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ORIGINAL ARTICLE

Environmental isotopes as the indicators of the groundwater recharge in Tunisian Chotts region

Samir Kamel · Lahmadi Moumni · Younes Jedoui

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Abstract Hydrogeological investigations in arid zones tend to be logistically difficult and costly. However, isotopic techniques can be used to gain valuable reconnaissance information, for example, in advance of new drilling programmes and also during exploitation. Thus, the most cost-effective exploration in arid zones will include both good hydrogeological data combined with isotopic and supporting geochemical information. The question of recharge is one of the most critical for groundwater management in dry areas. Is the recharge currently taking place and at what rate? If recharge is occurring, further important problems arise dealing with possible mechanisms of recharge, which may occur through direct infiltration, upward leakage, lateral recharge from areas of rainfall, and lateral seepage of river (Fontes and Edmunds, Technical documents in hydrology 77, 1989). In this study, which is of interest for an important aquifer system in southern Tunisia, conjunction of environmental isotopes, i.e.: ^{18}O, ^{2}H, ^{3}H, ^{14}C and ^{13}C and chloride contents was used to understand the mode of recharge of the shallow Plio-Quaternary (PQ) and the intermediate Complexe Terminal (CT) aquifers. Both are unconfined in the vicinity of the Tozeur uplift and the Dahar upland and show relatively modern water that originated from present-day rainfall. It has been demonstrated that the Continental Intercalaire deep groundwater contributes to the CT aquifer recharge, the latter to the upper PQ shallow aquifer. The shallow PQ is mainly recharged by return flow irrigation and upward leakage in oases areas. Away from oases zones, sporadic recharge may occur at the inter-dunes especially between the Chott Djerid and Chott El Gharsa, in the Bir Roumi region and in the Kebili sand fields.

Keywords Groundwater recharge · Carbon-14 · Tritium · Inter-dunes · Tunisian Chotts region · Southern Tunisia

S. Kamel (✉) · Y. Jedoui
Unité de Recherches: Hydro Sciences Appliquées, Institut Supérieur des Sciences et Techniques des Eaux de Gabès, Cité Erriadh, Campus Universitaire, Zrig, 6072 Gabès, Tunisia
e-mail: samir.kamel@isstegb.rnu.tn

Y. Jedoui
e-mail: Younes.Jedoui@isstegb.rnu.tn

L. Moumni
Commissariat Régional au Développement Agricole, Route de Nefta, 2200 Tozeur, Tunisia
e-mail: Moumni@hexabyte.tn

Introduction

Tunisian Chotts region is part of the "Grand Erg Oriental basin" extending over much of Algeria and southern Tunisia. It is bordered by Saharan Atlas and Tunisian Atlas in the North, Matmata Mountains and Dahar uplands in the east, Tinhert Plateau in the south and Tademait Plateau in the west. The surrounding mountains are made up mainly of Upper Cretaceous rocks. Triassic evaporite, constitute the oldest rocks outcropping in the eastern part of the Tunisian–Libyan border and in the southern flank of the Tinhert highlands (Bishop 1975; Coque 1962). The Oligocene sediments are encountered only in the southern limit of the basin (Fig. 1).

The study area is known as Chotts region and located at the northeast part of the "Grand Erg Oriental Basin". It encloses Djerid and Nefzaoua regions (Fig. 2).

The study area is characterised by an arid type climate with a mean annual precipitation of <100 mm. The mean annual temperature is 21 °C and evapotranspiration rate

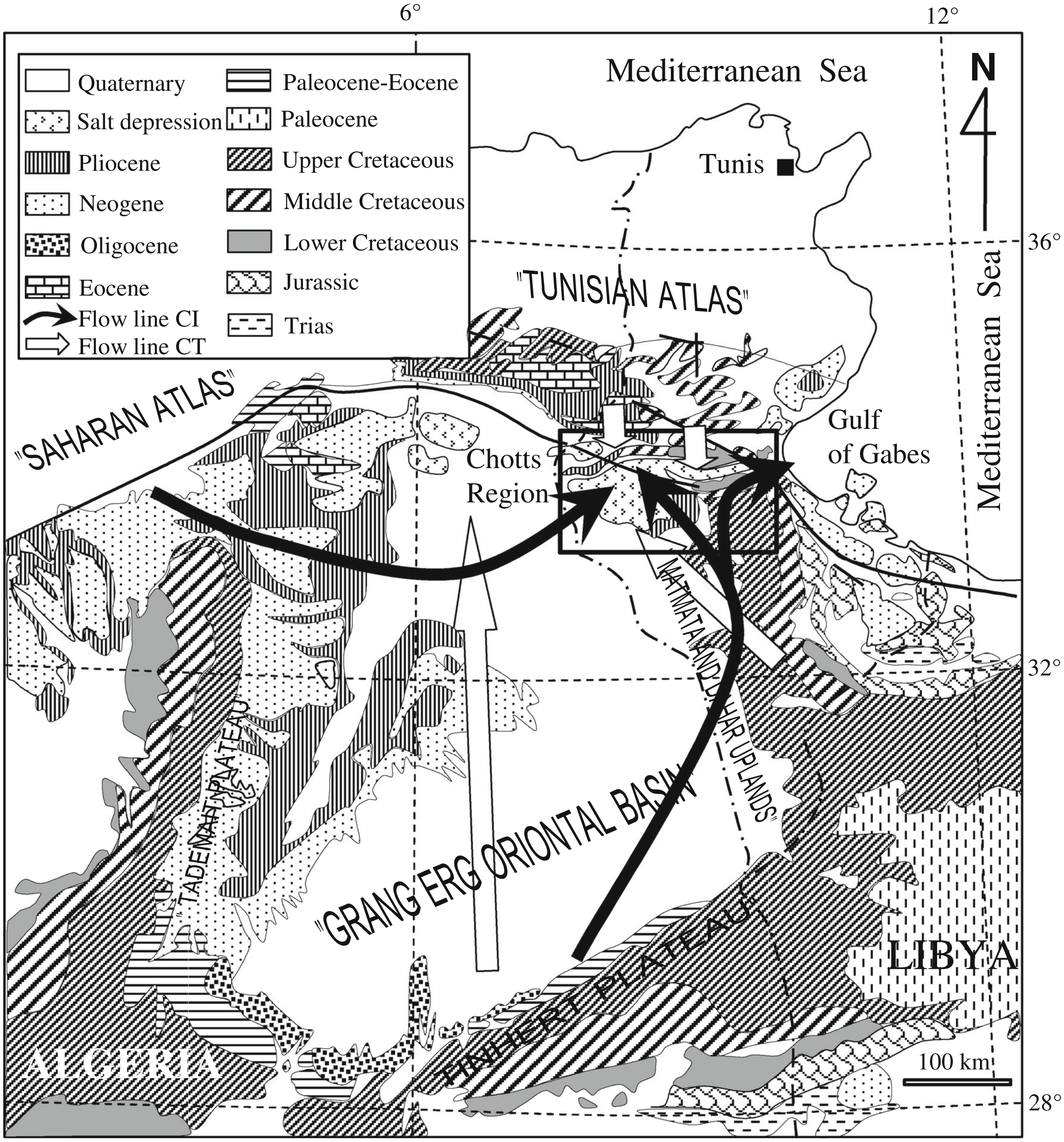


Fig. 1 Simplified geologic map and location of the study area

exceeds 17,000 mm/year. The drainage network is insignificant and mainly constituted by non-perennial Wadis, which collect runoff water from the northern Chotts chain and Dahar uplands.

The study area makes part of the Grand Erg Oriental Basin, which hosted the two largest aquifers in the North Africa: the Continental Intercalaire (CI) and the CT. Continental Intercalaire and CT are shared between Algeria, Tunisia and Libya. Chott Djerid and the Gulf of Gabes constitute the main discharge area of both CI and CT (Fig. 1).

In Tunisian Chotts region, the aquifer system is composed mainly of a local Plio-Quaternary aquifer (PQ) with a high water salinisation, exploited only in summer time as irrigation complement, an upper confined/unconfined "Complexe Terminal: CT" which supplies about 80 % of water demand and a deeper CI aquifer used for geothermal purpose.

Recharge characteristics of the 'Grand Erg Oriental Basin' and adjacent part in Libya was largely studied by several authors (UNESCO 1972; Edmunds et al. 1997; Swezey 1999; Ould Baba Sy 2005). This paper aims to provide a better understanding of mechanisms that contribute to unconfined groundwater local recharge in Tunisian Chotts region despite overexploitation and the scarcity of the precipitations in this part of the referred basin.

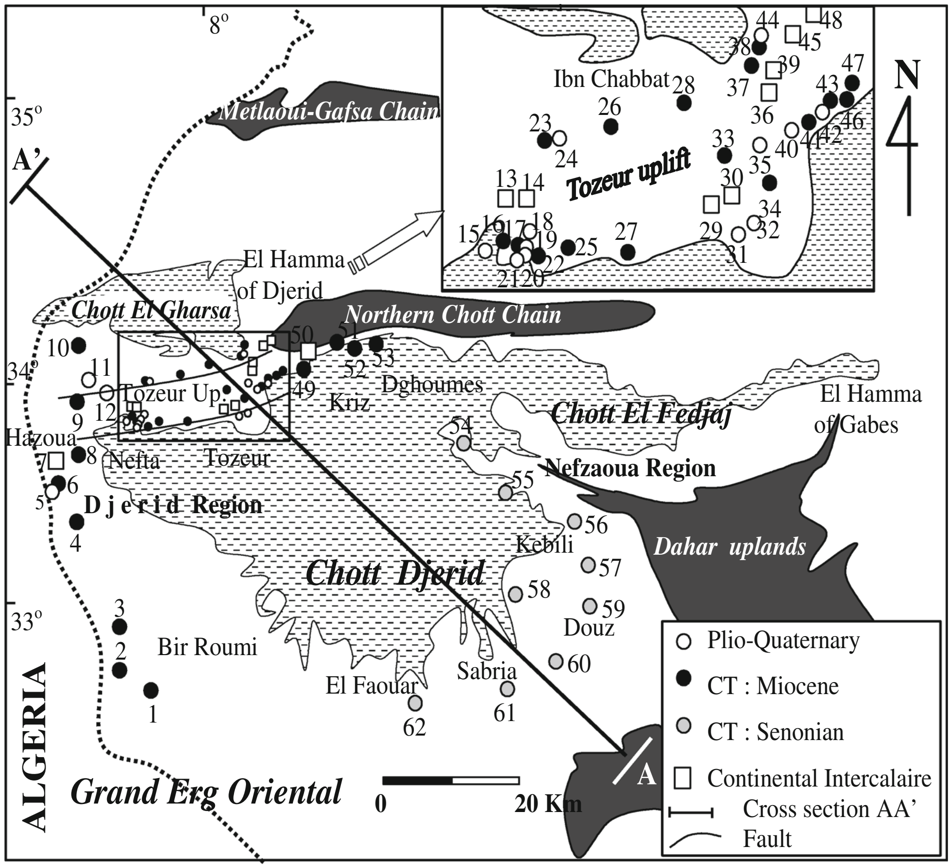


Fig. 2 Localities and sampling map

This manuscript also proposes to emphasise the mechanisms of the confined deep aquifers to recharge the shallow unconfined water table aquifers.

Geology

The Chotts area occupies an intermediate position between two tectonic domains distinguished by their deformation style (Ben Youssef et al. 1985). The southern Tunisian Atlas is characterised by major structural features, which controlled the distribution of Mesozoic and Cenozoic deposits (Castany 1982). The east–west Chotts features (Fig. 2) represent the most southern structures of the Atlasic domain (Abdeljaoued 1983).

In the year 1998, deep borehole Hazoua CI (no 7 on Fig. 2) was performed in the southwestern Tunisian/Algerian borders in order to precisely understand the deep geological Cretaceous setting in this region and the CI hydrogeological potentialities.

A total of 16 cutting samples have been collected at different depths during the welling progression. Analyses including lithology, micro fauna and deposit conditions were done at the Entreprise Tunisienne des Activités Pétrolières Laboratories, using standard techniques, as shown in Table 1.

The well Hazoua CI penetrated 435 m of Quaternary and Tertiary sediments, 1,236 m of Upper Cretaceous, 552 m of Lower Cretaceous series and terminated at the depth of 2,225 m.

Table 1 shows the absence of the different formations of the Oligocene and the Upper Eocene. The detrital series of the Neogene overlays unconformably on the phosphates-limestone and the marl of Thelja formation (Thanetian age). It seems that the Kef Dour limestone block and phosphate clays of Chouabine series, constituting the Metlaoui formation and outcropping in the Metlaoui–Gafsa Chain, are rigorously eroded under Djerid region (Moumni 2000).

Clay stone and thin phosphate layers of the Palaeocene that mark the transition of the Cretaceous to the Tertiary, present a thickness of 101 m (from 166 to 267 m).

Limestone and marls-limestone of the Berda formation, with its three members, show a thickness of 164 m (436–600 m). The large marls-gypsum series associated with limestone and dolomite at the base of the Aleg formation (Coniacian–Santonian age), is 459 m thick. This order of thickness is common in the Djerid and in the adjacent regions.

Table 1 Litho-stratigraphic units and proposed age at the Hazoua CI (borehole no 7)

Depth (m)	Lithology	Formation	Proposed age	Potential aquifers
0–73	Alternation of sand, clayey sand with gypsum levels	Segui	Quaternary	Unconfined aquifer (PQ)
74–120	Red compact clay		Pliocene	
121–165	Yellow sand with thin clay layers	Beglia	Miocene	Confined/unconfined aquifer (CT: Miocene)
166–267	Crystalline limestone with phosphate pellets	Lower Metlaoui/ Thelja	Lower Eocene/ Palaeocene	
268–435	Mainly marl	Lower Metlaoui/El Haria	Thanetian/Dano-Montian	
436–500	Predominant Glauconitic limestone	Upper Berda	Maastrichtian	Confined/unconfined aquifer (CT: Senonian)
501–552	Series mainly clayey-marl with dolomite	Medium Berda	Lower Maastrichtian to Campanian	
553–600	Limestone, marl and silt	Lower Berda	Campanian	
601–700	Marl and limestone	Aleg	Coniacian to Santonian	
701–760	Abundant conglomeratic lumachel with rudists associated to marl			
761–855	Oolithic fossiliferous limestone associated to lumachelic Rudist and green marls			
856–1,060	Predominant conglomeratic lumachelic rudists, green marls, lignite in traces			
1,061–1,258	Abundant oolitic fossiliferous limestone, dolomite, marl with crystalline limestone	Aleg and Bireno	Turonian-Coniacian	Confined aquifer (Turonian)
1,259–1,672	White anhydrite and dolomite	Zebbag	Upper Cenomanian Lower–Turonian	
1,673–1,822	Dolomite with thin clay layers	Orbata	Albian–Aptian	
1,823–2,225	Coarse sand and sandstone	Sidi Aich	Barremian	Confined aquifer (CI)

Dolomite and gypsum (Beida formation) with the limestone/dolomite (Guettar member), forming the upper member of the Zebbag formation (Turonian age), is of about 200 m (1,061–1,258).

Below 1,673 m depth lie alternating dolomite, marl, green clay, gypsum and sandstone, which turn into coarse sandstone between 1,823 and 2,225 m depth (Sidi Aich formation).

Massif dolomite, attributes to the Aptian age, overlain the Sidi Aich formation between 1,673 and 1,822 m depth. It is known as a very good seismic marker with its constancy thick in the Djerid and the Nefzaoua regions, thus indicates the top of the Sidi Aich formation.

Three main aquifers were recognised at a depth between 10 and 73 m depth for the shallow PQ hosted in the sandy and clayey sandy levels. The intermediate CT, the most important one in the Djerid region, reached between 121 and 165 m depth in the sandy Beglia formation (Miocene). The deeper CI, hosted in the Sidi Aich sandstone formation and is known as the geothermal CI aquifer between 1,825 and 2,225 m depth (Table 1).

Limestone of Maastrichtian/Campanian and Dolomite of Turonian constitute non-exploited aquifers in the Djerid region. The referred aquifer levels are strongly exploited in Nefzaoua region and further at the west part of the study area, respectively.

Only the CI aquifer is aimed in this borehole, thus different casing diameters were cemented until the top of the CI aquifer. A Johnson $6''^{5/8}$ filter was installed between 1,784 and 2,071 m depth to assure the CI aquifer catchments.

Outflow amounts to over 150 l/s with high total dissolved water, passing 1,800 mg/l. Wellhead temperature at maximum outflow amounts to over 68 °C at 22 bar pressure.

Hydrogeology

Cross-hydrogeological section AA′ (Fig. 3) shows the aquifer system architecture in the Djerid–Nefzaoua region.

The deep confined CI is contained in the lower Cretaceous formations (Cornet 1964). It is located within a

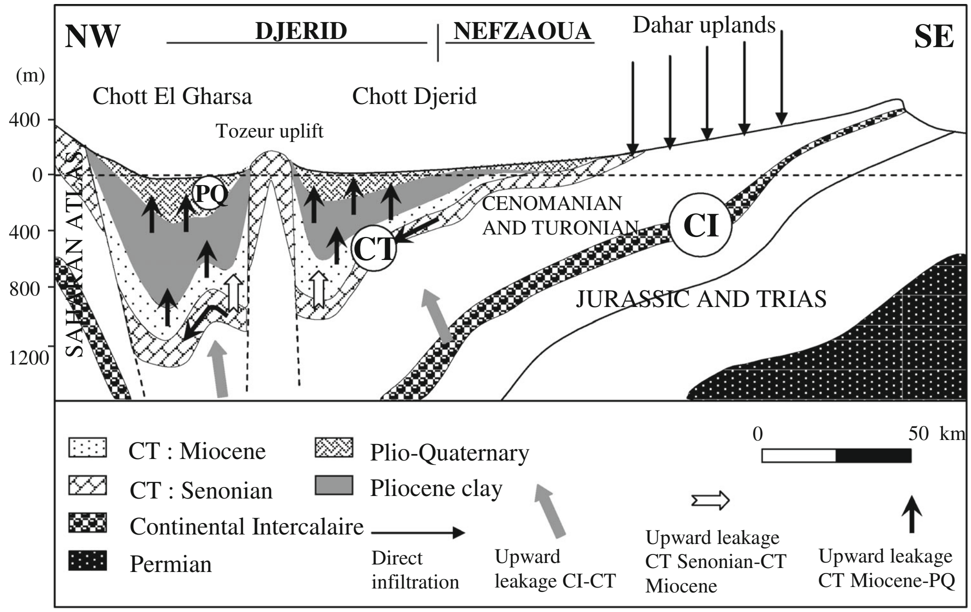


Fig. 3 NW–SE hydrogeological cross-section in the Tunisian Chotts region (AA′) (After Rouatbi, modified)

complex sequence of clastic sediments of Mesozoic age, the thickness and lithology of which show significant lateral variation. It is a multilayer aquifer system, which extends over a surface area of 600,000 km^2. Its depth reaches locally 2,500 m while its thickness ranges between 200 and 400 m (UNESCO 1972; Fezzani et al. 2005). More than 50 boreholes are exploited from this artesian aquifer in the study area. Their flow rates vary from 20 to 100 l/s and are mainly used for geothermal issues and oases irrigation.

The principal areas of current or former CI recharge are in the South Atlas Mountains of Algeria, the Tinhert plateau of Algeria and the Dahar Mountains of Tunisia (Mamou 1989) (Fig. 1). The CI is mainly confined and discharges in the Chotts of Tunisia and in the Gabes gulf (Mediterranean Sea) (Fig. 1). Only the west–east flow component coming across the Algerian–Tunisian border seems to ensure hydraulic continuity of the CI in the Djerid region (Fig. 1). Groundwater flow in the CI of the Grand Erg Oriental takes place towards gulf of Gabes through major el Hamma fault and under Djerid Chotts (Cornet 1964; Aranyossy and Mamou 1985; Edmunds et al. 1997; Gries 2002; Abidi 2004).

The CI aquifer covers mainly 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 and well pressure varies between 6 (Nefta CI3) and 20 bars (Hazoua CI) above the wellhead.

Transmissivity of the CI aquifer (Sidi Aich Formation), obtained from pumping tests, ranges from 0.8×10^{-3} to 4.5×10^{-3} m^2/s and storage coefficient ranges from 0.2×10^{-4} and 1.4×10^{-4} (Kamel et al. 2005).

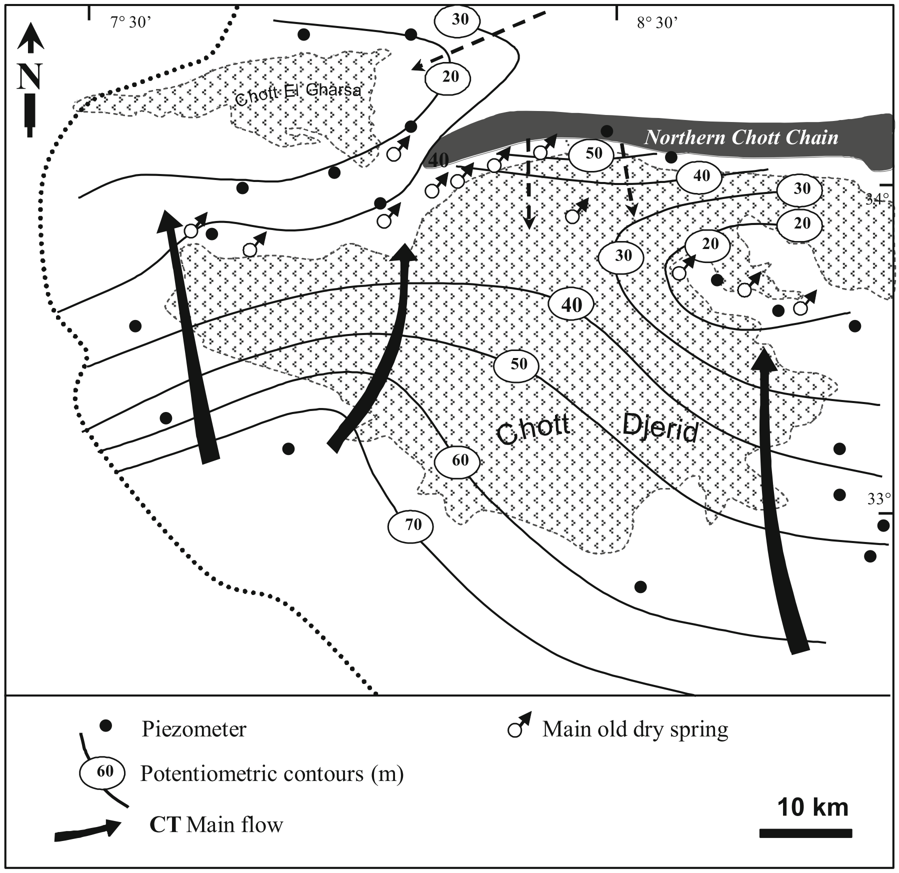
In the study area, since spring drought in 1984, 80 % of water needs are supplied by the CT aquifer. The effect of intensive use of this aquifer began to appear since 1995 by the same way of intensive irrigation used for the old oases extension and the creation of new oases (Observatoire du Sahara et du Sahel (OSS) 2008).

Hydrogeologically, the CT groups under the same term several aquifers combining different geological formations. In the Djerid, the CT is formed by the Miocene sand and in the Nefzaoua and Chott El Fedjaj by Campanian-Maestrichtien. The cross-section AA′ connecting Saharan Atlas in Algeria to Dahar uplands in Tunisia through the Chotts region (Rouatbi 1977) (Fig. 3) shows that the Senonian limestone rocks, form the main CT aquifer system in the Nefzaoua region at depth not passing 300 m. In the Djerid region, the Miocene sands constitute the main aquifer of the CT at 100–800 m depth. The thickness of this aquifer varies between 70 and 250 m in the Nefzaoua region and a mean of 120 m in the Djerid region.

More than 500 dugwells were inventoried over the Djerid and Nefzaoua region with annual discharge flow exceeding only in the Djerid region 150 Mm^3/year. The permeability of the CT layers is variable (10^{-4}–10^{-5} m/s). The transmissivity varies from 10^{-2} to 10^{-3} m^2/s (UNESCO 1972). Because of the aquifer intensive exploitation, artesianism has totally disappeared. However, upward leakage to the phreatic aquifer can still occur favoured by the semi-permeable strata or by the ancient boreholes' deteriorated tubing (Guendouz et al. 2006).

The main groundwater flow direction, from the southeast to the northwest, converges to Chott Djerid and Chott Gharsa depressions, which constitute the main discharge areas of the CT (Fig. 4). The flow from the Senonian

Fig. 4 Potentiometric CT surface contour (2001)



Carbonates to the Miocene Pontian sands takes place under the relatively high piezometric pressure, just to the south of the Chott Djerid. There the freshwater of the Miocene aquifer is protected from saline surface water of the Chotts by 300–400 m-thick clay layers of similar age (Edmunds et al. 1997; Besbes and Horriche 2007).

The CT aquifer is generally confined in the Djerid region. It produces a maximum head of 40 m above the ground surface (UNESCO 1972) which steadily declined under intensification of pumping. However, it is phreatic in the east of Nefzaoua region, close to the Dahar hills and near the Tozeur uplifted ridge, where the Miocene sands crop out (Mamou 1989).

The recharge to the CT aquifer is probably from the Dahar uplands in the southeast and from the northern chain of Chotts in the north. Direct infiltration of rainfall through the superficial PQ deposit and return flow waters could also constitute other source of recharge (Aranyossy and Mamou 1985).

At the surface, the Quaternary formations contain the phreatic waters. It is mainly composed of fine grain size aeolian sand with local gypseous and sandy clayey intercalations. It may also contain locally at the top 1.5–2 m thick layers of saline gypsum encrustments and at its base a layer of clayey sandstone and carbonate (Kamel et al. 2005). The aquifer depth varies from 10 to 40 m and its thickness reaches locally 100 m. The farmers through more than 3,000 dugwells exploit it. This aquifer is essentially recharged by the excess of irrigation water coming from the CI and the CT deep aquifers, in oases area. Out of these cultivable zones, the PQ aquifer is recharged during the rare rainfall events and the upward leakage. The main subsurface flow direction is toward south (toward Chott Djerid) southern Tozeur uplift, and toward north (toward Chott El Gharsa) northern Tozeur uplift (Fig. 5).

Sampling and water analyses

A representative set of groundwater samples was collected during June 2001. A total of 62 samples was collected from boreholes tapping the deep CI aquifer (1,368–2,584 m depth), the CT aquifer (53–738 m depth) and the shallow dugwells (1.9–50 m depth) (Table 2). Figure 2 shows the spatial distribution of sampled water in the aquifer system.

Field determinations were made for pH, alkalinity, temperature, and conductivity.

TDS measurements were performed at the "Laboratoire de Radio-Analyses et Environment" of the "Ecole Nationale d'Ingénieurs de Sfax", Tunisia.

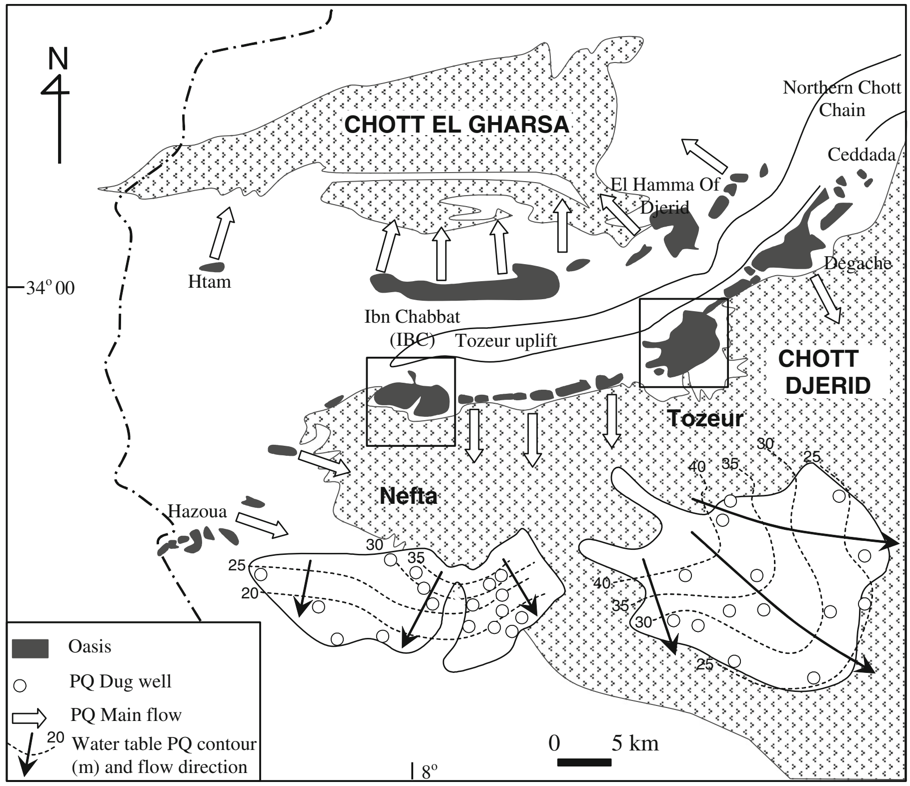


Fig. 5 Water table map of the Plio-Quaternary (2001)

Stable isotope ($\delta^{18}O$, $\delta^{2}H$) analyses were performed at the "Centre National de Recherche Scientifique d'Orsay", France, by using standard methods. Hydrogen and oxygen isotope analyses were made by respectively employing the standard CO_2 equilibration method and the zinc reduction technique, followed by analysis on a mass spectrometer. All oxygen and hydrogen isotopes analysis are reported in the usual δ notation relative to Vienna Mean Oceanic Water standard, where $\delta = [(RS/RSMOW) - 1] \times 1{,}000$; RS represents either the $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of the sample, and RSMOW is $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of the SMOW. Typical precisions are ±0.2 and ±2.0 ‰ for the oxygen and deuterium, respectively.

The tritium contents on groundwater samples collected from CT and PQ, have been accomplished in the IAEA laboratories (Vienna) using electrolytic enrichment and liquid scintillation counting method. Tritium is expressed in Tritium Unit (UT), in which one UT equals one tritium atom per 10^{18} hydrogen atoms.

In 2001, tritium content of 20 samples collected from the CT and the PQ in the Djerid region, were measured.

Radiocarbon analyses were done at the Laboratory of Radio-analyses and Environment at National Engineering School of Sfax (Tunisia). Selected samples were collected for the analysis of ^{14}C and $\delta^{13}C$ (Table 2). ^{14}C radiocarbon analyses were done by scintillation counting on C_6H_6 synthesised from $BaCO_2$ stripped in the field from 100 to 200 l water samples. Results are reported as percentages of modern carbon (p_{mC}) and (PDB), respectively, for ^{14}C and $\delta^{13}C$ (Table 2).

The major chemical elements for each sample were determined in the laboratory using analytical methods (atomic absorption spectrometry; UV spectrophotometry, acid–base titration).

Deuterium and Oxygen-18 composition of groundwater

Oxygen-18 and deuterium values of the CI groundwater samples range respectively from −7.6 to −6.8 ‰ with a mean of −7.34 ‰ and from −54.6 to −61.7 ‰ with a mean of −59.23 ‰. Data from the sandy Complex Terminal (Miocene) range from −6.21 to −3.85 ‰ and from −43.4 to −54 ‰, with mean values of −5.09 and −47.98 ‰. Data from the limestone CT (Senonian) range from −5.62 to −4.52 ‰ and from −45.9 to −51.5 ‰, with mean values of −5.21 and −48.66 ‰ respectively. Those of PQ groundwater are relatively more enriched and vary from −2.17 to −5.12 ‰ for the $\delta^{18}O$ and from −49.4 to −28.9 ‰ for the $\delta^{2}H$ with mean values of −4.15 and −43.49 ‰ respectively (Table 2).

In Fig. 6, the $\delta^{18}O$ and $\delta^{2}H$ data of all groundwater samples were plotted together with the Global Meteoric Water Line (GMWL) and the Meteoric Water Line of the Nefta station (NMWL) (Kamel 2010).

Table 2 Physico-chemical and isotopic contents in groundwaters

No on Fig. 2	Locality	Aquifer	Depth (m)	T °C	pH	EC (µS/cm)	TDS (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	$\delta^{18}O$ ‰ vs SMOW	$\delta^{2}H$ ‰ vs SMOW	^{14}C (p_{mC})	$\delta^{13}CI$ (PDB)
5	Hazoua F5	PQ	30–50	25	6.6	10,400	7,500	1,149	183	−5.12	−49.10		
18	Nefta foret	PQ	4.5–15	24	8.0	7,000	5,280	875	104	−3.86	−43.60	72.10	−10.41
20	A. Nasr	PQ	8.5–12	26	7.3	7,050	5,540	1,139	305	−5.32	−49.40		
19	L. zouni	PQ	6.5–32	22	7.5	7,155	5,600	1,128	310	−3.53	−42.40		
24	A. Legtari	PQ	24–44	24	7.8	5,230	5,200	942	153	−4.58	−46.00		
44	A. Amamra	PQ	13–15	25	7.7	9,030	6,800	1,439	366	−5.04	−43.90		
42	K. Rhouma	PQ	5.6–10	24	7.1	10,000	7,700	1,953	226	−4.43	−44.70	87.50	−9.96
21	M Tatta	PQ	1.9–5	23	7.3	7,950	6,480	750	183	−4.82	−49.20	85.50	
15	M. zaeter	PQ	7.5–12	21	6.9	8,260	6,280	1,633	366	−4.90	−46.70	77.60	
31	Jhim Foret	PQ	4.5–14	23	7.1	9,300	7,340	1,686	275	−3.19	−40.90	83.00	
35	A. Sekala	PQ	3.5–9	23	7.2	7,580	6,500	1,065	244	−3.48	−42.30	100.00	
32	A. Jhimi	PQ	5.5–32	22	7.8	9,870	7,580	1,420	280	−3.63	−43.40	99.40	
40	H. Maklouf	PQ	2.8–8	22	7.5	10,550	7,040	2,308	244	−3.57	−42.50	93.90	
11	B. Touil	PQ	18–25	21	6.8	10,710	7,640	2,485	98	−4.71	−39.40		
12	B. Hod	PQ	15–25	21	7.3	5,920	4,940	977	104	−2.17	−28.90		
10	Htam	CT: Miocene	666–738	37	7.5	5,000	3,100	514	168	−5.29	−49.30	4.40	
16	Nefta 4b	CT: Miocene	401–486	29	7.5	4,000	3,200	690	178	−5.11	−48.50		
26	IBC 10	CT: Miocene	596–680	30	7.3	4,010	3,100	590	128	−4.99	−48.10		
28	Chemsa 1b	CT: Miocene	591–655	30	7.5	3,930	3,100	617	188	−5.01	−47.90		
34	Tozeur 8	CT: Miocene	320–400	30	8.1	2,800	2,100	527	125	−3.85	−43.60	18.30	−8.29
47	A Torba 3t	CT: Miocene	96–172	31	7.7	2,200	1,800	417	122	−5.85	−51.30		
53	Ceddada 4b	CT: Miocene	550–635	35	7.7	4,300	3,190	1,073	151	−5.93	−50.60		
9	Mzara	CT: Miocene	323–361	27	7.4	3,780	2,800	604	122	−4.83	−47.40	3.20	−6.36
8	G. Jaballah	CT: Miocene	325–395	28	7.7	3,000	2,920	746	268	−4.77	−47.60	7.90	−6.94
41	O Koucha	CT: Miocene	285–342	32	7.7	2,800	1,890	426	151	−4.79	−46.20	11.90	
38	Hamma 15	CT: Miocene	40–105	33	7.7	2,500	2,340	462	268	−4.80	−43.40	6.60	
23	IBC 1	CT: Miocene	414–510	26	7.5	4,200	3,240	657	158	−4.75	−45.40	17.00	−6.18
4	A O Ghrissi	CT: Miocene	443–489	30	8.0	3,600	2,720	960	183	−4.60	−46.90	5.80	−7.46
27	PK 14b	CT: Miocene	507–578	30	8.0	2,910	2,160	500	102	−4.07	−45.00	6.10	−7.27
33	D CRDA	CT: Miocene	56–68	28	7.2	2,400	1,930	494	143	−5.72	−51.80	17.90	−6.14
25	Ghardga. 4b	CT: Miocene	285–380	31	7.0	3,800	3,310	390	174	−6.11	−53.90	10.40	−5.46
37	Hamma 14b	CT: Miocene	99–118	34	7.2	4,900	4,290	497	122	−5.44	−49.50	28.50	
2	Matrouha	CT: Miocene	190–288	28	5.6	3,490	2,940	604	134	−4.02	−44.90	8.80	
3	B Roumi	CT: Miocene	287–341	27	7.5	3,940	3,010	568	214	−5.24	−49.10	1.75	
54	Dghoumes 4	CT: Miocene	550–620	38	8.0	5,300	4,100	1,751	136	−5.98	−51.74	37.00	

Table 2 continued

No on Fig. 2	Locality	Aquifer	Depth (m)	T °C	pH	EC (µS/cm)	TDS (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	$\delta^{18}O$ ‰ vs SMOW	$\delta^{2}H$ ‰ vs SMOW	^{14}C (p_{mC})	$\delta^{13}CI$ (PDB)
49	Kriz 5	CT: Miocene	64–105	32	7.2	6,360	4,100	1,398	103	−5.85	−47.94	44.90	
52	Tazrarit 1	CT: Miocene	49–91	35	7.7	8,400	5,880	2,449	137	−5.92	−47.92	0.00	
46	Deg. Senon	CT: Miocene	538–604	33	7.7	2,600	2,420	497	125	−4.43	−41.51	2.10	
17	Nef 2bis	CT: Miocene	62–142	29	7.5	4,100	3,100	639	104	−4.80	−47.10	0.00	
43	Manach 2b	CT: Miocene	180–216	29	7.3	3,060	2,020	462	153	−5.59	−48.90	2.30	
1	Rej Matoug	CT: Miocene	123–220	27	6.0	2,510	2,316	424	137	−4.16	−45.20	10.30	
6	Hazoua 1b	CT: Miocene	422–540	30	7.9	3,750	2,740	639	128	−4.45	−46.40	7.90	
22	Zafrana	CT: Miocene	612–672	30	7.2	3,850	3,240	817	183	−6.21	−54.00	6.00	
59	Douz 2b	CT: Senonian	53–67	25	7.6	4,580	3,250	1,136	128	−5.48	−49.60		
57	Jemna	CT: Senonian	103–200	24	6.1	1,700	1,470	341	137	−5.13	−45.90	10.80	−3.60
56	Rasel Ain	CT: Senonian	72–78	26	6.4	4,620	4,560	1,125	214	−5.53	−49.60		
54	Fatnassa 2	CT: Senonian	92–185	26	6.3	4,030	3,406	835	156	−5.03	−47.70	27.80	
61	Sabria Mol	CT: Senonian	118–200	24	6.4	1,490	1,132	222	137	−5.62	−51.50	6.10	−5.90
62	Faouar 4	CT: Senonian	88–195	25	6.6	2,070	1,634	426	116	−4.52	−46.50	9.60	−4.59
60	Zafrane 3 b	CT: Senonian	95–122	24	6.1	1,250	1,234	307	128	−5.13	−47.00	21.10	
55	Negga 6	CT: Senonian	150–250	27	6.5	1,960	1,968	460	146	−5.15	−51.10	11.60	−6.70
58	Zarcine 1	CT: Senonian	103–200	26	5.9	2,400	1,974	443	137	−5.35	−49.10	11.60	−5.77
14	Nefta CI1	CI	2,068–2,122	70	7.3	5,130	3,368	600	140	−7.1	−58.00		
13	Nefta CI2	CI	2,326–2,584	67	7.1	3,400	2,665	320	132	−7.5	−57.90	0.48	−8.96
30	Toz CI 2	CI	1,757–1,877	57	7.1	4,640	3,574	520	110	−7.4	−61.70	0.44	−8.47
29	Tozeur CI3	CI	1,856–2,002	66	7.1	4,200	4,200	366	110	−7.6	−61.00		
36	Hamma CI2	CI	1,469–1,586	64	8.2	5,030	3,377	360	256	−6.8	−67.00		
45	Hamma CI 4	CI	1,368–1,475	63	7.3	3,460	2,811	320	153	−7.4	−58.80	0.38	−8.80
50	Ceddada CI	CI	2,257–2,371	71	6.9	3,360	2,401	446	150	−7.4	−54.60	0.27	−8.51
7	Hazoua CI	CI	1,870–1,988	63	7.0	2,390	1,766	286	136	−7.3	−57.30	0.42	−9.65
48	Mahacen CI1	CI	1,370–1,430	70	6.9	3,160	2,288	371	179	−7.4	−56.40	0.69	−8.88
39	Hamma CI1b	CI	1,444–1,550	70	6.9	3,470	2,742	305	139	−7.5	−59.60	2.40	−8.25

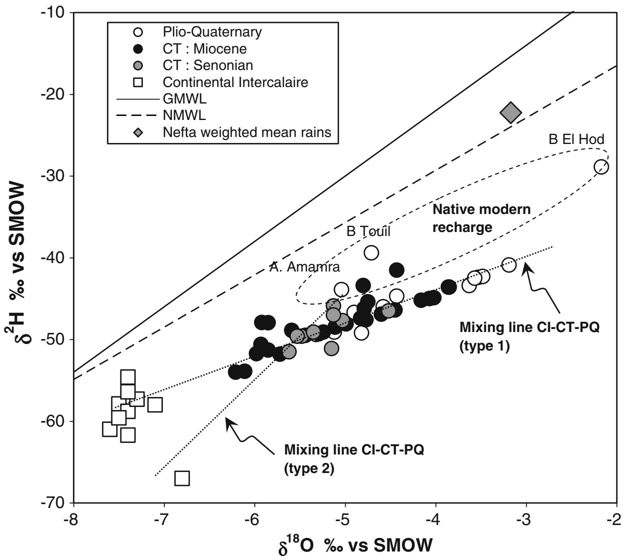


Fig. 6 $\delta^{18}O/\delta^{2}H$ diagram of the groundwaters

Groundwater of the deep CI aquifer has relatively homogenous signatures of $\delta^{18}O$ and $\delta^{2}H$ which are significantly more depleted than those of the modern rainfall in the Nefta city. These isotopic signatures are characteristic of paleowaters in northern Africa. This observation agrees with the results obtained in the southern Tunisia, which were interpreted as recharge occurring during the late Pleistocene period (Gonfiantini et al. 1974; Fontes 1976; Zouari 1988; Edmunds et al. 2003; Guendouz et al. 2003; Kamel et al. 2008).

Waters from the CT intermediate aquifer are isotopically more enriched than those of the CI. In the $\delta^{2}H/\delta^{18}O$ diagram, all samples are located largely below the GMWL and the NMWL indicating their old origin, probably in relation with humid periods of the Pleistocene. However, two main trends are apparent when examining in detail the relation between $\delta^{18}O$ and $\delta^{2}H$ (Fig. 6). One trend follows a line, which extends parallel to the GMWL towards the paleoclimatic waters of the CI aquifer (type 1). This trend follows an estimated line, which samples collected from the sandy Miocene in the Djerid region. These wells fall on a line (with a slope of 4), which shifts from the GMWL indicating an evaporation effect. The end member of this line is formed by PQ samples collected in the Djerid oases mainly recharged by return irrigation flow. This trend represents a mixing line CI–CT–PQ and probably related to the CI flow line originate from Saharan Atlas through western Tunisian border (Fig. 1).

The second trend encloses the samples, collected from the CT limestone (Senonian) wells located in Nefzaoua region and fall on a line with a higher slope (type 2), obviously showing a lower evaporation effect. This trend represents a mixing line CI–CT–PQ and probably related to the CI flow line originating from Dahar uplands in Tunisia and the Hoggar mountains (Tinhert Plateau) in south Algeria (Fig. 1). The lower evaporation effect in this trend is probably related to the shorter transit of CI flow from Dahar uplands to the study area.

The main source of recharge of the PQ aquifer is insured by the return flow of irrigation waters which exploits about 150 Mm^3/year pumped from the CT reservoir (Moumni 2000). Thus, the excess irrigation water returns to CT aquifer and mixes with water from the regional groundwater flow system. The $\delta^{2}H$ and $\delta^{18}O$ of the return flow water fractionate and concentrate at different rates in the irrigation channels and in the PQ aquifer itself and provide to the CT groundwater an evaporated apparent character. The old origin of the PQ groundwater is also confirmed by the position of the representative points in the $\delta^{2}H/\delta^{18}O$ diagram which fall largely below the global and the Nefta meteoric lines. However, the insignificant native modern recharge of this shallow aquifer is indicated by the position of some samples closer to the NMWL.

Stable isotope/chloride relationship

Generally, chloride is considered to be a conservative i.e. a non-reactive chemical tracer. In our case of study, the discussed aquifer systems differ from each other by their typical chlorinity. Thus, the distinguishing between the two processes, evaporation and mixing, can be assumed when plotting Cl concentrations against $\delta^{18}O$ (Fig. 7) and $\delta^{2}H$ (Fig. 8). The results show the different trends of mixing and evaporation already displayed in the $\delta^{2}H/\delta^{18}O$ relationship. The first trend indicating the mixing between CI–CT and PQ aquifers includes isotopically depleted waters with high chloride concentrations. The type 1 mixing water is related to the component of CI flow coming from the west (Algeria) and confirms the faraway origin of these waters (reliefs of the Algerian of the Saharan Atlas). On the contrary, the second trend showing the mixing between CI–CT and PQ waters as well as the evaporation effect involves isotopically enriched waters at considerably lower chloride concentrations. The type 2 mixing is in relation with the CI flow from the Hoggar Mountains and Dahar uplands and interest waters with relatively low concentrations in chloride due to their proximity of recharge zones (the Dahars reliefs).

In the Figs. 7, 8, points representative of CI, CT and PQ groundwater are aligned on the two mixing lines (type 1 and type 2), where the CI waters constitute the end member of both of them.

In fact, the main source of recharge of the PQ aquifer is insured by the CT return irrigation flow. The old origin of the PQ groundwater is confirmed by the position of the

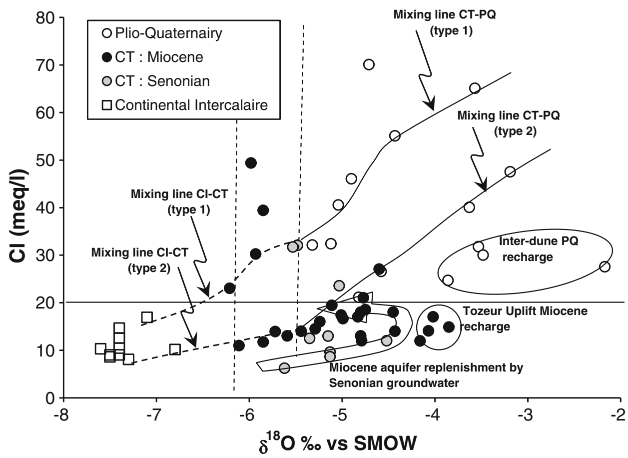


Fig. 7 δ^{18}O/Cl diagram of the groundwaters

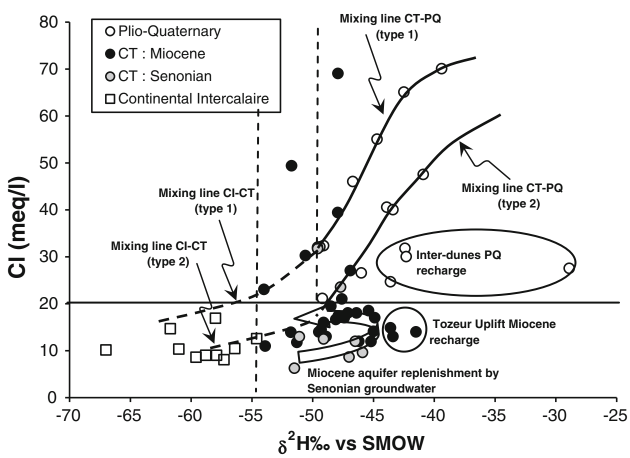


Fig. 8 δ^{2}H/Cl diagram of the groundwaters

representative points in the δ^{2}H/δ^{18}O diagram which fall largely below the global and the Nefta meteoric lines. In addition to this recharge by return of irrigation, a recent water component would recharge PQ aquifer apart from the oases. This type of recharge is materialised by the existence of three relatively evaporated points (A. Amamra no 44, B. Touil no 11 and B. Hod no 12) which are detached from the mixing line CT–PQ (type 2). The referred points are located between Chott Djerid and Chott El Gharsa where the recent recharge may occur probably at inter-dunes zones, under special conditions (high sporadic precipitation amount, sufficient size and permeability of grain sands, presence of gypsiferous crust as a local substratum…).

In sand dune regions, the runoff over the surface of the sand can be neglected for practical purposes. Even after heavy and short duration rains, there was no sign of surface runoff on the surface of the sand dunes in the vicinity. Experiments made using 1 m long sand columns indicated that the depth of penetration of an input of 50 mm of water in 24 h was 35 cm in well-graded dune sand with a particle size of 0.15 mm and was more than 100 cm for the dune sand having a mean particle size of 0.3 mm. These results already indicate the opportunity of the precipitation to penetrate in the coarse sand deeply enough to escape evaporation. In arid zones the mean annual precipitation may be extremely low, as in the case of Saudi Arabia, but the distribution of the precipitation on a daily or annual basis is highly skewed and heavy showers once in 2 or 3 years are not uncommon (Dincer et al. 1974).

Other points in evaporated matter, representing the CT groundwater, are also detached from the mixing line and correspond to the existence of a recent component at Tozeur uplift where the CT aquifer is unconfined.

In addition to the process of mixing, correlations ^{18}O vs Cl and ^{2}H vs Cl shows a significant hydrodynamic "hydrogeological relay". This mechanism is materialised by the passage of water of limestones of the CT of Nefzaoua towards sands of the CT of Djerid under the effect of the increase in pressure of the stratigraphic column near the Tozeur uplift. This passage of water is clearly illustrated by the succession of the representative points of the CT of Nefzaoua towards those of Djerid. This arrangement of the points reflects a passage of the water relatively evaporated, because of the presence of a component of recent recharge near the reliefs of Dahar, towards water of Djerid relatively impoverished because of their old origin.

Carbon-14 and ^{3}H contents

Carbone isotopes in groundwater have been used to provide additional information on the age as well as to support evidence of the mixing process obtained from the stable isotopes and tritium data. ^{14}C is a reliable age dating tool of moderately old water (5–35 k years), but correction must be made to account for water–rock interactions.

Measured 14-C activities in selected well samples range from 0 to 100 p_{mC} (Table 2). The lowers 14-C activities, ranging from 0.27 (Ceddada CI) to 2.4 (Hamma CI 1 bis) have been recorded in the CI groundwater samples (Fig. 9).

The activities of the sampled CT groundwater are very heterogeneous and vary between 0 p_{mC} (Tazrarit 1) and 44.9 p_{mC} (Kriz 5) (Fig. 9).

The activities ^{14}C measured in the groundwater of the PQ are very high (Fig. 9), they lie between 72.1 p_{mC} (Nefta foret) and 100 p_{mC} (Abdallah Sekala) (Fig. 9).

The low carbon-14 activities, which characterise the CI waters, in agreement with their impoverished contents of stable isotopes, confirm their old origin. The CI is unconfined in all the study area with a depth of its roof exceeding 1,500 m. Thus, CI groundwater cannot be in balance with the contemporary recharge whatever the permeability considered for the sandy facies of the aquifer and the water, which

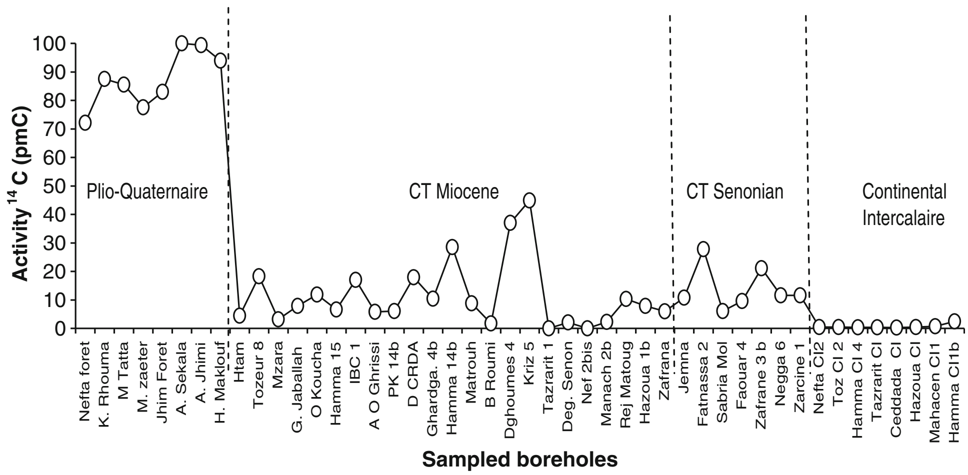


Fig. 9 ^{14}C contents in CI, CT and PQ sampled waters

appeared with emergences had left the zones of recharge several thousands of years earlier. CI recharges occurred from precipitated meteoric water under different present climatic conditions (Fontes 1976). These activities cannot be interpreted in term of age since they exceed the limit of the method. However, studies carried out using noble gas (Edmunds et al. 2003, of Guendouz et al. 1997 and Gries 2002) and Chlorine isotopes confirm the CI groundwater recharge is in relation to the wet periods of Pleistocene.

"This indicates that the recharge coincides with the humid period of the late Pleistocene (20–40 ka), which has been demonstrated to have exist across the whole of northern Africa" (Guendouz et al. 1997).

Figure 10 represents the spatial ^{14}C distribution activities of the CT groundwater. The activities ^{14} C decrease by the West towards the East (Algerian component) and by the SE towards NO (coming from Tunisian Dahar) in concordance with the main flow piezometric directions.

The lowest activities (<12 p_{mC}), are recorded in the South and the West of Djerid (Htam 4.4 and in Mzara 3.1 p_{mC}) justifying Chott Djerid as a discharge area of CT water coming from Algeria (Fig. 10).

The highest activities are recorded in the Northern Chotts chain piedmont (44 p_{mC} at Kriz 5, and 37 p_{mC} at Dghoumes), justifying a recent CT recharge contribution in this relief.

Activities ranging between 12 and 18 p_{mC} are recorded between Nefta and El Hamma of Djerid, probably in relation to a local recharge through the major accidents skirting the Tozeur uplift (Fig. 10).

The activities recorded in Nefzaoua region where the aquifer is formed by Senonian limestone, range between 11 and 28 p_{mC} suggesting a local young recharge source (Dahar uplands and Matmata). These groundwaters exhibit ^{3}H contents ranging from 1.06 to 2.81 UT, which is an indication of post-nuclear recharge water (Fig. 11).

In the PQ groundwater, high ^{14}C activities are found in the area located at the vicinity of wadi curses and at the dune fields apart the oases where the CT groundwater insure more than 80 % of irrigation needs. The relatively recent water in the shallow PQ aquifer is composed of mixed water resulting from upward leakage, sporadic meteoric recharge and return flow irrigation in oases area.

The PQ shallow wells featured by hight ^{14}C activities and enriched stable isotopes are located at oases. Water pumped from CT groundwater, after equilibration with the atmospheric CO_2, infiltrates to the superficial aquifer increasing the ^{14}C activities of the shallow PQ groundwater and masking the upward leakage effect.

B. Hod is probably drilling at perched aquifer where ancient soil turning to a caliche (gypsiferous hard crust) forming a local discontinuous impermeable layer in the field dunes.

Except IBC 1 (no 23), Ghardgaya 4 (no 25) and Dghoumes 4 (no 54) samples with respectively 1, 1.09 and 1 UT, all the samples collecting from the CT show contents lower than 0.7 UT. The samples of the PQ shallow aquifer exhibit values lower than 0.7 UT in oases areas and values ranging between 1.6 (Bir Erroumi) and 8.59 UT (Bir El Hod) far from the irrigated zones.

In the eastern part of the study area, values ranging between 1.06 and 2.81 UT are recorded in 2004. El Khanga Dam, in Piedmont of the Tunisian Atlas, shows contents of 8.23 UT representing the current tritium content of the rains in the area.

High ^{3}H content recorded at B. Hod can be interpreted as a recent recharge through the inter-dunes without mixing by ancient water from upward leakage (Fig. 11).

^{14}C activities/^{18}O relationship

Plot of ^{14}C activities versus ^{18}O (Fig. 12) clearly evidenced the mixing process in parts of the aquifer system. It shows

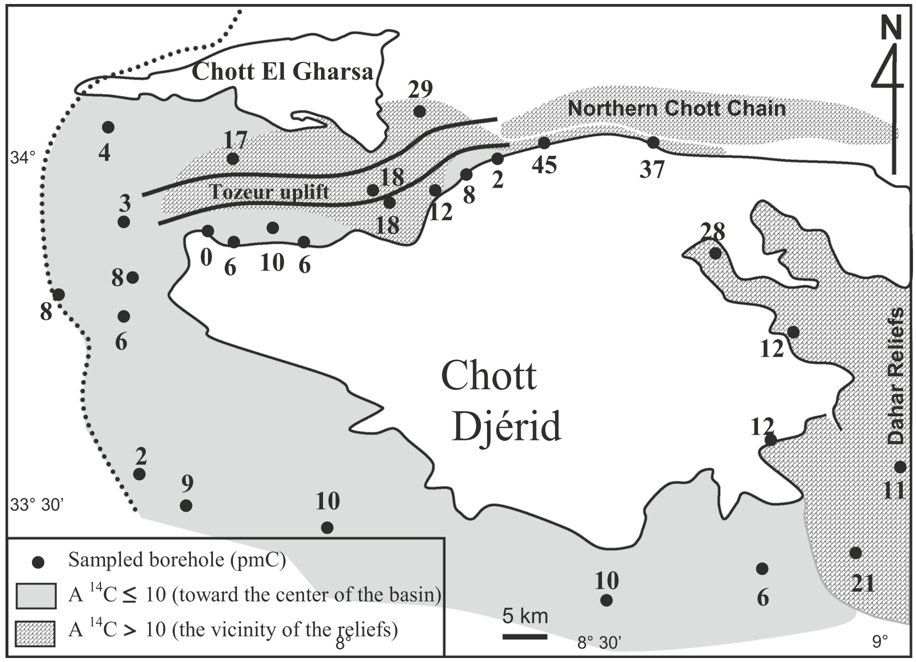


Fig. 10 Spatial distribution of ^{14}C in the CT groundwater

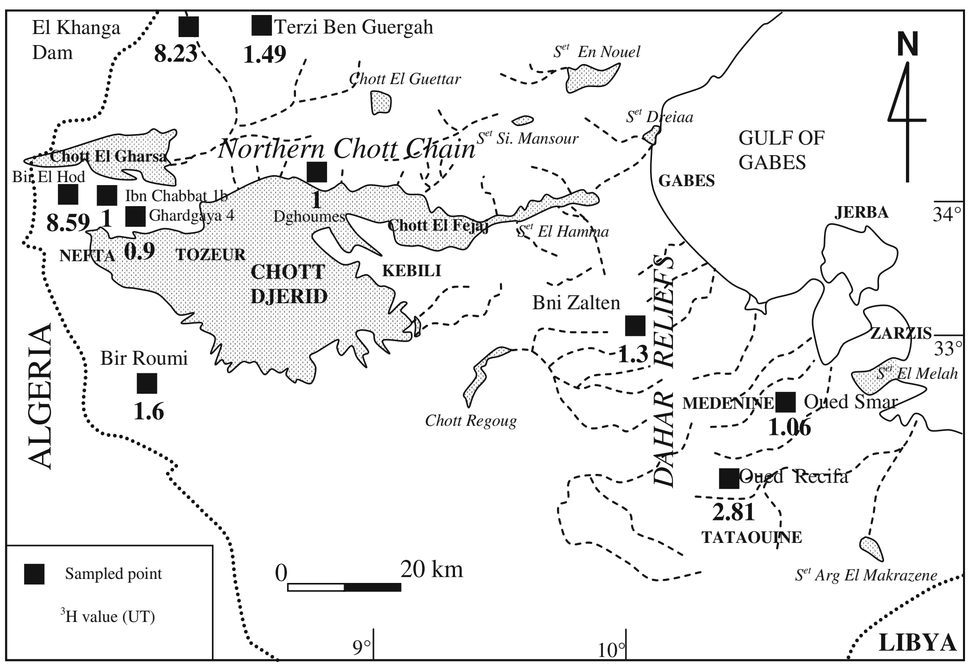


Fig. 11 Spatial distribution of tritium in the shallow PQ and unconfined CT groundwaters

distinguishable patterns related to mixing, evaporation and atmospheric CO_2 equilibration processes.

The CI and the deep CT wells featured by low ^{14}C activities and depleted stable isotopes shows ^{14}C activities not passing 10 p_{mC}.

PQ shallow wells featured by high ^{14}C activities and enriched stable isotopes are located at oases. Water pumped from CT groundwater, after equilibration with the atmospheric CO_2, infiltrates to the superficial PQ. Enriched mass water return flow recharge can affect as well the less deep CT wells at the vicinity of Tozeur uplift where the CT outcrops. Theses wells present intermediate values of the activities ^{14}C ranging from 10 to 28 p_{mC} (Fig. 12).

Apart from the oases, an upward leakage from the CT and a possible contribution by the rainy events, are recorded at Nefta foret and Jhim foret wells with 72 and 83 p_{mC} ^{14}C activities, respectively. Unfortunately B.Touil and B.Hod ^{14}C activities were undone. In Fig. 6, the B.Touil

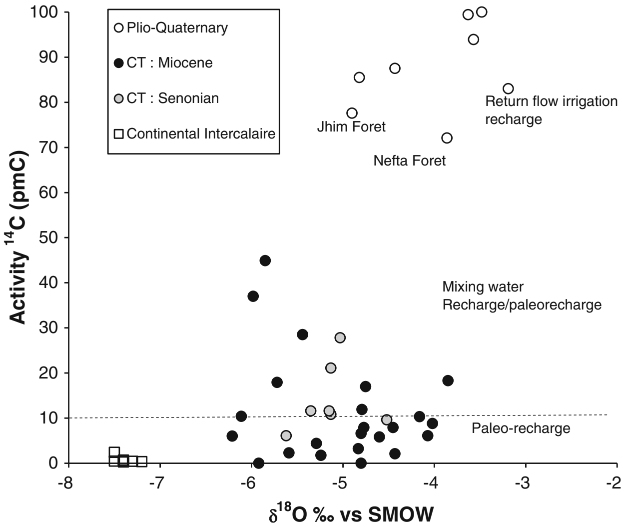


Fig. 12 $\delta^{18}O/^{14}C$ activity of the groundwaters

and B. Hod fall near the NMWL, indicating that little evaporation occurred during infiltration of the sporadic local precipitation.

^{18}O/corrected age relationship

There were several methods of correcting the initial ^{14}C activity for dead-C dilution (Vogel et al. 1970; Pearson 1965; Mook 1976; Fontes and Garnier 1979). These methods considered either only chemical mixing between the carbon compounds, or isotopic fractionation. Generally, the concentration of dissolved inorganic carbon (DIC) was controlled initially by variations in dissolved CO_2 present in the soil zone, which was then taken up by reactions within the aquifers (Fontes and Garnier 1979). The $\delta^{13}C_{DIC}$ values of PQ samples had a range of −10.41 (Nefta foret) to −9.96 ‰ (K. Rhouma). Nefta foret (no 18) and K. Rhouma (no 42) wells have been achieved in the margin of oases, near Saharan desert (sandy formation) and cannot be representative of PQ groundwater in oases. The highest values of ^{13}C have been recorded in Nefzaoua region where the aquifer is formed by fissured carbonate rocks. $\delta^{13}C_{DIC}$ values vary from −6.70 to −3.6 ‰. The possible sources of $\delta^{13}C_{DIC}$ were dissolved CO_2 and the dissolution of calcite (Tables 2, 3).

The CI aquifer is a relatively homogeneous sandy formation formed at 1,500 m depth and shows low ^{13}C values variation between −9.65 and −8.25 ‰ (Table 2).

The large variation in ^{13}C contents recorded in the Djerid CT groundwater samples (−8.29 to −5.46 ‰) is related to the heterogeneity of the CT aquifer in this area (sandy Miocene with thin clay layers) (Table 3).

The values of parameters, used to carry out calculations according to various models are:

$\delta^{13}C_{atm} = -7$ ‰ (atmospheric CO_2 currently presents ^{13}C content ranging between −7.3 and −6.7 ‰ vs PDB, Maliki 2000).

$\delta^{13}C_g = -21$ ‰ vs PDB (the percentage of carbon 13 in the CO_2 of the ground in the recharge zone is ranging between −22.21 and −25.75 ‰ (Daoud Dahmane 1995).

δApart from the oases, an upward leakage$^{13}C_s = 0$ (about 0 ‰ in the case of marine carbonate, Fontes 1976).

A $^{14}C_g = 100$ %. It corresponds to the modern activity at the infiltration (100 % of modern carbon for water prior to the nuclear tests).

A $^{14}C_s = 0$

The chemical concentrations, such as TAC and H_2CO_3, are calculated by the programme, WATEQ.

The values of the initial activities are consigned in Table 3.

To calculate the ages of groundwater recharged prior to 1952, an assumption was made in the first approximation that calcite was dissolved under fully closed system conditions, where there was no exchange with soil CO_2 during calcite dissolution. In this case, more than 50 % of the carbon of DIC was derived from dissolving carbonate minerals (Tamers 1975). A second, alternative approach was to apply the $\delta^{13}C$ mixing model (Pearson 1965). It considered the $\delta^{13}C$ enrichment during dissolution of CO_2 and the evolution of $\delta^{13}C$ of DIC (Clark and Fritz 1997). Finally, the International Atomic Energy Agency (IAEA) model was used (Salem et al. 1980) to consider the mixing and isotope exchange. The model of Mook gives negative initial activities and cannot be applied in the case of this study. The model of Tamers gives initial activities ranging between 52 and 60 %, meaning an equivalent dilution between a biogenic pole and a mineral pole. This model cannot be applicable in a basin where the CT aquifer is formed by carbonate rocks in the east (Nefzaoua region) and sand in the west (Djerid region).

The highest initial activities and the corresponding ages are given by the models of the IAEA and Fontes model (Table 3).

Pearson and the Evans models seem to take in account the activities and the calculated ages in agreement with relatively recent recharge water of the CT groundwater (Chabbat 1b well).

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

Table 3 Estimated age of waters using carbon-13 and carbon-14 activities

No (map)	Locality	Aquifer	^{14}C (p_{mC})	^{13}C (‰ PDB)	Uncorrected age (year BP)	Tamers model age (year BP)	Pearson Model A_0/age (year BP)	IAEA model age (year BP)	Fontes-Garnier Model age (year BP)	Evans Model age (year BP)
18	Nefta foret	PQ	72.1	−10.41	2,640	Actual	47.3/actual	467	Actual	Actual
42	K. Rhouma	PQ	87.5	−9.96	1,080	Actual	45.3/actual	Actual	Actual	Actual
34	Tozeur 8	CT: Miocene	18.3	−8.29	14,039	–	37.7/5,971	9,356	–	5,188
9	Mzara	CT: Miocene	3.2	−6.36	28,454	24,086	28.9/18,195	21,758	21,346	17,165
8	G. Jaballah	CT: Miocene	7.9	−6.94	20,983	16,604	31.5/11,446	14,949	1,436	10,497
23	IBC 1	CT: Miocene	17.0	−6.18	14,648	9,441	28.1/4,152	7,777	8,008	3,133
4	A O Ghrissi	CT: Miocene	5.8	−7.46	23,538	17,977	33.9/14,597	17,982	17,979	13,666
27	PK 14b	CT: Miocene	6.1	−7.27	23,121	17,895	33/13,967	17,381	17,248	13,019
33	D CRDA	CT: Miocene	17.9	−6.14	14,222	9,427	27.9/3,672	7,175	7,169	2,529
25	Ghardga. 4b	CT: Miocene	10.4	−5.46	18,710	–	24.8/7,190	10,517	–	5,624
57	Jemna	CT: Senonian	10.8	−3.60	18,398	–	16.4/3,435	7,249	–	1,638
61	Sabria Mol	CT: Senonian	6.1	−5.90	23,121	18,365	26.8/12,241	15,991	16,023	11,271
62	Faouar 4	CT: Senonian	9.6	−4.59	19,372	14,075	20.9/6,417	10,167	11,398	5,035
55	Negga 6	CT: Senonian	11.6	−6.70	17,808	–	30.5/7,979	11,543	–	7,027
58	Zarcine 1	CT: Senonian	11.6	−5.77	17,808	12,255	26.2/6,744	10,399	11,050	5,649

carbon concerning CI groundwater to about 50 % in CT groundwater to reach 100 % in PQ groundwater (Table 2).

According to correspondence carbon-14 (corrected Pearson age)/infiltration period (age) scaling by several authors in Saharan platform and North Africa (Edmunds et al. 1997; Guendouz et al. 2003), $\delta^{18}O$ data (‰) are plotted against corrected Pearson age (year BP) for the CT and the PQ groundwaters in the study area (Fig. 13). Continental Intercalaire waters activities cannot be interpreted in term of corrected Pearson age since they exceed the limit of the ^{14}C method dating.

The range in Pearson corrected age in the PQ shallow groundwater corresponds with actual recharge (Fig. 13). Most CT Senonian samples correspond to the Holocene Period recharge. Some CT Miocene samples collected from implanted dugwell with a flow component from Dahar uplands present the same range in age (3–8 k years BP).

The IBC 1 (no 23), D CRDA (no 33) and Jemna (no 57) dugwells form a subgroup between 3 and 6 k years, the second subgroup is formed by El Faouar 4 (no 62), Zarcine 1 (no 58) Negga 6 (no 55), Ghardgaya 4 (no 25) and Tozeur 8 (no 34) with 5.8–7.9 k years age. These waters can be related to two humid phases of the Holocene. The first phase, signalled at the Moulouya valley (Morocco) and had place between 5,000 and 3,000 years BP (Lefèvre 1984; Fontes et al. 1988).

The second phase, signalled at the Oued Akarit (Tunisia) (Fontes and Edmunds 1989; Zouari 1988; Ouda et al. 1999) in the Meknassi basin (Tunisia) and had place between 10 and 7 k years BP.

Some CT Miocene samples collected from implanted dugwell with a flow component from Dahar uplands present the same range in age (3–8 k years BP).

The oldest group is formed by four samples collected at CT Miocene groundwater (PK 14 bis, A O Ghrissi (no 4), G Jaballah (no 8) and Mzara) (no 9) in the region of Hazoua, southern the study area. The waters of this group, characterised by the corrected Pearson ages (11–18 k years BP), represent the recharge during the period of the Pleistocene. Sabria Mol (no 61) dugwell (CT Senonian) seemed recharged by component flow from Algerian through western Tunisian border as well as dugwells achieved in Hazoua region (Fig. 13). This Pleistocene recharge phase has been signalled in Sebkha Mellala (Morocco) (Fontes et al. 1988).

Conceptualization of the model system recharge aquifers in southern Tunisia

Hydraulic heads of aquifers and isotopic composition of groundwaters allowed the identification of distinctive waters recharged at different rates depending upon the hydrostratigraphic architecture.

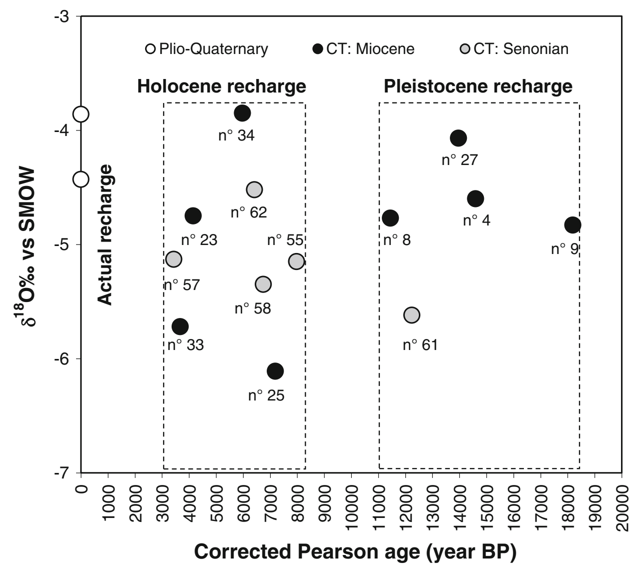


Fig. 13 Corrected Pearson age/δ^{18}O relationship

The main component of the shallow PQ recharge is provided by excess irrigation water pumped from the Saharan CT and the CI groundwaters. Long time residence and the large potentiometric head difference between the deep CI groundwater and the shallow PQ still allow artesian conditions by upward leakage. Sporadic rainfall events contribute recharging the CT and the shallow PQ aquifer at the vicinity of reliefs and at the inter-dunes (Fig. 14).

Overexploitation of the CT aquifer has contributed to the decline in potentiometric level to equalise the PQ. Consequently, local signs of brine invasion were recorded in the oases surrounding the Chotts areas (Fig. 14).

Conclusion

Oxygen-18, tritium and carbon-14 concentrations in groundwaters were used to precise the recharge mechanisms of the Chotts region aquifer system. It has been demonstrated, based on the spatial distribution of the carbon-14 contents, that CT groundwaters in the study area are classified into two groups. The first group includes boreholes located in the west part of the study area with carbon-14 activities not exceeding 10 p_{mC} and tritium content less than 0.7 UT. This group highlights the significant role of the palaeo-recharge demonstrated by several authors in the Saharan desert. The second group encloses boreholes located in the vicinity of Dahar uplands and Tozeur uplift. This group provides an indication of contribution of the local recharge.

Recharge of PQ waters originate from relatively modern rainfall was recorded at the vicinity of wadis which collected runoff water from the Dahar uplands and in the inter-dune where the aquifer is locally perched.

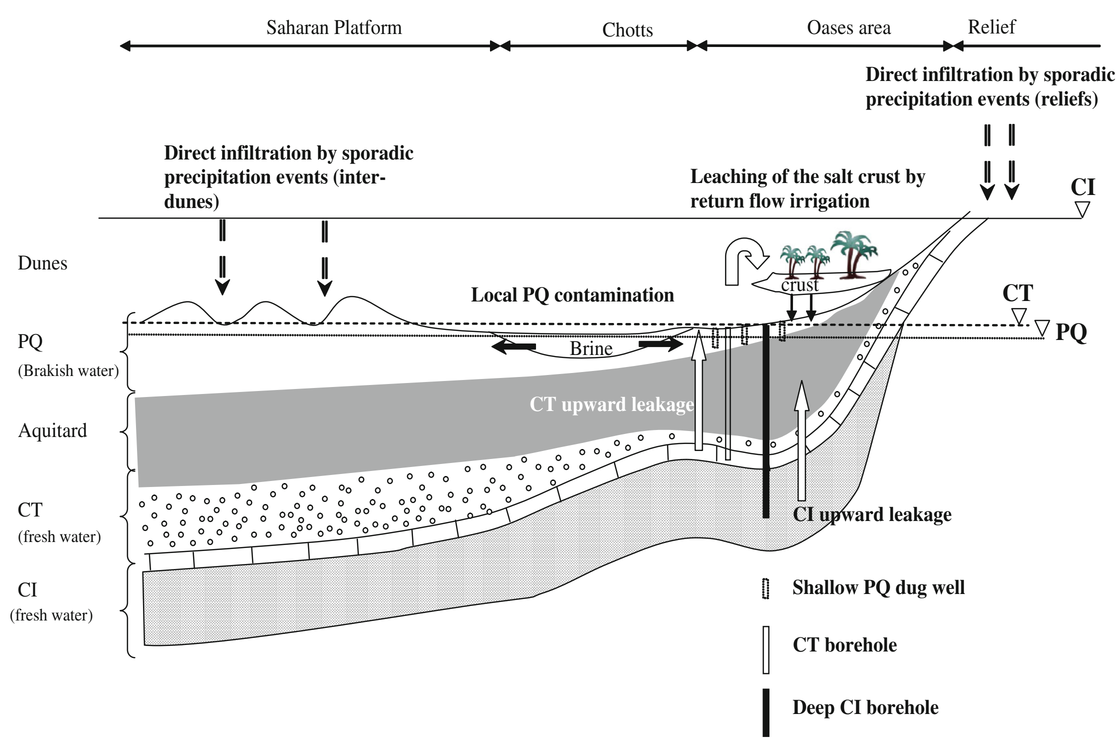


Fig. 14 Conceptual model system recharge aquifers in southern Tunisia

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