Hydrochemical and isotopic behaviour of a Saharan phreatic aquifer suffering severe natural and anthropic constraints (case of Oued-Souf region, Algeria)

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Abstract An approach combining the use of water dissolved chemical species and isotopic fingerprints has been used to understand the behavior of a phreatic aquifer and to determine the origin of its different water components. This aquifer is located in the large sedimentary basin of the Great Oriental Erg (Algeria) and overlies two deeper aquifers: the Complexe Terminal (CT) and the Continental Intercalaire (CI). Besides the deterioration of its groundwater quality, its water table has risen during the last 20 years. A water budget surplus between 950 and 2500 $\mathrm{l\ s^{-1}}$ was estimated. Down-gradient groundwater evolution (south-north) has shown that the mineralisation increases from 1.23 to 5.20 $\mathrm{g\ l^{-1}}$ due to evaporite minerals dissolution. Chemical and isotopic data demonstrated that in addition to rainfall there is a contribution from the CT and CI aquifers. The latter are tritium-free and less mineralized than the phreatic aquifer. Their radiocarbon contents are very low ($<$10 pmC, percent modern Carbon) (Pleistocene recharge) whereas quite the contrary is observed for the superficial aquifer which exhibits fairly high and variable C-14 activities (50–100 pmC), evidence of recent recharge. On the basis of tritium contents, two groundwater groups were identified for the phreatic aquifer.

Résumé Comportement hydrochimique et isotopique d'un aquifère phréatique saharien subissant des pressions naturelles et anthropiques sévères (Cas de la région de Oued-Souf, Algérie). Une approche combinant l'utilisation des espèces chimiques dissoutes et des traceurs isotopiques de l'eau a été utilisée dans le but de comprendre le comportement d'un aquifère phréatique et de déterminer l'origine de ses différentes composantes. L'aquifère se situe sur le grand bassin sédimentaire du Grand Erg Oriental (Algérie) et se superpose à deux aquifères plus profonds : le Complexe Terminal (CT) et le Continental Intercalaire (CI). Outre une détérioration de la qualité de l'eau souterraine, son niveau piézométrique a crû au cours des vingt dernières années. L'excédent estimé du bilan en eau est compris entre 950 et 2500 L/s. L'évolution de l'eau souterraine vers l'aval hydraulique (du sud vers le nord) montre une augmentation de la minéralisation de 1.23 à 5.20 $\mathrm{g\ L^{-1}}$, du fait de la dissolution des minéraux évaporitiques. Les données chimiques et isotopiques ont démontré qu'une contribution des aquifères du CT et du CI s'ajoutait aux précipitations. Ceux-ci ne présentent pas de traces de tritium et ont des eaux moins minéralisées que l'aquifère phréatique. Leurs concentrations en radiocarbone sont très faibles ($<$10 pcm, % de carbone moderne) du fait de la recharge pléistocène, alors que l'inverse a été observé dans l'aquifère superficiel. Ce dernier est caractérisé par des activités ^{14}C relativement élevées et variables (50 à 100 pcm), caractéristiques d'une recharge récente. Les concentrations en tritium ont permis d'identifier deux groupes d'eaux souterraines dans l'aquifère phréatique.

Resumen Se ha utilizado un enfoque que combina el uso de especies químicas disueltas en agua y huellas isotópicas para entender el comportamiento de un acuífero freático y de esta manera poder determinar el origen de los diferentes componentes hídricos. Este acuífero se localiza en una cuenca sedimentaria grande del Erg Oriental Grande (Argelia) y sobreyace dos acuíferos profundos: el Terminal Complejo (CT) y el Intercalado Continental (CI). Además del deterioro de la calidad del agua subterránea, el nivel freático ha subido durante los últimos veinte años. Se ha estimado un excedente de balance hídrico que varía entre 950 y 2500 $\mathrm{l\ s^{-1}}$. La evolución aguas abajo del agua subterránea (sur-norte) ha mostrado que la mineralización incrementa de 1.23 a 5.20 $\mathrm{g\ L^{-1}}$ debido a la disolución de minerales evaporíticos. Los datos isotópicos y químicos demostraron que además de la lluvia existe contribución de los acuíferos CT y CI. Este último acuífero no contiene tritio y se encuentra menos mineralizado que el acuífero freático. Los contenidos de ambos acuíferos, CT y CI,

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en radiocarbono son muy bajos (<10 pmC, por ciento de Carbono moderno) (recarga Pleistocena) mientras que se observa todo lo contrario para el acuífero superficial el cual presenta actividades bastante altas y variables de C-14 (50 a 100 pmC), lo cual es evidencia de recarga reciente. Basado en el contenido de tritio se identificaron dos grupos de aguas subterráneas para el acuífero freático.

Keywords Hydrochemistry · Stable isotopes · Radioisotopes · Sahara · Algeria

Introduction

The Oued Souf region is located in the north-eastern part of the Algerian Sahara. It extends over some 14,500 km^2. The topography of the region is fairly flat and monotonous with altitudes ranging between 20 and 120 m above sea level. It is mainly composed of sand dunes and occurs in the Great Oriental Erg basin (Fig. 1). The investigated region is limited in the north by the salt lakes zone (Chott Melrhir and Chott Merouane), in the south by the extension of the Great Oriental Erg dunes, in the west by the wadi Rhir valley and in the east by the Tunisian border.

Phreatic waters are contained in the most superficial level of the Quaternary formations. This level is part of the huge ensemble of sand dunes known as the Great Oriental Erg. It is composed of several meters of thick fine grain size aeolian sand.

The first survey of the piezometric level variation for this aquifer started between 1953 and 1956, a time span during which a decline in the range of 50–150 cm was recorded (Dervieux 1956).

Thereafter and because of the extensive drilling of many deep boreholes in the 1970s, the inverse phenomenon started gradually to take place to reach alarming proportions during the last decade. Consequently, ponds appeared within the so-called Ghouts flooding them and drowning several thousands of date-palm trees and threatening even the buildings foundations in some districts of El-Oued city. Ghouts are crater-shaped gardens dug out by local farmers in between dunes to bring plant roots closer to the groundwater.

There exist more than 40 deep boreholes tapping the Miopliocene (Pontien) sandy-clayey formations of Complexe Terminal (CT). In addition, there are three deeper boreholes (1800 m) tapping the Albo-baremian sandy clayey sandstones. These are all used for water supply and irrigation and their waters are collected within the Quaternary shallow aquifer. The phreatic aquifer has shown considerable rise of its water table due to a certain number of factors that will be identified thereafter.

A number of major studies have been carried out on the phreatic aquifer. Chemical and isotopic information on the groundwaters were gathered from several earlier studies (Guendouz 1985; Guendouz et al. 1992, 1993; ANRH 1993; BNEDER 1992; Moulla et al. 1992, 1995, 1996).

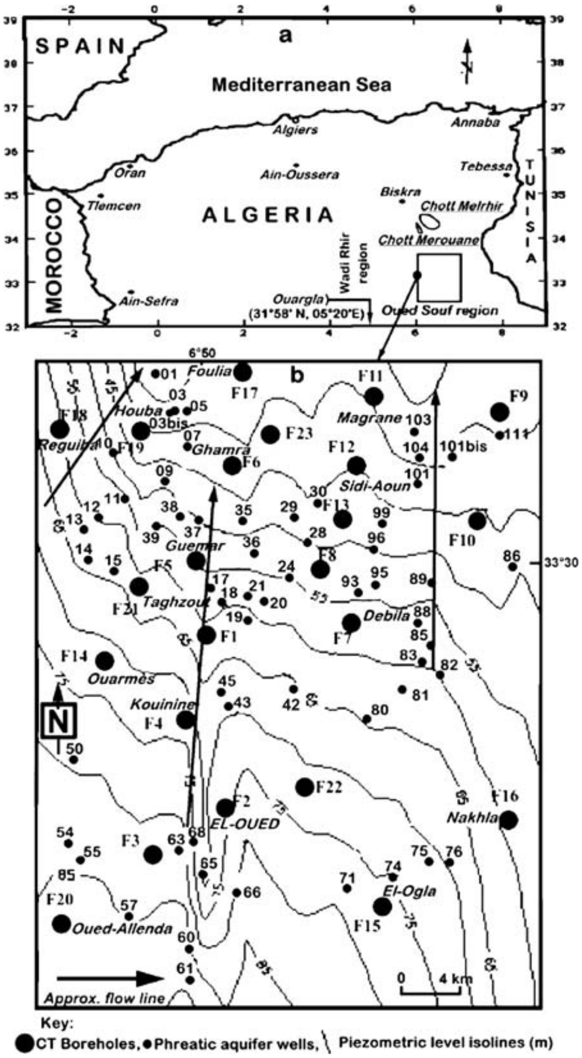

Fig. 1 **a** Map showing geographic location of the investigated area and **b** groundwater flow and the location of sampled wells in the Quaternary phreatic and Miopliocene aquifers

Other investigations dealt especially with hydrodynamic aspects as well as modeling, in order to predict the long-term aquifer behavior (Levassor 1978; Cote 1993; Bonnard and Gardel 1998).

The focus of this study was to investigate the origin of these rising piezometric levels using chemical and isotopic tools. The principal objectives were to

- study water origin (likelihood of mixing between different water bodies),
- determine the areas affected by the rise in water level,
- determine the origin and evolution of phreatic waters salinity,
- determine the relative ages of the groundwaters, and
- investigate the timing of aquifer recharge and its origins.

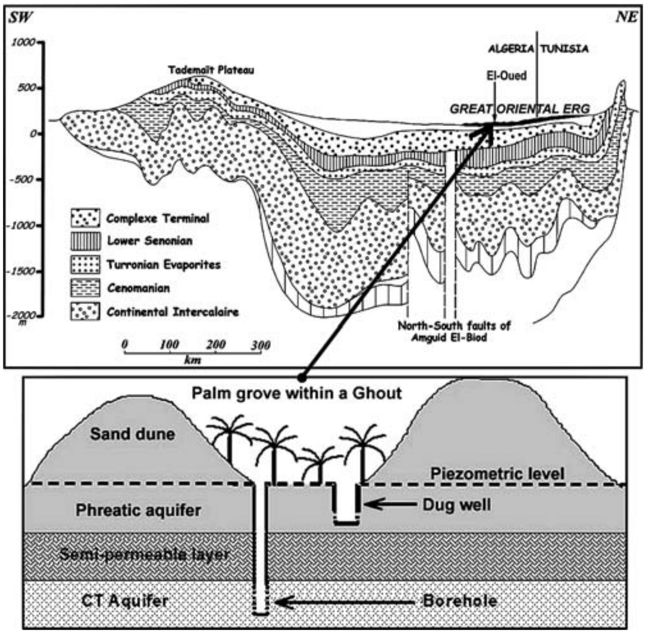

Fig. 2 Hydrogeological cross-section of the Saharan basin and the schematic cross-section of a Ghout in the Oued Souf region

Climatic and hydrogeological settings

The Souf region is characterized by an arid climate and by variable weak and irregular precipitation. Hydroclimatic data (precipitation and temperature), recorded at the station of Guemar airport, were acquired for different time spans. Regarding mean annual precipitation, three date ranges were used namely, 1913–1953: 75 mm (Dubief 1959), 1975–1984: 76 mm (ONM 1975–1984) and 1967–2001: 72 mm (ANRH 1993). Inter-annual variations are considerable and calculated mean annual amounts are very similar. However, the statistical analysis of the 1967–2001 mean inter-annual precipitation series revealed a good adjustment with the Gaussian-logarithmic probability law, with an average value of 73 mm (Saibi 2003). The mean annual temperature prevailing in the area is ∼22°C but the difference between the highest and the lowest daily temperature may reach 15°C between January and July. Data on evaporation and evapotranspiration are very scarce. Few measurements were recorded by the National Office for Meteorology (ONM). Figures recorded at Guemar station over a 10-year period of time (1990–2000), revealed a mean interannual rate of 2300 mm per year for evaporation (ONM 1990–2000). On the other hand, mean annual evapotranspiration as estimated by means of empirical formula such as those of Thornthwaite, Turc, and Penman gave results ranging from 2000 to 2800 mm per year (BNEDER 1992; ANRH 1993). The evaporative losses from the phreatic aquifer through a 6 m thick unsaturated zone were estimated to be 2 mm per year (Moulla et al. 1996).

From the hydrogeological viewpoint, the three separate aquifer systems that are exploited (Fig. 2) are the following:

- At the base, the deep confined Continental Intercalaire (CI) aquifer which is contained in the lower Cretaceous formations. It is located within a 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 2000 m while its thickness ranges between 200 and 400 m (Bel and Demargne 1966; UNESCO 1972). Only three boreholes are exploited from this artesian aquifer in the region of interest. Their flow rates vary from 100 to 200 l s^{-1} and are mainly used for potable water allocation.
- In the middle, there occur the very heterogeneous Complexe Terminal formations. They embody the bases of the permeable Senonian limestones as well as the clayey sands and sandstones of the Miopliocene. The depth of this aquifer is between 100 and 600 m and its mean load is 300 m. It is confined within the limits of the investigated area and extends over the major part of the northern Sahara basin (∼350,000 km^2) (Paix 1956; Bel and Cuche 1970; Bel et al. 1970; UNESCO 1972). More than 40 boreholes were inventoried over the whole Souf region (ANRH 1993). The aquifer piezometric level as established at the scale of the whole Great Oriental Erg (UNESCO 1972; OSS 2003) shows that the main flow proceeds from the south (recharge area: southern margin of the Erg and Tinrhert plateau) towards the north (discharge area: Chott Melrhir and Chott Merouane). The permeability of the CT layers in Oued Souf region is variable (10^{-4} to 10^{-5} m s^{-1}). Their transmissivity varies from 10^{-2} to 10^{-3} m^2 s^{-1} (UNESCO 1972; Levassor 1978). Because of the aquifer intensive exploitation, artesianism has totally disappeared. However, upward leakage to the phreatic aquifer can still occur favored by the semi-permeable strata or by the ancient boreholes' deteriorated tubing.
- 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. The aquifer depth varies from 10 to 40 m and its thickness reaches locally 100 m. It is exploited by the farmers through more than a thousand dug wells. The mean permeability of the phreatic aquifer is of the order of 10^{-4} m s^{-1} (Dervieux 1956). Its horizontal transmissivity and its storage coefficient were estimated to be respectively 10^{-2} m^2 s^{-1} and 0.2 (Levassor 1978).

Except results gathered during two field campaigns effected in February and April 1993 (ANRH 1993), very few piezometric data are available for the phreatic aquifer. The short time span between those campaigns does not allow one to foresee any noticeable fluctuations. However, piezometric maps may indicate the following features (Fig. 1):

- The main direction of flow is from south to north.
- The average flow gradient is estimated to be 1.2%. It exhibits some local variations which indicate heterogene-

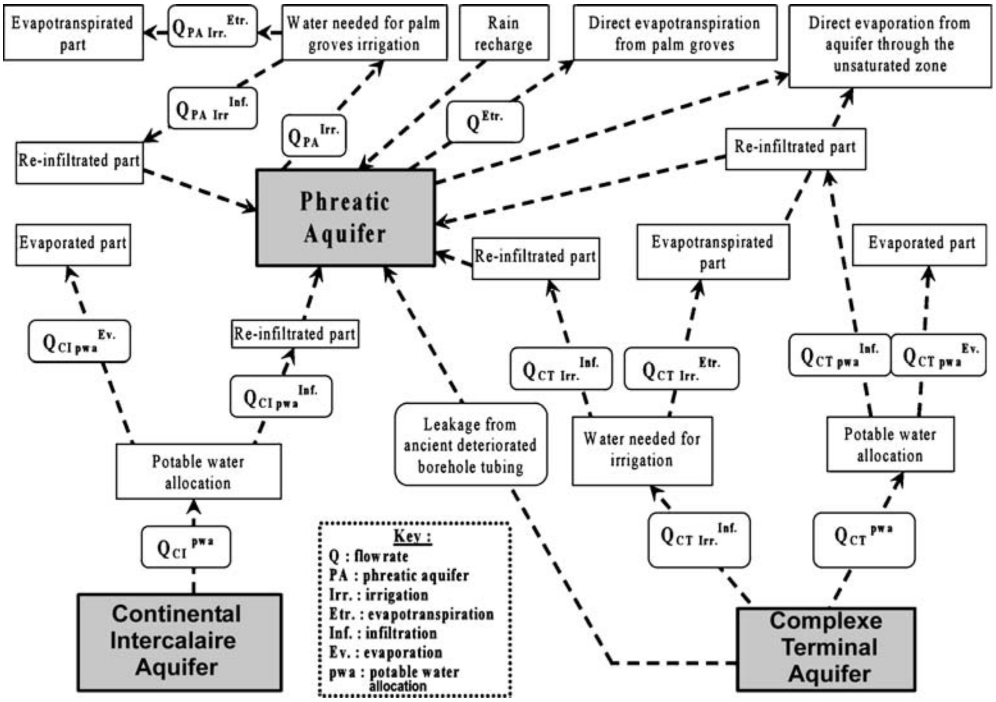

Fig. 3 Flow chart of the water budget parameters and their relationships (in Bonnard and Gardel 1998, modified)

ity in the permeability and/or a variation of the aquifer thickness.

- If one assumes a 20% porosity for aeolian sands (Levassor 1978), a flow velocity of around 20 m per year is obtained for the phreatic aquifer, which is in accordance with carbon-14 data (Guendouz et al. 1993).
- The aquifer recharge zones are essentially located on the south and south south-west border and in the northern area around the chotts Melrhir and Merouane for the discharge area.

Because of the lack of piezometric level records, many trials have been made in order to assess the importance of the studied phenomenon by quantifying the water budget making use of MODFLOW model (BNEDER 1992; ANRH 1993; Bonnard and Gardel 1998). Both hydrostatic and hydrodynamic aspects have been dealt with while computing the water budget. Input and output parameters were very well identified and, except the recharge and discharge rates, these are (see Fig. 3):

- Water abstracted from dug wells intended for irrigation. Its major part evaporates or is evapotranspirated while a minor part reinfiltrates through irrigation return flow (110 wells with a flow rate of 1.6 l s^{-1}).
- Natural evapotranspiration from palm groves and associated crops within the Ghouts and evaporation from bare terrains, respectively 2000 mm per year (Dervieux 1956) and 2 mm per year (Moulla et al. 1996).
- Water extracted from the CT aquifer (total exploited flow rate 770.7 l s^{-1} for potable water allocation and 243 l s^{-1} for irrigation). The deep CI aquifer is used only for potable water allocation (flow rate supplied by the three artesian boreholes ~400 l s^{-1}).
- Recharge, discharge and upward leakage to the phreatic aquifer from the CI and CT groundwater systems locally favored by deteriorated ancient borehole tubing.

The results of such a water budget for the phreatic aquifer led to a surplus in the range of 950–2500 l s^{-1}. Such a wide range of values may find its explanation in the differences made in estimating the terms of the budget and notably those related to: leakage from deeper aquifers, evapotranspiration rates and lateral exchanges (recharge and discharge).

Results and discussion

Geochemical evolution of groundwater and origin of salinity

The results are considered and interpreted according to a generalized south-to-north transect (main flow line). The samples are projected normal to the flow direction. This is a simplification to aid the interpretation. In reality, there may also exist several flow paths from the south (Great Oriental Erg) and the south-west (wadi Rhir valley). The evolution and the origin of salinity were investigated according to the distribution of chemical dissolved species concentrations. Non-conservative physico-chemical water parameters (temperature, pH, electrical conductance and alkalinity) were measured in the field (Table 1). The physical and chemical parameters of the shallow waters indicate large spatial variations. The electrical conductance (EC) and total dissolved salts (TDS) increase progressively

Table 1 Field and analytical data for phreatic waters of El-Oued region (sampling campaign of May 1991)

Water sample	*T* (°C)	pH	EC (µS cm^{-1})	Sal. (g l^{-1})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	NO_3^- (mg l^{-1})	HCO_3^- (mg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	K^+ (mg l^{-1})	O-18 (‰)	H-2 (‰)	H-3 (TU)	C-14 (pmC)
01	18.8	7.45	4,070	2.00	1484	354	124	61	436	191	268	22	−1.1	−20.6		
03	17.5	7.40	5,300	2.63	1721	605	183	76	556	211	418	33	−1.1		1.0±0.7	18.9±3
03bis	17.8	7.35	3,940	1.93	1585	359	97	49	492	180	238	21	−1.8			
05	18.4	7.57	3,200	1.57	1607	200	93	58	480	162	162	14	−2.9		8.4±1.2	
07	18.5	7.25	3,440	1.69	1509	195	76	52	468	164	123	21	−1.1	−18.1	11.8±2.1	
09	19.1	7.70	4,220	2.07	1889	257	76	85	412	269	280	21	−2.2			
10	17.2	7.32	5,790	2.86	1933	594	97	82	391	247	536	21	−3.0			85.0±7.1
11	20.5	7.58	3,920	2.00	1562	231	91	82	444	199	182	17	−0.3	−15.4		
12	21.5	8.80	4,440	2.18	1572	374	118	24	440	202	260	25	−0.3		0.0±0.1	
13	21.5	9.18	3,670	2.79	1361	327	131	30	456	127	221	17	−3.0			
14	18.2	7.40	4,930	2.42	1784	372	118	67	392	283	260	42	−3.1			
15	22.0	7.65	6,170	3.00	825	112	63	43	336	51	84	13	−1.7	−28.2	18.5±2.3	
17	20.5	9.70	4,140	2.03	1390	300	157	0	488	204	142	22	−2.0			
18	13.5	7.30	2,300	2.11	1800	320	19	290	442	231	201	38	−2.0			
19	16.5	7.70	3,700	1.80	1117	323	86	52	340	131	201	15	−2.2		1.0±1.0	
20	20.8	7.85	3,950	1.97	1600	432	247	49	344	282	241	19	−2.6	−30.0	8.2±1.5	
21	17.6	7.38	3,510	1.72	1789	179	79	58	372	228	182	23	−2.5			
24	20.0	7.30	2,540	1.23	1013	105	49	58	340	90	83	23	−2.6	−28.6	2.9±1.2	46.8±2.7
28	14.8	7.37	4,430	2.20	1740	335	93	97	300	314	280	19	−3.0		2.1±0.8	
29	20.0	7.35	7,160	3.53	1327	699	55	101	300	403	634	38	−2.7		7.2±1.2	
30	22.5	7.55	4,900	2.40	1995	386	73	98	280	343	398	33	−3.6	−43.8	13.1±1.0	
35	22.2	7.16	3,650	1.77	1613	252	83	76	296	271	123	22	−2.0		8.1±0.6	45.3±3.0
36	16.2	7.15	3,200	1.58	1485	152	58	49	368	201	103	19	−3.0		6.9±0.9	
37	14.2	7.25	5,690	2.74	1740	256	91	88	268	343	202	23	−2.8		13.7±1.4	88.9±5.2
38	16.3	7.45	4,000	1.96	1906	231	64	64	272	324	241	46	−3.3			
39	16.0	7.50	3,960	1.97	1790	322	77	80	248	309	221	23	−2.4	−28.9		
42	22.2	7.61	5,420	2.67	3227	1056	46	332	172	516	1241	63	−2.0		1.0±0.5	
43	16.5	7.55	3,260	1.62	1519	150	70	55	308	273	143	17	−0.3	−14.7		95.5±6.4
45	14.2	7.15	3,410	1.70	1500	158	99	40	340	216	182	21	−2.9			82.3±3.5
50	18.2	7.30	4,600	2.24	1720	406	78	76	328	310	320	23	−2.1	−29.4		
54	18.5	7.30	6,460	3.18	1958	712	55	109	356	344	516	38	−2.0			
55	15.0	7.10	5,530	2.72	1475	458	38	119	320	271	320	19	−2.4			
57	22.0	7.30	4,200	2.11	1603	428	68	64	340	282	320	15	−2.3			
60	22.0	7.30	3,200	1.55	1687	197	60	64	356	265	123	19	−2.6	−28.7	3.9±1.0	
61	21.0	7.20	4,620	2.26	1936	370	79	95	300	321	281	22	−3.5			
63	21.5	7.32	6,030	2.96	2274	642	71	88	304	377	359	38	−3.2	−35.5	25.7±2.8	123.0±8.2
65	21.2	7.35	3,460	1.69	1467	209	51	76	276	317	96	19	−3.8			101.0±6.3
66	21.1	7.20	4,850	2.34	1800	538	88	162	260	251	212	22	−2.9	−32.5	5.7±0.6	
68	22.6	7.07	5,200	2.53	2082	642	46	332	200	519	286	67	−1.9	−26.3	5.7±0.9	77.4±3.2

Table 1 Continued

Water sample	*T* (°C)	pH	EC (μS cm^{-1})	Sal. (g l^{-1})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	NO_3^- (mg l^{-1})	HCO_3^- (mg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	K^+ (mg l^{-1})	O-18 (‰)	H-2 (‰)	H-3 (TU)	C-14 (pmC)
71	21.1	7.23	4,520	2.16	1621	217	217	144	244	322	106	19	−3.7		4.3±1.0	
74	19.8	7.23	4,330	2.11	1683	321	88	85	276	293	164	17	−2.2	−28.4	2.9±0.5	
75	21.6	7.20	5,760	2.84	1902	630	93	158	220	363	307	38	−3.2		13.8±1.1	
76	20.4	7.27	7,800	3.84	2048	830	58	189	252	447	349	47	−3.6		1.0±0.8	
80	21.6	7.42	4,210	2.04	1735	259	92	61	316	260	380	13	−3.7			
81	18.0	7.75	3,870	1.79	1640	356	100	58	300	302	126	13	−2.9	−25.3		
82	14.4	7.50	4,300	2.10	1713	230	89	55	332	271	117	17	−3.4		12.1±1.3	70.7±4.1
83	17.5	7.36	3,700	1.85	1657	234	88	46	316	275	102	19	−3.4	−27.7		
85	21.2	7.28	6,180	3.03	2034	733	68	134	272	389	359	30	−2.3	−28.1	1.3±0.8	
86	20.8	7.3	10,450	5.20	3149	1495	76	186	280	568	824	57	−3.1	−31.9		
88	18.0	7.35	3,930	1.90	1696	257	68	52	280	299	152	22				
93	21.0	7.25	7,000	3.45	2020	994	149	140	509	218	637	38				
95	21.0	7.30	6,340	3.05	2103	767	122	115	138	437	532	25				
96	21.1	7.32	9,750	4.86	2547	1242	150	174	129	581	649	38	−3.3	−34.4		
99	11.7	7.45	9,970	4.96	2304	1340	157	183	109	573	637	74	−3.7	−36	0.0±0.1	55.3±2.5
101	18.8	7.34	3,480	1.70	1456	312	119	58	109	355	128	34			0.0±0.1	
101bis	18.2	7.32	8,840	4.40	3047	1157	97	152	105	585	900	51	−2.2	−30.3		
103	18.8	7.39	8,650	4.30	2423	1151	106	125	448	545	532	38				
104	21.2	7.33	7,200	3.53	1995	896	170	97	134	468	382	29			22.5±1.9	83.6±5.7
111	18.5	7.00	3,020	1.45	1531	146	65	45	366	253	68	22				

Sal.: salinity expressed as the total dissolved solids, TU: Tritium unit, and pmC: percent modern carbon from around 2000 μS cm^{-1} to 10,400 μS cm^{-1} and from 1.23 g l^{-1} to 5.20 g l^{-1} along the flow line (Fig. 4a). The chemical hydrofacies are essentially as follows: SO_4–Cl–Ca and Na (54%), and SO_4–Cl–Na and Ca (46%).

Discussion of the behaviour of major elements

The spatial evolution of each major element concentration could be deduced from its relationship with the total mineralisation (TDS) (Fig. 4b). There exists a correlation with the total salinity showing an increase along the flow path for the whole of the major elements except for calcium. The latter shows an inverse trend that might probably be due to some exchange reactions occurring within the aquifer matrix.

Major ion trends

The major ion relationships in the phreatic aquifer are relatively straightforward. Chloride concentrations largely reflect the input conditions at the time of recharge and may be modified subsequently by inputs from formation waters or evaporites (Herczeg and Edmunds 1999). There exists an increase of chloride and sodium ions concentrations along the flow path for the majority of the samples.

The plot of Na^+ vs. Cl^- (Fig. 5) shows that the representative points of phreatic aquifer are distributed close to the halite dissolution line. The Na/Cl weight ratio (Fig. 5) remains relatively constant around 1±0.5 which is consistent with stoichiometric dissolution of halite. This suggests a unique origin for these species. However, some samples show sometimes a Na/Cl ratio that gets further away from unity. Those groundwaters whose ratios are <1 generally correspond to waters coming from the southern area. They might be affected by the contribution of precipitation (recent recharge). On the other hand, those waters whose Na/Cl ratios are >1 match the samples collected in the northern downstream area (01, 05, 09, 10, 11, 30 and 37). This fact may be explained by a sodium excess due to ion exchange between water and some minerals notably clayey ones that are present within the aquifer matrix in that area. This is perfectly in accordance with the decrease of calcium concentrations with respect to salinity (Fig. 4b).

Sulfate concentrations are relatively high in the southern part close to the presumed recharge zone. They exhibit a relative variation along the flowpath from 1680 to 3000 mg l^{-1}. These concentrations may be explained by the dissolution of superficial saline gypsum encrustments during recharge and/or irrigation return flow. The very high SO_4/Cl ratio in the south ($SO_4/Cl = 10$) diminishes noticeably along the direction of flow ($SO_4/Cl = 2$). This indicates that the concentrations in these ions are monitored by their respective solubilities. It also confirms gypsum dissolution in the first instance, for which saturation is gradually attained as water flows. On the other hand, halite which is more soluble continues to dissolve. Calcium concentrations remain around 300 mg l^{-1} along most of the flow transect. Nevertheless, a decreasing trend is observed towards the

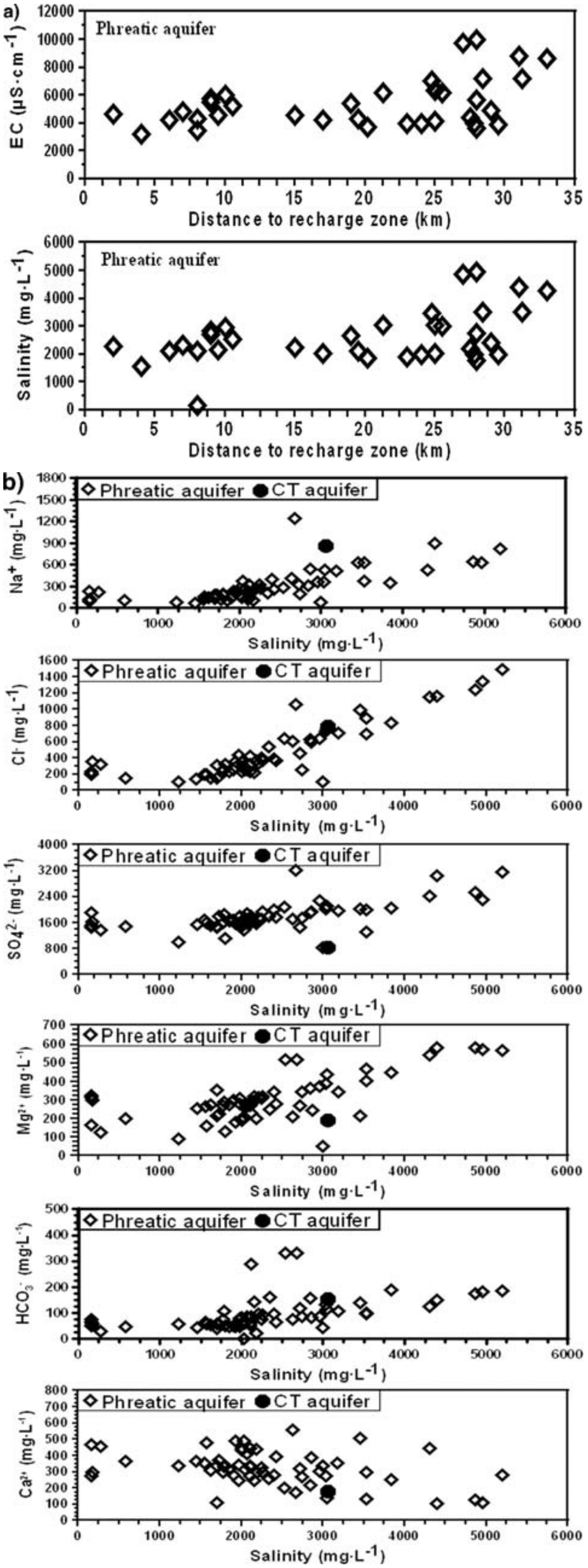

Fig. 4 **a** Relationships between both salinity and electrical conductance (EC) vs. distance to recharge zone. **b** Relationships between salinity and major ion concentrations (Na, Cl, SO_4, Mg, HCO_3, and Ca)

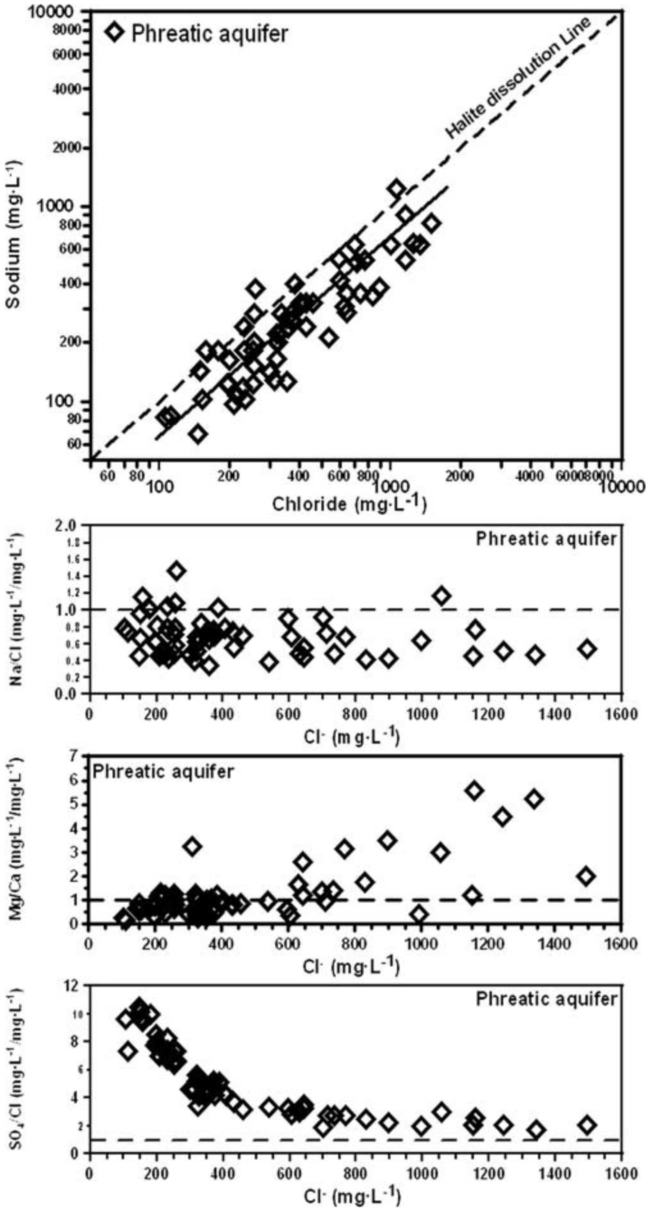

Fig. 5 Relationship between sodium, Na/Cl, Mg/Ca and SO_4/Cl ratios and chloride

north with a Mg/Ca ratio which becomes >1. The latter may find its origin in a base exchange. Magnesium concentrations show a progressive increase and a good relationship both with sulfates (Fig. 6) and bicarbonates, which suggests that gypsum and calcite dissolve in parallel. Figure 6 shows that Mg and SO_4 points lay between two end-members. The first end-member might be represented by CT groundwaters. The other one is the phreatic waters part that is not submitted to the water table rise and where saline gypsum carbonated minerals are more present.

Table 2 shows that the great majority of samples are in equilibrium with calcite and dolomite but remain undersaturated with regard to gypsum.

The physico-chemical properties of the Complexe Terminal aquifer indicate large spatial variations. The electrical conductance (EC) increases progressively from around 1300 to 5200 μS cm^{-1} along the flow line in the south to north direction (Table 3) (UNESCO 1972; Edmunds et al. 1997; Guendouz et al. 2003). The samples show a good chemical homogeneity with SO_4–Cl–Na and Ca respectively as the dominating species. The spatial evolution shows an increase along the flow path (south to north) for all major elements. In effect, the major ions exhibit a good relationship with the total salinity (Fig. 4b). These regional evolutions are in agreement with the hydrochemi-

Table 2 Saturation indices for the phreatic aquifer in El-Oued region

Water sample	Saturation index		
	Calcite	Dolomite	Gypsum
01	0.210	0.820	−0.510
03	0.145	0.708	−0.493
05	0.069	0.540	−0.237
12	0.250	0.132	−0.359
14	0.163	0.508	−0.247
17	0.157	1.040	−0.615
19	0.050	0.550	−0.450
20	0.228	0.900	−0.287
24	0.141	0.552	−0.361
35	0.109	0.358	−0.150
36	0.145	0.275	−0.184
43	−0.143	0.250	−0.100
45	0.197	0.540	−0.217
50	0.150	0.350	−0.120
60	0.105	0.140	−0.375
61	−0.127	−0.120	−0.600
65	0.065	0.010	−0.425
68	0.150	0.075	−0.360
71	0.100	0.010	−0.375
75	0.020	0.095	−0.460
80	0.106	0.180	−0.250

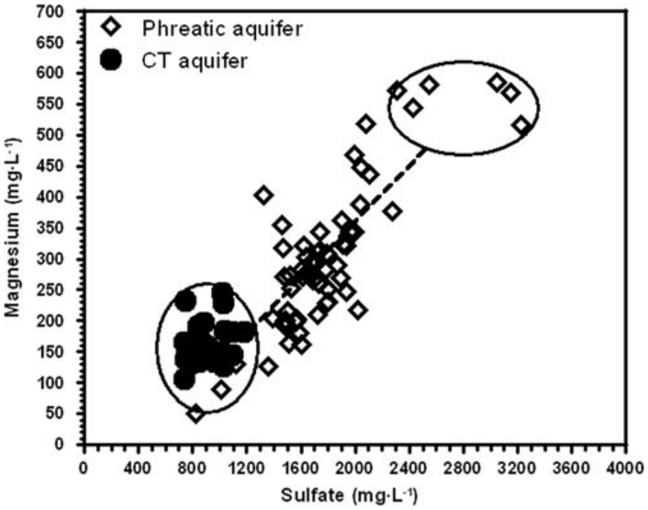

Fig. 6 Magnesium vs. sulfate relationship

Table 3 Field and analytical data for Complexe Terminal aquifer in El-Oued region (sampling campaign of February 1992)

Water sample	*T* (°C)	pH	EC (µS cm^{-1})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	NO_3^- (mg l^{-1})	HCO_3^- (mg l^{-1})	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^+ (mg l^{-1})	K^+ (mg l^{-1})	O-18 (‰)	H-2 (‰)	H-3 (TU)	C-14 (pmC)
F1 Tiksebt	29.2	7.4	3875	842	791	39	156	176	192	865	25	−4.3		0.2	
F2 Pont. Chott	29.0	7.4	3700	742	772	37	160	166	166	144	13	−3.8	−42.0	2.3	2.1±1.1
F3 Pont. Mehri	28.6	7.4	4040	801	890	34	159	326	133	750	21	−4.8		1.7	
F4 Kouinine	29.6	7.4	3960	1091	855	36	156	352	146	750	18	−4.5	−46.4	3.6	4..8±1.2
F5 Guemmar 2	29.0	7.4	3760	845	797	36	159	318	134	750	15	−4.5		3.7	3.1±1.5
F 6 Ghamra 2	29.5	7.4	3830	921	794	31	159	288	158	272	13	−4.5		2.3	3.1±1.7
F 7 Debila N°3	23.7	8.3	1345	746	819	28	162	164	233	1055	20	−4.6		0.0	
F8 Drimini	28.8	7.4	3470	856	816	25	159	220	170	232	14	−4.3		2.6	
F9 Hassi-Khalifa	29.2	7.6	3470	1024	734	26	163	320	127	656	15	−4.4		0.9	
F10 CT3 Debila	29.6	7.4	3820	1021	757	22	165	215	246	1006	30	−4.6			
F11 Magrane N° 1	29.6	7.9	3850	956	795	21	152	322	134	767	19	−4.5		4.0	5.2±2.2
F12 Sidi-Aoun N° 1	29.6	7.7	3740	911	771	33	160	224	143	645	21			0.3	
F13 Dhokkar	29.3	7.5	3770	1020	769	31	156	165	148	272	13	−4.1		4.0	2.9±1.5
F14 Ouarmes	30.2	7.4	4390	1036	923	38	150	256	185	1255	11	−4.8		1.4	12.6±2.5
F15 El-Ogla	28.1	7.6	3560	885	773	32	165	185	198	1105	21	−3.1		0.0	12.1±2.5
F16 Nakhla	27.8	7.5	3420	739	787	35	157	266	106	465	21	−3.0		0.0	0.0±1.0
F17 El-Foulia	28.6	7.7	4620	939	878	32	154	362	150	805	22	−4.7		0.1	
F18 Reguiba 1	29.7	7.6	4600	1030	835	30	159	265	228	1255	18	−4.5		0.0	
F19 Hobba 1	29.8	7.5	4050	1179	883	30	143	242	182	1005	25	−4.2		0.0	0.0±1.5
F20 O-Allenda AL 1	27.7	7.9	4190	1098	849	60	139	192	183	1505	25	−4.1	−43.1	0.7	
F21 Taghzout 1	29.0	7.9	3790	757	812	36	157	326	156	805	21	−4.5		1.8	
F22 El-Bama Bayada	27.7	7.8	3400	745	772	37	157	244	137	1100	25	−3.5	−41.0		
F23 Houd F2	28.9	7.6	5180	879	796	34	153	302	146	805	25	−4.5		4.0	

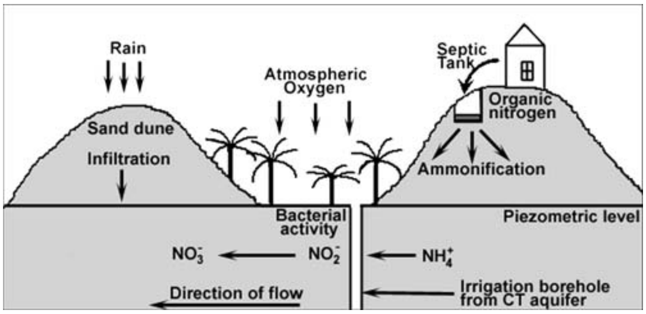

Fig. 7 Schematic diagram explaining the nitrification process occurring within a Ghout

cal features of CT aquifer at the Great Oriental Erg global scale (Guendouz et al. 2003). CT mineralisation is found to increase from south to north in the direction of flow. Its dissolved salts originate from the dissolution of evaporites and carbonates but also from other base exchanges (Edmunds et al. 1997; Guendouz et al. 2003).

Nitrates

Nitrates in drinking water are a major contaminant. They are nowadays frequently found in aquifers. In arid and semi-arid regions, sources of nitrates in groundwaters have either been linked with direct anthropic pollution in towns or with leaching of fertilizers in agricultural areas (Girard and Hillaire Marcel 1997). Nitrate (NO_3) concentrations of the phreatic waters (Table 1) were found far above the World Health Organization (WHO 1985) recommended limit (45 mg l^{-1}) especially for those samples occurring in rural areas. Almost 90% of sampled dug wells showed concentrations greater than 45 mg l^{-1}.

The presence of high nitrate concentrations in the phreatic waters is not only the direct consequence of a massive usage of artificial fertilizers, but is also a consequence of contamination by domestic septic tanks. The latter are unfortunately favored by the absence of a sanitation network in the whole region and where more than 1000 septic tanks are in use (BNEDER 1992). This fact contributes to the nitrification of groundwaters according to the process explained in Fig. 7.

In effect, the sand dunes being very porous, oxygen is thus permanently present due to contact with the atmosphere. Waste waters containing organic nitrogen transform with the help of some aerobic bacterial activity into nitrites then into nitrates.

Furthermore, nine wells were selected, sampled and analyzed for the presence of bacteria. The results of such an analysis are presented in Table 4. It can be noticed that while all of the nine samples contained neither salmonella nor clostridium, seven of them were positive to colibacillus and faecal coliforms. *Streptococcus faecalis* (enterococcus) was also detected in eight of them. Also, the absence of clostridium, which is an anaerobic bacterium, confirms the aerobic conditions which prevail in the studied environment.

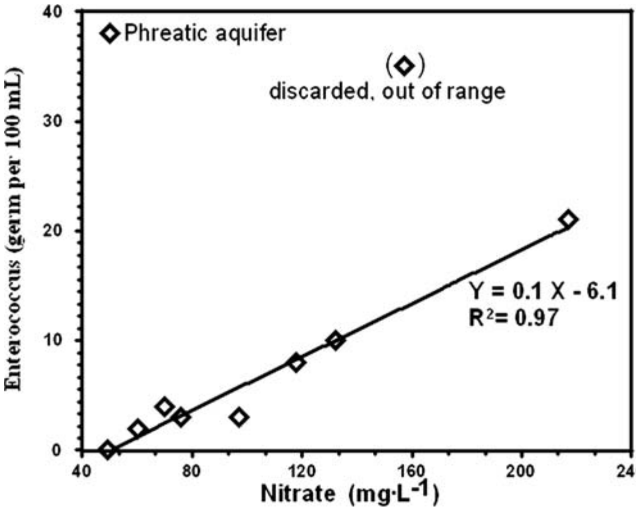

Fig. 8 Relationship between detected germ number and nitrate concentration

An attempt was made to relate the measured number of enterococci per unit volume to the nitrate concentrations. The plot of Fig. 8 reveals a good correlation between the above-mentioned parameters. This confirms a contribution of sanitation waters (domestic waste waters) to the phreatic aquifer. At this stage, it is worth a reminder that only 20% of the area is covered by a sanitation network (Guendouz et al. 1993).

Isotope data

Stable and radioactive isotopes (^{18}O,^{2}H,^{14}C)

Stable isotope ratios are also used as conservative tracers of water origin. They do not exhibit wide variations. Stable isotope contents for the shallow aquifer were found to vary from −0.3 to −3.8‰ in ^{18}O with a mean of −2.60±0.8‰ (n=52) and from −43.8 to −15.4‰ in ^{2}H with a mean of −28.2±5.7‰ (n=22) (Guendouz et al. 1993). In the $\delta^{2}H$–$\delta^{18}O$ plot (Fig. 9), it can be seen that these isotope signatures are higher than those of mean inter-annual precipitation recorded in Ouargla and Ain-Oussera and are located below the Global Meteoric Water Line (GMWL). This is the evidence of an evaporated feature as they are distributed following an evaporation line of slope 6.2. The overall isotopic signature of these waters corresponds to that of rainfall which has undergone evaporative enrichment before or during infiltration through the aeolian deposit (Gonfiantini et al. 1974; Fontes et al. 1986).

Regarding radioisotopes, tritium and radiocarbon were measured for both the phreatic and CT aquifers (Moulla et al. 1996). The superficial aquifer results ranged respectively from 0 to 28 TU (Tritium Unit) and 20 to 120 pmC (percent modern Carbon). C-13 measurements are nevertheless unavailable. However, referring to the existing 1992 rainfall data for Ouargla station ($\delta^{18}O = -5.1‰$ weighted mean value, tritium content = 16.3 TU), one can state that phreatic waters are a mixture of both recent and old water components.

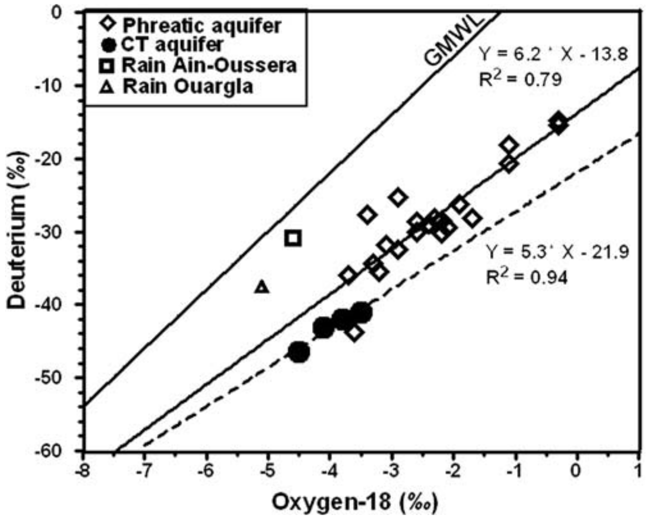

Fig. 9 δ^2H vs. δ^{18}O relationship for groundwater in both the phreatic and CT aquifers

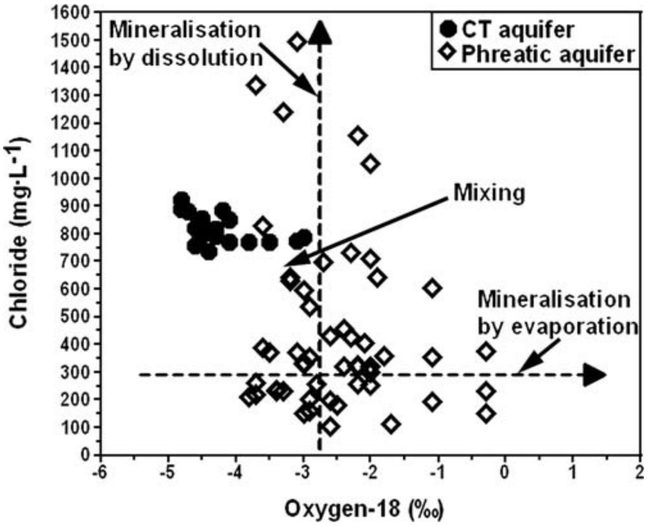

Fig. 10 Chloride and oxygen-18 relationship

At the scale of the studied region, waters from the underlying aquifer of the Complexe Terminal exhibit more depleted but homogeneous stable isotope contents. Values are centered around the following means: $\delta^{18}O = -4.1\pm0.5‰$ (n=44) and $\delta^2H = -43.1\pm4‰$ (n=4). In the delta diagram of Fig. 9 modern rainfall is represented by weighted mean values for Ain-Oussera for years 1994, 1995 and 1996 (Edmunds et al. 1997) and for Ouargla for years 1965, 1967, 1992 and 1994 (Guendouz 1985; Moulla et al. 1996). The groundwaters are related by a line with a slope of 5.3, and an intercept on the GMWL of −11.8‰. Tritium contents ranged from 0 to 4.8 TU and ^{14}C activities from 0 to 12 pmC with corrected ages ranging from 20 to 30 ka (kilo annum). This means that these groundwaters correspond to a late Pleistocene recharge which is in agreement with previous studies that were carried out in the Great Oriental Erg basin (UNESCO 1972; Guendouz 1985; Guendouz et al. 2003; Edmunds et al. 2003).

Chloride, oxygen-18 (mixing zone)

The contribution from the CT aquifer (irrigation and water supply) to the rise of the phreatic water table does not take place in a homogeneous manner throughout the region. It is in fact linked with the spatial distribution and the density of built up areas and Ghouts. The contribution is thus different from one location to another and diagrams such as chlorides vs. O-18, tritium vs. mineralisation may shed light on the more concerned areas (mixings between different water bodies).

The chloride vs. O-18 plot of Fig. 10 shows that phreatic waters seem to be spread according to a scheme giving an account of the mineralisation process and marking off from CT samples. In effect, the latter are less scattered and distributed around means of 900 mg l^{-1} for chloride and δ^{18}O of −4.5‰. The phreatic aquifer recharge component exhibits an evaporated feature ($\delta^{18}O = -3.5‰$ and 180 mg l^{-1} of chloride). It undergoes two mineralisation processes. The first one takes place by evaporation leading to waters whose δ^{18}O varies from −2‰ to 0‰, a chloride concentration of ~250 mg l^{-1} and a deuterium excess in the range of +10‰ to +15‰. On the plot, the samples can be distinguished from others as the ones that are the farthest from CT points. Actually in the field, they represent the areas that are far from irrigated and/or urban concentrations. The second mineralisation process occurs by mineral dissolution giving up waters with mean δ^{18}O of −2.5‰ and chloride concentrations ranging from 150 to 1350 mg l^{-1}. These correspond to the major part of the areas which experienced the most severe water table rises. On the plot, they position in a cluster of points close to the CT samples. On site, they are located along the following transect: El-Ogla-Nakhla-El-Oued (city)-Kouinine-Taghzout-Guemar (17, 18, 19, 20, 42, 43, 45, 71, 74, 75, 76, 80).

Table 4 Results of bacteriological analyses and respective nitrate concentrations for the analyzed samples

	Water sample								
Nature of bacterium	07	12	13	24	43	60	71	99	101
Salmonella	None								
Clostridium	None								
Colibacillus	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
Coliforms	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
Enterococci (germ/100 ml)	3	8	10	0	4	5	21	35	3
Nitrate concentration (mg l^{-1})	76	118	131	49	70	60	217	157	97

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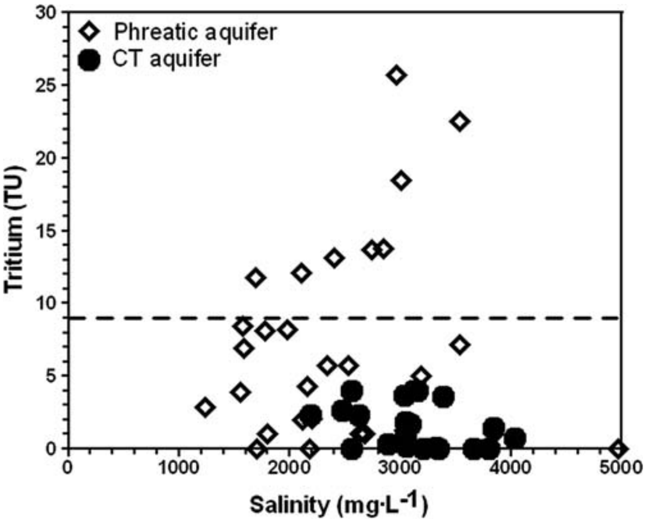

Fig. 11 Relationship between tritium activities and mineralisation

Tritium content data that are available for the phreatic aquifer were measured in the samples collected during May 1991. They are fairly variable (0–28 TU), and reflect the different contributors to the phreatic aquifer. Analysis of Fig. 11 allows one to distinguish two water components:

– A component with H-3 contents lower than 9 TU, and mineralisation in the range of 1.2–5.2 g l^{-1}, which would correspond to the majority of the points located on the El-Ogla-Nakhla-El-Oued (city)-Kouinine-Taghzout-Guemar transect, with an appreciable contribution from CT.

– A second water component with tritium contents varying between 10 and 28 TU and a mineralisation around 2.5 g l^{-1}. This would correspond to recent recharge waters very weakly or not at all affected by CT groundwaters. In order to quantify the samples ages, it is possible to refer to rain survey stations close to the region namely Ouargla and Ain-Oussera. For Ouargla station, rain mean annual tritium contents for 1991 and 1992 were, respectively, 15 and 16.2 TU. For Ain-Oussera, they are respectively 16, 13, 15 and 14 TU for the individual years between 1991 and 1994 (Bouzenboua et al. 1998). By comparison, these values more or less match those measured for the second group. Nevertheless, 11 of the phreatic aquifer samples exhibit high tritium ranging from 18 to 8 TU. These would probably correspond to singular precipitation events that took place during spring 1991. In effect, 20 and 28 TU were measured for rain at Ain-Oussera on 27th and 28th May 1991 (Bouzenboua et al. 1998).

Conclusions and recommmendations

The factors that contribute to the rise of the phreatic aquifer water table have been clearly identified. Formerly, water requirements for the sparse and small population living in the Souf region were met by the phreatic aquifer traditional exploitation. Nowadays, such an equilibrated single aquifer system has been abandoned and replaced by an extensive pumping programme from the two deeper aquifers, both for water supply and irrigation. One of the major reasons for this is linked with the disorganised and rapid demographic and economic growths of the region that led to deficient management of a water supply programme relying on defective pipe networks, inadequately designed for pressure and temperature variables. This is aggravated by the 500 l per person per day potable water allocation scheme, whereas the national regulations allows only for 150 l per person per day. Moreover, the non-existence of a natural discharge zone for the region led to the stagnation of both irrigation and waste waters (septic tanks) within the superficial aquifer. Another cause for such a phenomenon is the change in farmers' agricultural practices with irrigation schemes involving higher and unlimited water volumes than in the past.

The main features of the groundwaters evolution are summarised as follows: the main flow path of the phreatic aquifer in the Souf region is south to north, but some flow contributions from the SSW and the SSE may also converge to the north. The rare existing data on the piezometric level of the phreatic aquifer do not allow one to precisely infer the fluctuations of the water table. However, the modeling trials that were undertaken in order to quantify the water budget led to an excess ranging from 950 to 2500 l s^{-1}.

The physico-chemical characteristics of the Complexe Terminal aquifer indicate large spatial variations. The samples exhibit a chemical homogeneity with SO_4–Cl–Na and Ca, respectively, as the dominating species. The spatial evolution shows that there exists an increase in concentration along the flow path (south to north) for all major elements along with the total salinity.

There is a smooth increase in Cl from 112 mg l^{-1} to 1340 mg l^{-1}, and the corresponding total dissolved solids concentrations range from 1550 to 4960 mg l^{-1}. The salinity as shown from the Na/Cl vs. Cl and the Na vs. Cl correlations is derived from evaporites dissolution (halite). The SO_4/Cl ratio remains far greater than 1 over the southern part and is close to unity in the north. This suggests that gypsum-halite dissolution reactions take place along the flowpath.

Nitrate concentrations were found to be high. Almost 90% of sampled dug wells showed concentrations greater than 45 mg l^{-1}. The presence of high nitrate concentrations in the phreatic waters is not only the result of a massive usage of artificial fertilisers. This fact is unfortunately favoured by the absence of a sanitation network in the whole Souf region where more than 1000 septic tanks are in use.

Isotope signatures of the phreatic aquifer are found higher than those of mean inter-annual precipitation recorded in Ouargla and Ain-Oussera and exhibit an evaporated feature. Their isotopic fingerprint corresponds to that of rainfall which has undergone evaporative enrichment before or during infiltration through the aeolian deposits. Tritium contents measured for the phreatic aquifer samples confirm a recent recharge by precipitation. Similarly, their radiocarbon activities were found to be fairly high. This is evidence of a young water component which agrees with tritium results.

Groundwater from the underlying Complexe Terminal aquifer exhibits homogeneous stable isotope contents. In a delta diagram where modern rainfall is represented, the groundwaters are related by a line of slope 5.3, and an intercept on the GMWL of $-11.8‰$. Tritium contents ranged from 0 to 4.8 TU and ^{14}C activities from 0 to 12 pmC with corrected ages ranging from 20 to 30 ka. These groundwaters flowed from the recharge area that is located further south of the studied region (Great Oriental Erg and Tinrhert plateau). They correspond to a late Pleistocene recharge. Chemical and isotope data enabled one to pinpoint the areas where CT contribution to the phreatic aquifer is consistent confirming thus that the rise of the water table is closely linked with the exploitation of the deep aquifers.

For the sake of, first, slowing down and then, hopefully, stopping this phenomenon, the following recommendations are made. The installation of an appropriately designed sanitation network to cover the whole region starting from the critical areas and also a small waste water decontamination plant seem to be an unavoidable priority.

Meanwhile, it is essential to make the rural population become aware of the danger of using water from traditional dug wells for their domestic purposes. In addition, a new policy favoring the decrease of fertilizers use should be imposed by the public authorities of the region. Furthermore, the implementation of other irrigation techniques (such as the drip-irrigation, the aspersion, the capillarity, and so on) rather than the classical high water-consuming ones which are in application at present is strongly recommended. Presently, there is a trend towards planting eucalyptus trees which are known to be large water consumers.

The design and the installation of both a drainage station and drainage network that would serve to convey irrigation waters towards locations where return of flow should be impossible as well as the setting up of several evaporation ponds are also important to take into consideration.

Finally, a survey of the piezometric level and both the chemical and the bacteriological quality of the phreatic waters are to be carried out on a regular basis. The fragility of the ecosystem requires population redeployment towards other virgin areas to lower the stress on crowded areas. An integrated management of the resource aiming at preventing any over-consumption and/or misuse of allocated water is necessary with limitations on the daily amount of 150 l per person per day.

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