16	0,17	-0,31	-5,1
P25	3,02	25,76	-0,51	0,14	0,28	0,37	-0,28	-5,1
P26	2,99	25,99	-0,51	0,21	0,35	0,46	-0,27	-4,98
P27	2,12	25,67	-0,5	-0,03	0,12	-0,05	-0,26	-4,98
P28	3,29	26,28	-0,5	0,52	0,67	1,15	-0,27	-5
P29	4,39	24,25	-0,55	0,28	0,42	0,59	-0,31	-5,1
P30	3,82	30,24	-0,44	0,59	0,73	1,32	-0,21	-4,96
P31	2,82	26,39	-0,49	0,27	0,42	0,64	-0,26	-4,98
P32	2,24	28,22	-0,46	0,1	0,25	0,29	-0,23	-4,93
P33	3,26	26,88	-0,48	0,36	0,51	0,8	-0,25	-4,96
P34	4,38	28,99	-0,44	0,62	0,76	1,31	-0,21	-4,9
P35	2,15	27,29	-0,46	0,25	0,4	0,51	-0,23	-4,98
P36	3,61	27,2	-0,46	0,34	0,49	0,71	-0,22	-4,97
P37	2,36	28,73	-0,46	0,39	0,54	0,87	-0,23	-4,97
P38	3,59	26,97	-0,51	0,31	0,45	0,77	-0,29	-4,96
P39	4,35	30,77	-0,43	0,76	0,91	1,6	-0,19	-4,88
P40	3,46	29,43	-0,46	0,28	0,42	0,68	-0,23	-4,9

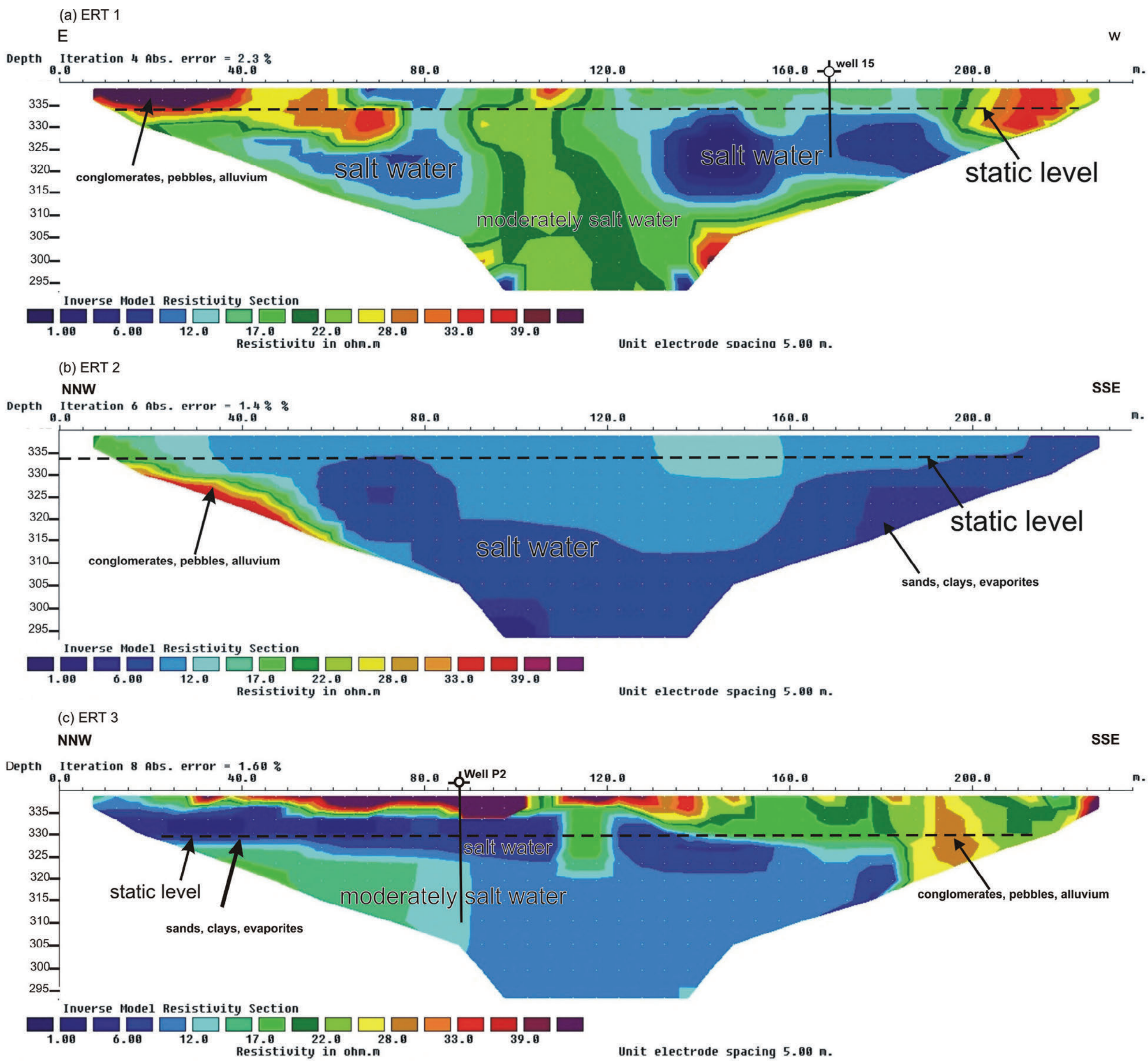


Fig. 6 - 2D resistivity sections.

Fig. 6 - Sezioni 2D di resistività.

saline load in the waters of the Tabeditt Plio-Quaternary layer. Sodium (Na^+) shows a good correlation with the sum of the cations, showing a correlation coefficient very close to 1 (R^2 = 0.939), followed by calcium (Ca2+) (R^2 = 0.904) (Fig. 9). Similarly, sulphate (SO_4^{2-}) shows a good correlation with the sum of anions (R^2 = 0.921), followed by chloride (Cl^-), which has an equal correlation coefficient (0.936) (Fig. 9). However, bicarbonate shows a poor correlation with the sum of anions. This indicates that Calcium (Ca^{2+}), Sulphate (SO_4^{2-}), Sodium (Na^+), and Chloride (Cl^-) play an important role in the acquisition of the saline load of the groundwater studied.

A plot of sodium content as a function of chloride concentration (Fig. 10) shows a good correlation between the two ions.

Water from the Tabeditt Plio-Quaternary aquifer shows a negative halite saturation index, reflecting water under saturation for this mineral. Furthermore, the evolution of the ratio between these negative saturation index (SI) values and the sum of (Na^+ + Cl^-) confirms the dissolution of this mineral and demonstrates the NaCl phase of some groundwater samples. The graphical representation of the evo-lution of calcium as a function of sulphate (Fig. 11) shows a good correlation between these two ele-ments with a correlation coefficient close to unity. In addition, they are characterized by negative va-lues of the saturation indices vs. gypsum and anhydrite (Fig. 11), showing a state of under-saturation of the waters vs. of these two minerals. All these arguments suggest a common origin for these two elements, probably related to the dissolution of gypsum and/or anhydrite.

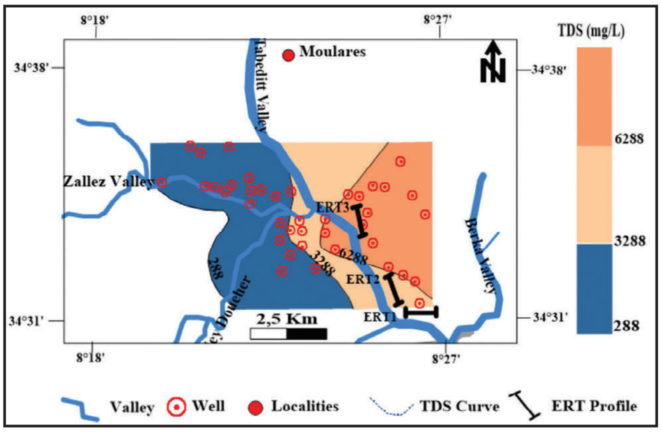


Fig. 7 - Total Dissolved Solids map.

Fig. 7 - Carta della Salinità Totale.

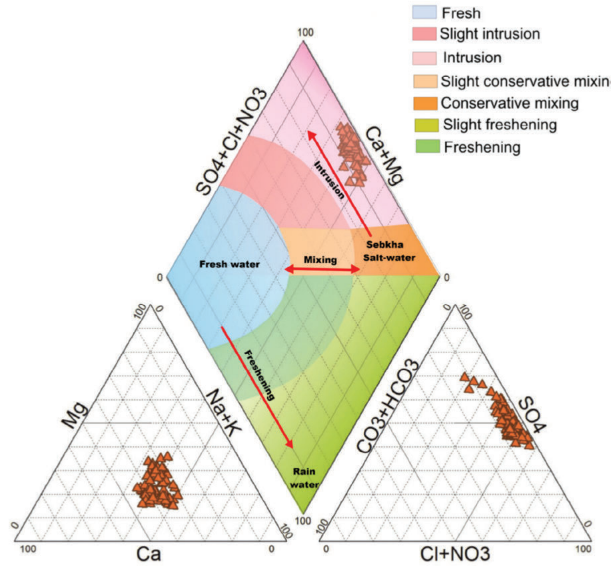


Fig. 8 - Piper diagram of the Plio-Quaternary groundwater samples.

Fig. 8 - Diagramma di Piper dei campioni di acqua del Plio-Quaternario.

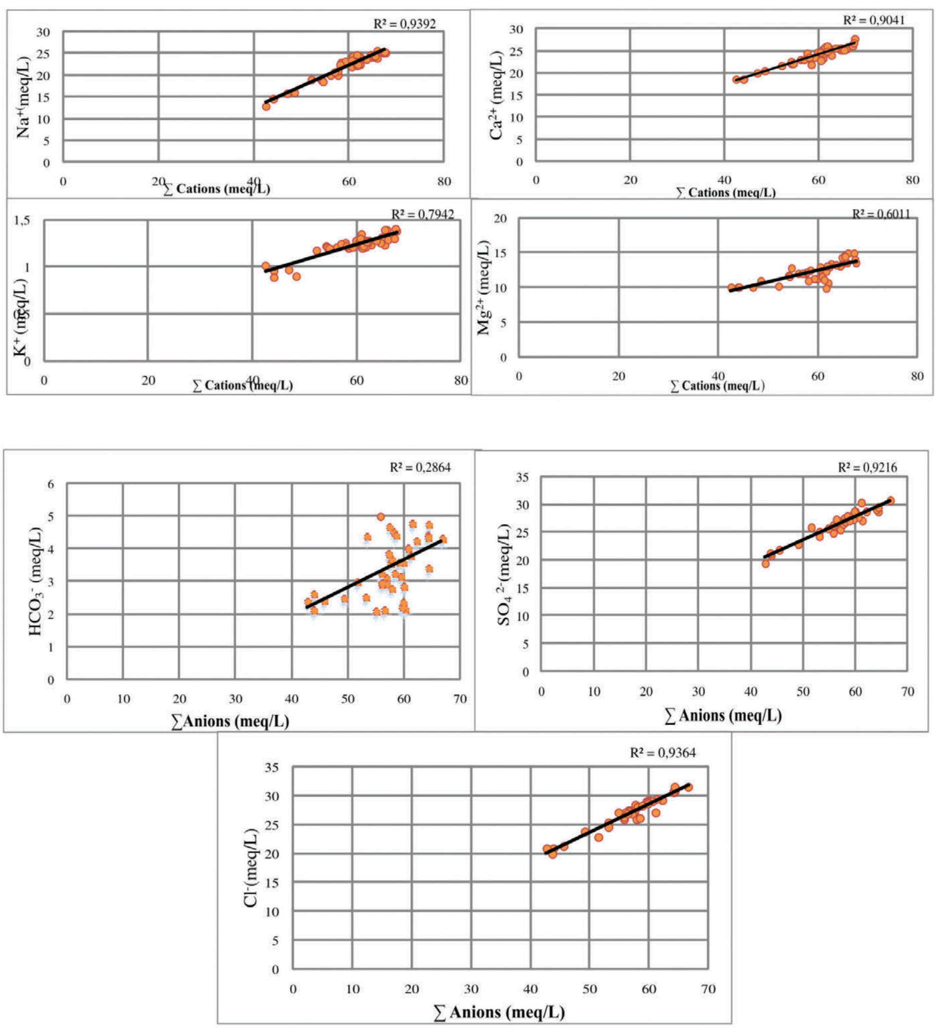


Fig. 9 - Hydrochemical relationships of ∑cations vs. each cation and ∑anions vs. each anion.

Fig. 9 - Correlazione idrochimica tra ∑cationi vs. ciascun catione e tra ∑anioni vs. ciascun anione.

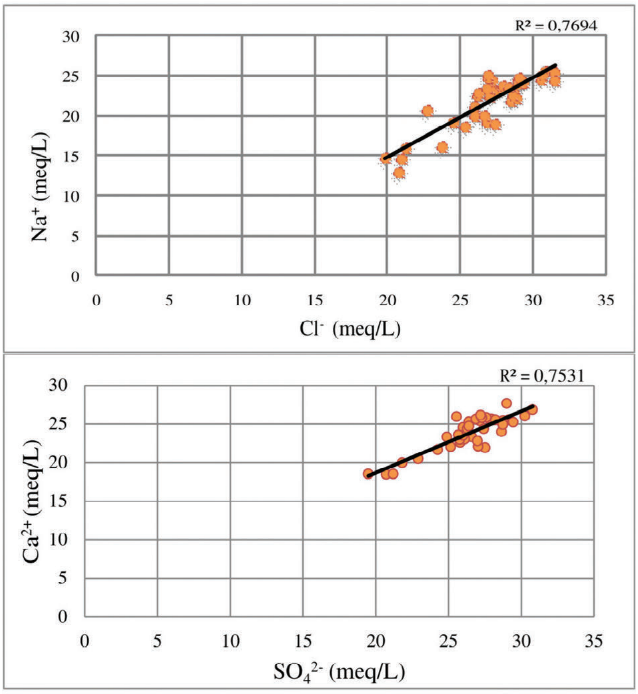


Fig. 10 - Plots of Na vs. Cl and Ca vs. SO_4.
Fig. 10 - Rapporti tra Na vs. Cl, Ca vs. SO_4.

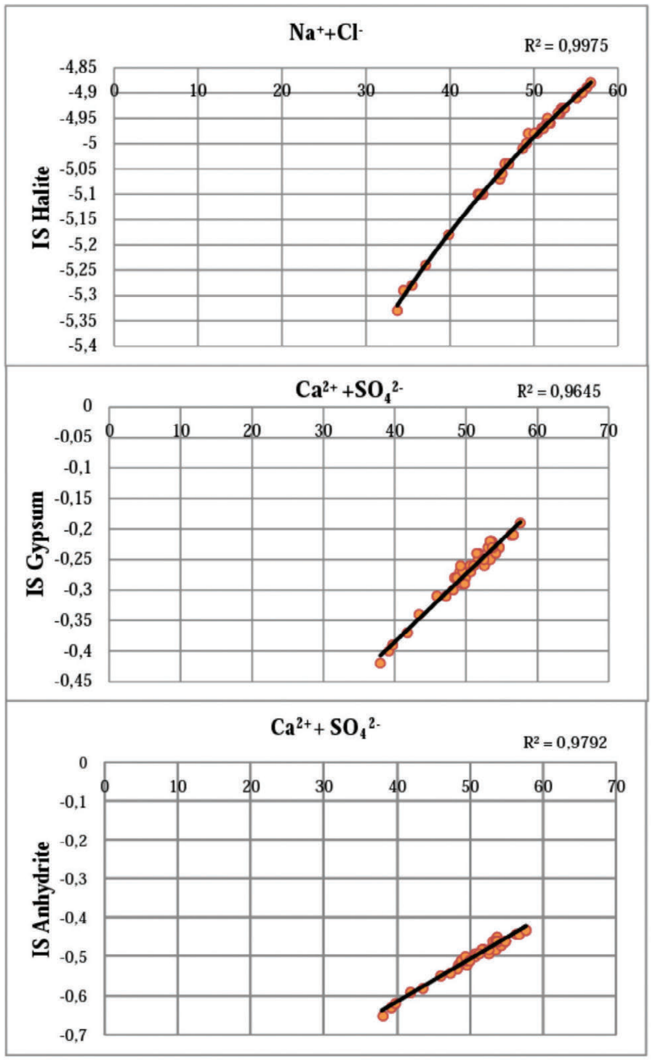


Fig. 11 - Plots of (Na + Cl) vs. SI_{Halite}, (Ca + SO_4) vs. SI_{Gypsum}, (Ca + SO_4) vs. $SI_{Anhydrite}$.
Fig. 11 - Rapporti di (Na + Cl) vs. SI_{Halite}, (Ca + SO_4) vs. SI_{Gypsum}, (Ca + SO_4) vs. $SI_{Anhydrite}$.

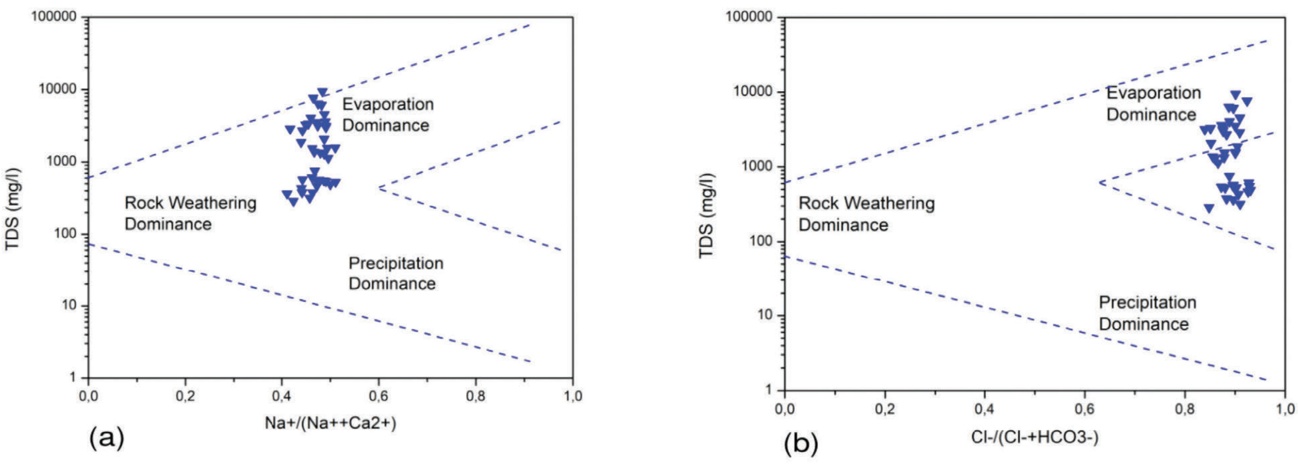


Fig. 12 - Gibbs diagram showing the TDS vs. Na/(Na+Ca) (a) and the TDS vs. Cl/(Cl+HCO_3) (b).
Fig. 12 - Diagramma di Gibbs che mostra la TDS vs. Na/(Na+Ca) (a) e la TDS vs. Cl/(Cl+HCO_3)

Discussion

The Moulares-Redayef phosphate mining basin, located in the southwest of Tunisia, between the Sa-haran Atlas Range and the Saharan Platform, contains groundwater, which is mainly exploited by the industry. In recent years, agriculture and have started to develop more rapidly. All these factors are putting increasing pressure on the demand for potable and irrigation water to meet both industrial and agricultural needs. The Plio-Quaternary is made up of a succession of sandy to sandy-clayey levels, sometimes ending with gypsum. The surface level, mainly made up of fine to medium sands and thin passes of sandy clay, is captured by shallow wells. The hydrodynamic of the Tabeditt valley and the flood waters feed the aquifers of the Plio-Quaternary with fresh water. The lateral variation of the fa-cies is enriched in clay and becomes increasingly thin and rich in gypsum at El Berka.

The main factor influencing groundwater quality is geogenic activity, i.e., the mixing of the rock, rock-water interaction, climatic influence and hydrogeological influence, e.g., high water level, soil compo-sition, and anthropogenic factors, covering human, agricultural, and industrial activities (Lakshmi et al., 2018). For agricultural activities, the assessment of irrigation water quality should focus on salt con-centration, which is the source of soil salinity and affects soil fertility and agricultural yields (Kouadri et al., 2022). Therefore, assessment of the chemical quality of groundwater is essential for the mana-gement of future exploration and exploitation of aquifers and preventing soil contamination.

The mineralization of the Plio-Quaternary layer of Tabeditt is due to the dissolution of evaporate mine-rals. It can be explained by the combined action of water-rock interaction and saltwater intrusion. The wide range of salinity and the presence of some relatively high TDS values are probably related to vertical and horizontal variations in aquifer lithology (Rasheed et al., 2022) and the predominance of highly soluble evaporite deposits in some areas (Ehya and Mosleh, 2018; Al-Harahsheh et al., 2020). In addition, evaporite dissolution processes could explain the high TDS values. Moreover, the climatic conditions characterizing the study area (arid) favour evaporation, which plays an important role in groundwater mineralization. The dominant effect of the evaporation process is confirmed by the Gibbs diagrams (Fig. 12) obtained for the sampled groundwater. Indeed, intensive irrigation, which leads to the leaching of evaporate minerals from the surface soils into the groundwater, is an additio-nal factor (M'nassri et al., 2018, Oussama et al., 2023).

The origin of the salinity of the waters of the Plio-Quaternary layer in the Tabeditt zone is acquired from the flood waters of the Tabeditt valley and its main tributaries that infiltrate during floods. It also comes from runoff from the northern flank of J. Alima and the southern flank of J. Bellil, which flow over the different marl and gypsum formations. These waters are enriched in salts following the leaching of some rocks. These waters then flow to Tabeditt, one part of which seeps into the water table of Tabeditt, and another part evaporates. Hence, a quantity of salts accumulates at the surface level. Thus, in the setting of evaporation, the climate (arid) represents the motor of the evaporation phenomenon. It is from these waters that the dissolved salts will concentrate until they form evaporite minerals (gypsum, anhydrite, and halite) in the Tabeditt region. Rainfall and particularly intensive irriga-tion cause the leaching of evaporite minerals from the surface to the aquifer. As a result, the ground-water will therefore be increasingly enriched with salts.

A strong probable source is the intrusion due to phosphate discharges (Badamasi et al., 2019) in the receiving environments (Redayef valley, Tabeditt valley, Moulares valley, etc.).

The combined use of geophysics (electrical tomography) and hydrochemical analysis has proven to be an effective method for spatial characterization of the Plio-Quaternary aquifer, assessment of groundwater quality (salt and fresh water), and identification of mineralization processes (Abdelkader et al., 2022; Marwa et al., 2023).

Conclusions

In this work, we have involved several disciplines that are both necessary and complementary, namely geology, hydrogeology, hydrochemistry, and geophysics, for the characterization of the Plio-Quaternary at Tabeditt study area.

For hydrogeological understanding the piezometric map of the Tabeditt layer was used to trace the piezometric curves of the unconfined Plio-Quaternary aquifer. The general direction of the under-ground flow is oriented Northwest, Southeast towards Rass el Layoun. The appearance of the izo-piezes west of El Berka suggests a direction towards this sector, the main outlet of the waters of the Plio-Quaternary groundwater.

Chemical analyses show that the waters are of calcium sulphate chlorinated types. These results made it possible to determine the origin of the salinization of the Tabeditt Plio-Quaternary layer, es-pecially in the area near El Berka. This evolution reflects that the mineralization of waters is acquired through interaction with minerals, namely the dissolution of halite, gypsum and, anhydrite.

The water quality assessment revealed that in some parts of the study area, groundwater is chemically unsuitable for drinking or irrigation. The results of the ERT survey, allowed to determine the saliniza-tion extent . Analysis of the tomographic profiles confirms the lenticular aspect of the geometry of the aquifer and determines the extent of salinization. In fact, water quality is assessed using the resis-tivity values of the tomographic profiles, as resitivity and electrical conductivity are intrinsic properties of groundwater chemistry. Since, high resistivity values result from the presence of freshwater and absence of clays and/or evaporites, while low resistivity values could be explained by the presence of saltwater and/or clays and evaporites.The ERT profiles show the presence of two main areas. The first area near Tabeditt Wadi is characterized by low resistivity. The second is located on the right bank of the Jmal Valley. It is characterized by variable resistivity, generally high. The ERT results are confirmed by geochemical interpretation. These results will guide future work on groundwater re-sources. For future research, it is also necessary to improve the study by carrying out additional ana-lyses, such as phosphate, nitrate, and trace elements.These analyses are essential to determine the impact of water on human health.

In addition, more ERT profiles should be planned to be conducted in agricultural areas in order to delineate salinization over a large area of cultivated land. Elsewhere, the control of high salinity, re-medial measures, and proper regulation and monitoring of saline water ingression have become impe-rative. It is necessary to adopt measures based on the control and prohibition of certain human prac-tices, such as intensive irrigation (Habib et al., 2020), overpumping (Meriem et al., 2020), and illegal drilling. Another effective measure is to raise awareness among farmers about the proper use of groundwater. Encouraging farmers to opt for water saving irrigation methods such as dropper and sprinkler irrigation. These irrigation methods reduce water waste and make irrigation more efficient In order to further improve the efficiency of irrigation water, the decision of irrigation timing and irrigation volume is particularly important (Zhang et al., 2018). These measures are particularly important in the study area, which is characterised by an arid climate where freshwater resources are very limited.

Competing interest:

All authors, declare no competing interests.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Dalanda Ltifi], [Abdelkade Mhamdi], and [Lahmadi Moumni]. The first draft of the manuscript was written by [Abdelkade Mhamdi] and [Dalanda Ltifi]. All authors commented on previuos versions of the manuscript and they read and approved the final manuscript. The authors agree to be accountable for the aspects of the work.

Additional information

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