

The hydro geochemical characterization of ground waters in Tunisian Chott's region

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Abstract Tunisian Chott's region is one of the most productive artesian basins in Tunisia. It is located in the southwestern part of the country, and its groundwater resources are developed for water supply and irrigation. The chemical composition of the water is strongly influenced by the interaction with the basinal sediments and by hydrologic characteristics such as the flow pattern and time of residence. The system is composed of an upper unconfined "Plio-Quaternary" aquifer with a varying thickness of 20–200 m, an intermediate confined/unconfined "Complex Terminal" aquifer about 100 m in thickness and a deeper "Continental Intercalaire" aquifer about 150 m in thickness separated by thick clay and marl layers. The dissolution of evaporites and carbonates explains part of the contained Na^+ , Ca^{2+} , Mg^{2+} , K^+ , SO_4^{2-} and Cl^- , but other processes, such carbonate precipitation, also contributes to the water composition. The stable isotope composition of

waters establishes that the deep groundwater (depleted as compared to present corresponding local rainfall) is ancient water recharged probably during the late Pleistocene and the early Holocene periods. The relatively recent water in the Plio-Quaternary aquifer is composed of mixed waters resulting presumably from upward leakage from the deeper groundwater.

Keywords Chott · Dissolution · Stable/radiocarbon isotopes · Paleoclimatic groundwater · Tunisia

Introduction

The situation in North Africa, as elsewhere in the developed world, mainly in the past 100 years, has been transformed with the development of the ability to drill deep wells and to exploit groundwater using mechanized pumping. The demand for water during this time and especially since the Second World War has increased out of proportion creating a transient state whose main short-term consequences were water-level decline, loss of artesian condition and drying up of discharge areas (OSS 2003).

The hydrogeologic balance of deep aquifers has been done for the first time in 1972 as a part of the ERESS project (UNESCO 1972). The model has then served for simulations of potential exploitation. The so-called "Plan Directeur des Eaux du Sud" (PDES) that means "The Directory Plan of Southern Waters Use", was elaborated on the basis of obtained results. This plan fixed a quota of 13,500 l/s for Chott's region that can be pumped from the main deep aquifer of Complex Terminal.

Quotas were fairly respected in the study area and the 2003 sampling campaign for chemical and isotopic studies

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aims to quantify content variation rates for water salinity and piezometric levels according to the PDS.

One of the objectives of this paper is to provide a better understanding of mechanisms that contribute to ground-water mineralization in Tunisian Chott's region, 30 years since the first sampling campaign.

Study area

The 'Grand Erg Oriental basin' extends over much of Algeria and southern Tunisia (Fig. 1). It is underlain by two major aquifer systems the continental intercalaire (CI) and the complex terminal (CT), which contain mainly fresh water.

The Chott's Region constitutes the main discharge area of CI and CT groundwaters.

The study area is located in southwestern Tunisia between the longitudes $7^{\circ} 30' - 8^{\circ} 30'$ east and the latitudes $33^{\circ} 30' - 34^{\circ} 30'$ north. It is limited in the west by the Algerian frontier, in the north by Metlaoui-Gafsa Mountains and in the east by Sehib Mountain and Cherb Range. The southern limit is constituted by Recent Chott Djerid sediments (Fig. 2). The study area encloses Chott el Gharsa, Chott Djerid and the Djerid Region, which located between the two depressions. The word "Chott" is a North African term for a salt flat within a hydrologically closed basin (Gautier 1953 in Swesey 2003).

Meteorological records from the town of Gafsa and from Tozeur indicate that annual rainfall in the study area is 95–160 mm, and that mean monthly pan evaporation at Gafsa ranges from 90 to 365 mm (Yermani 2002). In addition, winds at Gafsa blow predominantly from the northeast

toward the Chott El Gharsa, whereas winds at Tozeur have a strong component from the east (Mamou 1989). Occasionally, a very hot, dry wind blows out of the Sahara from the southwest during April and May, which are also the months during which sandstorms occur most frequently in the area. The drainage network in the region consists of El Khanga River (about 50 l/s). Melah and Tselja are non-perennial rivers (locally known as wadi). El Khanga River is derived from the springs of the Upper Cretaceous and Miocene groundwater. Melah and Tselja wadi collect the surface runoff from surrounding hills. Chott El Gharsa constitutes the discharge area of these wadis (Fig. 2).

Geology and hydrogeology

As shown in the geological map (Fig. 2), the oldest outcrops in the study area belong to the Middle Cretaceous units, which crop out at different zones in the surrounding mountains.

The chart of relation between stratigraphic and hydrogeologic units (Mamou 1989; Kamel 2005) shows the main formations and potential aquifers (Fig. 3). These units are given below in chronological order, from the oldest to the youngest.

The continental intercalaire aquifer

The CI aquifer of North Africa is one of the largest confined aquifers in the world, comparable in scale to the Great Artesian Basin of Australia and covers some 600,000 Km² with a potential reservoir thickness of between 120 and 1,000 m (Castany 1982).

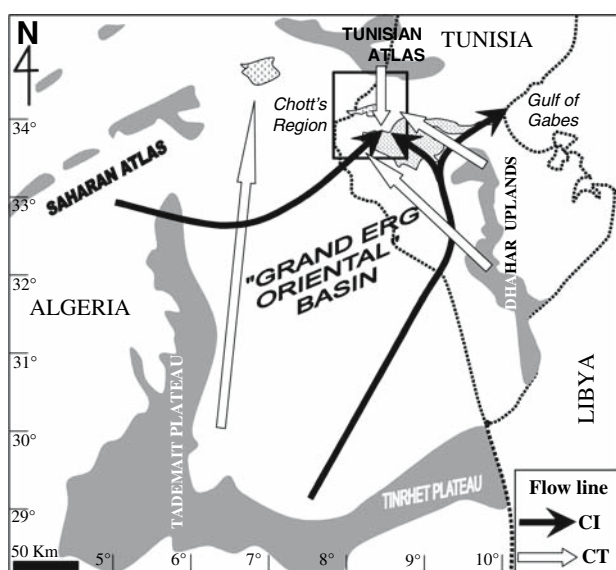


Fig. 1 Location of the study area

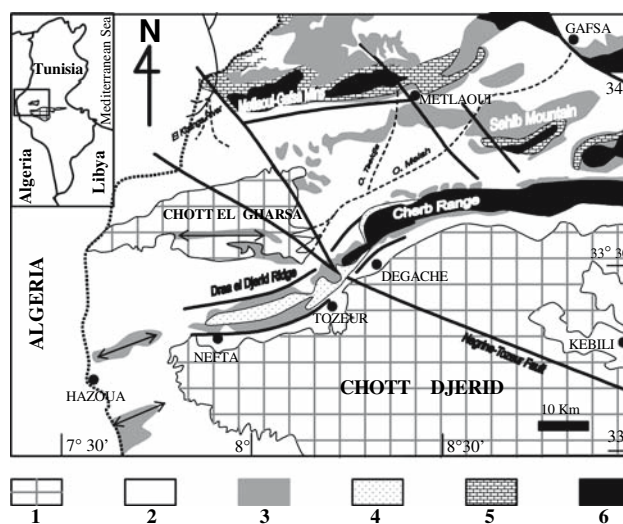


Fig. 2 Geologic map of the study area (1 Recent Chott sediments, 2 Quaternary sediments, 3 Mio-pliocene, 4 Miocene, 5 Eocene, 6 Upper and Middle Cretaceous)

Hydrogeological Units	Stratigraphic Units	Formation name	Lithology	Aquifers
PLIO-QUATER. (PQ)				
COMPLEX TERMINAL (CT)	Mio-Pliocene	Segui		
		Beglia		
	Eocene	Metlaoui		
	Paleocene	El Haria		
	Maestrichtian	Abiod		
	Campanian			
	Santonian	Aleg		
	Coniacian			
	Turonian			
CONTINENTAL INTERCALAIRE (CI)	Cenomanian	Zebbag		
	Albian	Orbata		
	Aptian	Sidi Aich		
	Barremian	Bou Hedma		
SUBSTRATUM	Valangénien-Hauterivien	Sidi Kralif- Melloussi		
	Malm - Dogger	Nara		

1 2 3 4 5 6

Fig. 3 Relation between stratigraphic and hydrogeologic units in Nefta region (1 gypsum, 2 sand and sandstone, 3 clayey sand, 4 clay, 5 limestone, 6 dolomite). After Mamou (1989)

The geological formations, which host the CI aquifer, undergo changes in facies and in thickness moving from the Metlaoui-Gafsa Mountain toward the Saharan platform. Changes in sedimentation within the fluvio-deltaic continental deposits produced alternations of detrital levels with horizons of clayey silts with frequent gypsum intercalations.

In the Chott's region, the continental formations extend from the Neocomian at the base to the Albian. The Lower Cretaceous may be subdivided into five main formations (Mamou 1989; Kamel 2006). Only Boudinar and Sidi Aich formation constitute the potential levels of the CI aquifer in Chott's region.

Bou Dinar formation (Hauterivian-Barremian)

An alternating sequence of sandy and clayey sediments, the thickness of each varying between several meters to 60 m. It forms an aquifer in Tozeur region, but with a performance inferior to the younger Sidi Aich sands.

Sidi Aich formation (Aptian)

Friable white and fine-grained sands of rather constant thickness (about 150 m) and forming the main aquifer unit

in the CI of the study area. Dolomitic flags, characteristic of the Albian, overlie the sands.

The CI aquifer covers mainly the regions of Tozeur, Kebili and Tunisian extreme south. The most important production takes place at Kebili and Tozeur geothermal fields with 1,000 and 600 l/s, respectively. At the Djerid region, depth of the CI reservoir ranges from 1,500 to 2,400 m; with the well-pressure varying between 60 (Nefta CI3) and 200 m (Hazoua CI) above wellhead and with water temperature ranging around 70°C.

Transmissivity of the CI aquifer (Sidi Aich Formation), obtained from pumping tests, ranges from 0.8×10^{-3} to $4.5 \times 10^{-3} \text{ m}^2/\text{s}$ and storage coefficient ranges from 0.2×10^{-4} and 1.4×10^{-4} (Mamou 1989).

The CI has its recharge source in the Algerian Atlas Mountains. It is mainly confined and discharges in the Chotts of Tunisia and in the Gabes gulf (Mediterranean Sea, Fig. 1) (Guendouz et al. 2003).

Geothermal water is utilized mainly: in agriculture ; to help irrigate oases, to heat and irrigate greenhouses, for bathing purposes and in some cases for watering of animals (El Guedri 1999).

The CT aquifer

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 either in the carbonated levels of the Upper Cenomanian (Zebbag Formation in Gafsa region) and Upper Senonian (Abiod Formation in Kebili region) or in the Tertiary sandy formation (Beglia Formation in Tozeur region).

Zebbag formation (Cenomanian-Turonian)

Represented in Tozeur by two distinct members: at the base, dolomite and chalky dolomite with a thickness varying between 120 and 150 m and at the top by intercalations of marl, clay, gypsum and thin levels of limestone. The thickness of the superior member of this formation varies between 300 and 400 m.

Abiod formation (Senonian)

In Tozeur region, the Upper Senonian is formed by flag-white limestone and chalky marl levels, reaching 100 to 200-m thickness. The lower Senonian starts by an intercalation of limestone and gypsum and can reach a thickness of 500 m in the Hazoua region.

Beglia formation (Mio-Pliocene)

It is constituted by coarse sand with thin levels of red clay and quartz. The thickness of sand ranges from 250 to 300 m. At Draa Djerid Ridge, where the Beglia outcrops, it is only 50 to 120-m thick. Beglia Formation is covered by a thick clayey Formation (Segui), whose thickness varies between 200 and 500 m, to reach under the Chotts 700–800 m.

Transmissivity of the CT aquifer, obtained from pumping tests, ranges from 0.1×10^{-2} to 4.5×10^{-2} m²/s in Beglia formation.

Most of the recharge of CT aquifer occurs at outcrops around the margins of the Grand Erg Oriental (southwestern study area, in Algeria), although there is some minor recharge by direct infiltration from the Grand Erg Oriental itself. Discharge from the aquifer occurs by vertical percolation at the sabkha surfaces, upwelling at natural springs and spring mounds, and upwelling from water wells. Most of this discharge is concentrated in southern Tunisia around Chott Djerid, where natural upwelling occurs at a relatively constant rate throughout the year (Coque 1962).

The principal areas of recharge are in South Atlas Mountains of Algeria, in Dhahar uplands (Tunisia) and Tunisian Atlas. The discharge area is in Chotts area (Fig. 1).

The Plio-Quaternary aquifer

Quaternary features on the northern margin of the Chott El Gharsa basin consist primarily of alluvial fans, glacia and terraces.

The southern margin of Chott El Gharsa Basin is very different from the northern margin. Instead of terraces, most of the Quaternary stratigraphic units on the southern margin are discontinuous, wind-eroded outcrops that have been interpreted as eolian, sabkha, and lacustrine deposits (Swesey 1997).

Clayey Segui Formation is considered as the footwall of Quaternary sequence (Mamou 1989) and has been reached by several wells at southern and northern Chott el Gharsa depression.

Quaternary formation on the northern margin of Chott El Gharsa is much thicker (270 m at Oudia PQ) and is formed by alternation of sand, clayey sand and sandy clay with thin quartz gravel levels. Gypsum is generally associated with a fine to medium grain to clayey sand horizons.

The Plio-Quaternary deposit contains a phreatic aquifer, which is exploited especially as irrigation complement in Tozeur, Nefta and Hezoua oases. This aquifer is essentially recharged by the excess of irrigation water coming from CI and CT deep aquifers, in oases area. Out of these cultivable zones, the PQ aquifer is recharged during the rare rainfall events. The main subsurface flow direction is

toward south (toward Chott Djerid) southern Draa Djerid Ridge, and toward north (toward Chott El Gharsa) northern Draa Djerid ridge.

Results and discussion

Hydrochemical study

The pH, temperature, EC, TDS and major ion concentrations for water samples from the CI, CT and PQ aquifers are presented in Table 1. Only analyses of water whose charge balance errors are less than 5% are used in this study.

Samples collected from the CI aquifer are characterized by high temperature varying from 60 to 74°C. However, low temperature ranging from 22 to 39°C characterizes CT and PQ groundwater.

EC in the groundwater CI samples ranges from 2,390 to 4,400 μ S/cm. Those of the CT aquifer vary between 2,380 and 9,360. Higher values have been found between Chott El Gharsa and Metlaoui-Gafsa Mountain. EC Shallow PQ samples values are very close and range from 5,800 to 6,300 μ S/cm.

A total of 43 groundwater samples from the three aquifers and spring samples were collected (Fig. 4) during June 2003. Samples were immediately conditioned in hermetic polyethylene bottles (unacidified) and sent to the laboratory, two days after the campaign.

The major cation (Ca, Mg, Na and K) and anion (Cl, SO₄) concentrations were determined by liquid-ion chromatography (HPLC Beckman type) located at the Laboratory of Radio-analyses and Environment/National Engineering School of Sfax (Tunisia). The chromatograph was equipped with columns for cations, using H₂SO₄ as eluant, and columns for anions, using Na₂CO₃ and NaHCO₃ as eluant. The relatively high salinity of samples required dilution and filtration (hand-held syringe using 0.45- μ m membrane filters) before analyses. The alkalinity was measured by titration with 0.1N HCl (in field) and 0.02N H₂SO₄ (in laboratory).

Electro Neutrality results show non-significant deviation (less than 5%), and duplicate analyses were not done.

The major ion composition from 43 representative water analyses is shown in the Piper diagram (1944), where the relative content of a cation or an anion is defined as the percentage of the milliequivalent per litre (meq/l), respectively, of the total cations or total anions. SO₄, Cl, Na and Ca are major contributors for most waters. Two main groundwater types are differentiated: Na–Cl and Ca–SO₄–Cl (Fig. 5).

The total dissolved solids of many of water samples is quite high (1,600–6,560 mg/l) and this is the result primarily of the dissolution of evaporite minerals (Table 1).

Table 1 Physico-chemical parameters of groundwater

No.	Sample	Aquifer	Region	Catch (m)	pH	T°C	EC ($\mu\text{S/cm}$)	TDS (mg/l)
1	Ali Ben Ammar Merzougui	PQ	Chott El Gharsa	7	7.9	23	6,300	5,180
2	Boujemaa Merzougui			9	8.1	23	6,060	5,040
3	Oudia PQ			106	7.2	25	5,840	4,600
4	Oudia PDIARI			72	7.6	26	6,150	4,600
5	O, Shili 3	CT	Chott El Gharsa	505	7.8	30	5,370	5,000
6	Segdoud 3			870	7.6	39	5,400	4,820
7	Gouifla 8			538	7.9	35	6,450	6,000
8	Ain Bidha Camp Maest			Spring	7.5	22	5,270	3,690
9	Sce Chebika Camp-Maes			Spring	7.5	27	4,257	2,980
10	Ain Morchane Eoc			Spring	7.5	25	9,360	6,560
11	Draa CRDA			56	7.2	28	2,400	1,930
12	IBC 14			502	7.6	29	3,960	3,200
13	Hamma 9b			90	7.4	30	7,980	5,900
14	Neflayet 2			240	7.1	33	4,260	3,250
15	Jhim 1 b			482	7.3	30	3,050	2,240
16	IBC 7			634	7.2	29	3,970	3,100
17	Rgherdgaya 4			285	7.1	31	3,840	3,210
18	Hotel Sarra			50	6.8	28	4,760	4,000
19	Moncef 3b			561	7.2	31	3,420	2,680
20	Mrah Lahouar 6			555	7.3	31	3,200	2,320
21	Chemsa 1 b	CT	Djerid	591	7.2	30	3,860	3,100
22	Castilia 3b			85	7.4	30	2,910	1,960
23	Tozeur 9			74	7.6	25	2,750	2,000
24	El Faouz			403	6.8	30	3,980	2,900
25	Choucht Zerga			385	7.8	28	3,970	2,900
26	El Farej 2			362	7.3	30	4,060	3,200
27	Nefta 12			71	7.1	29	3,760	3,100
28	Nefta SONEDE			91	7.2	29	3,270	2,300
29	Htam			666	7.2	37	4,820	3,100
30	Mzara			323	7.4	25	3,820	2,500
31	Hazoua 1 ter			473	7.4	29	3,730	2,700
32	Ain Ouled Ghrissi			443	7.3	29	3,720	2,700
33	Degache CT			125	7.7	23	2,690	1,700
34	Ain Torba 1 ter			75	7.6	30	2,380	1,600
35	Koudiet Lakoua			414	7.4	27	4,010	3,100
36	Hamma 21	CI	Djerid	219	7.2	32	3,900	2,900
37	Hamma 14b			98	7.6	30	3,600	2,600
38	Nefta CI3			2,126	7.6	66	4,400	3,500
39	Hamma CI 4			1,368	8.2	69	3,510	2,860
40	Ceddada CI			2,257	7.9	74	3,200	2,470
41	Hazoua CI			1,870	7.0	60	2,390	1,800
42	Mahacen CI 2			1,370	6.9	69	3,160	2,300
43	Hamma CI 1bis			1,444	7.5	73	3,230	2,742

Bivariate diagrams of major elements are used in order to separate different mechanisms that contribute to groundwater salinization. In particular sodium (Fig. 6a) is

positively correlated with chloride. This indicates the possible dissolution of gypsum-bearing rocks relatively abundant in the aquifers.

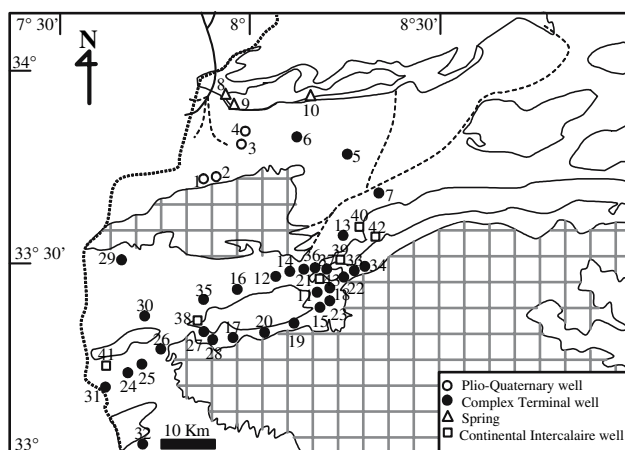


Fig. 4 Location of sampled wells

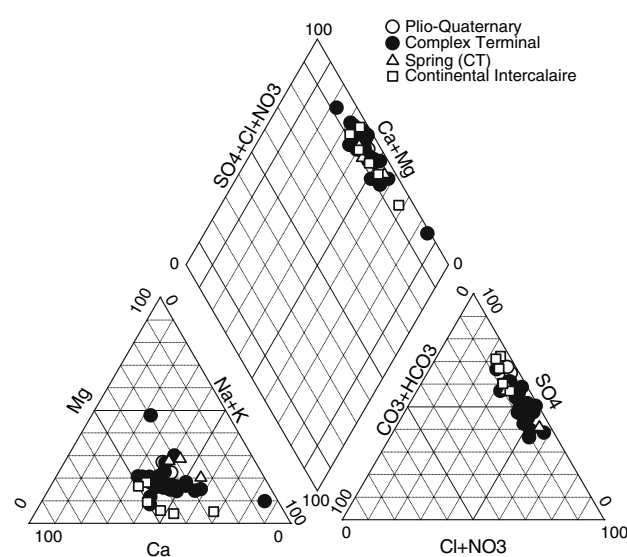


Fig. 5 Piper diagram of the groundwater

Normally, gypsum dissolution produces Ca and SO_4 in one-to-one equivalent ratio. However, for the Djerid-Chott El Gharsa groundwater samples, the plot of SO_4 versus Ca (Fig. 6b) shows a relative Ca depletion. On the other hand SO_4 versus (Ca + Mg). Figure 6c, shows a good positive correlation. Thus, the deficiency of calcium is probably related to carbonate precipitation. Carbonates replacing evaporates (anhydrite/gypsum) are microbially generated by bacterial sulphate reduction, based on ^{13}C values that support an organic origin of the carbon (Henchiri et al. 2006).

To study this assumption, saturation state of the waters with respect to gypsum, dolomite, calcite and halite were performed using WATEQP. Saturation conditions can be expressed as the ratio between IAP (ion activity product) and K (solubility product), for example as the saturation state $\Omega = \text{IAP}/K$.

Thus for $\Omega = 1$, there is equilibrium, $\Omega > 1$ (supersaturation and $\Omega < 1$ subsaturation. For larger deviations from equilibrium, a logarithmic scale can be useful like the saturation index SI. Normally, however, equilibrium is not found and then the saturation state merely indicates in which direction the processes may go; for subsaturation dissolution is expected, and supersaturation suggests precipitations (Appelo and Postma 1994).

Most of the water sampled are saturated with respect to calcite ($\text{SI} < 1$, Fig. 7c) and $\text{SI}_{\text{calcite}}$ is approximately correlated versus respective species. Calcite precipitation may occur systematically for all groundwater samples. (Except for Oudia PDIARI, Hamma CI4 and Ceddada CI).

Thirteen samples are not saturated with respect to dolomite (Fig. 7d) and $\text{SI}_{\text{dolomite}}$ is not well correlated versus respective species. Dolomite dissolution is less expected than calcite dissolution in Tunisian Chott's region.

For all groundwater samples, there is an equilibrium state with gypsum ($1 < \text{SI} < -1$). $\text{SI}_{\text{gypsum}}$ versus ($\text{Ca}^{2+} + \text{SO}_4^{2-}$) positively well correlated, reinforces strongly gypsum dissolution (Fig. 7b).

The same equilibrium state with halite, reinforcing evaporates dissolution, is noticed (Fig. 7a).

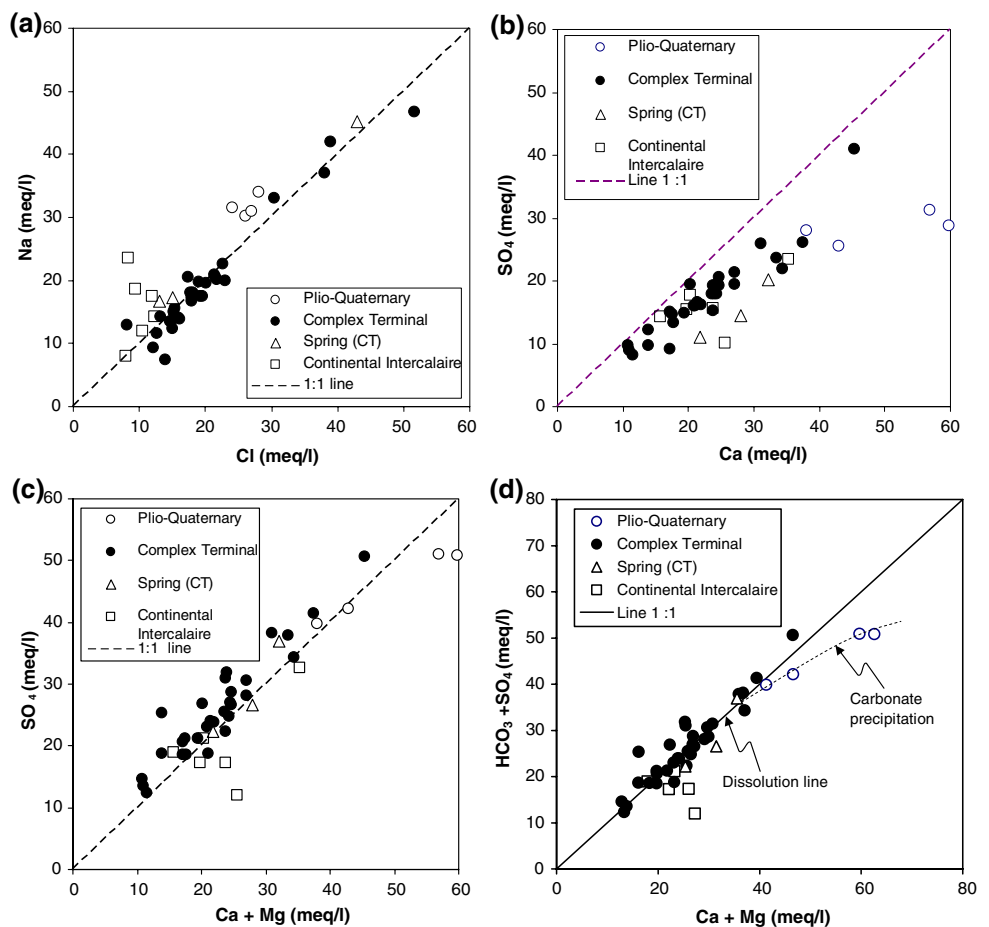
Figure 6d shows a positive correlation between ($\text{HCO}_3 + \text{SO}_4$) versus (Ca + Mg) reinforcing evaporites and carbonate dissolution minerals (Kamel et al. 2006). However, shallow samples form a group trending away from the dissolution line probably in relation with the carbonate precipitation process kinetic under evaporative conditions.

Isotopic study

Stable isotope (^{18}O , ^2H) analyses were performed at the "IAEA Laboratories, Vienna", by using standard methods. Hydrogen and oxygen isotope analyses were made by respectively employing the standard CO_2 equilibration (Epstein and Mayeda 1953) and the zinc reduction technique (Coleman et al. 1982), followed by analysis on a mass spectrometer. All oxygen and hydrogen isotopes analysis are reported in the usual δ notation relative to Vienna-Standard Mean Oceanic Water (VSMOW) standard, where $\delta = [(\text{RS}/\text{RSMOW}) - 1] \times 1000$; RS represents either the $^{18}\text{O}/^{16}\text{O}$ or the $^2\text{H}/^1\text{H}$ ratio of the sample, and RSMOW is $^{18}\text{O}/^{16}\text{O}$ or the $^2\text{H}/^1\text{H}$ ratio of the SMOW. Typical precisions are $\pm 0.2\text{‰}$ and $\pm 2.0\text{‰}$ for the oxygen and deuterium, respectively.

Radiocarbon analyses were done at the Laboratory of Radio-analyses and Environment/National Engineering School of Sfax (Tunisia), by scintillation counting on C_6H_6 synthesized from BaCO_2 stripped in the field from 100-l water samples. Results are reported as percentages of modern carbon (pm C) (Table 2).

Fig. 6 Bivariate diagrams of major elements. **a** Na/Cl relationships. **b** Ca/SO₄ relationship. **c** (Ca + Mg)/SO₄ relationship. **d** (Ca + Mg)/(SO₄ + HCO₃) relationship



Deuterium and oxygen-18 composition of groundwater

The stable isotope ratios ($\delta^{18}\text{O}$, $\delta^2\text{H}$), can be used in the present study to obtain information on the possible source of water, its mode of recharge and whether it forms part of the modern hydrological regime or constitutes paleowater. The composition of CI and CT groundwater beneath the study area has a signature, which is significantly more depleted than modern rainfall recorded in Sfax City ($-4.6 \delta^{18}\text{O}/-23.3 \delta^2\text{H}$). These isotopic signatures are characteristic of paleowaters in North Africa and agree with the results of several authors, obtained in southern Tunisia (Edmunds et al. 2003; Zouari et al. 2003; Kamel et al. 2005).

The observed variation in stable isotope content in deep CI wells ranges from -7.5 to -7.3 for $\delta^{18}\text{O}$ and from -60 to -55 for $\delta^2\text{H}$. The data for Djerid and Chott El Gharsa CT wells and springs show a $\delta^{18}\text{O}$ content variation of -7.29 to -4.11 for $\delta^2\text{H}$.

The stable isotope composition of shallow PQ aquifer is represented by four samples and ranges from -7.24 to -6.65 for the $\delta^{18}\text{O}$ and from -52 to -45‰ for $\delta^2\text{H}$ (Table 2).

In Fig. 8, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data of all groundwater samples were plotted together with the Global Meteoric

Water Line (GMWL) (Craig 1961) and the regional Meteoric Line of the Sfax city SMWL (SMWL : $\delta^2\text{H} = 8 \delta^{18}\text{O} + 13.5$ (Maliki 2000; Celle et al. 2001), located at a distance of 300 Km in Mediterranean coastal eastern study area.

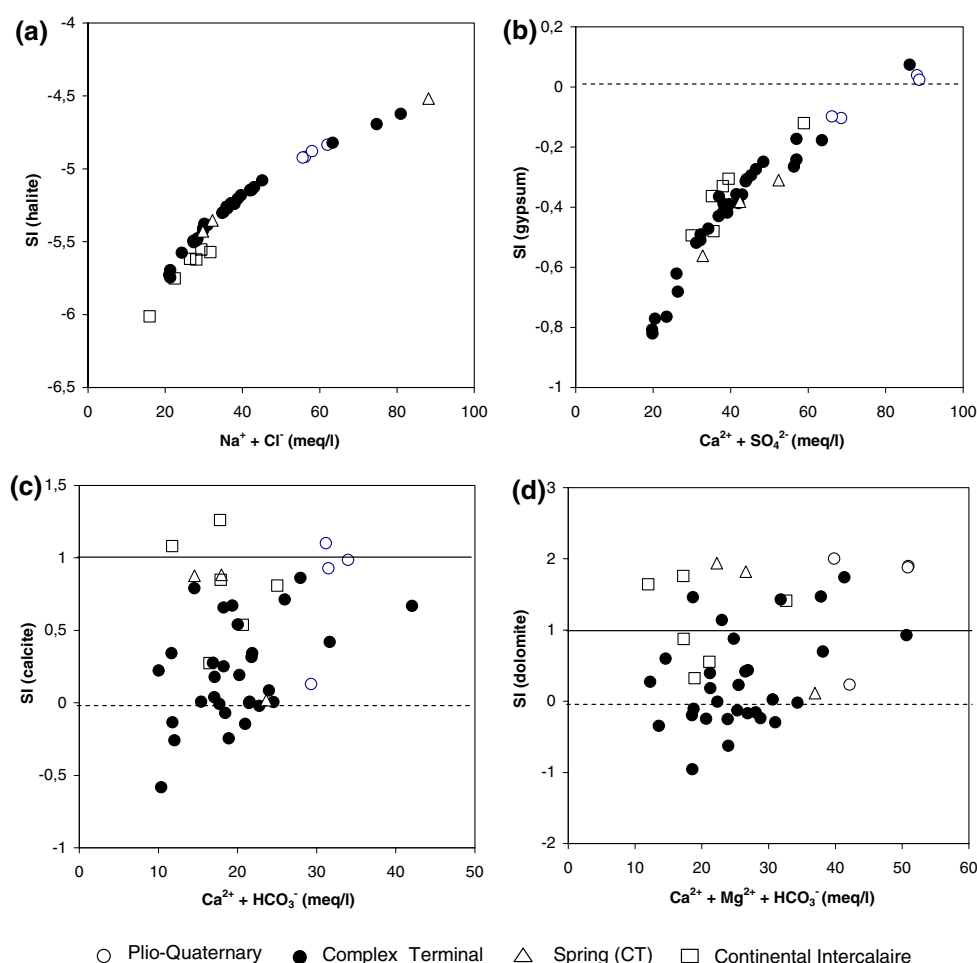
The plot of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Fig. 8) shows that there is a clear separation between two groups in respect with their position regarding GMWL and SMWL.

Group A samples lie widely below the SMWL and encloses CI and CT Ca–SO₄–Cl type groundwater sampled beneath the Djerid region.

Groundwater of the deep CI aquifer has relatively homogenous isotopic signatures; those of CT present a larger signatures isotopic range ($-4.13/-6.94 \delta^{18}\text{O}$ and $-52/-42 \delta^2\text{H}$).

CI and CT isotopic data define in group A, a line with a slope lower than the GMWL and SMWL. This line can be interpreted as evaporation line instead of as a mixing line between CI and CT groundwater. These changes in isotopic pattern are typical for waters that have been affected by evaporation in closed-basin lakes (Kharaka and Carothers 1968) and in fossil lakes where isotope composition remains in the pore water of the low permeability sediments

Fig. 7 a–d Mineral saturation index (SI)/respective species relationship



(Ortega et al. 1997). The first situation seems to prevail in Tunisian Chott's region

Group B samples lie on or just below the regional Sfax Meteoric Water Line and GMWL enclosing Chott El Gharsa Na–Cl type groundwater samples.

The composition of isotopic data, in this group, has a signature, which is significantly more depleted than modern rainfall recorded in Sfax City, supporting an enrichment from the parent rainfall and it is probable that the latter would have originated from a rainfall with $\delta^{18}\text{O}$ value of about -10‰ (obtained by intersection between the mean passing by the representative samples of A group and GMWL).

Therefore, the radiocarbon results indicate that a component of modern water is present in the springs and also in the shallower boreholes in Chott El Gharsa region.

Carbon-14 tracer and infiltration periods

The evolution of groundwater in CI and CT aquifers has been described from an area which today is completely arid but which is known from past climatic records to have been wetter in the late Pleistocene and Holocene (Petit Maire

and Riser 1982; Gasse 2000; Maley 2000). The radiocarbon data show an abrupt trend, from about 0% modern carbon concerning CI groundwater to about 34% in CT groundwater (Table 2)

The results from the CI and CT may be compared with the regional trends recorded in the stable isotope record in dated groundwaters across northern Africa (Sonntag et al. 1997; Edmunds et al. 2003). Air mass circulation over Africa during the late Pleistocene was significantly different from the present day, with evidence of a reinforcement and southward shift of the Atlantic westerly flow across the present Sahara during the period. A corresponding decline of monsoon rains also occurred at this time. Evidence then is found for a northward extension of the African monsoon, with increased rainfall intensity notably during the early to mid-Holocene, coinciding with a retreat of the Atlantic system to the north.

The groundwater isotopic evidence in different places records strong variations in humidity of the air masses supplying moisture across the continent at different times over the past 30,000 years.

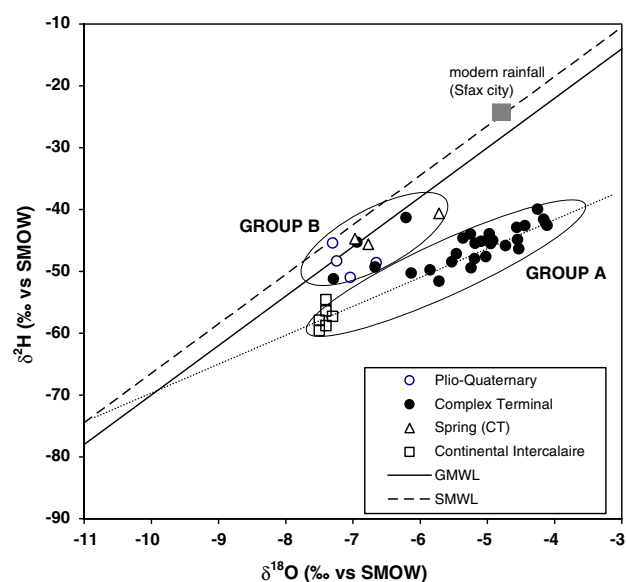
According to correspondence carbone-14 (‰)/Infiltration period (age) scaling by several authors in Saharan platform

Table 2 Chemical and isotopic data of groundwater

No.	Sample	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	HCO ₃ (mg/l)	CO ₃ (mg/l)	NO ₃ (mg/l)	SI _{Calcite}	SI _{Dolomite}	SI _{Gypse}	SI _{Halite}	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	^{14}C (%)
1	Ali Ben Ammar Merzougui	624	240	782	14	994	2,736	170	0	0	0.985	1.900	0.038	-4.835	-6.65	-48.62	
2	Boujemaa Merzougui	576	268	694	12	923	2,880	164	0	0	0.928	1.880	0.023	-4.919	-7.04	-52.29	
3	Oudia PQ	512	201	726	14	852	2,064	225	0	0	0.128	0.231	-0.104	-4.924	-7.30	-45.40	
4	Oudia PDIARI	560	144	713	11	958	1,832	195	0	0	1.103	2.006	-0.098	-4.880	-7.24	-48.30	24.9
32	O. Shili 3	817	119	757	60	1,078	2,180	73	12	0	0.669	0.925	0.074	-4.823	-6.21	-41.30	15.15
33	Segdoud 3	470	174	848	17	1,344	1,609	149	2	0	0.861	0.861	-0.178	-4.623	-7.29	-51.20	11.9
34	Gouflla 8	521	186	966	39	1,382	1,805	115	18	0	0.712	1.738	-0.242	-4.694	-6.67	-49.30	
35	Ain Bidha Camp Maest	289	148	395	11	532	1,343	213	0	0	0.884	0.884	-0.382	-5.353	-6.77	-45.63	
36	See Chebika Camp-Maes	219	137	385	15	461	1,049	216	0	0	0.876	0.876	-0.562	-5.428	-6.97	-44.70	17.50
37	Ain Morehane Eoc	404	203	1038	34	1,527	1,546	207	0	0	0.018	0.018	-0.310	-4.519	-5.72	-40.60	34.00
5	Draa CRDA	194	190	169	4	494	664	143	0	0	-0.260	-0.130	-0.765	-5.746	-5.72	-51.60	17.80
6	IBC 14	360	168	460	7	817	1,152	82	0	0	0.671	1.430	-0.387	-5.126	-5.02	-47.63	17.00
7	Hamma 9b	439	151	1076	27	1,834	1,655	158	24	0	0.004	-0.023	-0.265	-3.843	-6.94	-45.26	
8	Nefayet 2	388	90	463	22	773	973	128	24	0	0.006	-0.170	-0.390	-5.149	-4.94	-45.01	
9	Jhim 1 b	184	114	283	16	533	826	70	0	0	-0.583	-0.958	-0.681	-5.495	-4.25	-39.97	
10	IBC 7	411	100	386	20	637	1,188	134	24	0	-0.021	-0.237	-0.294	-5.304	-5.09	-45.13	
11	Rgherdgaya 4	428	112	310	15	520	1,303	159	0	0	0.085	0.023	-0.249	-5.492	-6.13	-50.29	10.40
12	Hotel Sarra	519	148	471	27	618	1,492	347	12	0	0.419	0.698	-0.173	-5.241	-5.46	-47.15	
13	Moncef 3b	324	93	326	23	469	1,056	134	6	0	-0.070	-0.251	-0.389	-5.504	-5.25	-43.99	
14	Mrah Lahour 6	302	67	317	14	569	825	158	6	2	-0.009	-0.247	-0.491	-5.424	-4.44	-42.60	
15	Chemsa 1 b	385	143	470	28	767	1,141	104	18	0	-0.147	-0.299	-0.358	-5.145	-4.98	-44.66	
16	Castilia 3b	178	56	321	16	563	524	176	6	0	-0.135	-0.349	-0.820	-5.406	-4.16	-41.61	
17	Tozeur 9	245	78	267	15	449	664	140	12	0	0.790	1.463	-0.621	-5.576	-4.13	-42.22	
18	El Faouz	330	91	454	27	674	1,033	146	6	0	-0.246	-0.625	-0.418	-5.207	-4.92	-45.02	
19	Choucht Zerga	321	84	448	15	712	1,004	134	24	0	0.657	1.143	-0.43	-5.182	-4.56	-42.9	
20	El Farej 2	385	88	396	14	634	1,183	152	6	0	0.316	0.416	-0.314	-5.296	-4.95	-45.53	
21	Nefia 12	389	105	309	14	529	1,303	122	12	0	-0.002	-0.157	-0.274	-5.477	-5.53	-48.44	
22	Nefia SONEDE	267	62	356	24	547	852	122	18	0	0.007	-0.198	-0.519	-5.386	-4.11	-42.59	
23	Htam	306	85	480	0	760	1,146	106	18	0	0.039	-0.010	-0.418	-5.147	-5.19	-47.93	4.40
24	Mzara	320	33	297	25	288	1,009	134	6	0	0.251	-0.109	-0.365	-5.728	-4.73	-45.82	3.20
25	Hazoua 1 ter	294	79	416	16	632	841	134	18	0	0.275	0.395	-0.510	-5.262	-4.55	-44.87	
26	Ain Ouled Ghriissi	296	78	401	23	696	935	140	18	0	0.177	0.183	-0.472	-5.237	-4.53	-46.35	5.80
27	Degache CT	164	49	345	29	537	555	109	18	0	0.223	0.272	-0.808	-5.377	-5.24	-49.46	2.10
28	Ain Torba 1 ter	193	59	212	11	430	521	122	12	11	0.341	0.595	-0.771	-5.696	-5.85	-49.77	
29	Koudiet Lakoua	391	89	401	25	683	1,179	140	18	0	0.341	0.436	-0.307	-5.251	-4.97	-43.94	
30	Hamma 21	358	92	416	15	639	1,131	140	12	37	0.191	0.225	-0.357	-5.272	-5.18	-45.48	
31	Hamma 14b	357	84	517	65	802	1,168	134	12	0	0.539	0.878	-0.36	-5.081	-5.36	-44.64	
38	Nefia CI3	470	111	402	25	421	1,701	91	3	0	0.807	0.807	-0.121	-5.555	-7.50	-57.9	0.48
39	Hamma CI 4	201	24	539	73	294	1,227	103	12	0	1.080	1.640	-0.48	-5.571	-7.40	-58.8	0.38

Table 2 continued

No.	Sample	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	HCO ₃ (mg/l)	CO ₃ (mg/l)	NO ₃ (mg/l)	SI _{Calcite}	SI _{Dolomite}	SI _{Gypse}	SI _{Halite}	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	^{14}C (%)
40	Ceddada CI	308	22	326	53	437	950	146	6	0	1.200	1.760	-0.364	-5.619	-7.40	-54.6	0.27
41	Hazoua CI	285	57	182	61	286	757	136	0	0	0.274	0.323	-0.494	-6.013	-7.30	-57.3	0.42
42	Mahacen CI 2	355	41	277	89	371	975	179	0	0	0.537	0.554	-0.330	-5.752	-7.40	-56.4	0.69
43	Hamma CI Ibis	314	19	427	38	334	1146	134	6	0	0.848	0.873	-0.306	-5.622	-7.50	-59.6	

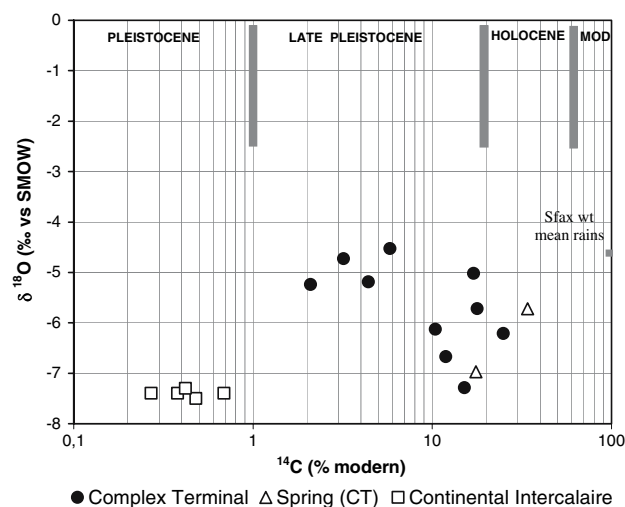
Fig. 8 $\delta^{18}\text{O}/\delta^2\text{H}$ diagram of the groundwater

and North Africa (Edmunds et al. 1997; Guendouz et al. 2003), ^{18}O data (‰) are plotted against ^{14}C (% modern) for CI and CT groundwaters in the study area (Fig. 9).

The range in pcm (0.27–0.69) in the CI deep groundwater corresponds with Pleistocene recharge (Fig. 9).

Most CT samples correspond to late Pleistocene period. It is worth noticing that in the same period, four samples from deep boreholes (oldest) were isotopically more enriched (-4.53 and -5.19 ‰), in contrast with younger water at the end of the same period and Holocene age (-5.72 and -7.2 ‰).

Only Ain Morchane Spring and Shallow Oued Shili 3 shallow borehole located at Northern east study area correspond to Holocene recharge period (Fig. 9).

Fig. 9 $^{14}\text{C}/\delta^{18}\text{O}$ relationship

Conclusion

The Chott's Djerid hydrogeological aquifer system constitutes the discharge areas of deep CI and CT groundwater where there is also the risk of highly saline near-surface waters from the Chotts being drawn down and entrained during abstraction.

A detailed hydrogeochemical survey made on Tunisian Chott's region has provided data on groundwater chemistry patterns and on the main process of water mineralization.

It shows two main groundwater types: Na–Cl and Ca–SO₄–Cl.

Two major mechanisms are responsible for groundwater composition (1) evaporite dissolution and (2) carbonate precipitation. The first process is well known. The second process is confirmed by silification of sulphate evaporites and their carbonate replacements in study area sediment (Henchiri 2006).

Saturation state of waters with respect to gypsum, dolomite, calcite and halite reinforce mineralization assumption.

Isotopic study shows two groups.

Group A encloses CI and CT Ca–SO₄–Cl type groundwater sampled beneath the Djerid region. CI and CT isotopic data define group A affected by evaporation in closed-basin lake conditions.

Group B samples enclose Chott El Gharsa Na–Cl type groundwater samples.

The composition of isotopic data has a signature which is significantly more depleted than modern rainfall in Sfax city, supporting an enrichment from the parent rainfall with $\delta^{18}\text{O}$ value of about -10‰ .

Carbon-14 tracer evidences late Pleistocene and Holocene as infiltration period, respectively, of CI and CT groundwaters.

The natural salinities already give cause for concern, being close to or above the limits of use, both domestic and agricultural. The groundwaters of CI and CT provide a large reserve of relatively low salinity water which needs to be carefully managed, possibly enhanced in the future by desalinization to provide water of higher quality.

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