

Review paper

Study of Rejim Maatoug groundwater in southern Tunisia using isotope methods

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Abstract

The Rejim Maatoug aquifer, which located in south-western Tunisia, constitutes a good example of overexploited resources. Hydrogeological and geochemical data were examined to determine the main factors and mechanisms controlling the groundwater chemistry and the hydro-dynamic functioning of this aquifer based on a multi-tracer approach. Thirty-one groundwater samples from the CT Miocene aquifer of Rejim Maatoug and Djerid regions were collected in 2010 for major chemical element analysis. Physical parameters such as temperature, pH and electrical conductivity (EC) were measured in the field. Three groundwater samples were selected for ^{14}C measurements. Four groundwater samples were chosen for ^3H measurements. The chemical data indicates that dissolution of evaporate minerals, evaporation and cation exchange processes seem to be the main factors controlling groundwater mineralization. The geological and hydrogeological studies show the important role of the deep existing faults in controlling the hydrodynamic functioning of the aquifer systems in southern Tunisia. The isotopic data shows that groundwater in this area is a mixture of recent shallow waters located in the Mio-Plio-Quaternary sands and paleo-deep waters of the carbonate Senonian aquifer. Low ^3H and ^{14}C contents, observed in some sampled wells ($^3\text{H} = 0.15 \text{ TU}$ in C1N1, $^{14}\text{C} = 8.8 \text{ pmc}$ in Matr2), indicates that the recharge of the Miocene aquifer occurs mainly through upflow leakage of Senonian deep aquifer while there is no evidence of significant recharge in major part of the plain and mountains piedmonts that can be observed.

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1. Introduction

Chemical and isotope tracers are used to better understand groundwater origin, quantify water–rock interaction, mixing process and recharge rates, as well as to provide timescales of groundwater flow in groundwater systems, on large spatial and temporal scales (Fritz et al., 1979; Fontes, 1980; Gat, 1981; Edmunds et al., 1987).

This study is focused on southern Tunisia which forms a part of the Western Sahara sedimentary basin. It contains two important aquifer systems extending over an area of 780.000 km² (Guendouz et al., 2003): the Continental

Intercalaire (CI) aquifer which overlain by the Complex Terminal (CT). This CT aquifer is considered as one of the main water resources of Rejim Maatoug, Djerid and Nefzaoua regions. In the Rejim Maatoug and Djerid regions, the aquifer is contained in the sequence of sandy and clayey sediments of Miocene. Whereas, in the Nefzaoua region, it is hosted in the carbonate and marl formations of Senonian.

Available surface water is insufficient for current domestic, industrial and agricultural needs of the region. Consequently, groundwater constitutes the main water resource in southern Tunisia.

Exploitation of groundwater in the Rejim Maatoug aquifer started at the end of last century. The conditions in this aquifer system were originally artesian. Nowadays, many wells were drilled to meet the rapidly growing demand for water in the

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agricultural sector essentially. In 2008, the exploitation of the Rejim Maatoug aquifer reached 38.95 million m³ (38.23 million m³ for agriculture uses, 0.71 million m³ for the drinking water supply and 0.01 million m³ for industry uses) (Aggoune, 2008).

Exploitation of groundwater in the Rejim Maatoug aquifer was started since 1977 with artesian well. Nowadays, the water static levels decrease due to the intensive exploitation. This piezometric level declining was appreciably accentuated to reach 8 m–10 m in 1985 and 1993 (case of Rejim Maatoug N°2 and El Guetirai) (Mamou and Baccar, 1994).

Nowadays, piezometric level declining is between 0.5 and 1 m/year (Aggoune, 2005).

Isotope study is an important complementary tool in the evaluation of hydrogeological and hydrochemical controlling processes in any groundwater system. However, isotope studies are only contributory to the solution of hydrogeological and hydrochemical problems and should be considered within the framework of the total hydrogeological knowledge (Lloyd and Heathcote, 1985). The environmental isotopes investigated include the common stable isotopes, oxygen-18 and deuterium, as well as the radioactive isotope of hydrogen, tritium. Excepting in geothermal aquifers, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are conservative properties of the water mass during subsurface flow which can be related to the isotopic composition of the long-term weighted average precipitation at recharge, dependent on surface temperature (Darling and Bath, 1988). Like ^{14}C , both tracers reflect a continuous atmospheric input source, barring any discontinuity in recharge. Signatures emplaced at recharge may be preserved in aquifers on the regional-scale such that downgradient groundwaters effectively act as an archive of past climatic changes which can be used as time markers to further constrain water ages (Fontes et al., 1993). Dissolved signatures significantly different from modern recharge values may indicate different climatic recharge conditions and potentially corroborate palaeo-groundwater ages, i.e. they may reflect past climate changes which for dated palaeowaters reflect surface paleotemperatures of recharge.

A large number of studies (e.g. ERESS, 1972; Gonfiantini et al., 1974; Mamou, 1990; Edmunds et al., 1997, 2003; Gries, 2000; Guendouz and Michelot, 2006; Chkir and Zouari, 2007; Kamel, 2007, 2011; Trabelsi et al., 2009; Abid, et al., 2011, 2012) have been undertaken worldwide to understand the hydrodynamics of the CT aquifer system in such regions and assess the appropriate policies required to maintain the fragile equilibrium between natural evolution and human needs. It has been established that the Complex Terminal is one of the important aquifers in the world.

Intensive exploitation of the aquifer during last decades induced declining water levels, drying up of springs and increased risk to groundwater quality due to salinization. To implement efficient management of these groundwater resources under heavy anthropogenic stress, quantitative information on the dynamics, origin and regional mixing patterns of groundwater in the Djerid and Rejim Maatoug aquifers are needed.

Previous works focused on mixture process in Djerid sector (Nefta and Hzoua) (Kamel, 2011) and Senonian/Turonian

aquifer, treating the recharge conditions and its relationship with the CI (Abid et al., 2012).

However, this study concerns especially regional groundwater in Rejim Maatoug. It aims to identify the relationship between CT aquifer in the Djerid area and the Rejim Maatoug groundwater.

2. Study area, geology and hydrogeology

The study area is situated in northern Africa, between the Algerian border (Ourgla) in the West, the Mediterranean Sea in the East, the Atlas Saharan Mountains in the North, and Libyan–Algerian border in the South (Fig. 1).

The climate of the study area is arid and presents an extreme irregularity due to the fact that it is submitted to (i) the dry and hot Saharan air coming from the west-north (from November to April) and south-western (Sirocco in summer) and to (ii) relatively wet and moderate air from the Mediterranean Sea (from May to October).

Precipitations are rare and irregular, occurring mostly during winter. The mean annual precipitations are about 83.7 mm (DGRE, 2006a,b), varying across the region, and with time. Potential evapotranspiration is about 2546.5 mm per year (Grira, 1986) and most of the rainwater is lost by evaporation.

The CT aquifer is hosted in the Upper Cretaceous and Tertiary formations. The CT formations are relatively heterogeneous and are composed of three main aquifer horizons separated by semi-permeable to impermeable strata. The main productive levels are located in the Upper Senonian (Abiod Formation in Kebili region) or in the Tertiary sandy formation (Beglia Formation in Tozeur and Rejim Maatoug regions).

The calcareous formation of Senonian constitutes the principal aquifer of Nefzaoua region. It outcrops in the Dahar upland and it is reached in Rejim Maatoug region at depth of 400 m (RM6 well, Fig. 2). The West-East cross section (Fig. 2), extending between Matrouha 2 and Sabria Mol Miocene wells, shows the continuity of upper Senonian limestones from Nefzaoua to Rejim Maatoug regions.

The Mio-Pliocene is constituted by a sandy formation with intercalation of red clay and quartz levels. The RM6 well crossed the totality of sandy Miocene reservoir where the thickness is about 131 m. The aquifer formation is covered by 131 m of compact clay levels (Fig. 2).

This cross section shows that the West of Rejim Maatoug constituted a faulted area. These NW-SE faults seem to be responsible for the compartmentalization of groundwater flow patterns and can play a part of intercommunication between the sandy Miocene aquifer and carbonated Senonian. In addition, they act as a factor that controls the salinization mechanism of groundwater.

In Rejim Maatoug region, the CT aquifer is characterized by some artesian wells, with a depth varying between 225 m and 400 m. Currently, the rate of water extraction far exceeds the rate of water recharge, resulting in the gradual depletion of the Complex Terminal aquifer. Indeed, since 2000 all springs

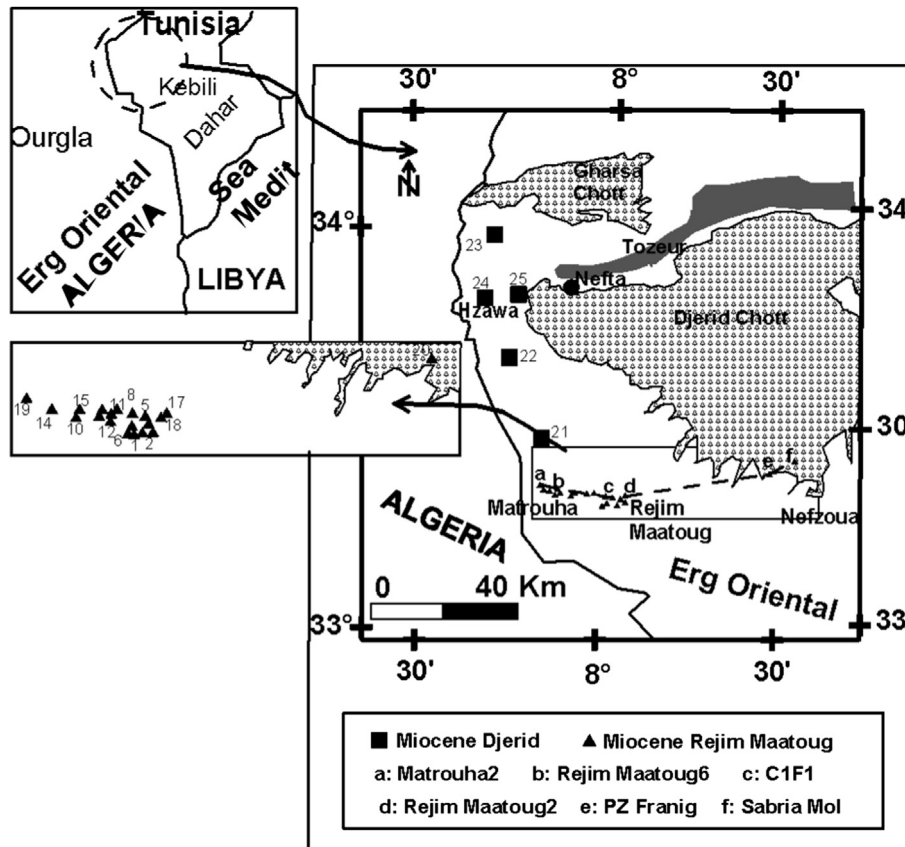


Fig. 1. Schematic map of the study area and sampled boreholes wells.

dried up and all water need is exclusively coming from deep aquifers.

The transmissivities obtained from the flow tests ranges between $5.09 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ (C3A1 well) and $198 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ (RM7 well) (DGRE, 1990, 2006a,b).

The storage coefficient varies between 18×10^{-6} (PZ1) and 259.2×10^{-6} (C2N2 well) (DGRE, 1995). This wide range of the transmissivities and the storage coefficient is due to: the heterogeneity of the groundwater, tectonic activity, lithology variation, and the depth of wells.

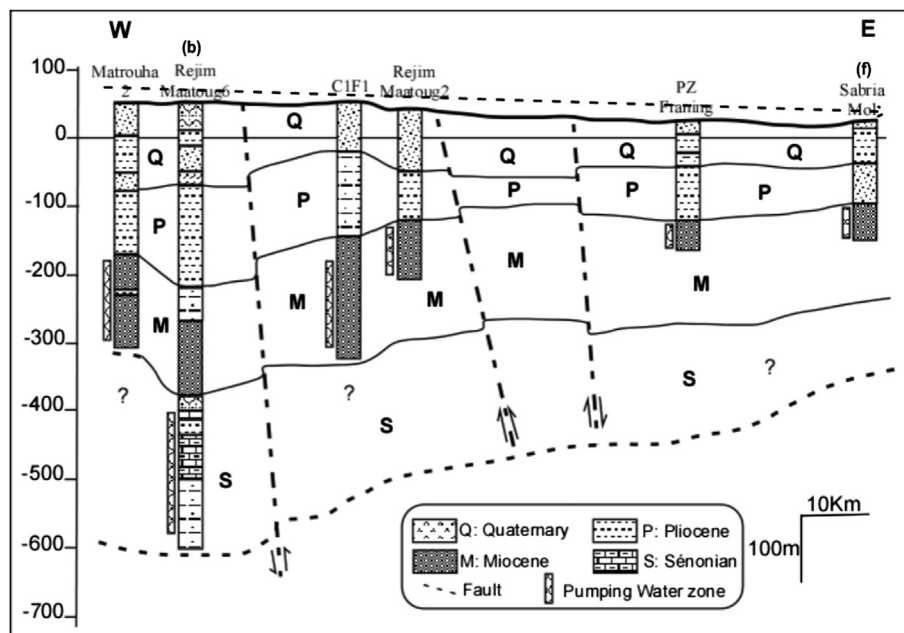


Fig. 2. Hydrogeological cross section in the study area.

The CT aquifer flows from the Grand Erg Oriental in Algeria towards a single discharge zone in the Chott Djerid and Gharsa Chott.

According to the piezometric map of the CT in Djerid (DGRE, 2000) (Fig. 3), the main flow directions are those from south and south-western towards the north and north-eastern. The northern Chott range is a local zone of recharge area of the CT aquifer (Kamel et al., 2006; Abidi, 2007). The Rejim Maatoug piezometric map (DGRE, 1997) presents the same flow direction of the Djerid CT aquifer (Fig. 2). It seems the possible connection of permeable horizons that control groundwater flow and hydraulic continuity.

3. Analytical sampling and techniques

Thirty-one groundwater samples from the CT Miocene aquifer of Rejim Maatoug (Table 1) and Djerid regions were collected in 2010 (Fig. 1). Physical parameters such as temperature, pH and electrical conductivity (EC) were measured in the field. All samples for major chemical analyses were collected in low density polyethylene bottles and filtered in the laboratory through 0.45 μm membrane filters. Major elements (Cl^- , SO_4^{2-} , NO_3^- , HCO_3^- , Ca^{2+} , Mg^{2+} , Na^+ , and K^+) were analysed by ion liquid chromatography (HPLC) on a Waters chromatograph equipped with columns IC-PakTM CM/D for cations, using EDTA and nitric acid as eluent, and on a Metrohm chromatograph equipped with columns CI SUPER-SEP for anions using phthalic acid and acetonitrilic as eluent. The overall detection limit for ions was 0.04 mg/l. The error margin for major elements is lower than 5%; that to lead to an acceptable quality of the analysis results.

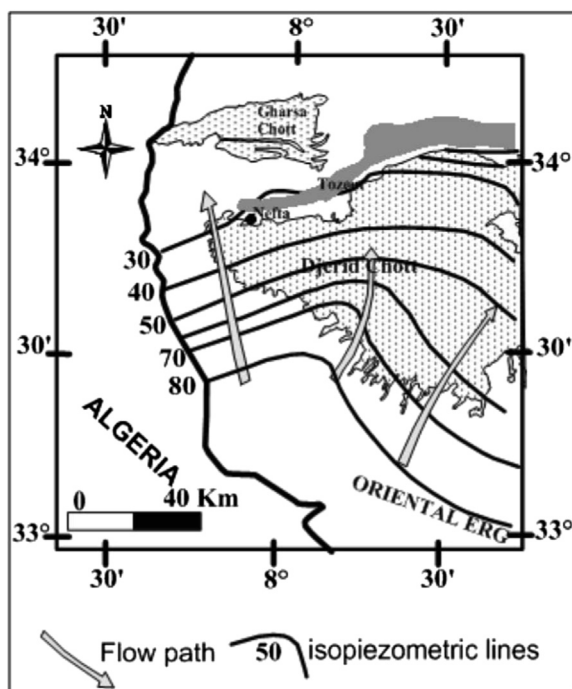


Fig. 3. Piezometric map of CT aquifer in Djerid in 2000 (Data reported from DGRE, 2000).

Three groundwater samples were selected for ^{14}C measurements. Dissolved inorganic carbon was precipitated in the form of BaCO_3 in the field from 160 l of water. The ^{14}C content in BaCO_3 samples was determined using benzene synthesis and liquid scintillation spectrometry (Fontes, 1971) and ^{14}C abundances are expressed as percent modern carbon (pmc).

Thirty-one groundwater samples were selected for stable isotope composition ($\delta^{18}\text{O}$, $\delta^2\text{H}$) analyses. All samples for stable isotope analyses were collected in 30 ml polyethylene bottles with poly-seal caps.

Four groundwater samples were selected for ^3H measurements. Tritium content was measured by electrolytic enrichment and liquid scintillation spectrometry (Taylor, 1976, 1977). Tritium concentration is reported in Tritium Units (TU). One TU is defined as the isotope ratio $^3\text{H}/^1\text{H} = 10^{-18}$.

Chemical, radiocarbon, Tritium and Stable isotope composition of water samples analyses were performed at the Laboratory of Radio-Analyses and Environment of the National Engineering School of Sfax (ENIS: Tunisia).

Analytical uncertainties are in the range of ± 0.10 to 0.20‰ for the $\delta^{18}\text{O}$, ± 0.30 to 1‰ for the $\delta^2\text{H}$, ± 0.2 TU for ^3H and between 0.8 and 1.5 pmc for ^{14}C .

4. Results and discussions

4.1. Hydrochemistry

4.1.1. Salinity and chemical facies

The TDS in the groundwater samples has a mean value of 2816 mg/l. Salinity increases from the south-western part (Matrouha 2: 3 g/l) to north-eastern part (RM7: 2.15 g/l) of the study area along the possible direction of groundwater flow (Fig. 3). However, some samples from the southeastern part of the study area (e.g. C2ES2, C3A1) located in the tectonic zone of Rejim Maatoug region, have elevated mineralization (TDS reaches 3 g/l), which may derive from mixture with water from the lower confined Senonian carbonate formation (Fig. 2), knowing that the TDS in Rejim Maatoug 6 well, capturing the Senonian limestone, was 5.06 g/l in reception (DGRE, 1985). This mixture process of recent water located in the Miocene sands (recent Rejim Maatoug Miocene aquifer samples) and paleo-deep waters of the carbonate Senonian aquifer (RM6) may be due to the role of fault in this region (Fig. 2). The groundwater of Miocene aquifer formation in Rejim Maatoug region reveals the lowest TDS values (2.15 g/l in RM7). The salinity of Miocene sands aquifer in Djerid reaches 2.81 g/l (Chouchet Zarga CT).

The proportions between main cations and anions are presented in the form of a Piper diagram in Fig. 4. Major cations reveal similar concentrations in the CT aquifer of Rejim Maatoug and Djerid regions, intermediate between Na^+ and Ca^{2+} content. According to the piper diagram (Fig. 4), most of the CT groundwater samples reveal similar water type: Sulphated-mixed.

Table 1
Isotopic and geochemical data for the Miocene and Senonian aquifers.

N°	Names	Aquifer names	Na ⁺	Ca ²⁺	Mg ²⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	TDS	EC	T (°C)	pH	³ H (TU)	δ ¹⁸ O	δ ² H	¹⁴ C	Well depth (m)
			(meq/l)							(mg/l)	(mS/cm)				(‰ VSMOW)		(pmc)	
1	C5F1	1	10.84	10.56	9.3	22.0	13.13	18.39	2.3	2193	2990	25	6.9		-4.18	-46.18		300
2	C4F1	1	11.16	13.69	9.23	18.8	13.34	17.86	2.2	2184	2980	28	6.7		-4.24	-44.97		300
3	C2F1	1	10.42	14.19	9.55	17.5	12.78	18.13	2.1	2286	3100	19	6.5		-4.54	-46.71		343
4	C3F1	1	10.86	10.65	8.63	20.2	12.92	16.52	2.3	2160	2970	25	6.7		-4.33	-45.85		300
5	C1F1	1	12.35	20.72	13.08	22.4	15.26	27.28	2.3	2859	3600	27	6.7		-5.4	-50.75		320
6	C5F2	1	11.07	11.95	10.02	23.5	13.77	19.24	2.2	2381	3200	27	6.5		-4.09	-47.08		300
7	C4F2	1	14.04	17.43	11.93	23.8	14.23	23.4	2.3	2923	3600	26	6.8		-5.21	-52.34		300
8	C2F2	1	11.3	10.4	8.91	22.0	13.53	15.73	2.3	2177	3000	25	6.8		-4.03	-46.66		300
9	C2N2	1	13.88	15.63	10.79	28.7	15.06	22.67	2.2	2834	3600	27	6.9		-5.2	-50.95		300
10	C1N2	1	12.6	17.05	11.54	23.3	15.71	22.92	2.1	2798	3600	27	7.1		-5.41	-51.17		350
11	C1N1	1	12.06	17.76	12.13	23.8	15.4	23.15	2.3	2897	3600	27	7.3	0.15	-5.43	-50.67		352
12	C2N1	1	12.95	17.5	12.6	26.1	16.5	26.07	2.2	2884	3600	27	7.2		-5.01	-51.48		301
13	C1A1	1	13.59	15.97	11.37	24.4	16.29	24.36	2.1	2912	3800	26	7.4	0.79	-5.76	-53.18	14.7	368
14	C2ES2	1	15.47	17.47	10.87	20.9	16.6	25.76	2.5	3120	3800	26	7.4		-6.09	-51.37		251
15	C3A1	1	14.81	18.35	13.32	37.7	18.19	28.21	2.2	3069	3800	26	7.5		-5.89	-51.62		300
16	C2A1	1	13.49	17.04	11.36	23.7	15.9	25.88	2.3	2962	3840	25	7.3		-5.92	-51.88		300
17	RM7	1	10.57	12.91	8.55	25.0	12.42	16.35	2.2	2150	2700	20	7.5	0.2	-4.31	-45.19	10.3	236
18	RM2	1	11.09	13.93	10.63	7.0	13.7	20.79	2.34	2504	2700	26	7.4	0.42	-4.84	-47.54		225
19	Mat 2	1	14.11	18.29	10.46	7.4	18.07	25.19	2.5	3034	3600	20	7.2		-5.25	-47.21	8.8	302
20	PZ Franig	1	9.04	6.39	3.95	15.0	10.01	8.08	0.79	1300	1700	25	7.2					
21	Bir roumi	2	14	20.29	10.48	29.2	15.82	23.61	2.65	2745	3910	27	7.53		-5.15	-40.09		
22	Ouled ghrissi	2	16.32	15.19	9.56		19.64	19.39	2.35	2575	3085	30	8		-4.76	-46.45		
23	Htam	2	16.27	23.94	8.38	12.5	21.03	21.24	2.21	2876	4820	37.4	7.5		-5.35	-46.18		
24	Mzaara CT	2	15.44	21.05	5.05	5.3	17.45	19.14	2.38	2535	3820	27	7.4		-4.82	-45.41		
25	Chouchet Zerga	2	15.57	22.63	9.84	11.4	21.4	20.07	2.33	2818	3970	28	7.6		-4.79	-45.79		
1	Fatnassa 2	3					22									-5.03	-47.7	
2	Bechni	3					13.86									-5.51	-49.2	
3	El Faouar 4	3					11.49									-5.13	-45.9	
4	Bir El Haj brahim	3					17.3									-5.53	-49	
5	Bazma 8	3					13.31									-5.48	-49.6	
6	Ben Zitoun 4	3					18.03									-5.62	-51.5	

1: Miocene aquifer of Rejim Maatoug region; 2: Miocene aquifer of Djerid region; 3: Senonian aquifer.

Moreover, Chemical composition of the analysed ground-water samples shows a mineralization dominated by sulphate, calcium and sodium.

The chemical results reflect certain similitude between groundwater samples of the different sectors that strongly supports the hypothesis of the continuity of the sandy Miocene groundwater in Rejim Maatoug and Djerid

4.1.2. The saturation index (SI)

The saturation index (SI), calculated using WATEQ4F programme (Ball and Nordstrom, 1991), is a measure of the departure from equilibrium of the water with respect to mineral phases.

$$SI = \log(IAP/KT)$$

Where IAP is the ion activity product of the components of the mineral phase, and KT is the solid phase solubility equilibrium product at the specified temperature. The saturation state merely indicates in which direction the processes may go: a saturation index value of zero, with an associated range of uncertainty, indicates that the water is in equilibrium or saturated with respect to the mineral phase, a value less than zero indicates undersaturation (mineral dissolution is possible), and

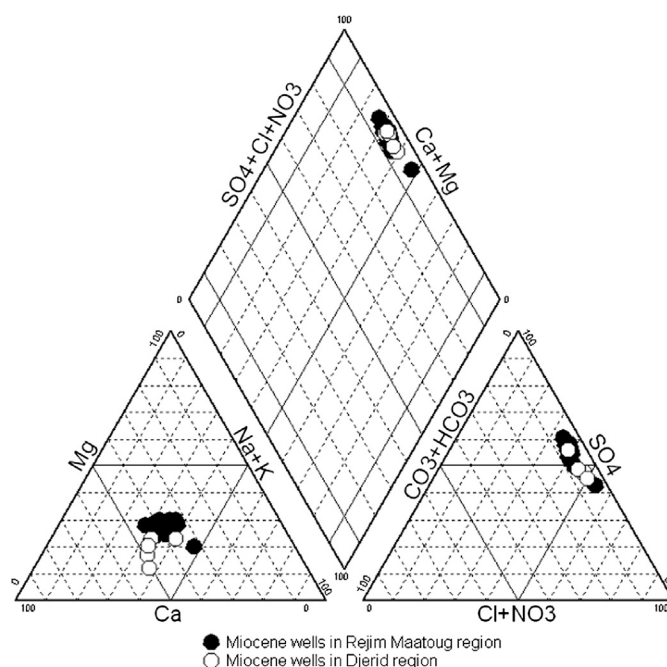


Fig. 4. Piper diagram of the current groundwater samples.

a value greater than zero indicates supersaturation (mineral precipitation is possible) (Appelo and Postma, 1993).

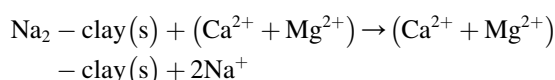
4.1.3. Mineralization origin in Rejim Maatoug aquifer

To identify the different elements contributing to the groundwater mineralization, plots of various major elements as a function of electrical conductivity were established. Fig. 5 shows that Na^+ , Cl^- , Ca^{2+} , Mg^{2+} and SO_4^{2-} versus EC display well-defined correlations, which may indicate that the mentioned ions contribute significantly to the groundwater salinization.

In order to find out the origins of the referred ions and the processes that control their concentrations in Rejim Maatoug groundwaters, scatter diagrams of major chemical constituents in the analysed groundwater samples were established. The Na^+ versus Cl^- diagram shows that the majority of samples displays a well-defined relationship ($R^2 = 0.86$), suggesting that the same origin of sodium and chloride is likely related to the halite dissolution (Fig. 6a). The dissolution of this mineral, which has already been described in the mineralogy of the study area, is confirmed through the negative saturation index of groundwater indicating an undersaturation state (Table 2).

Besides, Fig. 7 illustrates the correlations between the saturation index with respect to halite, the anhydrite and the gypsum according to $(\text{Na} + \text{Cl})$ and $(\text{Ca} + \text{SO}_4)$ respectively. These results reinforce the assumption of the evaporate dissolution.

However, the position of the majority of water samples below the line 1:1 shows the importance of evaporation and ion exchange processes that affects cation contents (Fig. 6a). During this process Ca^{2+} and Mg^{2+} in the waters are exchanged with Na^+ previously adsorbed on the surface of clay minerals in the aquifer matrix as shows the following equation (Guo and Wang, 2005):

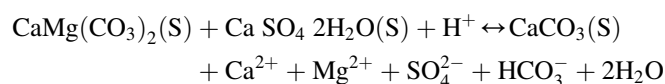


The referred exchange is confirmed through the plot of (Na/Cl) versus $[(\text{Ca} + \text{Mg})/(\text{SO}_4 + 0.5\text{HCO}_3)]$ that exhibits an inverse proportional evolution (Fig. 8). The ratios carried out in the two parameters $[(\text{Na}^+/\text{Cl}^-)]$ and $[(\text{Ca}^{2+} + \text{Mg}^{2+})/(\text{HCO}_3^- + \text{SO}_4^{2-})]$ makes it possible to separate the ions resulting from other reactions than dissolution of carbonated and evaporitic minerals. In the absence of this exchange all analytical points should lie close to the point with coordinates (1; 1).

On the other hand, the majority of groundwater samples show a deficiency of Ca^{2+} versus SO_4^{2-} (Fig. 6b). The calculated saturation index (SI) versus carbonates minerals (calcite, dolomite and aragonite) ranging from -2.3 to 1.2 (Table 2), indicates a progression from an undersaturation state to a supersaturation state with respect to those mineral phases (Parkhurst et al., 1992).

In the Rejim Maatoug region, the highest saturation index values with respect to carbonates minerals are observed in the tectonic zones of the aquifer. They can be explained by the

upflow leakage of the deep Senonian groundwater showing saturation to supersaturation states with respect to these minerals (Table 2). However, all groundwater samples are undersaturated with respect to gypsum and anhydrite (Table 2), indicating the eventual dissolution of sulphate minerals. The increase in Ca^{2+} concentration due to gypsum dissolution and cation exchange processes supersaturates the groundwater with respect to calcite and causes its precipitation. Moreover, as calcite precipitates the concentration of bicarbonate decreases in groundwaters, which causes the undersaturation with respect to dolomite and enhances the incongruent dissolution of this mineral known as dedolomitization (Appelo and Postma, 1993). On the plot of $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ versus $[\text{SO}_4^{2-} + 0.5\text{HCO}_3^-]$, the dedolomitization reaction yields a straight line with a slope of 1 (Jacobson and Wasserburg, 2005) (Fig. 9). This process that contributes to the increase of magnesium concentration is represented by the following reaction (Mokrik and Petkevicius, 2002):



4.2. Isotopic study

Stable isotope contents of groundwater samples are quite homogeneous. Stable isotope values of groundwater range from -4.03 to -6.09‰ for $\delta^{18}\text{O}$ and from -40.09 to -53.18‰ for $\delta^2\text{H}$ (Table 1). Data are plotted with reference to the global meteoric water line (GMWL) and the local Sfax meteoric water line (SMWL) in Fig. 10. The local meteoric water line is defined by the equation: $\delta^2\text{H} = 8 \times \delta^{18}\text{O} + 13$ (Abid, 2011). The points are generally situated under the Global Meteoric Water Line. Stable isotope contents of groundwater are much lower than the weighted mean of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for present precipitation (Weighted Mean Sfax precipitation (WMSP) values $\delta^{18}\text{O} \sim -4.4\text{‰}$; $\delta^2\text{H} \sim -24.9\text{‰}$ (Abid, 2010), indicating either a recharge altitude effect or a palaeoclimatic effect (recharge under colder climatic conditions than at present). The estimation of the recharge altitudes can be made by the use of following equation: (Abid, 2010)

$$A_{\text{Recharge}} = A_{\text{GNIP}} + 100(\delta^{18}\text{OWMSP} - \delta^{18}\text{OGS}/G) \quad (1)$$

With, A_{Recharge} : estimated altitudes of recharge,

A_{GNIP} : altitude of the Sfax meteorological station (4 m amsl),

$\delta^{18}\text{OWMSP}$: $\delta^{18}\text{O}$ of the WMSP (-4.4),

$\delta^{18}\text{GS}$: $\delta^{18}\text{O}$ range of variation of the groundwater samples (-6.2 to -4‰).

G: altitudinal gradient of ^{18}O of -0.30‰ per 100 m in precipitation.

Considering an ^{18}O altitudinal gradient of -0.30‰ per 100 m in precipitation (Zuppi and Bortolami 1983; Blavoux, 1978; Maliki et al., 2000), and taking into account the

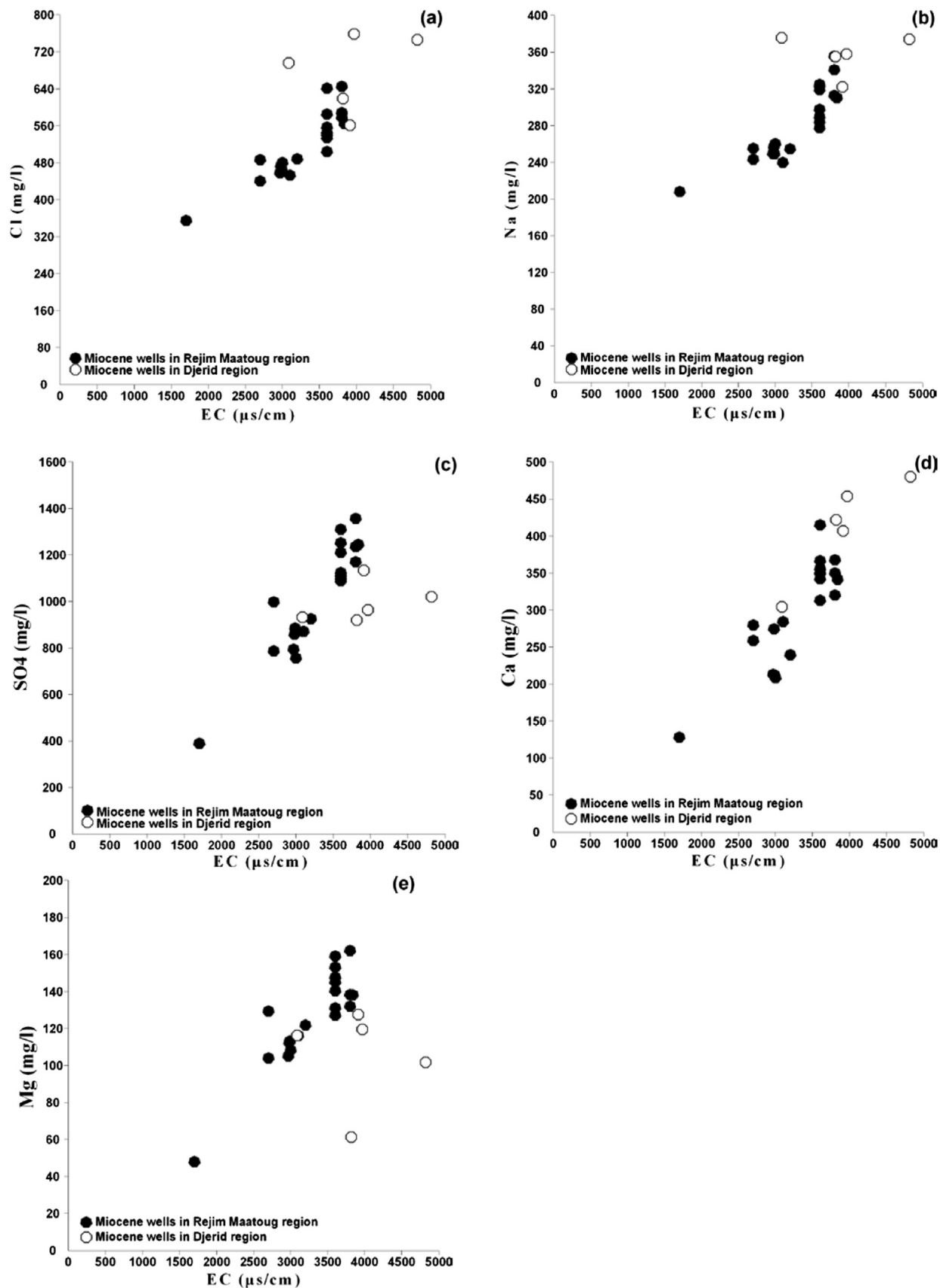


Fig. 5. Major elements versus EC relationships.

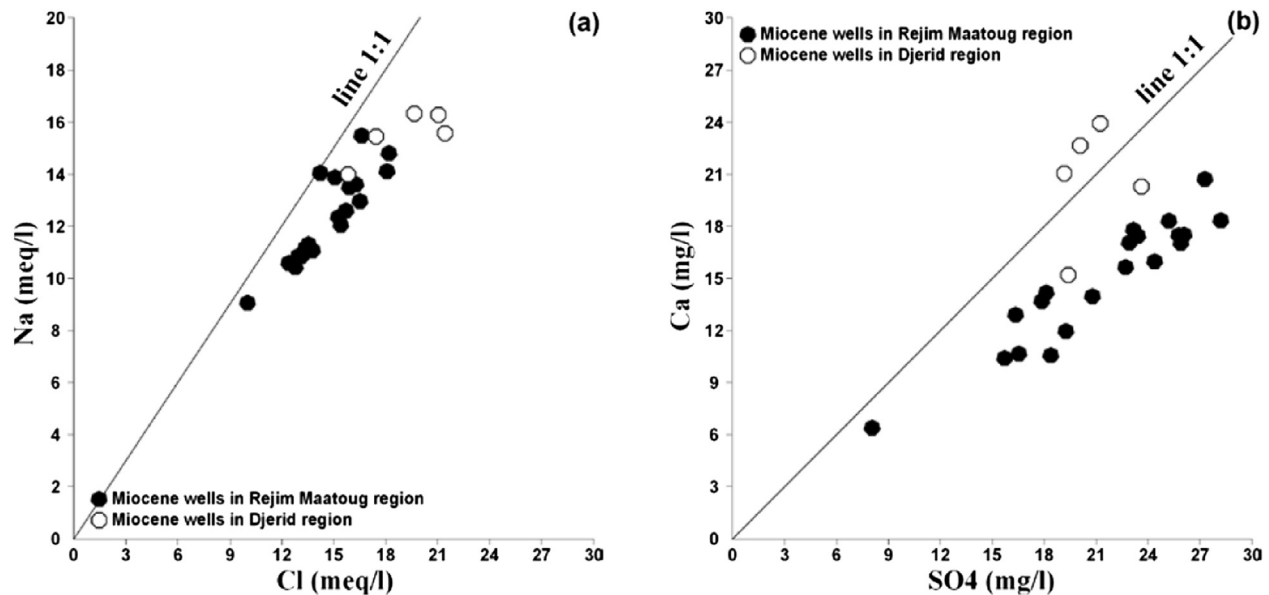


Fig. 6. Relationships between major elements in the analysed groundwater samples: Na/Cl (a) and Ca/SO₄ (b).

equation (1), the recharge altitude of the referred groundwaters would be between 140 and 604 m. The mean recharge altitude of the most depleted deep groundwater (~580 m) is higher than the Upper Miocene and Senonian outcrops. Therefore, the difference between the isotopic composition of deep groundwater and that of present precipitation is likely to be a result of a palaeoclimatic effect. The hypothesis of palaeorecharge is in good agreement with the low ¹⁴C contents of deep groundwater, which corresponds to ‘ages’ greater than 10,000 years

(Abid, 2010). The homogeneity of the stable isotope and ¹⁴C contents suggests a slow flow, with very weak fluxes, in the system. The almost ‘stagnant’ state of this deep aquifer could be related to the tectonic activity which is at the origin of changes in pressure, water temperature and chemistry.

The plot of the stable isotope results as presented in Fig. 10 and the separation of the samples into semi deep saline waters and underground deep water reveals that the latter have lighter isotopic composition, suggesting a possible ancient source.

Table 2
Saturation indexes of the groundwater.

N°	Names	Aquifer names	Aragonite	Calcite	Dolomite	Gypsum	Anhydrite	Halite
1	C5F1	1	1.8	1.94	3.18	1.2	1	-2.9
2	C4F1	1	1.7	1.85	2.87	1.3	1.1	-2.88
3	C2F1	1	1.49	1.64	2.46	1.32	1.12	-2.93
4	C3F1	1	1.62	1.76	2.79	1.17	0.97	-2.91
5	C1F1	1	1.87	2.01	3.17	1.58	1.39	-2.75
6	C5F2	1	1.44	1.58	2.44	1.26	1.06	-2.87
7	C4F2	1	1.9	2.05	3.28	1.46	1.27	-2.74
8	C2F2	1	1.72	1.86	3.01	1.15	0.95	-2.87
9	C2N2	1	1.94	2.09	3.36	1.41	1.22	-2.72
10	C1N2	1	2.12	2.26	3.7	1.45	1.26	-2.74
11	C1N1	1	2.4	2.55	4.28	1.47	1.27	-2.77
12	C2N1	1	2.08	2.23	3.66	1.5	1.31	-2.7
13	C1A1	1	2.42	2.56	4.33	1.44	1.25	-2.69
14	C2ES2	1	2.53	2.67	4.49	1.49	1.3	-2.62
15	C3A1	1	2.59	2.74	4.68	1.54	1.35	-2.59
16	C2A1	1	2.38	2.52	4.22	1.48	1.29	-2.7
17	RM7	1	2.47	2.61	4.4	1.25	1.05	-2.93
18	RM2	1	2.4	2.55	4.32	1.34	1.14	-2.87
19	Mat 2	1	2.38	2.52	4.15	1.51	1.32	-2.62
20	PZ Franig	1	1.55	1.7	2.54	0.84	0.63	-3.08
21	Bir roumi	2	2.23	2.37	3.82	1.52	1.33	-2.68
22	Ouled ghrissi	2	2.09	2.23	3.62	1.36	1.17	-2.52
23	Htam	2	2.26	2.4	3.71	1.57	1.38	-2.48
24	Mzaara CT	2	2.23	2.37	3.49	1.49	1.3	-2.6
25	Chouchet Zerga	2	2.26	2.41	3.82	1.53	1.34	-2.49

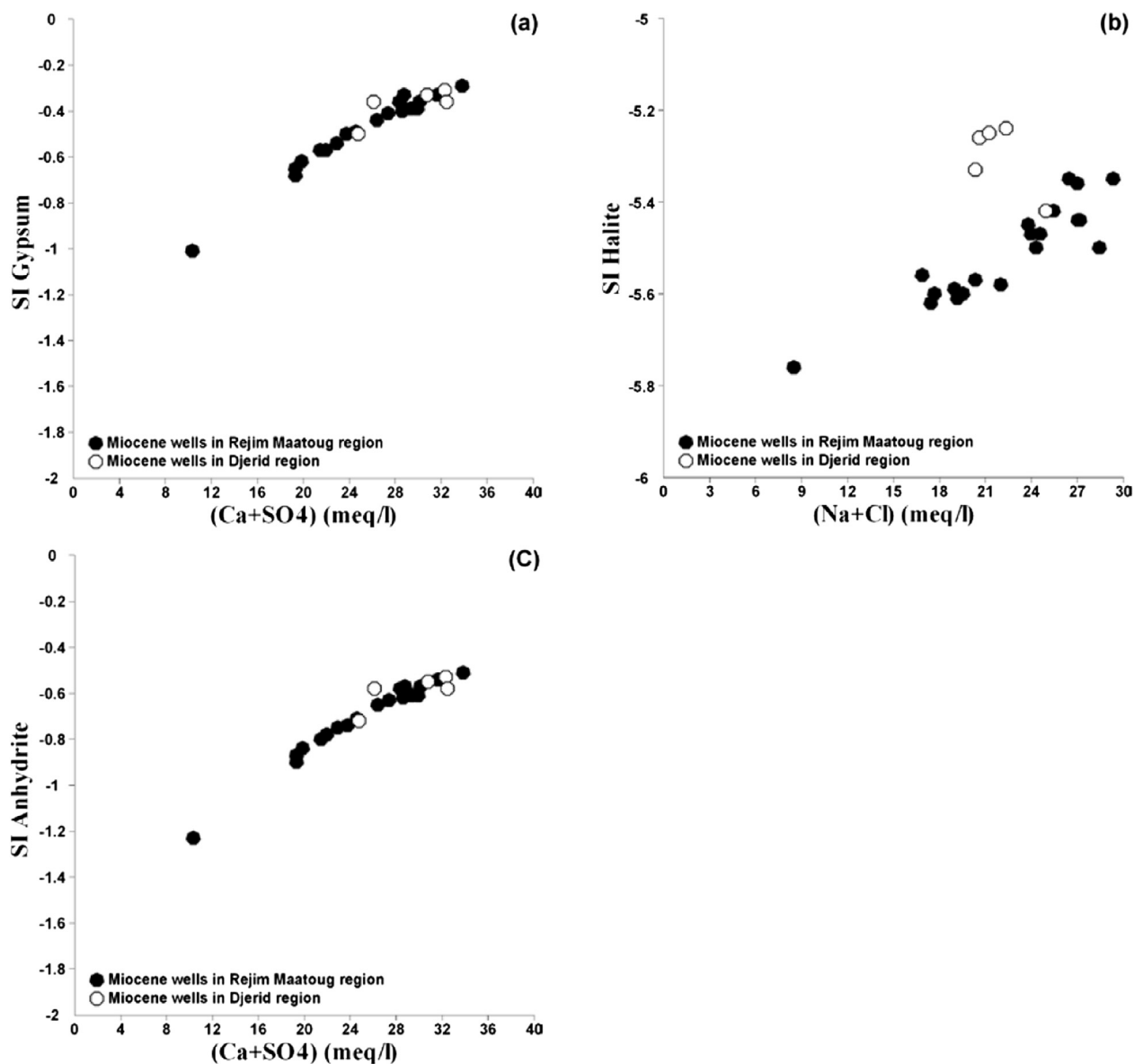


Fig. 7. Saturation index of groundwater with respect to halite, anhydrite and gypsum in Rejim Maatoug.

It seems to be a result of a mixing influence of recent near-surface meteoric water, precisely from precipitation infiltration, with an old water system. Therefore, as shown in Fig. 10 stable isotopes ranges tend to cluster by both geographic location and well depth. Two groups of water can be distinguished. The first group, which is constituted mainly by the samples collected from the deep level of the aquifers, is characterized by the more depleted isotopic contents. This group (group A) is characterized by contents impoverished of stable isotopes (from -6.09 to -5.01‰ versus SMOW for ^{18}O and from -53.2 to -49‰ versus SMOW for ^2H). The resemblance between the isotopic signature of water representing this group of points located at the West and South-west of Rejim Maatoug, and those of water of the Djerid groundwater, suggests the water mixture of the two aquifers (mixing line in Fig. 10). Besides, the Samples of this group reveal the

lowest ^{14}C concentrations (Matrouha 3 well: 5.5 pmc; Matrouha 2 well: 8.8 pmc) and no detected Tritium contents are recorded in this group.

The second group (group B) is represented by enriched contents of stable isotopes (from -5.25 to -4.03‰ versus SMOW for ^{18}O and from -49.1 to -44.97‰ versus SMOW for ^2H). This enrichment seems to be the result of the evaporation effect affecting water (irrigated water and/or of recent rainwater) during their infiltration. In general, water from this group with ^3H contents of <1 TU is regarded as having a pre-1952 age, a date which represents the peak of artificial release of tritium through nuclear (atomic bomb) tests. Such waters are said to have been affected by secondary processes such as evaporation prior to infiltration or isotopic exchange with the aquifer materials (Mazor, 1991). Therefore, the low precipitation rate (less than 90 mm/year and the high rate of

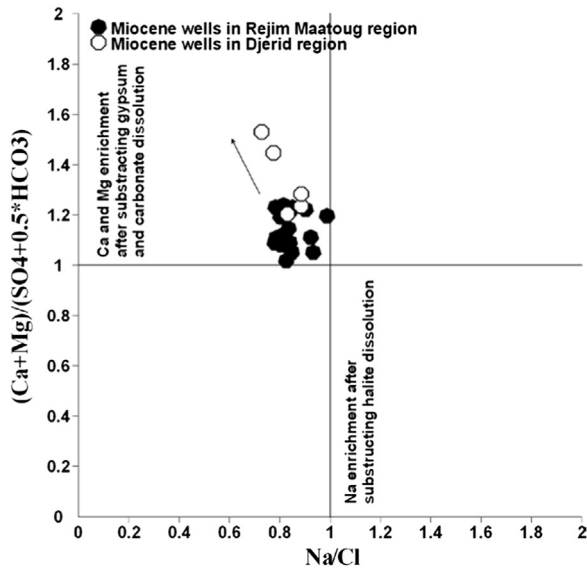


Fig. 8. $[(Ca + Mg)/(SO_4 + 0.5 \cdot HCO_3)]$ versus $[Na/Cl]$ relationship.

evapotranspiration (greater than 2500 mm/year) weaken the assumption of recent recharge.

The chloride content is plotted against deuterium isotope composition in Fig. 11, in order to discriminate more precisely the different waters involved in the mixing process and factors controlling groundwater salinization. In this diagram, it is much more apparent that at least three different processes are required to account for the scattering of the data. On the one hand, all saline samples in the extreme south-western of Rejim Maatoug region converge towards the composition of the Senonian aquifer, suggesting that salinization is caused solely by mixing with deep old waters of this aquifer through the fault. Waters from this group do not contain measurable 3H and have low ^{14}C , confirming the assumption of mixing with ascending older water, which is due to the tectonic activity,

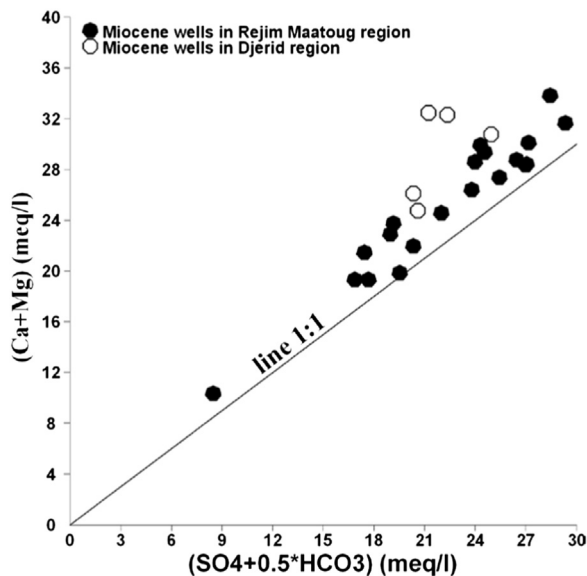


Fig. 9. $(Ca + Mg)$ versus $(SO_4 + 0.5 \cdot HCO_3)$ relationship.

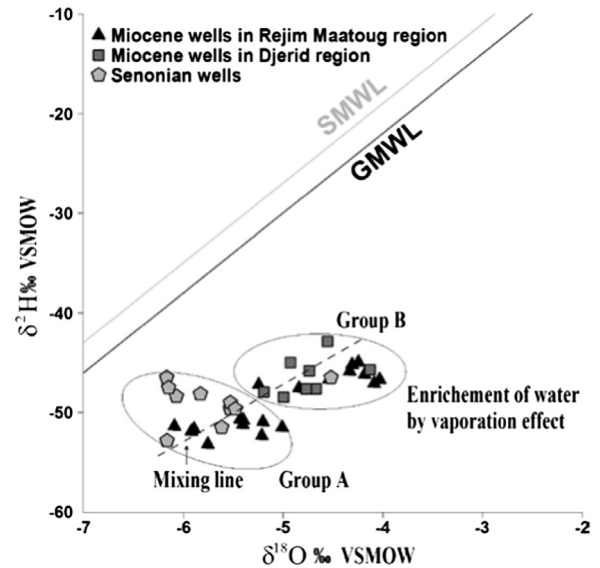


Fig. 10. The δ^2H – $\delta^{18}O$ relationship for the CT groundwaters samples in Rejim Maatoug, Djerid and Nefzaoua regions.

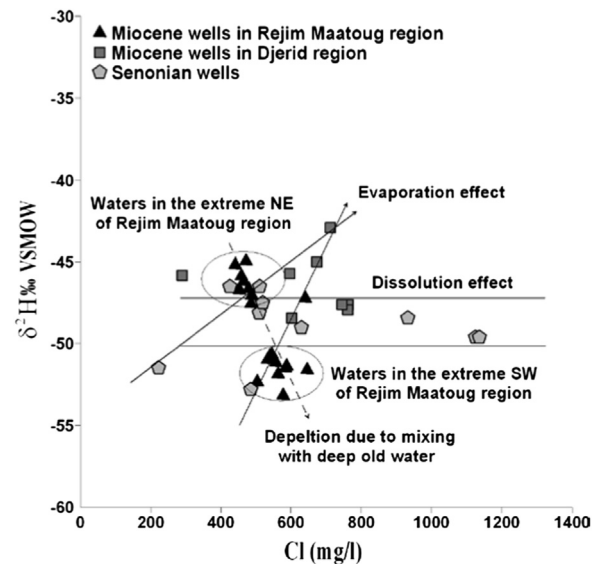


Fig. 11. δ^2H – Cl^- relationship for CT groundwaters samples in Rejim Maatoug, Djerid and Nefzaoua regions.

characterized by lower δ^2H values and higher Cl^- concentrations. On the other hand, this diagram also illustrates that evaporation effect occurs during infiltration of the local precipitation and/or the return of the irrigated water. Samples which constitute this trend show systematic increase in Cl^- and δ^2H values. Data indicating the dissolution effect includes higher chloride concentrations with relatively constant δ^2H values.

4.3. Conclusion

Simultaneous analysis of both hydrochemical and isotopic data allowed better understanding of the hydrodynamic functioning of the CT aquifer in Rejim Maatoug and Djerid

regions. The groundwater samples of CT aquifer in Rejim Maatoug are characterized by salinities varying from 2.15 to 3 g/l.

The geochemical exploration shows the dominance of sulphated mixed water type resulting from the dissolution of halite and gypsum, the dedolomitization and the cation–exchange processes. According to the piper diagram, most of the CT groundwater samples reveal similar water type: Sulphated-mixed. The chemical composition of the analysed groundwater samples shows a mineralization dominated by sulphate, calcium and sodium.

The chemical results reflect certain similarity between groundwater samples of the different sectors that strongly supports the hypothesis of the continuity of the sandy Miocene groundwater in Rejim Maatoug and Djerid regions.

In the Rejim Maatoug region, the highest saturation index values with respect to carbonates minerals are observed in the tectonic zones of the aquifer. They can be explained by the upflow leakage of the deep Senonian groundwater showing saturation to supersaturation states with respect to these minerals.

The mixture process of recent water located in the Miocene sands (recent Rejim Maatoug Miocene aquifer samples) and paleo-deep waters of the carbonate Senonian aquifer may be due to the role of fault in this region.

The stable isotope signatures reveal the existence of two groundwater groups: The first group, which is constituted mainly by the samples collected from the deep level of the aquifers, is characterized by the more depleted isotopic contents. The resemblance between the isotopic signature of water representing this group of points located at the West and South-west of Rejim Maatoug, and those of water of the Djerid groundwater, suggests the water mixture of the two aquifers. Besides, the Samples of this group reveal the lowest ^{14}C concentrations, a non evaporated groundwaters and no detected Tritium contents are recorded in this group.

The second group is represented by enriched contents of stable isotopes. This enrichment seems to be the result of the evaporation effect affecting water (irrigated water and/or of recent rainwater) during their infiltration. In general, water from this group with ^3H contents of <1 TU is regarded as having a pre-1952 age, a date which represents the peak of artificial release of tritium through nuclear (atomic bomb) tests. Therefore, the low precipitation rate (less than 90 mm/year and the high rate of evapotranspiration (greater than 2500 mm/year) weaken the assumption of recent recharge.

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