

## Suitability assessment of deep groundwater for drinking and irrigation use in the Djefara aquifers (Northern Gabes, south-eastern Tunisia)

Mohsen Ben Alaya · Salwa Saidi · Thouraya Zemni · Fouad Zargouni

Received: 5 December 2011 / Accepted: 12 August 2013 / Published online: 3 September 2013  
© The Author(s) 2013. This article is published with open access at Springerlink.com

**Abstract** The multilayered Djefara aquifer system, south-eastern Tunisia, has been intensively used as a primary source to meet the growing needs of the various sectors (drinking, agricultural and industrial purposes). The analysis of groundwater chemical characteristics provides much important information useful in water resources management. Detailed knowledge of the geochemical evolution of groundwater and assessing the water quality status for special use are the main objective of any water monitoring study. An attempt has been made for the first time in this region to characterize aquifer behavior and appreciate the quality and/or the suitability of groundwater for drinking and irrigation purposes. In order to attend this objective, a total of 54 groundwater samples were collected and analyzed during January 2008 for the major cations (sodium, calcium, magnesium and potassium), anions (chloride, sulfate, bicarbonate), trace elements (boron, strontium and fluoride), and physicochemical parameters (temperature, pH, total dissolved salts and electrical conductivity). The evolution of chemical composition of groundwater from recharge areas to discharge areas is characterized by increasing sodium, chloride and sulfate contents as a result of leaching of evaporite rock. In this study, three distinct chemical trends in groundwater were identified. The major reactions responsible for the chemical

evolution of groundwater in the investigated area fall into three categories: (1) calcite precipitation, (2) gypsum and halite dissolution, and (3) ion exchange. Based on the physicochemical analyses, irrigation quality parameters such as sodium absorption ratio (SAR), percentage of sodium, residual sodium carbonate, residual sodium bicarbonate, and permeability index (PI) were calculated. In addition, groundwater quality maps were elaborated using the geographic information system to delineate spatial variation in physico-chemical characteristics of the groundwater samples. The integration of various dataset indicates that the groundwater of the Djefara aquifers of the northern Gabes is generally very hard, brackish and high to very high saline and alkaline in nature. The water suitability for drinking and irrigation purposes was evaluated by comparing the values of different water quality parameters with World Health Organization (WHO) guideline values for drinking water. Piper trilinear diagram was constructed to identify groundwater groups where the relative major anionic and cationic concentrations are expressed in percentage of the milliequivalent per liter (meq/l), and it was demonstrated that the majority of the samples belongs to  $\text{SO}_4\text{-Cl-Ca-Na}$ ,  $\text{Cl-SO}_4\text{-Na-Ca}$  and  $\text{Na-Cl}$  hydrochemical facies. As a whole, all the analyzed waters from this groundwater have revealed that this water is unsuitable for drinking purposes when comparing to the drinking water standards. Salinity, high electric conductivity, sodium adsorption ratio and sodium percentages indicate that most of the groundwater samples are inappropriate for irrigation. The SAR vary from medium (S2) to very high (S4) sodicity. Therefore, the water of the Djefara aquifers of the northern Gabes is dominantly of the C4-S2 class representing 61.23 % of the total wells followed by C4-S3 and C4-S4 classes at 27.27 and 11.5 % of the wells, respectively. Based on the US Salinity

M. B. Alaya (✉) · T. Zemni · F. Zargouni  
Faculty of Mathematical, Physical and Natural Sciences  
of Tunis, Department of Geology, Laboratory of Geomatic  
and Applied Geology, University of Tunis El Manar,  
2092 Tunis El Manar II, Tunisia  
e-mail: benalaya.mohsen@gmail.com

S. Saidi  
National School of Engineering of Sfax (ENIS), Water,  
Energy and Environment Laboratory (LR3E),  
University of Sfax, 3038 Sfax, Tunisia

Classification, most of the groundwater is unsuitable for irrigation due to its high salt content, unless certain measures for salinity control are undertaken.

**Keywords** Physico-chemical analysis · Hydrogeochemistry · Drinking and irrigation utility · Djefara aquifers · Tunisia

## Introduction

Nowadays, fresh water resources are becoming more and more limited with increasing demand in the world. Thus, understanding the hydrochemical characteristics and water quality is becoming critical for groundwater planning and management, to ensure sustainable safe use of the resources for drinking, agricultural and industrial purposes. Groundwater resources of the Mediterranean coastal plains in the southern bank of the basin (Middle East and North Africa) show a qualitative and quantitative deterioration through time (Custodio and Bruggeman 1987; Edmunds et al. 2003) resulting from climatic constraints (semi-arid climate and low rainfall amount) and anthropological activities (limited resources, pumping higher rates than the present recharge, largely increased for urban, domestic supply and multiplication of the diffuse sources of pollution). Therefore, it is necessary to subject the water to routine quality analyses to assess its suitability for human consumption. The groundwater chemistry could have important information on the suitability of the groundwater for domestic, industrial and agricultural purposes, and its contamination has been recognized as one of the most serious problems in the world (Adams et al. 2001; Jalali 2007, 2009, Djabri et al. 2007; Wen et al. 2008; Giridharan et al. 2008; Khazaei et al. 2006; Tayfur et al. 2008; Anku et al. 2009; Trabelsi et al. 2009, 2011; Rouabhia et al. 2009; Fehdi et al. 2009). Groundwater chemistry depends on a number of factors such as general geology, degree of chemical weathering of the various rock types, quality of recharge water, and inputs from sources other than water–rock interaction. Such factors and their interactions result in a complex groundwater quality (Domenico and Schwartz 1990; Edmunds et al. 2003; Risacher et al. 2003; Guler and Thyne 2004; Vengosh et al. 2005; Boughriba et al. 2006; Ayenew et al. 2008; Giridharan et al. 2008; Han et al. 2009; Trabelsi et al. 2009, 2011). In Tunisia and other similar parts worldwide, common studies have been carried out to assess the geochemical characteristics of groundwater (Subba Rao et al. 1998; Graniel et al. 1999; Umar and Sami Ahmad 2000; Guler et al. 2002; Guler and Thyne 2004; Elango et al. 2003; Krishnakumar 2004; Jeevanandam et al. 2006; Ravikumar et al. 2009, 2010; Aghazadeh and Mogaddam 2011; Hamzaoui-Azaza et al.

2011, 2012; Ketata et al. 2011). The development of groundwater resources in these arid and semi-arid regions is a sensitive issue, and careful management is required to avoid water-quality degradation (Al-Bassam and Al-Rumikhani 2003; Al-Shaibani 2008; Dassi et al. 2005; Dassi 2010; Trabelsi et al. 2005, 2007).

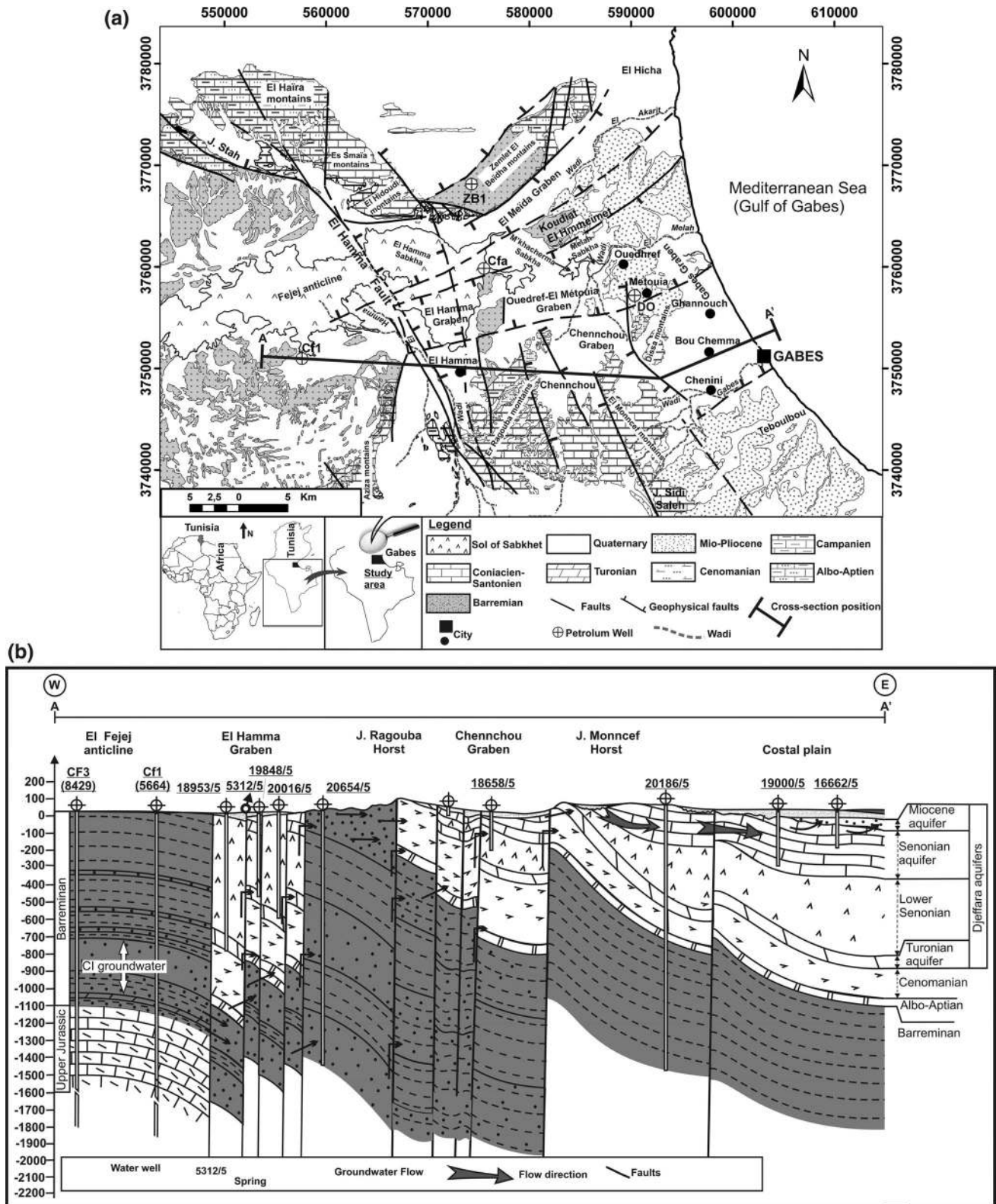
In Tunisia, the gradient of average annual rainfall decreases from north to south from approximately 1,300 to <200 mm. In fact, in the northern Tunisia, freshwater of dams are used for agricultural and domestic needs, while in southern Tunisia, surface waters are limited and water resources are based on groundwater of variable quality. As part of Southern Tunisia, the Gabes-north region has a semi-arid climate with very irregular rainfall, which makes the groundwater resources quite fragile.

The Djefara aquifers of the northern Gabes are well known by their groundwater potential and their artesian conditions. Recently, confining pressure was dramatically reduced due to overexploitation in agricultural and industrial purposes. This region has major difficulties in managing its water resources, which are in decline, especially since, for the last decades, the scarcity of groundwater.

This work represents a first attempt for the establishment of a comprehensive study in the area. It also intends to characterize the main factors and mechanisms controlling the chemistry and to assess the quality of groundwater with references to its suitability to drinking and irrigation. Further, water quality parameters were compared with the international standards (WHO 1996a, b, 2004) and to Wilcox (1955) and US Salinity (Richards 1954) diagrams were also prepared for the study of irrigation water quality.

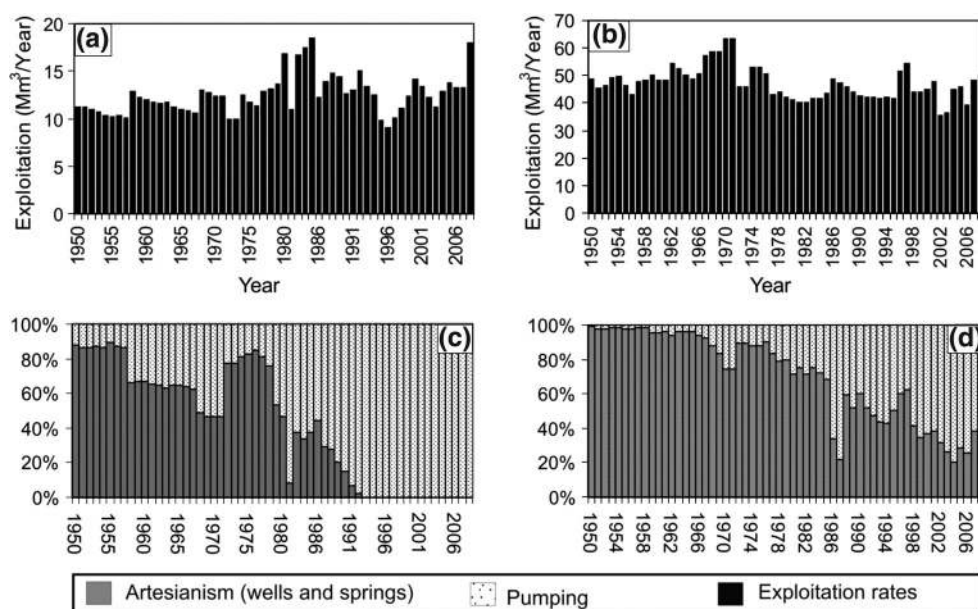
## Description of the study area

The deep Djefara aquifers of the northern Gabes are located in south-eastern Tunisia and have an extension of 1,000 km<sup>2</sup> comprising 36 km along the coast and are positioned approximately between the longitudes UTM X1 = 550,000 and X2 = 610,000 and latitudes UTM Y1 = 3740,000 and Y2 = 3780,000. The study area is limited by Zemlet El Beïdha Mountain in the north, Mediterranean Sea coast in the east, El Hamma faults to the west. The southern limit consists in Jebel Raguba, Jebel Monncef and Jebel Sidi Saleh (Fig. 1a). As representing a part of the Djefara coastal plain of Tunisia, the region has undergone an arid to semi-arid climate changes marked by seasonal contrasting climatic variables. Also the area is influenced by dry/hot and humid air masses coming respectively from the desert and from the Mediterranean Sea (Kallel 2003). The rainfall average is approximately 180 mm/year. However, the monthly average temperature ranges between 12 °C in winter (January) and 28 °C in



**Fig. 1** a Geologic map of the study area (after Abbès et al. 1986 and Ghanmi et al. 1984) and b schematic hydrogeological cross section in the studied area along the transect AA' (position marked in geological map)

**Fig. 2** a, b Parts of exploitation with pumping and artesianism (wells and springs) and c, d exploitation rates evolution of the Djeffara aquifers in El Hamma–Chennchou and northern Gabes (1950–2008)



summer (August), and the average annual temperature is 20 °C. The precipitation period in a typical year varies between October and March with the dry period extending from April to September. The potential evapotranspiration estimated by Thornthwaite method is very high (2,800 mm/year) and largely exceeds the rainfall. This situation makes the groundwater resources quite delicate. The wadis of Gabes region have an intermittent flow regime, because the dry season is typically very long (6–8 months/year). The main wadis in the north Gabes are the El Hamma wadi, El Melah wadi, Gabes wadi and El Akarit wadi, which receive many important flow tributaries, in particular from the Dahar, Er Ragouba, Monncef and Dissa mountains in the south of the study area and the Koudiat El Hmmeïmet and Zemlet Beïdha mountains in the north. Surface water resources are insufficient for current domestic, industrial and agricultural needs of the region and therefore the groundwater constitutes the main water resource in southern Tunisia.

The Djeffara plain hosts a large number of wells with depths varying from 200 to 550 m. Most of these wells, which tap the multilayered confined aquifer of Gabes-north, contain dolomites and limestones of the Turonian and Lower Senonian, and fine to gravel grained sandstones of the Miocene. Some of the hydraulic deep wells are used for drinking purposes (7 %), only few for chemical industry (9 %), and approximately 84 % of the water is used for irrigation. Consequently, groundwater constitutes the main water resource in southern Tunisia. In 2008, the total water extraction in this aquifer is estimated by the local water authorities in Hamma–Chennchou and northern Gabes is 18 and 50 million m<sup>3</sup>/year (Fig. 2a, b), respectively (DGRE 2008). These exploitation rates, which are

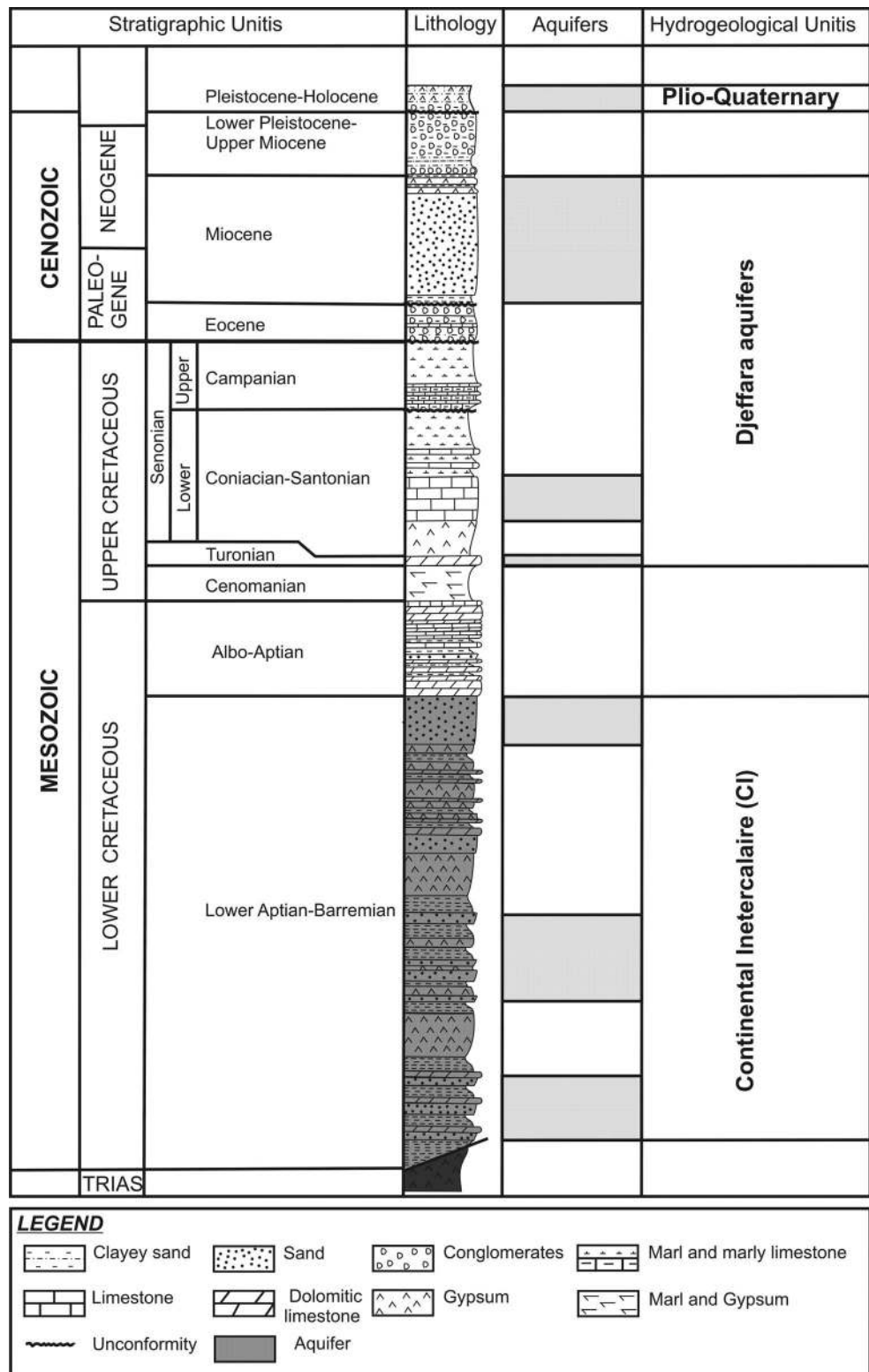
required to meet the increasing demands of the current agricultural practices, exceed the natural replenishment (30.5 Mm<sup>3</sup>/year, OSS 2003) of these basins and had led to depletion of the groundwater resources and degradation of their quality. The conditions in this aquifer system were originally artesian with numerous springs occurring across the plain (Fig. 2c, d). Actually, 96 of deep wells were drilled to meet the rapid growing demand for water. This over-pumping of the Djeffara aquifers has resulted in water-level declines ranging from 0.25 to 1 m/year during the past three decades (Abidi 2004).

### Geological and hydrogeological settings

A representative west–east cross section of the study area is shown in Fig. 1b. The regional geology has been discussed by several authors (Busson 1970; Abdeljaouad 1983; Bouaziz 1995; Abbès et al. 1986). From a geological point of view (Fig. 3), the investigated area is characterized by outcrops ranging from the Lower Cretaceous to Quaternary units and by lateral lithostratigraphic variations, with an unconformity from Palaeocene to Oligocene. The catchment area consists of limestone, dolomite, gypsum, halite, clayey sand and conglomerates (Fig. 3).

The relation between stratigraphic and hydrogeologic units is presented in Fig. 3. As shown in Figs. 1b and 3, the CI aquifer is situated within the continental formations of the Lower Cretaceous (Neocomian, Barremian, Aptian and Albian) which is located to the west of the study region. The aquifer is formed by a complex succession of clastic sediments, differentiated into several units of detrital sediments and separated by clay-rich strata, with the

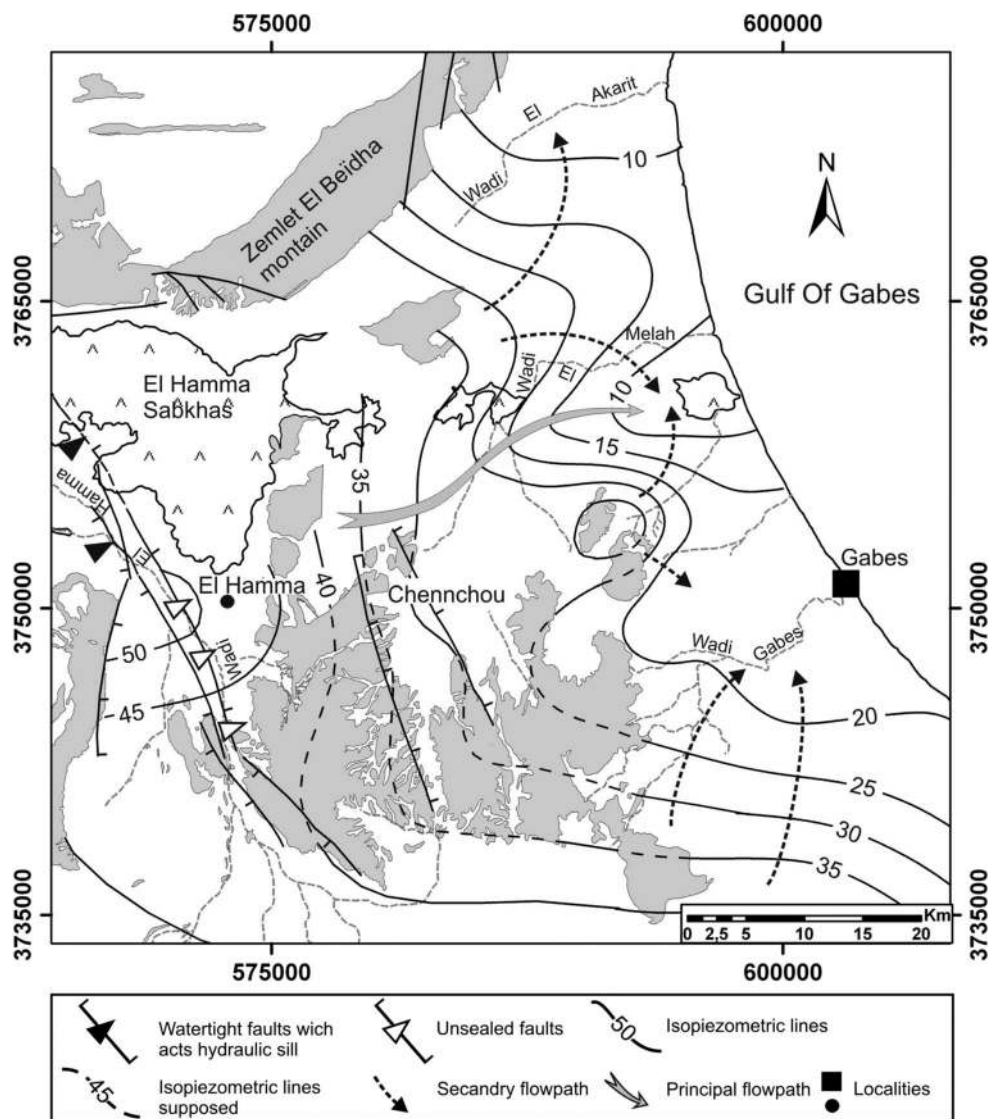
**Fig. 3** Relation between stratigraphic and hydrogeologic units in the Gabes region



maximum aquifer thickness exceeding 1,500 m (Edmunds et al. 2003). The Djeffara aquifer is hosted in the Upper Cretaceous (Turonian and Lower Senonian) and Tertiary formations (Miocene) which are located in the coastal plain. Tectonic movements have significantly influenced

hydrodynamic functioning of these aquifers. Moreover, the northern part of Djeffara basin is strongly affected by a complex system of NE/SW faults crossed by NW/SE ones detected by geophysical survey. These geophysical faults provoked a lateral compartmentalization and connections

**Fig. 4** Piezometric map of Gabes confined aquifer (January 2008)



between different aquiferous horizons. This is the case in the El Hamma–Chennchou where a hydraulic continuity between the Continental Intercalaire and the Djefjara aquifers has been recognized.

In the northern part of the basin (Djefjara of northern Gabes and El Hamma–Chennchou), Cretaceous and tertiary formations are characterized by lateral variation in depths and thickness. Moreover, in Zemlet el Beïda Mountain, Cenomanian and Turonian deposits are missing (Fig. 1a). Stratigraphic gaps in these areas reflect several factors such as the irregularity of the paleotopography, eustatic movements and tectonic instabilities (Castany 1954; Bouaziz 1995).

The Djefjara aquifer system is characterized by large changes in facies both in the vertical and lateral directions, and thickness of water-bearing horizons. In the north of Gabes, Djefjara waters are mainly hosted in the Miocene continental deposits with clays and sandy intercalation

produced after the post-Cretaceous erosion (Bouaziz 1995; Benton et al. 2000). The thickness of these sand deposits increases from east (30 m) to west (>80 m). They are characterized by coarse and fine grain size. Permeability of the Miocene horizon ranges from  $2 \times 10^{-5}$  to  $3 \times 10^{-4}$  m/s, while transmissivities obtained from pumping tests ranges from  $3$  to  $33.8 \times 10^{-3}$  m<sup>2</sup>/s (Mekrazi 1975).

The principal aquifer of Gabes is hosted in the Senonian horizon represented by two stratigraphic units. The first one constitutes a fractured limestone horizon with a thickness of approximately 200 m, and the second is formed by marl and gypsum characterized by variable thickness up to 500 m. These water-bearing formations are strongly fissured, with the transmissivity ranging from  $0.9$  to  $345 \times 10^{-3}$  m<sup>2</sup>/s (Mamou 1990).

The Turonian carbonates constitute the principal aquifer formation in Hamma–Chennchou region. The aquifer consists of dolomites and fissured limestones, whose

**Table 1** Physicochemical parameters of groundwater

Well no.	Aquifer	Region	UTM coordinates		pH	CE (μS/cm)	T (°C)	Depth (m)	Designation
			Latitude	Longitude					
1	CI	Chott El Fejej	3753294.31	558921.54	7.46	3,680	57.30	744	Drinking
2	CI	Chott El Fejej	3750547.02	558439.24	7.70	3,750	64.20	856	Drinking
3	CI	Chott El Fejej	3750999.02	557636.00	7.76	4,500	57.70	862	Drinking
4	CI	Chott El Fejej	3749981.98	563686.23	7.76	4,450	65	791	Drinking
5	CI	Chott El Fejej	3752232.87	564503.26	7.74	4,420	64.50	757	Drinking
6	CI	Chott El Fejej	3750365.60	553031.00	8.07	4,090	62.00	1,395	Irrigation
7	CI	El Hamma	3751526.87	576907.74	8.40	6,250	62.00	1,306	Irrigation
8	CI	North Gabes	3757330.31	590198.00	8.5	10,500	62	1,922	Irrigation
9	T	El Hamma	3742494.83	570400.17	8.30	5,700	62.00	171	Irrigation
10	T	El Hamma	3746146.72	572058.74	6.74	5,870	65.20	516.75	Irrigation
11	SL	El Hamma	3751210.37	574246.21	7.43	6,770	29.40	44.8	Irrigation
12	SL	El Hamma	3747174.46	574888.63	7.21	5,430	62.00	90	Irrigation
13	SL	El Hamma	3749806.95	574086.00	7.08	6,940	40.70	135	Drinking
14	SL	Chennchou	3751557.22	580569.24	7.14	5,150	56.70	48	Irrigation
15	SL	Chennchou	3750565.69	581326.73	7.05	6,660	35.70	40	Irrigation
16	SL	Chennchou	3750787.86	582396.00	7.19	5,230	45.00	42	Irrigation
17	SL	Chennchou	3749412.25	586331.11	7.27	6,610	30.50	40	Irrigation
18	SL	Sabkhet Melah	3759054.41	588710.01	7.29	8,320	24.90	44.4	Irrigation
19	SL	Sabkhet Melah	3757451.11	586454.70	7.29	13,648	23.80	88	Irrigation
20	SL	Sabkhet Melah	3755712.92	586206.30	7.71	6,620	24.60	45	Irrigation
21	SL	Sabkhet Melah	3755692.99	584191.86	7.80	7,290	26.30	77	Irrigation
22	SL	North Gabes	3749488.90	590381.77	7.80	7,700	26.30	272	Irrigation
23	SL	North Gabes	3746378.00	602068.28	7.18	6,130	35.10	137	Irrigation
24	SL	North Gabes	3743905.33	588721.59	7.24	8,060	33.40	168	Irrigation
25	SL	North Gabes	3747483.05	596280.31	7.22	7,210	28.10	49	Irrigation
26	SL	North Gabes	3744396.27	602974.85	7.20	6,500	25.60	138	Drinking
27	SL	North Gabes	3748336.62	599884.46	7.10	6,590	33.50	117	Irrigation
28	SL	North Gabes	3749642.03	599723.81	7.23	3,783	25.80	105	Irrigation
29	SL	North Gabes	3751014.70	597835.92	7.16	7,240	29.80	88.28	Drinking
30	SL	North Gabes	37550789.25	600268.17	7.07	5,830	32.60	120	Irrigation
31	SL	North Gabes	3750268.22	596697.71	7.20	4,700	18	71	Irrigation
32	SL	North Gabes	3754762.17	596343.34	7.21	5,800	28.70	67.5	Irrigation
33	SL	North Gabes	7558154.18	595854.71	7.42	6870	25.60	87	Irrigation
34	SL	North Gabes	3757792.95	594204.71	7.41	6,040	25.10	56	Irrigation
35	MS	North Gabes	3758160.74	597328.62	7.38	5,000	24.30	80	Irrigation
36	MS	North Gabes	3754967.07	598536.64	7.18	4,750	28.90	76	Irrigation
37	MS	North Gabes	3758062.08	591527.87	7.45	5,650	24.30	57.07	Irrigation
38	MS	North Gabes	3761018.25	589086.73	7.18	6,270	21.00	65	Irrigation
39	MS	North Gabes	3761922.63	589712.00	7.38	5,740	23.30	80	Irrigation
40	MS	North Gabes	3764775.09	593482.27	7.21	7,210	23.60	150	Irrigation
41	MS	North Gabes	3762655.31	592265.07	7.14	7,610	24.00	81.5	Irrigation
42	MS	North Gabes	3762655.31	592265.07	7.43	7,140	24.80	65	Irrigation
43	MS	North Gabes	3764165.57	595220.69	7.12	5,600	24.00	65	Irrigation
44	MS	North Gabes	3766599.17	595488.41	7.29	5,560	22.90	80	Irrigation
45	MS	North Gabes	3761800.90	585356.28	7.10	5,100	23.00	60	Irrigation
46	MS	North Gabes	3768185.11	590834.63	7.36	5,900	25.20	52.2	Irrigation
47	MS	North Gabes	3769367.35	586238.15	7.13	9,600	24.40	50	Irrigation

**Table 1** continued

Well no.	Aquifer	Region	UTM coordinates		pH	CE ( $\mu\text{S}/\text{cm}$ )	T ( $^{\circ}\text{C}$ )	Depth (m)	Designation
			Latitude	Longitude					
48	MS	North Gabes	3770282.73	586845.95	7.09	7,440	24.30	60	Irrigation
49	MS	North Gabes	3771797.00	590366.73	7.60	4,210	26.00	65	Irrigation
50	MS	North Gabes	3773064.88	594019.48	7.70	4,090	26.20	70	Irrigation
51	MS	North Gabes	3777325.72	591348.72	7.15	10,300	23.50	50	Irrigation
52	MS	North Gabes	3778615.55	591348.72	7.12	9,600	24.80	90	Irrigation
53	MS	North Gabes	3782803.01	590530.25	7.19	10,150	25.90	87	Irrigation
54	MS	North Gabes	3774549.39	589630.00	7.19	7,090	22.90	–	–

CI Continental Intercalaire, T Turonian, SL Senonian limestones, MS Miocene sands

maximum thickness reach exceeds 50 m (Rouatbi 1967). Although its thickness is limited, the Turonian aquifer is characterized by high transmissivity, generally around  $100 \times 10^{-3} \text{ m}^2/\text{s}$  (Rouatbi 1967).

The northern part of Djefara basin is largely affected by several normal faults in different directions as a result of tectonic activity (Bouaziz 1995). This extensive tectonic phase during the Upper Cretaceous caused lateral compartmentalization of Djefara aquifers. All water-bearing formations of the Djefara plain are hydraulically connected through the existing faults and semi-permeable strata.

The hydraulic continuity between the CI and Djefara aquifers has been demonstrated through the differences in hydraulic heads and a set of boreholes showing concordant hydrogeologic, hydrodynamic and hydrochemistry parameters (Rouatbi 1967; ERESS 1972; Mamou 1990; OSS 2003). The CI aquifer of North Africa is one of the largest confined aquifers in the world (Castany 1982), comparable in scale to the Great Artesian Basin of Australia and covers some 600,000 km<sup>2</sup>. The hydraulic heads of the CI aquifer indicate W–E flow, in the direction of Gulf of Gabes, with an artesian pressure head of about 200 m above ground surface (OSS 2003). On the other hand, the Djefara aquifers show a general W–E flow, from El Hamma region toward the Mediterranean Sea, in accordance with the plain structure (Fig. 4). Near El Hamma faults, the artesian pressure head is in the order of 50 m and is explained by the ascension of CI groundwater through El Hamma faults (OSS 2003). The piezometric gradient varies between 1 and 3 ‰.

### Sampling and analytical methods

A total of 54 samples of groundwater from boreholes tapping CI aquifer (8) and Djefara aquifers (46) (Tables 1, 2) have been collected in January 2008 (Fig. 5). For this study, sampling points were chosen according to their

geographic and stratigraphic locations in a way that they represent hydrochemical types and hydrogeological conditions typical for the diverse sectors and different depths of the aquifer. Water samples were collected from pumping wells after minimum of several hours of pumping prior to sampling. This was done to remove groundwater stored in the well. Water samples were collected in clean polyethylene bottles. Temperature, pH and electrical conductivity (EC) were measured using a portable field kit. To prevent changes in chemical equilibrium and adsorption on the inner surface of the bottles, the samples were acidified with 1:1 extra pure HNO<sub>3</sub> to 1 ‰ without disturbing the sample volume, and the final acidity of the samples during storage was around pH  $\leq$  2.0. Preservation and transportation of the water samples to the laboratory followed standard methods. The collected samples were brought to the laboratory and were filtered using 0.45  $\mu\text{m}$  millipore filter paper and acidified with nitric acid (Ultrapure Merck) for cation analysis. Prior to laboratory analysis, the samples were stored below 4  $^{\circ}\text{C}$ . Chemical analyses (Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, HCO<sub>3</sub><sup>-</sup>, F<sup>-</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> K<sup>+</sup>, Sr<sup>2+</sup> and B<sup>+</sup>) were carried out in Tunisian Chemical group Laboratory (GCT).

Chloride analysis was carried out by the standard titration method, or the Mohr method. Water alkalinity is primarily attributed to the presence of bicarbonates (HCO<sub>3</sub><sup>-</sup>) since the pH of most water samples ranges between 6.74 and 8.5. Bicarbonate (HCO<sub>3</sub><sup>-</sup>) is estimated by titrating with HCl. Using BaCl<sub>2</sub>, the gravimetric method was used to estimate sulfate concentrations (SO<sub>4</sub><sup>2-</sup>). Calcium (Ca<sup>2+</sup>) was analyzed titrimetrically, using standard EDTA. Magnesium (Mg<sup>2+</sup>) was computed, taking the difference between TH (Ca<sup>2+</sup> plus Mg<sup>2+</sup>) and Ca<sup>2+</sup> values. Sodium (Na<sup>+</sup>) and potassium (K<sup>+</sup>) were measured by flame photometer. Fluoride (F<sup>-</sup>) is analyzed using a spectrophotometer. Strontium (Sr<sup>2+</sup>) and boron (B<sup>+</sup>) concentrations were measured by inductively coupled plasma–optical emission spectrometry (ICP-OES). All the water quality parameters are expressed in mg/l, except EC, T and pH. The analytical error as inferred from the balance between



**Table 2** Chemical and irrigation water quality parameters of the analyzed groundwater samples

Well no.	TDS (mg/l)	Cl <sup>-</sup> (mg/l)	SO <sub>4</sub> <sup>2-</sup> (mg/l)	HCO <sub>3</sub> <sup>-</sup> (mg/l)	Ca <sup>2+</sup> (mg/l)	Mg <sup>2+</sup> (mg/l)	Na <sup>+</sup> (mg/l)	K <sup>+</sup> (mg/l)	F (mg/l)	B (mg/l)	Sr <sup>2+</sup> (mg/l)	Sr <sup>2+</sup> /Ca <sup>2+</sup> (‰)	Group	TH (mg/l)	SAR	%Na (%)	RSBC (meq/l)	RSC (meq/l)	PI (%)
1	2,940	839	925	92	360	70	540	43	0.96	0.32	4	5.08	GRI	1,186.97	6.82	50.86	-16.46	-22.22	51.18
2	2,760	646	1,060	122	360	72	410	34	0.57	0.3	4	5.08	GRI	1,195.20	5.16	43.88	-15.96	-21.89	45.20
3	3,180	665	1,296	116	428	74	472	41	0.83	0.49	5	5.34	GRI	1,373.23	5.54	43.98	-19.46	-25.54	44.70
4	3,300	981	1,121	122	400	74	540	45	0.56	0.52	4	4.57	GRI	1,303.31	6.51	48.57	-17.96	-24.05	49.14
5	3,001	815	1,064	110	376	70	520	43	0.57	0.43	4	4.87	GRI	1,226.92	6.46	49.13	-16.96	-22.72	49.69
6	2,736	720	1,026	98	352	77	468	42	0.55	0.34	4	5.20	GRI	1,195.80	5.89	47.24	-15.96	-22.29	47.72
7	3,600	1,099	1,234	140	480	69	680	70	0.59	0.65	6	5.72	GRI	1,482.50	7.68	51.38	-21.66	-27.33	51.00
8	7,750	2,414	1,992	189	484	96	2,047	68	-	-	-	-	GRI	1,603.59	22.23	73.89	-21.05	-28.95	73.94
9	3,100	641	1,476	134	408	65	585	68	0.59	0.44	5	5.61	GRI	1,286.25	7.09	51.35	-18.16	-23.51	50.94
10	3,120	860	1,043	140	400	82	495	68	0.72	0.44	5	5.72	GRI	1,336.23	5.89	46.51	-17.66	-24.41	46.14
11	4,280	1,394	1,270	171	460	98	720	74	1.4	1.45	8.32	8.27	GRII	1,551.89	7.95	51.66	-20.15	-28.21	51.39
12	3,240	883	1,132	134	388	79	497	68	0.57	0.42	5	5.89	GRI	1,293.92	6.01	47.40	-17.16	-23.67	46.96
13	3,595	975	1,208	153	500	84	585	76	0.61	0.57	6	5.49	GRI	1,594.16	6.37	46.18	-22.44	-29.35	45.64
14	3,100	849	1,057	134	384	86	487	68	0.67	0.52	5	5.96	GRI	1,312.74	5.85	46.57	-16.96	-24.04	46.13
15	4,370	1,338	1,454	153	596	132	572	36	2.1	0.7	6.5	4.99	GRI	2,031.39	5.52	38.83	-27.23	-38.09	39.86
16	3,490	633	1,350	153	428	84	485	32	0.78	0.6	7	7.48	GRII	1,414.38	5.61	43.64	-18.85	-25.76	45.20
17	3,600	870	1,260	153	428	86	560	34	0.75	0.6	7	7.48	GRII	1,422.61	6.46	46.98	-18.85	-25.93	48.35
18	5,176	2,275	2,273	183	702	345	880	80	2.1	2	12	9.60	GRIII	3,172.57	6.79	38.83	-32.03	-60.42	38.57
19	10,100	3,647	2,350	146	460	250	2,530	215	2.3	2.1	23	9.92	GRIII	2,177.37	23.58	72.61	-20.56	-41.13	70.20
20	3,868	1,375	1,439	171	516	150	620	40	2	1.9	5	5.50	GRI	1,905.70	6.18	42.33	-22.95	-35.29	43.35
21	4,248	1,515	1,610	79	576	152	673	70	2.1	1.7	12	9.53	GRIII	2,063.75	6.44	42.92	-27.45	-39.96	42.07
22	3,356	667	1,392	146	440	106	430	28	1.1	0.7	8	8.32	GRII	1,534.87	4.77	38.73	-19.56	-28.29	40.43
23	2,844	525	1,260	152	372	110	400	26	1.2	0.6	5	8.41	GRII	1,381.53	4.68	39.52	-16.07	-25.12	41.55
24	3,580	823	1,371	128	400	103	495	40	0.81	0.8	7	8.01	GRII	1,422.65	5.71	44.20	-17.86	-26.34	45.08
25	3,048	674	1,125	146	320	151	425	24	0.97	0.7	5	7.14	GRII	1,420.41	4.90	40.19	-13.57	-26.00	42.18
26	2,800	553	1,159	152	296	120	460	31	1.2	0.6	5	7.72	GRII	1,232.91	5.70	45.74	-12.28	-22.15	47.51
27	2,736	539	1,229	158	308	122	432	28	1.2	0.6	5	7.43	GRII	1,271.11	5.27	43.40	-12.78	-22.82	45.43
28	3,016	575	1,292	165	336	127	428	31	1.2	0.6	6	8.17	GRII	1,361.60	5.04	41.60	-14.06	-24.51	43.46
29	3,160	639	1,380	146	340	127	448	28	1.1	0.57	6	8.07	GRII	1,371.59	5.26	42.40	-14.57	-25.02	44.18
30	3,068	568	1,367	152	340	125	412	20	1	0.6	6	8.07	GRII	1,363.36	4.85	40.32	-14.47	-24.76	42.68
31	3,082	610	1,305	146	320	110	400	28	1.9	0.6	5	7.15	GRII	1,251.69	4.92	41.96	-13.57	-22.63	43.93
32	3,288	695	1,311	152	364	122	450	34	1.8	0.7	6	7.54	GRII	1,410.94	5.21	41.99	-15.67	-25.71	43.49
33	4,112	1,008	1,527	146	448	139	668	41	1.7	0.9	8	8.17	GRII	1,690.64	7.07	47.08	-19.96	-31.40	47.90
34	3,560	852	1,452	140	360	144	560	36	1.2	0.7	7	8.89	GRIII	1,491.48	6.31	45.85	-15.67	-27.52	46.97
35	3,276	688	1,300	146	368	115	496	27	1.9	0.5	5	6.22	GRI	1,392.12	5.78	44.42	-15.97	-25.43	46.16

Table 2 continued

Well no.	TDS (mg/l)	Cl <sup>-</sup> (mg/l)	SO <sub>4</sub> <sup>2-</sup> (mg/l)	HCO <sub>3</sub> <sup>-</sup> (mg/l)	Ca <sup>2+</sup> (mg/l)	Mg <sup>2+</sup> (mg/l)	Na <sup>+</sup> (mg/l)	K <sup>+</sup> (mg/l)	F (mg/l)	B (mg/l)	Sr <sup>2+</sup> (mg/l)	Sr <sup>2+</sup> /Ca <sup>2+</sup> (‰)	Group	TH (mg/l)	SAR	%Na (%)	RSBC (meq/l)	RSC (meq/l)	PI (%)
36	2,998	674	1,206	165	360	96	433	24	1.6	0.6	5	6.35	GRI	1,293.96	5.24	42.89	-15.26	-23.16	45.20
37	3,548	781	1,490	146	360	115	510	34	1.3	0.7	7	8.89	GRIII	1,372.15	5.99	45.64	-15.57	-25.03	47.02
38	3,640	923	1,306	171	420	108	600	42	1.2	0.7	7	7.62	GRII	1,493.16	6.75	47.62	-18.15	-27.04	48.72
39	3,394	816	1,325	153	380	98	493	38	1.2	0.6	7	8.43	GRII	1,352.13	5.83	45.30	-16.45	-24.52	46.59
40	4,120	1,136	1,400	153	420	144	750	39	1.3	0.6	7	7.62	GRII	1,641.30	8.05	50.58	-18.45	-30.30	51.50
41	4,400	1,250	1,494	153	464	120	860	41	1.3	0.8	9	8.87	GRIII	1,652.41	9.20	53.77	-20.65	-30.52	54.55
42	4,108	1,065	1,573	153	440	125	690	31	1.7	0.9	9	9.80	GRIII	1,613.06	7.47	48.84	-19.45	-29.73	50.12
43	3,312	710	1,400	171	360	115	443	24	1.7	0.7	6	7.62	GRII	1,372.15	5.20	42.00	-15.16	-24.62	44.27
44	3,176	639	1,421	171	356	115	415	23	1.6	0.7	4.97	6.39	GRI	1,362.16	4.89	40.61	-14.96	-24.42	43.01
45	5,440	1,030	1,050	173	392	115	450	28	2.3	2.2	6.48	7.56	GRII	1,452.05	5.14	41.11	-17.33	-26.79	42.73
46	3,330	784	1,100	153	300	167	470	50	2.1	1.6	5	6.02	GRI	1,436.31	5.39	43.03	-12.46	-26.20	43.69
47	5,615	1,980	1,750	154	612	155	1,049	27	2.3	2.1	13	9.91	GRIII	2,165.99	9.80	51.67	-28.34	-41.10	52.57
48	4,688	1,750	1,698	153	680	150	762	24	2.1	1.5	12	9.46	GRIII	2,315.21	6.89	42.16	-31.42	-43.77	43.39
49	3,016	1,781	1,239	134.2	604	146	650	14	2.84	2.3	5.23	7.87	GRII	2,108.98	6.16	40.43	-27.94	-39.95	42.03
50	3,120	674	1,188	146.4	316	158	439	12	1.14	1	5.93	8.58	GRII	1,439.22	5.03	40.26	-13.37	-26.37	42.85
51	5,735	1,906	1,690	153	512	206	1,170	46	2.4	1.3	10	8.93	GRIII	2,126.15	11.04	55.04	-23.04	-39.99	55.49
52	5,445	1,702	1,725	165	476	211	1,038	33	2.5	1.3	9.5	9.12	GRIII	2,056.84	9.95	52.78	-21.05	-38.41	53.72
53	5,382	1,668	1,731	153	476	216	1,016	28	2.3	1.4	10	9.65	GRIII	2,077.41	9.69	51.94	-21.24	-39.02	52.96
54	4,188	1,065	1,573	159	416	154	690	23	1.6	0.7	8	8.80	GRIII	1,672.46	7.34	47.77	-18.15	-30.82	49.39

%Na percent sodium, SAR sodium absorption ratio, RSBC residual sodium bicarbonate, RSC residual sodium carbonate, PI permeability index

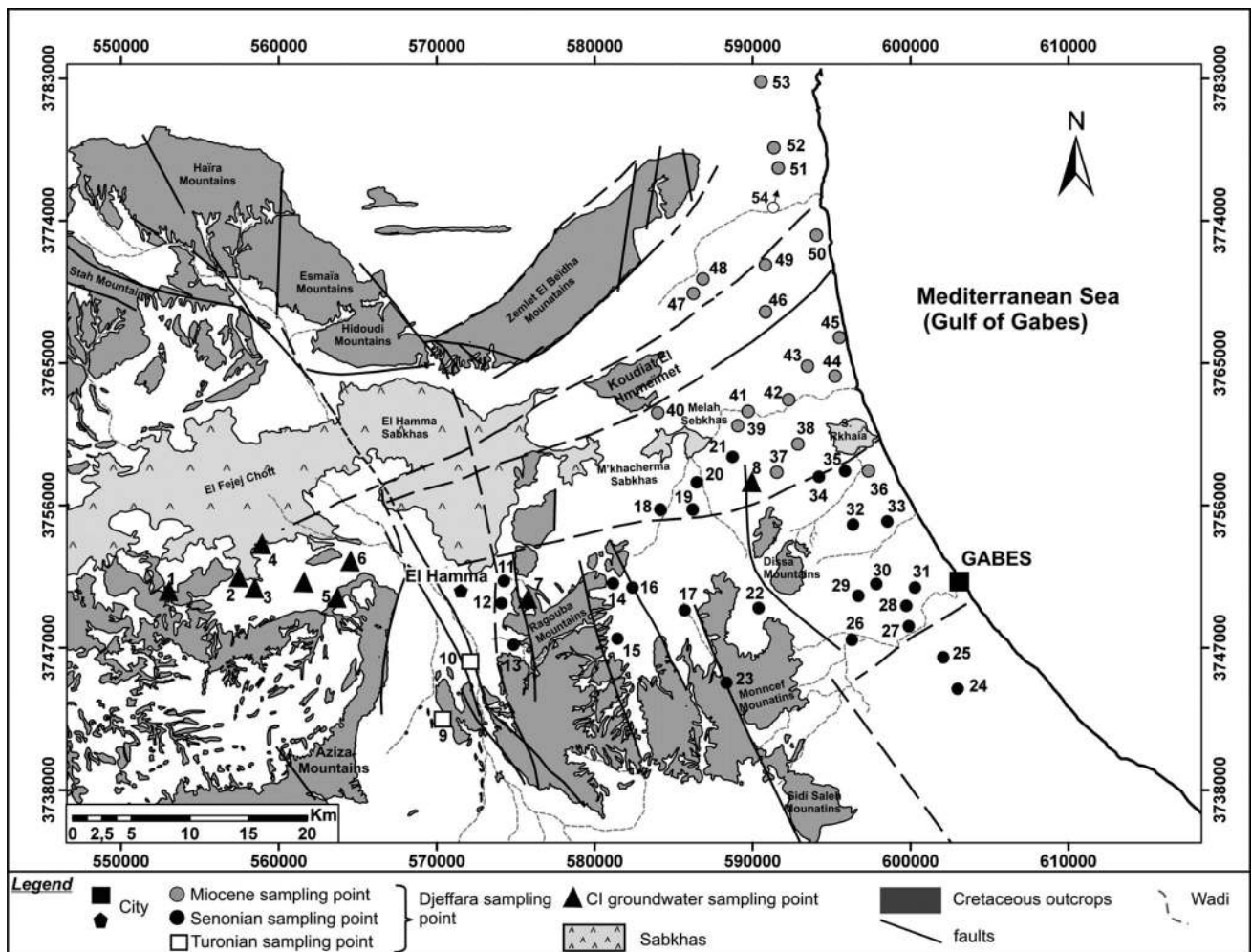


Fig. 5 Sampling wells' network

cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Sr}^{2+}$  and  $\text{B}^+$ ) and anions ( $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$  and  $\text{F}^-$ ) is observed to be within the stipulated limit of  $\pm 5\%$  (Mandel and Shifan 1981). Table 1 presents the groundwater characteristics data for sampling campaign during January 2008. Each parameter was compared to the standard desirable limit of that parameter stipulated for drinking water as prescribed by the WHO (1996a, b, 2004) for drinking and public health purposes.

The total hardness (TH) in ppm (Todd 1980; Hem 1985; Ragunath 1987) was determined by the following Eq. 1:

$$\text{TH} = 2.497 \text{Ca}^{2+} + 4.115 \text{Mg}^{2+} \tag{1}$$

where the concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  are represented in mg/l.

The development and maintenance of successful irrigation projects not only supply irrigation water to the land but also control salt and alkali in the soil (Haritash et al. 2008). Salinity and indexes such as sodium absorption ratio (SAR), sodium percentage (%Na), residual sodium

carbonate (RSC), residual sodium bicarbonate (RSBC) and permeability index (PI) are important parameters for determining the suitability of groundwater for agricultural uses (Srinivasa Gowd 2005; Raju 2007). The sodium adsorption ratio (SAR) values were calculated for each well by the following equation given by Richards (1954):

$$\text{SAR} = \text{Na} / [(\text{Ca} + \text{Mg}) / 2]^{1/2} \tag{2}$$

where the concentrations are expressed in meq/l.

The sodium percentage (%Na) was calculated using the formula given below (Todd and Mays 2005):

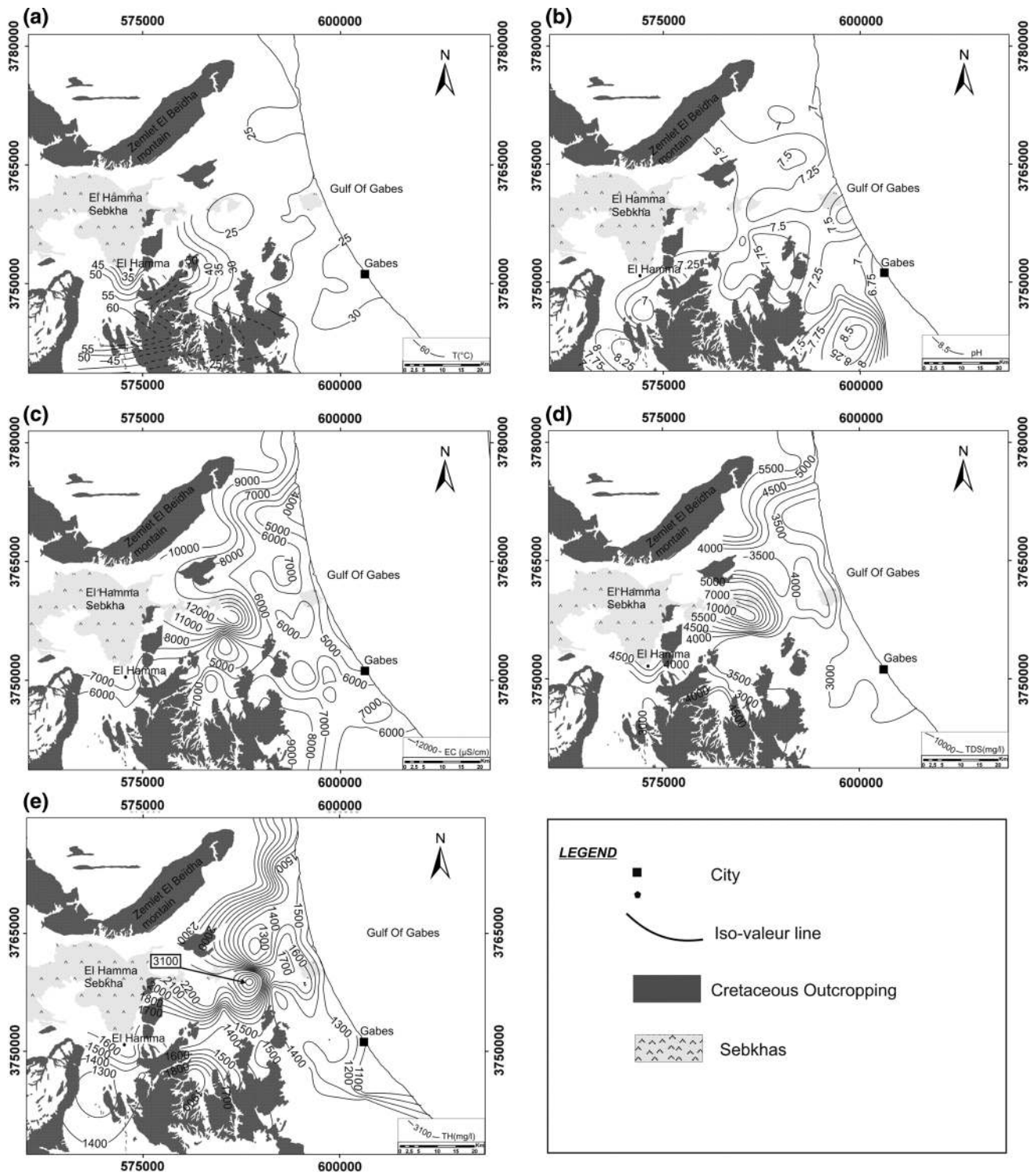
$$\% \text{Na} = (\text{Na}^+ + \text{K}^+) \times 100 / (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+) \tag{3}$$

where all ionic concentrations are expressed in meq/l.

The RSC index is calculated by the following equation (Ragunath 1987):

$$\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+}) \tag{4}$$

where concentrations are reported in meq/l.



**Fig. 6** Iso-concentration maps showing spatial variation in **a** temperature (°C), **b** pH, **c** electrical conductivity (µS/cm), **d** total dissolved salts (mg/l) and **e** total hardness in the deep Djefara aquifers

The RSBC, as defined by Gupta and Gupta (1987), is calculated by the following equation.

$$RSBC = (HCO_3^- - Ca^{2+}) \tag{5}$$

where concentrations are expressed in meq/l.

The permeability index (PI), as defined by Doneen (1964) and Ragunath (1987), is calculated by the following equation:

$$PI = \frac{[(Na^+) + [HCO_3^-]^{1/2})] \times 100}{(Na^+ + Ca^{2+} + Mg^{2+} + K^+)} \quad (6)$$

where all the ions are expressed in meq/l.

## Results and discussion

### In situ measurements interpretation

The groundwater samples belonging to the CI system are characterized by elevated temperatures that range between 57.3 and 65 °C (Table 1) indicating that the water in these wells is derived from the main horizons of the CI formations, as indicated in the cross section shown in Fig. 1b, without any significant leakage from the overlaying strata. The temperature of the Djefara groundwater is widely varying, from 18 to 65.20 °C, independently of the borehole depth. The water temperature is higher (between 35 and 65 °C) in the tectonic zones of El Hamma and Chenchou regions, which points to some inflow of groundwater from the CI aquifer through the existing normal faults (Fig. 6a). The lowest values of temperature (lower than 35 °C), probably due to the influence of the atmosphere, characterize the shallowest wells (Table 1).

The values of pH of the CI groundwater samples range from 7.46 to 8.5 with an average of 7.92. However, in the Djefara aquifers, pH values range from 6.74 to 8.3 (Fig. 6b; Table 1) with an average of 7.29. This shows that the groundwater of the study area is generally neutral. According to the WHO (2004), the range of desirable pH values of water prescribed for drinking purposes is 6.5–9.2. There are no water samples with pH values outside of the desirable ranges.

The measured conductivity of CI groundwater samples ranges from 3,680 to 10,500 µS/cm (Table 1), while the corresponding values for the Djefara aquifers vary between 3,783 and 13,648 µS/cm (Fig. 6c). The large variation in EC is mainly attributed to geochemical processes prevailing in this region. The spatial distributions of the EC, the TDS and major ions over the study area are somewhat similar. They show an increase from the mountainous regions (recharge areas) toward Sabkhas area. The highest values were measured in the Miocene sands in the northern part of Gabes region and in the Senonian limestone of the El Hamma region and Ouedref-El Metouia Graben. These high conductivity measurements are correlated with the high total mineralization which varies largely between 2,800 and 10,100 mg/l.

The total dissolved solid (TDS) of the Continental Intercalaire groundwater ranges from 2,760 to 7,750 and 2,736 to 10,100 mg/l in Djefara aquifers (Fig. 6d; Table 1). In Djefara aquifers, this variation conforms

partially with the main groundwater flow directions, indicating that the groundwater salinity is somehow controlled by the residence time in the aquifer. Indeed, in the El Hamma region, high salinities (TDS higher than 4,000 mg/l) appear near El Hamma sebkha which relatively disturbs the evolution of the mineralization in the direction of the groundwater flow. This sudden increase of groundwater salinity suggests an influence of the high saline waters originating from El Hamma sabkhas. The increase of salinity (TDS exceeds 5,000 mg/l) in some points located in Ouedref-El Metouia and the El Meïda grabens is due to the influence of highly saline waters originating from El Hamma and Melah-M'Khcherma sebkhas and interaction with evaporitic formations outcrops in Koudiat El Hmmeïmet and Zemlet El Beïdha mountain.

The high salinity of Miocene sand aquifer in the north of Gabes increases through time (Mamou 1990). This can be explained by the high groundwater extraction rates leading to the formation of depression cone, which facilitates the leakage of saline water from local shallow saline drainage aquifer formed by return flow irrigation. The lowest values of salinity are measured in the Djefara aquifers of the south part of the study area. This low salinity value (lower than 3,500 mg/l) reveals the dilution of the groundwater by the recharge coming from the fissured carbonate formation outcrops between El Hamma and Gabes.

The TDS in water is represented by the weight of residue left when a water sample has evaporated to dryness (Bahar and Reza 2009). The analytical results have been evaluated to ascertain the suitability of groundwater of the study area for drinking, by comparing with the specifications of TDS set to the standard guideline values as recommended by the WHO (1993). According to WHO specification, water containing <500 mg/l of dissolved solids is suitable for domestic use. Water containing more than 1,500 mg/l is maximum permissible (Table 3). Water containing more than 1,500 mg/l of dissolved solids is likely to contain enough of certain constituents to cause noticeable taste or make the water undesirable or unsuitable for drinking. Based on this classification, all groundwater samples exceed the maximum allowable limits and thus indicate the unsuitability of water for drinking purposes (Table 3).

To ascertain the suitability of groundwater for any purposes, it is essential to classify the groundwater depending on their hydrochemical properties based on their TDS values (Davis and DeWiest 1966; Freeze and Cherry 1979), which are presented in Table 4. According to Freeze and Cherry (1979), the groundwater of the area is of brackish water type for all samples of CI groundwater and for 97.83 % of Djefara aquifers, except for one sample from Djefara aquifers that represents saline water type. Davis and DeWiest (1966) have also classified

groundwater on the basis of TDS such as values up to 500 mg/l render the water desirable for drinking, whereas values ranging from 500 to 1,000 mg/l render the water permissible for drinking. Hence, classification of the groundwater of the study area based on TDS (Davis and DeWiest 1966) has been presented in Table 4. Based on this classification, all groundwater samples exceed the permissible limit for drinking.

The hardness values range from 1,187 to 1,603.59 mg/l with an average of 1,427.29 mg/l in the CI groundwater and from 1,233 to 3,173 mg/l with an average of 1,600 mg/l in the Djefara aquifers (Fig. 6e; Table 5). Cation concentrations and ratios can trace water–rock interaction processes, such as mineral weathering and cation exchange (Han et al. 2009). In determining the suitability of groundwater for domestic and industrial purposes, some chemical analyses are made. The presence of carbonates and bicarbonates indicates temporary hardness; sulfates and chlorides of calcium and magnesium indicate permanent hardness. Temporary hardness is due to the presence of bicarbonates of calcium and magnesium and can be removed by boiling, whereas permanent hardness is attributed to other salts such as sulfate and chloride salts, which cannot be removed by boiling. Despite all these problems, hard water is not considered to be a health hazard. However, water hardness of more than 200 mg/l causes noticeable taste or makes the water undesirable or unsuitable for drinking and scale formation (ACF 1996). Water hardness has no known adverse effects; however, it causes more consumption of detergents at the time of cleaning, and some evidences indicate its role in heart disease (Schroeder 1960).

The classification of groundwater based on total hardness (Sawyer and McMcarty 1967) shows that all of the groundwater samples fall in the very hard water category (Table 6). The maximum allowable limit of TH for drinking is 500 mg/l and the most desirable limit is 100 mg/l as per the WHO international standard. In CI groundwater and Djefara aquifers, 100 % of samples exceed permissible limit (Table 6). Groundwater exceeding the limit of 300 mg/l is considered to be very hard (Sawyer and McMcarty 1967). In our study, the classification of groundwater based on TH shows that all of the groundwater samples fall in the very hard water category (Table 6). Indeed, hardness values of all samples derived from the CI groundwater and Djefara aquifers were found to be above the specified safe limit and cannot be used for domestic proposes because it coagulates soap lather. Also, waters are characterized by high concentrations of calcium, magnesium, sulfate and chloride. Hydrogenocarbonate anions are at a limited concentration which is, however, sufficient for the formation of large quantifies of scale: 40–50 tons per year for each well (Rosset et al. 1999).

### Major elements geochemistry

In Djefara aquifers, concentration of sodium and chloride varies, respectively, between 432 and 2,530, and 539 and 3,647 mg/l, during the considered period (Table 5). The concentration of sodium and chloride varies, respectively, between 410 and 2,074, and 646 and 2,414 mg/l in the CI groundwater.  $\text{Na}^+$  has different roles in the human body. It plays an important role in the function of the nervous system, membrane system, and excretory system (Ketata et al. 2011). According to the WHO guidelines, the maximum admissible limit for drinking water is 200 mg/l. In the study area, all groundwater samples exceed the maximum permissible limit for drinking water (Table 3). The chloride ion concentration in groundwater of the study area exceeds the maximum permissible limit for drinking water of 600 mg/l (Table 3) in almost all samples collected from CI groundwater and Djefara aquifers. For both  $\text{Na}^+$  and  $\text{Cl}^-$ , the highest concentration levels characterize the wells situated to the north part (11, 18, 19, 20, 21, 47, 48, 49, 51, 52 and 53) of the Djefara aquifers, whereas the lowest ones characterize the wells situated to the south part (23, 26, 27, 28, 30 and 31). The spatial distribution of chloride and sodium concentrations illustrates a similar evolution as the salinity; they both decrease in the direction of the groundwater flow (Fig. 7a, b). Chloride and sodium are influenced by the contributions of water of the CI groundwater in El Hamma–Chennchou region ( $\text{Na}^+$  and  $\text{Cl}^-$  concentrations can reach, respectively, 680 and 1,099) and intrusion of salt water from sabkhas.

$\text{Ca}^{2+}$  concentration ranged between 300 and 702 mg/l in Djefara aquifers (Table 5). It varied from 352 to 702 mg/l in CI groundwater. Such concentrations of calcium have no hazardous effect on human health. Knowing that the maximum permissible limit of calcium concentration set by the WHO for drinking water was specified as 200 mg/l (Table 3), it is observed that all of CI groundwater and Djefara aquifer samples showed higher  $\text{Ca}^{2+}$  concentration than the permissible limit. The most elevated values were measured in wells 15, 18, 20, 21, 47, 48 and 49, F8, while the lowest levels were recorded in the well 26. The spatial distribution of calcium concentrations (Fig. 7c) decreased in the direction of groundwater flow, confirming the dominant influence of the infiltration waters charged in calcium (by change of the chalky and gypseous formations of Cretaceous). Calcium concentration is also influenced by the contribution of water of the CI groundwater in Hamma–Chennchou region ( $\text{Ca}^{2+}$  concentration vary between 352 and 480 m) and intrusion of salt water from sabkhas.

Magnesium concentration was found to be in the range of 65–345 and 69–96 mg/l for the studied samples collected from the Djefara aquifers and CI groundwater, respectively (Table 5). In the Djefara aquifers, 20 % of the samples exceeded the permissible limit of 150 mg/l,

**Table 3** Groundwater samples of the study area exceeding the permissible limits prescribed by WHO (1996a, b, 2004) for drinking purposes

Water quality parameter	WHO (2004)		Number of samples exceeding PL		Samples exceeding PL (%)		Undesirable effects
	Desirable limit (DL)	Maximum permissible limit (PL)	CI groundwater	Djeffara aquifer	CI groundwater	Djeffara aquifer	
pH	7–8.5	9	–	–	–	–	Taste
CE (μS/cm)	500	1,500	5	5	100	100	Gastrointestinal irritation
TDS (mg/l)	500	1,500	5	5	100	100	Gastrointestinal irritation
TH (mg/l)	100	500	5	5	100	100	Scale formation
Cl <sup>-</sup> (mg/l)	200	600	5	5	100	100	Salty taste
SO <sub>4</sub> <sup>2-</sup> (mg/l)	200	400	5	5	100	100	Laxative effects
HCO <sub>3</sub> <sup>-</sup> (mg/l)		240	–	–	–	–	–
Ca <sup>2+</sup> (mg/l)	75	200	5	5	100	100	Encrustations in water structure
Mg <sup>2+</sup> (mg/l)	50	150	–	1	–	20	Scale formation
Na <sup>+</sup> (mg/l)	–	200	5	5	100	100	Scale formation
K <sup>+</sup> (mg/l)	–	12	5	5	100	100	Bitter taste
F <sup>-</sup> (mg/l)	–	1.5	–	1	–	20	Dental fluorosis
B <sup>+</sup> (mg/l)	–	0.5	1	5	20	100	–
Sr <sup>2+</sup> (mg/l)	–	0.5	5	5	100	100	–

**Table 4** Groundwater classification based on TDS (Davis and DeWiest 1966 and Freeze and Cherry 1979)

TDS (mg/l)	Classification	Number of samples		Percentage of samples	
		CI groundwater	Djeffara aquifers	CI groundwater	Djeffara aquifers
Davis and DeWiest (1966)					
500	Desirable for drinking	–	–	–	–
500–1,000	Permissible for drinking	–	–	–	–
1,000–3,000	Useful for irrigation	3	4	37.5	8.7
<3,000	Unfit for drinking and irrigation	5	42	62.5	91.3
Freeze and Cherry (1979)					
<1,000	Fresh water type	–	–	–	–
1,000–10,000	Brackish water type	8	45	100	97.83
10,000–100,000	Saline water type	–	1	–	2.17
>100,000	Brine water type	–	–	–	–

while all the CI groundwater samples showed a magnesium concentration within the permissible limit for drinking water (Table 3). The higher values were recorded for wells 18, 19, 20, 21, 46, 47, 48, 49, 50, 51, 52, 53 and 45, whereas the lower ones were recorded for wells 9, 10, 12, 13 and 16. The spatial distribution of Mg<sup>2+</sup> correlates with the distribution of Ca<sup>2+</sup>, decreasing in the direction of the groundwater’s flow (Fig. 7d). Calcium and magnesium ions present in groundwater are particularly derived from leaching of limestone, dolomites, gypsum and anhydrites, whereas the calcium ions are also derived from cation exchange process (Garrels 1976; Haritash et al. 2008).

The carbonate and bicarbonate concentrations in groundwater are derived from carbonate weathering as well as dissolution of carbonic acid in the aquifers (Jeevanandam et al. 2006; Kumar et al. 2009). The contents in HCO<sub>3</sub><sup>-</sup> of the Djeffara aquifers of the northern Gabes vary from 79 to 183 mg/l (Table 5), with a maximum recorded for wells 18 and 45. It varied from 92 to 189 mg/l in the CI groundwater. As per the WHO guidelines, all samples show a bicarbonate concentration within the permissible limit of 240 mg/l for drinking water (Table 3, WHO 2004). Maps representing spatial distribution for bicarbonates concentrations (Fig. 7e) show a significant similar

**Table 5** Statistical summary of drinking water quality parameters determined in 10 groundwater samples of CI and Djefara aquifers

Aquifer		Minimum		Mean		Maximum		Standard deviation	
Parameters	Units	CI	Djefara	CI	Djefara	CI	Djefara	CI	Djefara
(a) Drinking water									
pH		7.46	7.06	7.68	7.18	7.76	7.36	0.12	0.11
CE	μS/cm	3,680	5,900	4,160	6,776	4,500	7,240	407.98	555.09
TDS	mg/l	2,760	2,840	3,036.2	3,409	3,300	4,120	210.38	482.73
<i>T</i>	°C	57.30	23.60	61.72	30.56	64.90	40.70	3.86	6.87
Cl <sup>-</sup>	mg/l	646	539	789.2	814.6	981	1,136	137.72	243.28
SO <sub>4</sub> <sup>2-</sup>	mg/l	925	1,100	1,093.2	1,263.4	1,296	1,400	134.3	125.70
HCO <sub>3</sub> <sup>-</sup>	mg/l	92	146	112.4	152.6	122	158	12.44	4.27
Ca <sup>2+</sup>	mg/l	360	300	384.8	373.6	428	500	29.17	85.11
Mg <sup>2+</sup>	mg/l	70	84	72	128.8	74	167	2	30.60
Na <sup>+</sup>	mg/l	410	432	496.4	537	540	750	55.72	133.33
K <sup>+</sup>	mg/l	34	28	41.2	44.2	45	76	4.26	19.98
F	mg/l	0.56	0.61	0.7	1.26	0.96	2.10	0.18	0.53
B	mg/l	0.3	0.57	0.41	0.78	0.52	1.6	0.09	0.45
Sr	mg/l	4	4.57	4.2	5.8	5	7	0.44	0.83
Sr <sup>2+</sup> /Ca <sup>2+</sup>	‰	4.57	5.49	4.99	6.98	5.34	8.07	0.28	1.15
TH	mg/l	1,187	1,233	1,245.43	1,455.3	1,373.2	1,641.3	79.05	166.32
(b) Irrigation water									
pH		8.07	6.74	8.32	7.41	8.5	8.5	0.22	0.267
CE	μS/cm	4,090	3,783	4,946.67	6,771.54	10,500	13,648	3,261.3	1,909.45
TDS	mg/l	2,736	2,736	4,695.33	4,097.79	7,750	10,100	2,680.46	1,296.58
<i>T</i>	°C	62	18	62	33.63	62	65.2	–	11.47
Cl <sup>-</sup>	mg/l	720	525	1,411	1,151.56	2,414	3,647	889	615.78
SO <sub>4</sub> <sup>2-</sup>	mg/l	1,026	1,026	1,417.33	1,438.37	1,992	2,350	508.42	276.69
HCO <sub>3</sub> <sup>-</sup>	mg/l	98	79	142.33	151.30	189	189	14.03	16.99
Ca <sup>2+</sup>	mg/l	352	308	438.66	434.44	484	702	45.54	98.27
Mg <sup>2+</sup>	mg/l	69	65	80.66	128.18	96	345	13.86	51.56
Na <sup>+</sup>	mg/l	680	400	1,065	711.2	2,047	2,530	857	361.79
K <sup>+</sup>	mg/l	42	12	60	43.86	70	215	15.62	32.59
F	mg/l	0.55	0.34	0.57	1.45	0.59	2.84	–	0.6
B	mg/l	0.34	0.42	0.495	0.94	0.65	2.3	–	0.56
Sr <sup>2+</sup>	mg/l	4	4.97	5	7.35	6	23	–	3.35
Sr <sup>2+</sup> /Ca <sup>2+</sup>	‰	5.20	4.99	5.46	7.89	5.72	9.92	–	1.34
TH	mg/l	1,195.8	1,233	1,427.29	1,600	1,603.59	3,173	209.42	400.53
SAR	–	5.89	4.68	11.93	7.60	22.23	23.58	8.96	3,112
%Na	%	47.24	38.73	57.50	47.23	73.89	73.89	14.32	6.22
RSBC	meq/l	–21.66	–32.03	–19.56	–19.23	–15.96	–12.78	3.13	4.93
RSC	meq/l	–28.95	–60.42	–26.19	–29.78	–22.29	–22.29	3.47	7.99
PI	%	47.72	38.57	57.55	48.20	73.94	73.94	14.28	5.59

evolution as Ca<sup>2+</sup> with a reduction of the contents in the direction of the groundwater's flow.

Concentrations of K are relatively low compared to the concentrations of other cations, with values varying between 12 and 215 mg/l (Table 5). It varied from 34 to 70 mg/l in the CI groundwater. As per the WHO guidelines, all the CI groundwater and Djefara aquifer samples

exceed this permissible limit of 12 mg/l (Table 3). The highest concentrations have been recorded for boreholes 18 and 19. The maps elaborated here (Fig. 7) show that the concentration of potassium are similar to those of salinity, chloride, sodium and calcium. Low concentrations of potassium in these waters would originate from alteration of the silicates which have low solubility rates. Potassium



**Table 6** Groundwater classification based on TH (Sawyer and McMearty 1967)

Total hardness (TH) as CaCO <sub>3</sub> (mg/l)	Type of water	Number of samples		Percentage of samples	
		CI groundwater	Djeffara aquifers	CI groundwater	Djeffara aquifers
75	Soft	–	–	–	–
75–150	Moderately high	–	–	–	–
150–300	Hard	–	–	–	–
300	Very hard	8	46	100	100

distribution is influenced by the chemical composition of the waters of infiltration and the waters from the CI groundwater, and intrusion of salt water from sabkhas.

The sulfate concentration of the waters in the Djeffara aquifers of the northern Gabes varied between 1,043 and 2,350 mg/l (Table 5). It varied from 925 to 1,992 mg/l in CI groundwater. Sulfate is unstable if it exceeds the maximum permissible limit of 400 mg/l (Table 3) and causes a laxative effect on humans, together with excess of magnesium in groundwater (Kumar et al. 2007; Arumugam and Elangovan 2009). This may result in gastrointestinal irritation in the human system. In the study area, all groundwater samples exceed the maximum permissible limit for drinking water (Table 3). The highest concentrations were measured for wells 18, 19, 21, 47, 48, 51, 52 and 53, while the lowest values are characteristic of wells 10, 14, 45 and 46. Spatial distribution maps show the same evolution with salinity (Fig. 7g). Since sulfates are the dominant anions, they control, along with Na<sup>+</sup>, Ca<sup>2+</sup> and Cl<sup>-</sup>, the saline load of the waters of the Djeffara aquifers.

*Water types*

The method of geochemical graphic represented by Piper diagram (Piper 1944) has been widely used in groundwater studies to characterize a large number of water chemical data. Piper trilinear diagram was constructed using scientific software to display the relative concentrations of the different ions from individual water samples from the study area. This diagram reveals similarities and differences among groundwater samples because those with similar qualities will tend to plot together as groups (Todd and Mays 2005).

The Piper diagram (Fig. 8) shows similarity in major cation proportions in the Djeffara aquifers, intermediate between Na<sup>+</sup> and Ca<sup>2+</sup> content. Results of chemical analyses indicate enrichment in SO<sub>4</sub><sup>2-</sup> relative to Cl<sup>-</sup>, except of groundwater samples from Senonian limestones and Miocene sands in Ouedref-El Metouia and El Meïda grabens, respectively, which are depleted in SO<sub>4</sub><sup>2-</sup> with respect to Cl<sup>-</sup> ions. Consequently, a Piper diagram shows that the water facies, in Djeffara aquifers, gradually changes from the Na–Ca–SO<sub>4</sub>–Cl type to the Na–Cl–SO<sub>4</sub> type

along the flow lines, i.e., from west to east of the study area.

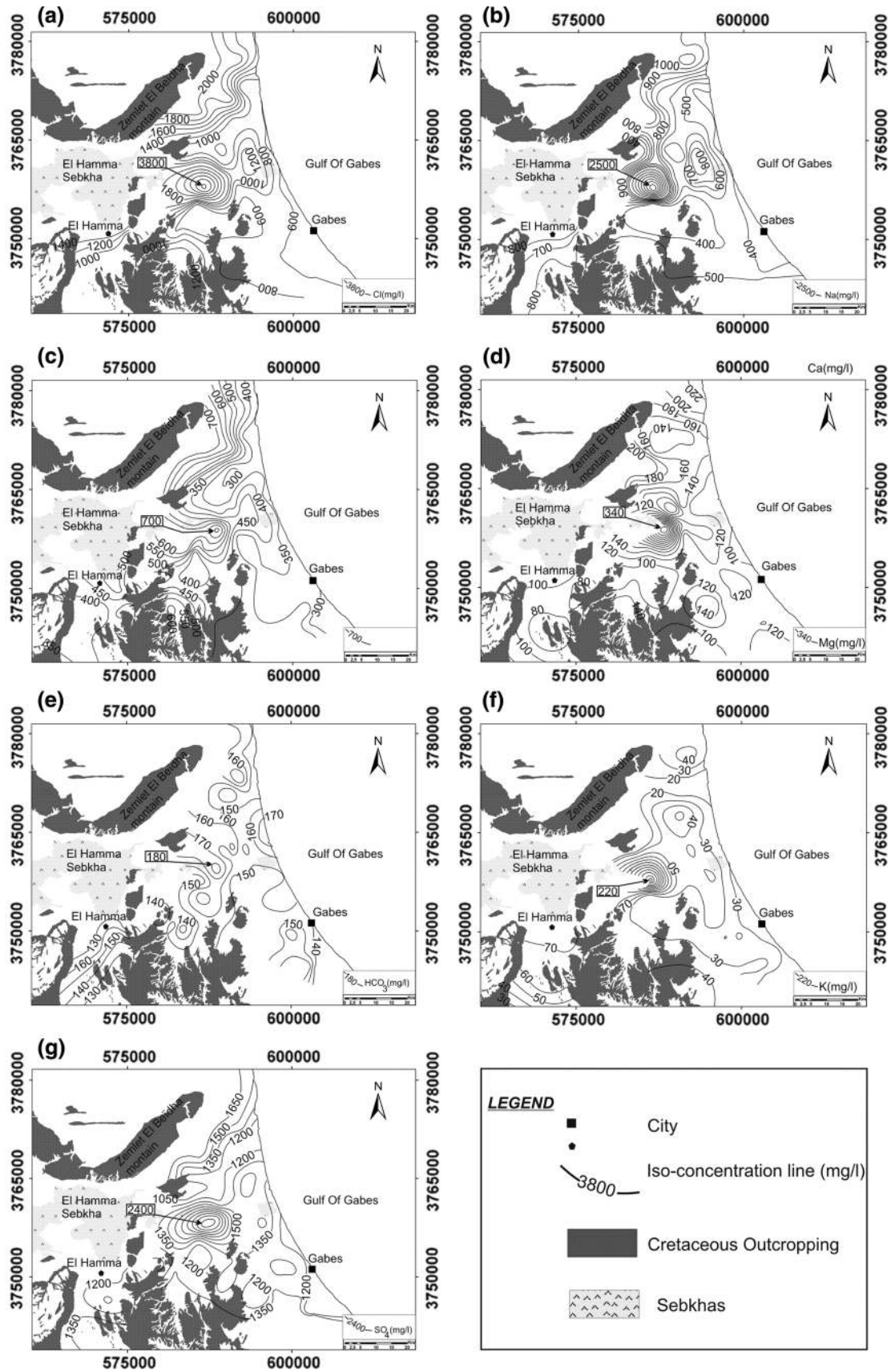
The Na–Ca–SO<sub>4</sub>–Cl type (corresponding to wells 9, 10, 14, 16, 22, 23, 24, 25, 26, 27, 28, 29, 30 and 31) occurs mainly in El Hamma–Chennchou and in the South-eastern part of the study area. The composition of this type is due to the mixtures of the two end members: CI water (average TDS = 3,500 mg/l) and recent recharge water (corresponding to wells 23, 26 and 27; TDS < 3,000 mg/l) from the recharge area toward El Hamma and Gabes (Mamou 1990; Trabelsi et al. 2009, 2011).

The Na–Ca–Cl–SO<sub>4</sub> and Na–Cl type (which corresponds to wells 11, 18, 19, 20, 21, 47, 48, 49, 51, 52 and 53) waters are highly mineralized and are more influenced by the chemistry of the rocks with which the waters is contact. This high salinity level is explained by salt water intrusion from sabkhas and leakage with underlying aquifer with evaporite dissolution during fluxes ascent for high salinity.

*Groundwater mineralization processes*

In order to highlight different mechanisms that contribute to groundwater mineralization, principal components analysis (PCA) has been applied to physicochemical parameters corresponding to sampling made in January 2008. The chemical composition of the groundwater is characterized by major cations and anions such as Ca, Mg, Na, K, Cl, SO<sub>4</sub>, HCO<sub>3</sub>, Sr, B and F. The correlation matrix of physicochemical parameters is reported in Table 7. Cation concentrations and ratios can trace water–rock interaction processes, such as mineral weathering, cation exchange and anthropogenic input in the groundwater system (Han et al. 2009; Chan 2001).

A correlation analysis is a bivariate method, which simply exhibits how well one variable predicts the other. In this study, the relationship between various elements has been studied using the Spearman rank coefficient, which is based on the ranking of the data and not on their absolute values (Kurumbein and Graybill 1965; Kumar et al. 2006, 2007, 2009). The numerical level of the relationships represented by the coefficient of correlation varies between – 1 and +1 according to the statistical significance of the



◀ **Fig. 7** Iso-concentration maps showing spatial variation in **a** chloride, **b** sodium, **c** sulfate, **d** calcium, **e** magnesium and **f** potassium in the deep Djefara aquifers of Gabes

estimated correlation. In general, the results show high correlations (>0.7) between some pairs of geochemical parameters, whereas a value between 0.5 and 0.7 shows moderate correlation (Giridharan et al. 2008). A negative coefficient indicates that the considered variables are evolving in opposite directions. The correlation matrices for 13 variables were prepared for CI groundwater and Djefara aquifers (Table 7) using the computer program STATISTICA 7.1 (StatSoft) software.

The correlation matrix of the 13 variables analyzed (pH, temperature (T), TDS,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{F}^-$  and  $\text{B}^+$ ) given in Table 7 allows us to distinguish high correlation coefficients, which indicate several relevant hydrochemical relationships. Sulfate, chloride, sodium, magnesium and calcium are the main ions responsible for the increase of the salinity of the waters of Djefara groundwater. A close correlation noted between the sulfate and calcium ( $r = 0.63$  and  $0.60$ ), sulfate and magnesium ( $r = 0.73$  and  $0.78$ ), chloride and sodium ( $r = 0.94$  and  $0.91$ ), strontium and sulfate ( $r = 0.76$  and  $0.85$ ), strontium and chloride ( $r = 0.72$  and  $0.88$ ), and between boron and chloride ( $r = 0.76$  and  $0.75$ ) indicates a dissolution of the sulfate and chloride evaporite rocks surrounding the aquifer and its substratum. The

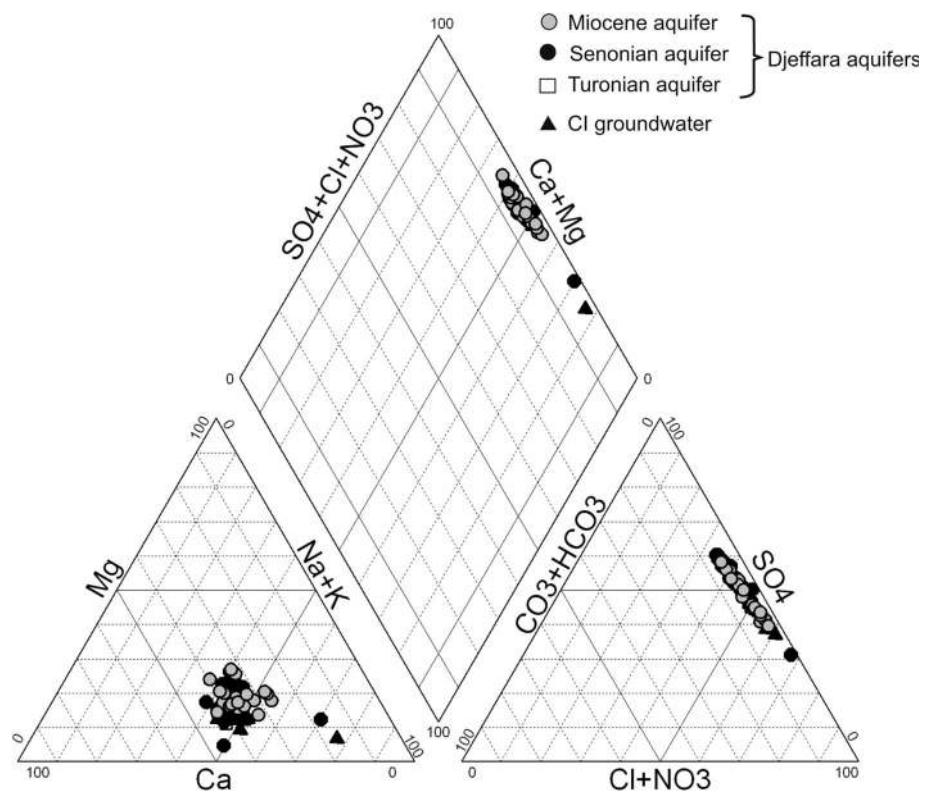
dissolution of sodium chloride salts induces an increase in the ionic strength of the water, which favors a greater dissolution of the sulfate salts and the enrichment of the waters by magnesium and calcium.

The relationship between  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  concentrations is characterized by a relatively low correlation coefficient ( $r = 0.6$  and  $0.63$ ) and a  $\text{SO}_4^{2-}$  ratio, in moles per liter, superior to 1. This indicates that calcium and sulfate are not involved in the same geochemical processes (Hounslow 1995). Actually, sulfates are mostly found in a dissolved form, whereas calcium can undergo a precipitation of calcite and/or a Ca/Na base exchange between clay minerals and water (Desbarats 2009).

The good correlation between  $\text{SO}_4^{2-}$  and  $\text{Mg}^{2+}$  ( $r = 0.73$  and  $0.78$ ) suggests that a part of the  $\text{SO}_4^{2-}$  and  $\text{Mg}^{2+}$  may also be derived by the weathering of magnesium sulfate mineral ( $\text{MgSO}_4$ ). There is no relation between  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$ , and correlation coefficient ( $r = -0.11$  and  $-0.02$ ) is not significant. This indicates that calcite may not be the source of  $\text{Ca}^{2+}$ . Indeed, the bicarbonate concentration in groundwater is derived from carbonate weathering as well as dissolution of carbonic acid in the aquifers.

Finally, the high correlation values between concentrations of  $\text{Ca}^{2+}$  and  $\text{Cl}^-$  ( $0.70$ ) can hardly be related to any of the salinization processes recognized, and only possibly with secondary processes such as ionic exchange, which become more evident in the more salinized water as the Cl concentration increases.

**Fig. 8** Piper diagram for the groundwater of the studied area



**Table 7** Correlation matrix of chemical constituents of groundwater in CI groundwater and Djefara aquifers

	pH	CE	TDS	<i>T</i>	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	Ca	Mg	Na	K	F	B	Sr
(a) CI groundwater														
pH	1.00													
CE	0.40	1.00												
TDS	-0.23	0.71	1.00											
<i>T</i>	-0.14	0.50	0.73	1.00										
Cl	0.84	0.46	0.01	0.30	1.00									
SO <sub>4</sub>	0.43	-0.46	-0.69	-0.74	0.25	1.00								
HCO <sub>3</sub>	0.45	-0.34	-0.46	0.05	0.66	0.56	1.00							
Ca	0.77	-0.20	-0.60	-0.41	0.67	0.86	-0.11	1.00						
Mg	-0.39	0.16	0.04	-0.25	-0.49	-0.25	-0.71	-0.53	1.00					
Na	0.96	0.32	-0.20	0.03	0.94	0.43	0.66	0.82	-0.57	1.00				
K	0.94	0.17	-0.40	-0.09	0.86	0.47	0.68	0.84	-0.53	0.97	1.00			
F	-0.06	-0.58	-0.55	-0.89	-0.35	0.80	0.04	0.38	0.11	-0.14	-0.10	1.00		
B	0.86	0.13	-0.32	-0.21	0.84	0.72	0.71	0.94	-0.48	0.91	0.86	0.21	1.00	
Sr	0.73	-0.34	-0.77	-0.53	0.52	0.80	0.72	0.94	-0.49	0.74	0.84	0.39	0.80	1.00
(b) Djefara aquifers														
pH	1.00													
CE	-0.12	1.00												
TDS	-0.10	0.83	1.00											
<i>T</i>	-0.03	-0.22	-0.27	1.00										
Cl	-0.02	0.77	0.90	-0.23	1.00									
SO <sub>4</sub>	0.10	0.76	0.77	-0.34	0.80	1.00								
HCO <sub>3</sub>	-0.34	0.00	0.10	-0.31	0.02	0.09	1.00							
Ca	0.06	0.42	0.47	-0.09	0.70	0.60	-0.02	1.00						
Mg	-0.03	0.61	0.63	-0.45	0.72	0.78	0.21	0.47	1.00					
Na	-0.03	0.84	0.94	-0.19	0.91	0.78	0.01	0.42	0.61	1.00				
K	0.06	0.55	0.68	0.22	0.65	0.48	-0.16	0.19	0.31	0.75	1.00			
F	0.00	0.36	0.54	-0.60	0.62	0.50	0.15	0.50	0.63	0.45	0.02	1.00		
B	0.15	0.42	0.62	-0.38	0.75	0.48	0.08	0.61	0.62	0.53	0.27	0.77	1.00	
Sr	0.00	0.82	0.91	-0.29	0.88	0.85	-0.07	0.53	0.62	0.90	0.67	0.45	0.57	1.00

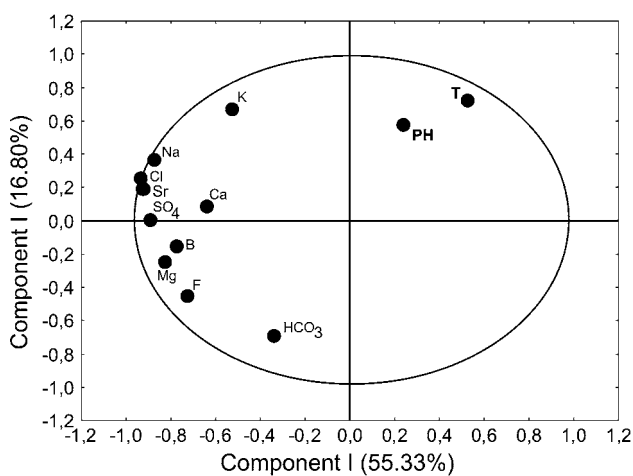
R-mode factor analysis for extraction was carried out using program STATISTICA 7.1 (StatSoft) software and all the factors were plotted (Table 8; Fig. 9). Table 8 shows that the variables TDS, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Ca<sup>2+</sup>, Na<sup>+</sup>, Sr<sup>2+</sup>, B<sup>+</sup> and F<sup>-</sup> have high factor loadings in factor 1 (55.33 % (marked in bold)), whereas (HCO<sub>3</sub><sup>-</sup>, T, K<sup>+</sup>) have moderate and high factor loadings in factor 2 (16.80 %), respectively. Therefore, factor 1 describes the salinization factor. It represents the weathering of halite and evaporates minerals from the underlying geology. A high similarity is observed when comparing the Turonian factor to Tunisian chott one region and Turonian groundwater salinization factor' in the western part of the study area (Kamel et al. 2008; Abid et al. 2010, 2011) and to processes of the evaporate dissolution rocks' in Alto Guadalentín, SE Spain (Ceron et al. 2000) and in Bou-Areg, NE Morocco (Yaouti et al. 2009). The potential sources of the F<sup>-</sup> and B<sup>+</sup> in the study area could be linked to natural origin. However, part

of the F<sup>-</sup> and B<sup>+</sup> is from natural F and B in the soil, released to the unsaturated zone due to intense irrigation and intrusion of salt water from sabkhas.

Factor 2 (16.80 %) opposes Mg<sup>2+</sup>, HCO<sub>3</sub><sup>-</sup>, B<sup>+</sup> and F<sup>-</sup> concentrations with temperature, pH, Ca<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup> contents. This axis, basically representing the calco-carbonic parameters, describes factor dilution of groundwater by water recharge and/or mineralization by water–soil/rock interaction. The opposite evolution of Ca<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup> in factor 2 indicates that the increase of Ca<sup>2+</sup> content in groundwater is essentially related to gypsum dissolution and cation exchange processes, and not to carbonate weathering. The positive loadings of pH values suggested that the major ion concentration is controlled by pH variations in the study area, whereas pH as a controlling factor rather than Mg<sup>2+</sup>, HCO<sub>3</sub><sup>-</sup>, F<sup>-</sup>, B<sup>+</sup> has low factor loadings in factor 2, which indicates that they may be derived from rock–water interaction processes.

**Table 8** Loading for varimax rotated factor matrix of two factors explaining 72.13 % of the total variance for groundwater system aquifer

Variable	Varifactors	
	Factor 1	Factor 2
T	0.52	<b>0.72</b>
pH	0.24	<b>0.58</b>
Ca	<b>-0.64</b>	0.09
Mg	<b>-0.83</b>	-0.25
Na	<b>-0.87</b>	0.36
K	-0.53	<b>0.67</b>
Cl	<b>-0.93</b>	0.26
SO <sub>4</sub>	<b>-0.89</b>	0.04
HCO <sub>3</sub>	-0.34	<b>-0.69</b>
Sr	<b>-0.92</b>	0.19
F	<b>-0.73</b>	-0.45
B	<b>-0.78</b>	-0.15
TDS	<b>-0.93</b>	0.19
Eigenvalues	7.75	2.35
% Total variance	55.33	16.80
% Cumulative variance	55.33	72.13



**Fig. 9** Representation of the principal components of the variables measured in field samples

Several bivariate diagrams of major elements are used to precisely determine the origins of the referred ions and the processes that control their concentrations in groundwaters. The plots of Na<sup>+</sup> versus Cl<sup>-</sup> and Ca<sup>2+</sup> versus SO<sub>4</sub><sup>2-</sup> content (Fig. 10a–c) are shown. The Na<sup>+</sup>–Cl<sup>-</sup> relationship has often been used to identify mechanisms responsible for the origin of water salinity in arid and semi-arid regions (Magaritz et al. 1981; Dixon and Chiswell 1992; Sami 1992; Guendouz et al. 2002; Jalali 2009). The relationship between these two ions shows that the majority of points cluster along the halite dissolution line (line of slope 1, Fig. 10a, b). Observed depletion in Cl<sup>-</sup> content relative to

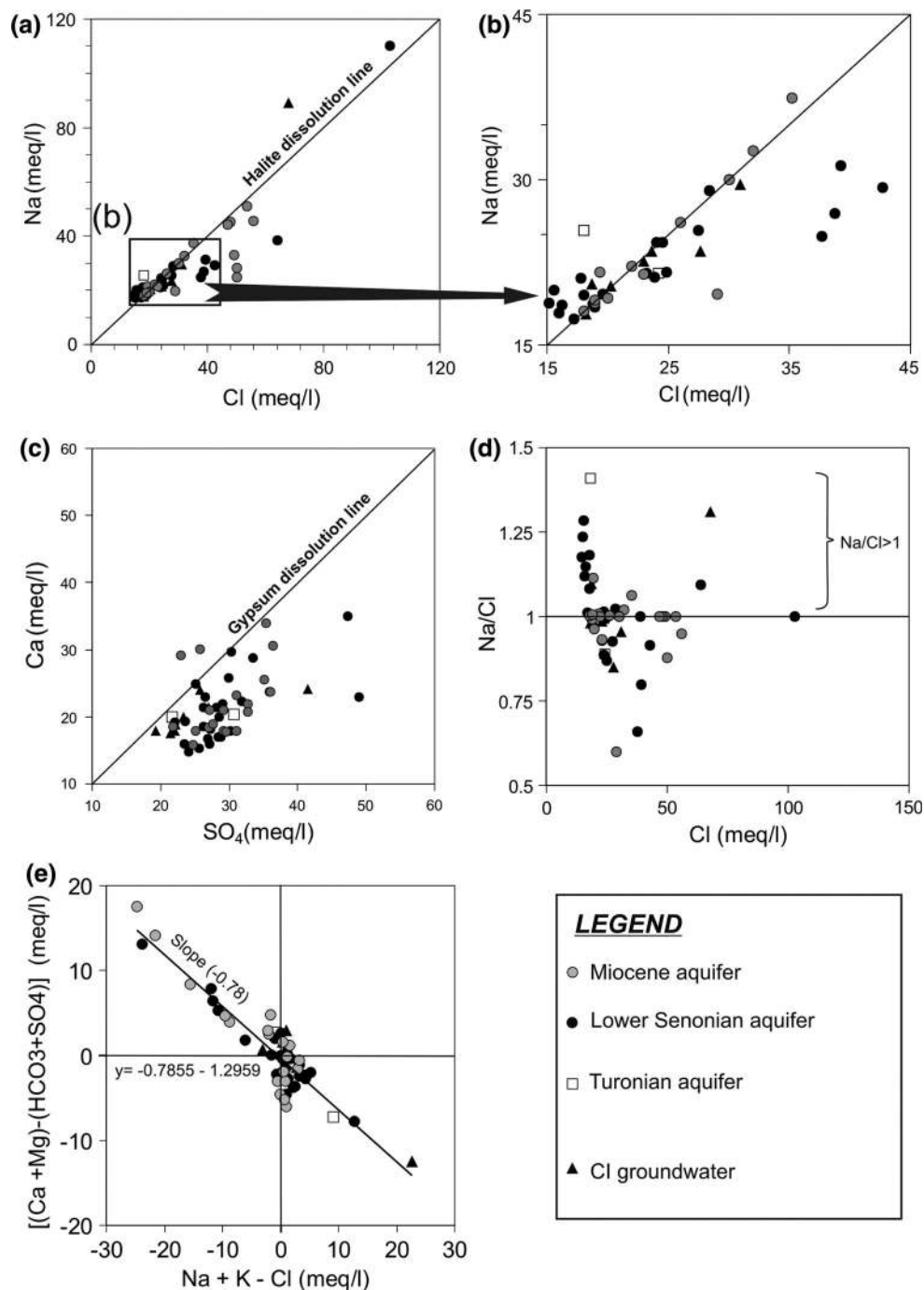
Na<sup>+</sup> concentration in some samples probably reflects the cation exchange reactions leading to adsorption of Ca<sup>2+</sup> on clay minerals and simultaneous releasing of Na<sup>+</sup> ions. Those samples in which Na<sup>+</sup>/Cl<sup>-</sup> molar ratios are higher than 1 (Fig. 10d) also show a deficit in Ca<sup>2+</sup> with respect to SO<sub>4</sub><sup>2-</sup> ions (samples located above the line of slope 1, Fig. 10c). This remains in good agreement with a Ca<sup>2+</sup>–Na<sup>+</sup> cation exchange theory leading to a softening of water (Hidalgo et al. 1995).

On the other hand, the SO<sub>4</sub><sup>2-</sup> versus Ca<sup>2+</sup> plot (Fig. 10c) shows a more pronounced loss of Ca<sup>2+</sup> with respect to SO<sub>4</sub><sup>2-</sup>. This may be the result of calcite precipitation controlled by gypsum dissolution which tends to maintain saturation or oversaturation with respect to calcium bearing minerals.

In some samples, a relative depletion of Na<sup>+</sup> with respect to Cl<sup>-</sup> is noted (Fig. 10a, b). This probably reflects the cation exchange process where Ca<sup>2+</sup> is removed from the aquifer exchangers and replaced by Na<sup>+</sup>. The referred cation exchange is confirmed through the relation characterized by a slope of -1 traced by the position of the samples (Garcia et al. 2001). In the absence of this exchange, all analytical points should lie close to the origin (McLean et al. 2000). Figure 10e shows the scatter plot for the relationship, which is characterized by a negative slope (-0.78), suggesting that cation exchange is probably a factor in the Djefara aquifers. Likewise, 31 % of the samples plot within the negative ordinate and positive abscissa zone. This implies that Na<sup>+</sup> and K<sup>+</sup> are enriched relative to Ca<sup>2+</sup> and Mg<sup>2+</sup> in most of the aquifers. Thus, the cation exchange sites preferentially adsorb Ca<sup>2+</sup> and Mg<sup>2+</sup> and discharge Na<sup>+</sup> and K<sup>+</sup> (direct cationic exchange). However, 43 % of samples plot within the positive ordinate and negative abscissa zone. Thus, the cation exchange sites preferentially adsorb Na<sup>+</sup> and K<sup>+</sup> and discharge Ca<sup>2+</sup> and Mg<sup>2+</sup> (reverse cationic exchange). The rest of the samples (26 %) lie close to the origin (absence of cationic exchange).

Figure 11 shows the saturation indices of halite, gypsum, calcite and dolomite, calculated using WATEQ-F computer code (Plummer et al. 1976), as a function of (Na<sup>+</sup> + Cl<sup>-</sup>), (Ca<sup>2+</sup> + SO<sub>4</sub><sup>2-</sup>), (Ca<sup>2+</sup> + Mg<sup>2+</sup> + HCO<sub>3</sub><sup>-</sup>) and (Ca<sup>2+</sup> + HCO<sub>3</sub><sup>-</sup>), respectively. Results of these calculations indicate that the water evolves from a state close to undersaturated with respect to gypsum and halite (Fig. 11a, b) and saturation with respect to calcite and dolomite toward an oversaturation (Fig. 11c, d). Once the system is saturated in calcite, the hydrochemical evolution is affected by the dissolution of gypsum. Interaction between groundwater and the gypsum layer would lead to the dissolution of gypsum (Qiyam and Baoping 2002). Common-ion effects tend to increase calcite deposition to keep the balance of calcite dissolution.

**Fig. 10** Relationships between major elements in the analyzed groundwater samples: **a**, **b**  $\text{Na}^+/\text{Cl}^-$ , **c**  $\text{Ca}^{2+}/\text{SO}_4^{2-}$ , **d**  $\text{Na}^+/\text{Cl}^-$  molar ratio versus  $\text{Cl}^-$  and **e**  $[(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{HCO}_3 + \text{SO}_4)]$  versus  $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)$



Trace elements geochemistry and fluoride

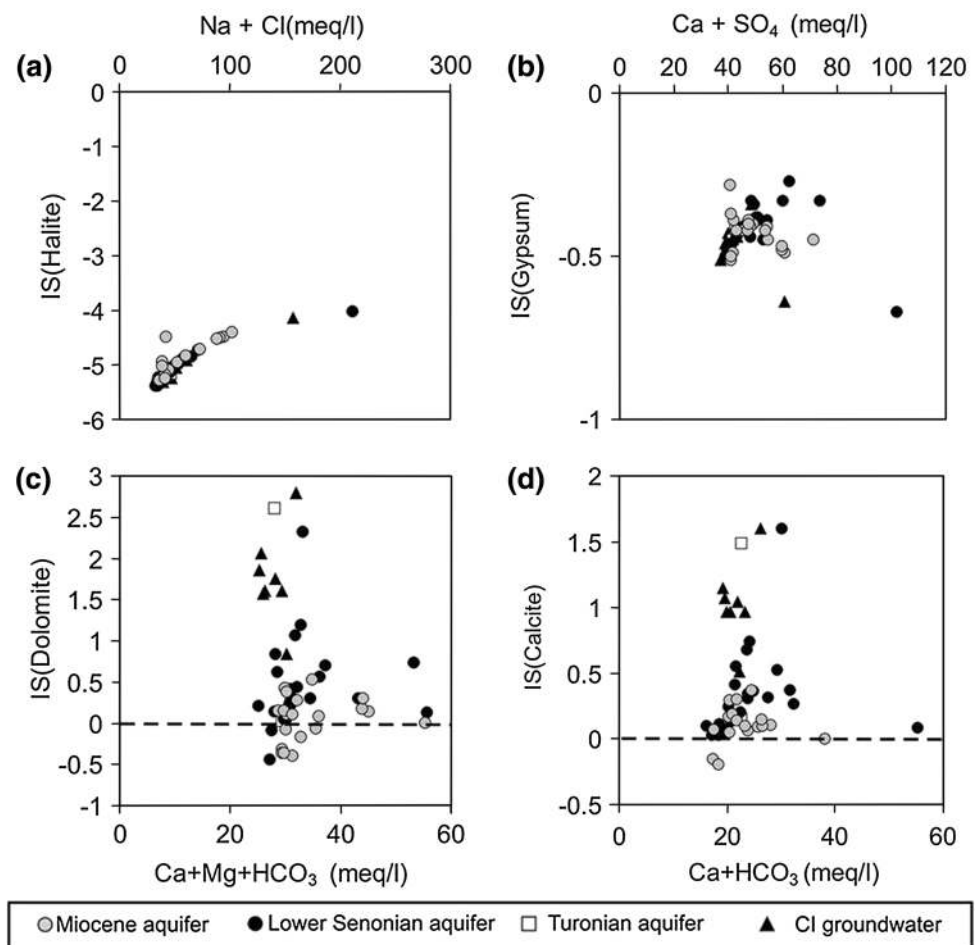
#### Strontium and strontium/calcium rate

The dosage of strontium is important because it indicates the influence of evaporite formations. In this study, the strontium concentration ranges between 4 and 6, and 4.97 and 23 mg/l for the studied samples collected from the CI groundwater and Djefara aquifers, respectively (Table 5). In the study area, all groundwaters exceed the maximum

permissible limit of 0.5 mg/l (WHO 2004) for drinking water (Table 3).

The groundwater acquires Sr during recharge and along its flow path as it interacts with Sr-bearing minerals such as celestite ( $\text{SrSO}_4$ ) associated with gypsum and strontianite ( $\text{SrCO}_3$ ), carbonate and clay minerals through adsorption and ion exchange reactions, accompanying calcium ion (Morgan-Jones and Eggboro 1981). In some waters, enrichment in Sr could be related to the time of residence of water in the aquifer, so that the ion is a good

**Fig. 11** Relationships between saturation indices and major elements in the analyzed groundwater samples: **a** IS (Halite)/(Na<sup>+</sup> + Cl<sup>-</sup>), **b** IS (gypsum)/Ca<sup>2+</sup> + SO<sub>4</sub><sup>2-</sup>, **c** IS (dolomite)/Ca<sup>2+</sup> + Mg<sup>2+</sup> + HCO<sub>3</sub><sup>-</sup> and **d** IS (calcite)/Ca<sup>2+</sup> + HCO<sub>3</sub><sup>-</sup>

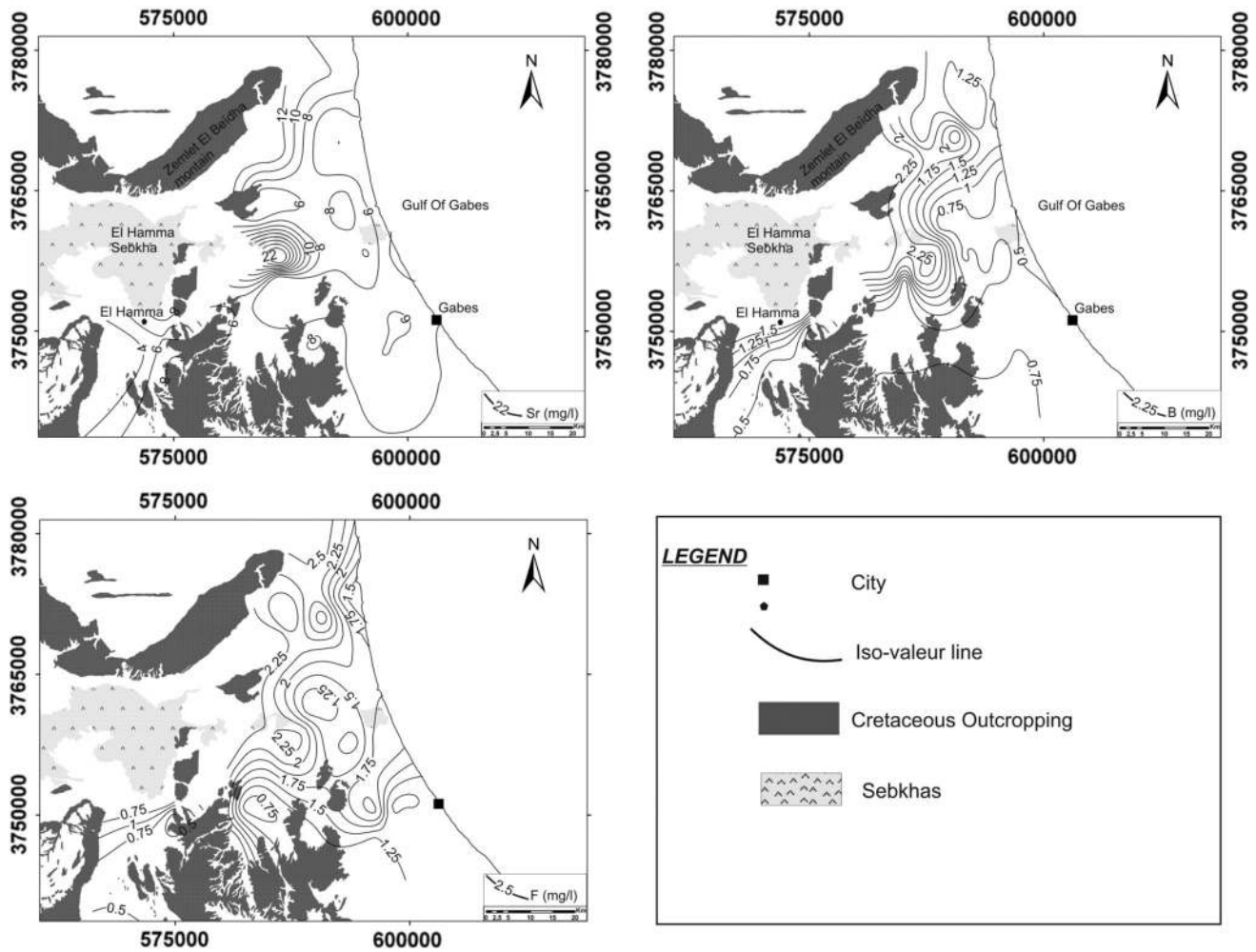


environmental tracer (Bronzi et al. 1983). Molar concentration ratio Sr<sup>2+</sup>/Ca<sup>2+</sup> is characteristic of evaporitic water if it is higher than 1 ‰ (Meybeck 1984). Besides, as each evaporitic set has its own Sr<sup>2+</sup>/Ca<sup>2+</sup> ratio value, Sr<sup>2+</sup> and Ca<sup>2+</sup> contents of water that dissolve an evaporitic formation would enable an identification of underground flow and a determination of their origin (Hsissou et al. 1996). Strontium concentrations are relatively high in Djefara aquifers, with values varying between 4.97 and 23 mg/l (Fig. 12a). Thanks to the ratio, different evaporitic origins can be distinguished (Fig. 13):

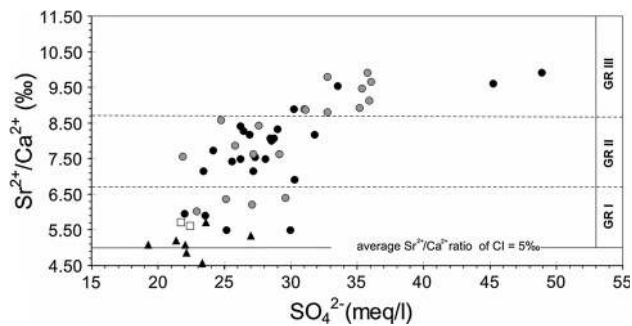
In the zone of hydraulic sill in Hamma and Chennchou, the Sr<sup>2+</sup>/Ca<sup>2+</sup> ratio (GRI) varies from 4.97 to 6.5 ‰, strontium varies from 4 to 6.5 mg/l, and SO<sub>4</sub><sup>2-</sup> contents range between 1,043 and 1,476 mg/l. In this area, the mixing process is mainly through the vertical leakage of the deep Lower Cretaceous groundwater (Sr<sup>2+</sup>/Ca<sup>2+</sup> = 5 ‰) replenishing the shallow Djefara aquifers. In this area, there are some evaporitic layers in Jebel Aziza and Jebel Ragouba outcropping Cretaceous (Lower Cretaceous, Cenomanian and Lower Senonian).

In the eastern part of Chennchou and in coastal plain, the well waters (GRII) are characterized by a Sr<sup>2+</sup>/Ca<sup>2+</sup> ratio which varies between 6.5 and 8.75 ‰, strontium varies between 6 and 8.32 mg/l and sulfates range between 1,050 and 1,400 mg/l. The high concentration of sulfates and strontium and Sr<sup>2+</sup>/Ca<sup>2+</sup> ratio indicate that it is due to the leaching of Lower Cretaceous evaporites levels and marly gypsum of Lower Senonian which act as substratum of sandy Miocene aquifer and limestone of Lower Senonian aquifer, respectively.

In the northern part of study area, waters (GRIII) show the highest Sr<sup>2+</sup>/Ca<sup>2+</sup> ratios (8.5–9.90), Sr<sup>2+</sup> contents varying between 7 and 23 mg/l and SO<sub>4</sub><sup>2-</sup> contents ranging from 1,452 to 2,350 mg/l, are mainly located close to El Hamma and Melah-M'Khacherma sabkhas. These waters are distinct from the previous ones. In this zone, the salinity may have several origins: intrusion of saline water from El Hamma and Melah-M'khacherma sabkhas and dissolution of the evaporite formations of Lower Cretaceous and Lower Senonian which act as substratums of sandy Miocene aquifer and limestone of Lower Senonian aquifer,



**Fig. 12** Iso-concentration maps showing spatial variation in **a** strontium, **b** boron and **c** fluoride



**Fig. 13** Relationships between  $\text{Sr}^{2+}/\text{Ca}^{2+}$  molar ratio and  $\text{SO}_4^{2-}$  in the analyzed groundwater samples

respectively in El Meïda and in Ouedref-El Metouia grabens.

#### Boron

Boron provides additional information on the groundwater evolution (Edmunds et al. 2003). High concentrations of

boron sometimes occur in groundwater by anthropogenic activities (Giménez and Morell 1992) and interaction with evaporate levels (Rose et al. 2000; Sánchez-Martos et al. 2002; Hébrard et al. 2006).

The boron concentrations of the waters in the Djefjara aquifers vary between 0.42 and 2.3 mg/l (Table 5). In the study area, almost all CI groundwater samples show a boron concentration within the permissible limit for drinking, whereas all groundwater from Djefjara aquifers exceeds this limit (Table 3). The spatial distribution maps of the boron concentration are similar to those of salinity and chloride (Fig. 12b).

The boron values are higher near El Hamma and Melah-M'Khacherma Sabkhas (wells 11, 18, 19, 20, 21, 45, 46, 47, 48, 49, 50, 51, 52 and 53). An increase in  $\text{B}^+$  and  $\text{Cl}^-$ , simultaneously, in waters in the Ouedref Metouia and Meïda grabens provides a good indicator for different origins of dissolved elements and water contributions as the area of the El Hamma and Melah-M'khacherma Sabkhas. The increase of boron concentration observed near Koudiat



El Hmmeimet in some wells (wells 45, 46, 47, 48, 49, 50, 51, 52 and 53) may be related to the thickness of the aquifer, or the lithological character of the formations in the recharge area. The  $B^+$  is probably from the evaporitic rocks leaching of the Mio-Pliocene and Quaternary formations outcropping in Koudiat El Hmmeimet. In fact, this part of  $B^+$  is from natural B in the soil, released to the unsaturated zone due to intense cultivation in recharge area of sandy aquifer. The other samples reflecting boron released from evaporites or syn-depositional clay minerals are characterized by low TDS values (2,736–3,581 mg/l), relatively low concentrations of boron (0.42–0.9 mg/l) and Cl (525–860 mg/l), and high concentrations of  $SO_4$  (1,125–1,527 mg/l) and  $Na^+$  (400–668 mg/l).

### Fluoride

Fluoride is one of the main trace elements in groundwater, which generally occurs as a natural constituent. In fact, fluoride related to groundwater has been studied intensively during the past decades (Roberston 1986, Zhaoli et al. 1989; Travi and Faye 1992; Hitchon 1995; Subba Rao 2003; Coetsiers et al. 2008). These studies show that fluoride is the result of water–rock interaction and leaching from minerals in various aquifers with different lithologies. Bedrocks containing fluoride minerals are generally responsible for high concentration of fluoride in groundwater (Handa 1975; Wenzel and Blum 1992; Bardsen et al. 1996). Subba Rao (2003) found that high fluoride concentrations in India are related to the evapotranspiration, long-term contact of waters in the weathered zone by virtue of its low hydraulic conductivity and stagnation of water in the aquifer zone caused by intrusive bodies, intensive and long-term irrigation, and heavy use of fertilizers.

During January 2008, the concentration of fluoride in the Djefara groundwater varies between 0.57 and 2.84 mg/l (Table 5). The presence of low concentration of fluoride in majority of wells for drinking water in the study area is of minor concern, as all the samples are found to have a fluoride concentration within the permissible limit of 1.5 mg/l for drinking water (Table 3, WHO 2004), except one sample (sample No. 46).

The spatial distribution of fluorine (Fig. 12c) shows that the highest concentration levels characterize the wells located in the northern part of the study area (wells 18, 19, 21, 45, 46, 47, 48, 49, 50, 51, 52, 53), where intense cultivation is applied in the recharge area of sandy aquifer. These contents decrease in the direction of groundwater flow. Fluorine may essentially be from a natural origin. Limestone (chalky) and marly gypsum formations can contain significant quantities of fluorine which can be liberated by the water–rock interaction. However, a part of the

$F^-$  is from natural F in the soil, released to the unsaturated zone due to intense cultivation.

### Irrigation purpose

Quality of groundwater is of paramount importance for irrigation in arid and semi-arid regions. Crop cultivation mainly depends on groundwater supply for irrigation in several arid and semi-arid areas in the world, e.g. in Tunisia. In fact, the suitability of groundwater for irrigation depends on the effects of constituent minerals of water on both the plant and soil. Excessive amounts of dissolved ions in irrigation water affect plants and agricultural soil, thus reducing the productivity (Ravikumar et al. 2010). The high salt content in irrigation water causes an increase in soil solution osmotic pressure. The chemical composition is directly affecting either the growth of plants and disrupts their metabolism. Also, it affects soil structure, permeability and aeration which indirectly affect plant growth. The important chemical constituents that affect the suitability of water for irrigation are the total concentration of dissolved salts, concentration of other elements that may be toxic to plants, relative proportion of bicarbonate to calcium, magnesium and relative proportion of sodium to calcium (Haritash et al. 2008). Water quality problems in irrigation include salinity and alkalinity. The important chemical constituents that affect the suitability of water for irrigation (Table 9) can be utilized to verify the suitability as follows:

- Salinity and indexes such as SAR (Eq. 1).
- Sodium hazard expressed as percent sodium of total cations (%Na, Eq. 2).
- Bicarbonate hazard or ( $HCO_3$ ) concentration as related to the concentration of calcium and magnesium such as RSC (Eq. 3) and RSBC (Eq. 4).
- Boron hazard (concentration of boron or other elements) that may be toxic.
- Permeability index (PI, Eq. 5).

### Electrical conductivity

Electrical conductivity is a good measure of salinity hazard to crops as it reflects the TDS in groundwater. The primary effect of high EC water on crop productivity is the incapability of the plant to compete with ions in the soil solution for water. The higher EC, the less water is available to plants (Tank and Chandel 2009). The US Salinity Laboratory (1954) classified ground waters on the basis of electrical conductivity (Table 9). The EC classification indicates that 33.3 % of CI groundwater and 14.64 % of Djefara aquifers are doubtful for irrigation; and for CI groundwater and Djefara aquifers, respectively, 66.7 and

**Table 9** Suitability of groundwater for irrigation based on several classifications

Quality of parameters	Range	Classification	Number of samples		Percentage of samples		
			CI groundwater	Djeffara aquifers	CI groundwater	Djeffara aquifers	
Based on EC ( $\mu\text{S}/\text{cm}$ ) after Wilcox (1955)	<250	Excellent	–	–	–	–	
	250–750	Good	–	–	–	–	
	750–2,250	Permissible	–	–	–	–	
	2,250–5,000	Doubtful	1	6	33.3	14.64	
	>5,000	Unsuitable	2	35	66.7	85.36	
Based on $\text{Cl}^-$ (meq/l) after Stuyfzand (1989)	<0.14	Extremely fresh	–	–	–	–	
	0.14–0.85	Very fresh	–	–	–	–	
	0.85–4.23	Fresh	–	–	–	–	
	4.23–8.46	Fresh brackish	–	–	–	–	
	8.46–28.21	Brackish	1	24	33.3	58.53	
	28.21–282.06	Brackish–salt	2	17	66.7	41.47	
	282.06–564.13	Salt	–	–	–	–	
Based on RSC after Richards (1954)	<1.25	Good	3	41	100	100	
	1.25–2.5	Doubtful	–	–	–	–	
	>2.5	Unsuitable	–	–	–	–	
Based on percent sodium (%Na) after Wilcox (1955)	0–20	Excellent	–	–	–	–	
	20–40	Good	–	4	–	9.75	
	40–60	Permissible	2	36	66.7	87.8	
	60–80	Doubtful	1	1	33.3	2.45	
Based on alkalinity hazard (SAR) after Richards (1954)	<10	Low (excellent)	2	39	66.7	95.12	
	10–18	Medium (good)	–	1	–	2.44	
	18–26	High (doubtful/fair poor)	1	1	33.3	2.44	
	>26	Very high	–	–	–	–	
Based on boron (mg/l) after McCarthy and Ellery (1994)	Semi-sensitive crops	<0.33	Excellent	–	–	–	–
		0.33–0.67	Good	3	14	100	34.15
		0.67–1	Permissible	–	15	–	36.6
		1–1.25	Doubtful	–	–	–	–
		>1.25	Unsuitable	–	12	–	29.25
	Semi-tolerant and tolerant crops	<0.67	Excellent	3	14	100	34.1
		0.67–1.33	Good	–	17	–	41.5
		1.33–2.0	Permissible	–	6	–	14.7
		2.0–2.5	Doubtful	–	4	–	9.70
		>2.5	Unsuitable	–	–	–	–
Based on permeability index Ragunath (1987)	<75	Safe	–	–	–	–	
	25–75	Moderate	2	41	100	100	
	>75	Unsafe	–	–	–	–	

85.36 % of collected samples are unsuitable for irrigation. This indicates leaching and dissolution of salts in deep Djeffara aquifer of Gabes.

#### Total dissolved solids (TDS)

To ascertain the suitability of groundwater for any purposes, the TDS should be below 500 mg/l (Catroll 1962;

Freeze and Cherry 1979). Based on Freeze and Cherry (1979), all groundwater samples collected from the CI groundwater and 97.83 % of those collected from the Djeffara aquifers are brackish in nature, except one sample from the Djeffara aquifers showing saline water type indicating high dissolved load in water (Table 4). Based on Davis and DeWiest (1966) classification (Table 4), 37.5 % of groundwater samples collected from the CI groundwater

and 8.7 % of those collected from the Djefara aquifers one can be used for irrigation purpose. High TDS in most of the groundwater clearly indicate the unsuitability of groundwater for irrigation purposes.

#### *Total hardness (TH)*

Hard water is a potential problem since the calcium and magnesium can combine with bicarbonate to form insoluble calcium and magnesium carbonate salts. These salts can affect media pH and reduce the amount of sodium available to a plant (Robbins 2010). According to United States Department of Agriculture method (USDA) specification of TH, up to 200 mg/l is the upper limit for water irrigation. The high TH values (Table 4) reveal that all the sampling sites are unsuitable for irrigation.

#### *Chloride classification*

Stuyfzand (1989) classified water on the basis of  $\text{Cl}^-$  ion concentration into eight divisions as shown in Table 9. Based on this classification, the groundwater of the area is of brackish water type for 33.3 % of the CI groundwater and for 58.53 % of the Djefara aquifers. The rest of the samples represent brackish–salt water type.

#### *Sodium adsorption ratio (SAR)*

High concentration of sodium in water produces harmful effects changing soil properties and reducing soil permeability (Kelley 1951; Domenico and Schwartz 1990; Todd and Mays 2005). Thus, sodium concentration is essential to classify the water for irrigation purposes. SAR is an important parameter for determining the suitability of groundwater for irrigation because it is a measure of alkali/sodium hazard to crops (Subramani et al. 2005). Indeed, it indicates the degree of which irrigation water tends to enter cation exchange reactions in soil. Sodium replacing adsorbed calcium and magnesium is a hazard causing damage to the soil structure, making it compact and impervious (Raju 2007).

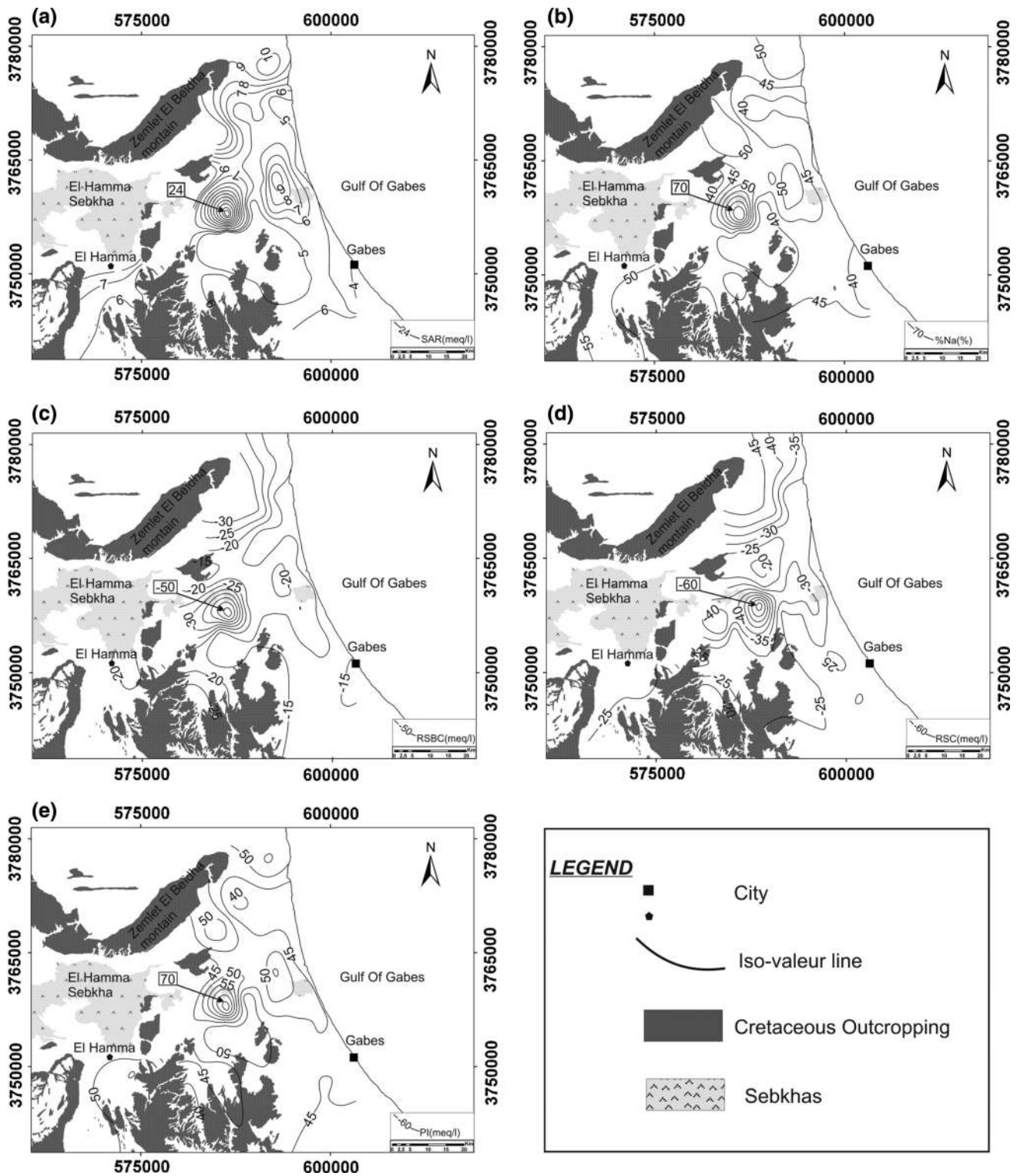
Based on SAR classification (Richards 1954), it is observed that 66.7 % of groundwater samples collected from CI groundwater and 95.12 % of those collected from the Djefara aquifers fall into the category of waters excellent for irrigation purposes in almost all soils (Table 9, Eq. 2). Therefore, the SAR value implies that most of the groundwater is suitable for irrigation. The spatial distribution maps of SAR values in groundwater is presented in Fig. 14a for the Djefara aquifers. A more detailed analysis for the suitability of water for irrigation can be made by plotting the SAR and electrical conductivity (Fig. 15) data on the US Salinity Laboratory (USSL) diagram (Richards 1954).

Based on salinity hazard, the types of water can be classified as C1, C2, C3, C4 and as S1, S2, S3, or S4 based on sodium hazard. The significance and interpretation of quality ratings on the USSL diagram is summarized as: (1) Low salinity hazard class (C1) can be used for irrigation of most crops and the majority of soils. However, some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability. (2) Medium salinity hazard class (C2) can be used if a moderate amount of leaching occurs. (3) High salinity hazard class (C3) is satisfactory for plants having moderate salt tolerance, on soils of moderate permeability with leaching. (4) High salinity hazard class (C4), (5) extremely high salinity water (C5) and (6) water where the salinity hazard is in excess (C6) cannot be used in soils with restricted drainage. Even with adequate drainage, special management for salinity control is required, and crops with good salt tolerance should be selected. Such areas need special attention as far as irrigation is concerned (Ravikumar et al. 2010).

Low sodium water (S1) can be used for irrigation on almost all soils with little danger of developing harmful levels of exchangeable  $\text{Na}^+$  (Ketata et al. 2011). Medium sodium water (S2) presents an appreciable sodium hazard in certain fine-textured soils, especially poorly leached soils (Subba Rao 2006). Waters belonging to this class are classified as excellent for irrigation and can be used safely on coarse-textured or organic soils having good permeability and may be used to irrigate salt-tolerant and semi-tolerant crops under favorable drainage conditions. High sodium waters (S3) are usually doubtful/fair poor for irrigation and cannot be used on clayey soils of low permeability. Waters belonging to this class may produce harmful levels of exchange sodium in most soils and will require special soils management such as good drainage and leaching and addition of organic matter. Very high sodium water (S4) is usually unsuitable for irrigation, except at low and perhaps medium salinity (Haritash et al. 2008).

#### *USSL diagram*

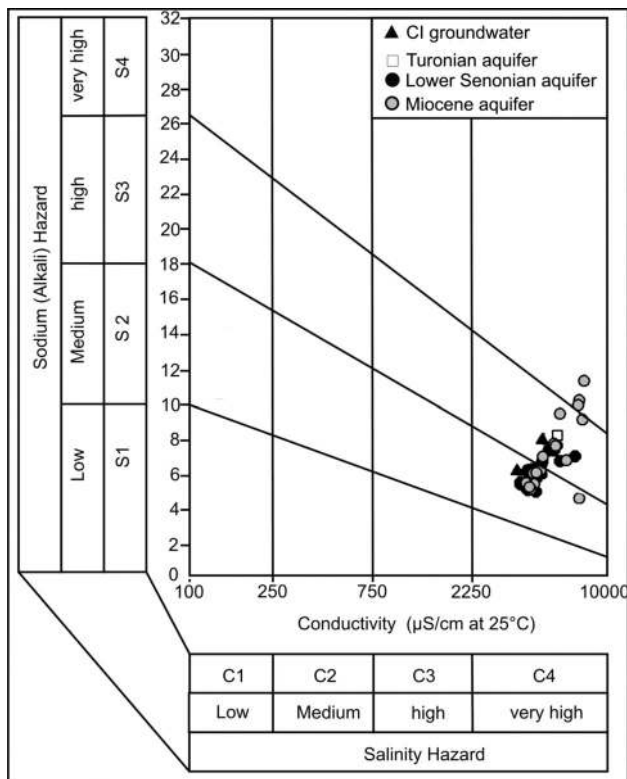
The USDA classification for salinity (C) and sodicity hazards (S) in the Djefara aquifers is shown in Table 10 and Fig. 15. All of the wells fall within the very high salinity hazard zone, which shows a substantial amount of the total dissolved salts in the water. Following the USDA classification system, the water from all groundwater samples fall in the salinity class C4, including all three sodicity classes. On the other hand, nearly 95 % of the wells have SAR values below 15, which is of a medium quality for irrigation waters. The percentage of sodium is not very high in the groundwater throughout the CI groundwater and Djefara aquifers, but the overall salt contents are very high. The combined EC/SAR



**Fig. 14** Iso-concentration maps showing spatial variation in **a** sodium adsorption ratio, **b** percent sodium, **c** carbonate residual sodium bicarbonate, **d** residual sodium, **e** permeability index in the deep Djeffara aquifers of Gabes

classification locates the Gabes water in the C4S2, C4S3 and C4S4 classes with 61.13, 27.27 and 11.5 % of the wells, respectively. Such water is rated as highly and very highly saline for irrigation, i.e., not suitable for irrigating

most crops except the tolerant ones. Special measures to control the salinity hazard are needed, including leaching and adequate drainage. The sodicity hazard is of less magnitude, with water from 61.23 % of the wells in the S2



**Fig. 15** Plots of calculated values of SAR and EC of groundwater samples (after Richards 1954; January 2008)

class, 27.27 % in the S3 class and 11.5 % in the S4 class. All water from wells may cause infiltration problems, especially with heavy textured and poorly drained salts.

Water from about 61.23 % of the wells corresponds to medium sodium water (S2) that may be of an appreciable sodium hazard in finely textured soils with a high cation exchange capacity. This water could be used for coarsely textured soils with good permeability. Water from 38.77 % of the wells corresponds to water with a high sodium content that produces harmful levels of exchangeable sodium in most soils and requires special soil amendments. From this classification, it is clear that the groundwater in the Djefara aquifers is unfit for irrigation.

*Percent sodium (%Na)*

Sodium content is usually expressed in terms of percentage of sodium or soluble-sodium percentage (%Na). The percent sodium is calculated by methods of Wilcox (1948) by Eq. (3). This method has been used to classify and understand the basic character of the chemical composition of groundwater. Indeed, the suitability of groundwater for irrigation depends on the mineralization of water and its effect on plants and soil.

Based on the percentage of Na as per Wilcox (Table 11), 66.7 % of CI groundwater is within the permissible, whereas 33.3 % is doubtful for irrigation. In the Djefara aquifers, 9.75 % of samples are good for irrigation, 87.8 % is within permissible limit, whereas 2.45 % is doubtful for irrigation. Spatial variation of percentage of sodium is shown in Fig. 14b for the Djefara aquifers. The high percentage of Na in most of the groundwater indicates its unsuitability for irrigation.

Wilcox (1948) proposed a method for rating irrigation waters, based on percentage of sodium and electrical conductivity. The significance and interpretation of quality ratings based on Wilcox (1948) diagram can be summarized as follows: (1) excellent to good, (2) good to permissible, (3) permissible to doubtful, (4) doubtful to unsuitable and unsuitable. Data of the groundwater samples of the studied area are summarized in Table 9 and show that all samples of the Djefara aquifers fall above the unsuitable categories indicating their unsuitability for irrigation. Indeed, this method is not applicable for the water of Djefara aquifers. The norms proposed by Wilcox (1948) appear very severe for the Djefara groundwater of the northern Gabes. When the concentration of Na<sup>+</sup> is high in irrigation water, sodium tends to be absorbed by clay particles, displacing Mg<sup>2+</sup> and Ca<sup>2+</sup> ions. This exchange process of Na<sup>+</sup> in water for Ca<sup>2+</sup> and Mg<sup>2+</sup> in soil reduces the permeability and eventually results in soil with poor internal drainage (Subramani et al. 2005; Kumar et al. 2007, Ravikumar et al. 2009). Hence, air and water circulation are restricted during wet conditions and such soil

**Table 10** Salinity and alkalinity hazard of irrigation water in US salinity diagram

Classification	Type of water	Number of samples		Percentage of samples		Percentage of samples CI groundwater & Djefara aquifers
		CI groundwater	Djefara aquifers	CI groundwater	Djefara aquifers	
C4S4	SAR very high EC very high	1	4	33.33	9.75	5 (11.5 %)
C4S3	SAR very high EC very high	1	11	33.33	26.83	12 (27.27 %)
C4S2	SAR medium EC very high	1	26	33.33	63.42	27 (61.23 %)

**Table 11** Classification of groundwater (Wilcox)

Classification	Number of samples		Percentage of samples	
	CI groundwater	Djeffara aquifers	CI groundwater	Djeffara aquifers
Excellent to good	–	–	–	–
Good to permissible	–	–	–	–
Permissible to doubtful	–	–	–	–
Doubtful to unsuitable	–	–	–	–
Unsuitable	3	41	100	100

is usually hard when dry (Collins and Jenkins 1996; Salesh et al. 1999).

The morphological study of soils by Hatira et al. (2007) showed the predominance of fine sand and silt conferring very important filtering capacity. In this study, all studied profiles are filled by gypsum. Indeed, concentrations of gypsum ranged between 2 and 61 %. Also, carbonate of calcium is present in all studied soils with an average value of 5.5 %, and more than 10 %. In fact, the soil features are presently dominated by the evolution of salinization and water-saturation processes either partially or totally affecting the soil profile. The visible salt deposits and soil salinization processes are generated by the salinity of water irrigation. These processes are strongly influenced by the weak soil leaching mechanisms, on the one hand, and the poor drainage schemes, on the other hand.

#### *Residual sodium carbonate*

In addition to the SAR and %Na, the excess sum of carbonate and bicarbonate in groundwater over the sum of calcium and magnesium also influences the suitability of groundwater for irrigation. The RSC was calculated to determine the hazard effects of carbonate and bicarbonate on the quality of groundwater for agricultural and irrigation purposes (Eaton 1950). The excess sum of carbonate ( $\text{CO}_3^{2-}$ ) and bicarbonate ( $\text{HCO}_3^-$ ) in groundwater over the sum of calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ) also influences the suitability of groundwater for irrigation because in waters having high concentration of bicarbonate ( $\text{HCO}_3^-$ ), there is a tendency for calcium and magnesium to precipitate as the water in the soil becomes more concentrated. An excess quantity of sodium bicarbonate and carbonate is considered to be detrimental to the physical properties of soils, as it causes dissolution of organic matter in the soil, which in turn leaves a black stain on the soil surface on drying (Ravikumar et al. 2010). Therefore, land irrigated with such water becomes infertile owing to deposition of sodium carbonate (Eaton 1950).

According to the US Department of Agriculture, waters having  $>2.5$  (meq/l) RSC are unsuitable for irrigation, 1.25–2.5 are marginal and  $<1.25$  are safe waters. The increase of RSC in groundwater is significantly harmful for

plant growth (Krishna Kumar et al. 2009). The groundwater in the study area is classified on the basis of RSC, and the results are presented in Table 9 for the CI groundwater and Djeffara aquifers (Fig. 14c). The calculated values (Ragunath 1987, Eq. 4) reveal that all the sampling sites are good for irrigation purpose.

#### *Residual sodium bicarbonate*

Gupta and Gupta (1987) classified water on the basis of “RSBC”. RSBC was calculated for each well by Eq. (5) given by Gupta and Gupta (1987) and classified as satisfactory ( $<5$  meq/l), marginal (5–10 meq/l) and unsatisfactory ( $>10$  meq/l). The calculated values (Ragunath 1987; Gupta and Gupta 1987, Eq. 5) of “RSBC” are presented in Table 5b for the CI groundwater and Djeffara aquifers.

The RSBC of CI groundwater ranged from  $-21.66$  to  $-15.96$  meq/l with an average value of  $-19.56$  meq/l and the corresponding values in Djeffara aquifers (Fig. 14d) ranged from  $-32.03$  to  $-12.78$  meq/l with an average  $-19.23$  meq/l (Table 5b). According to the RSBC values, all groundwater samples collected were found to be satisfactory ( $<5$  meq/l) according to the criteria set by Gupta and Gupta (1987). The RSBC values are  $<5$  meq/l and are therefore considered safe for irrigation purposes.

#### *Boron*

Scofield (1936) and McCarthy and Ellery (1994) proposed a table of permissible boron limits to assess water quality using five class (1–5) and three levels of crop tolerance (sensitive, semi-tolerant and tolerant). The proposed limits of boron concentration in irrigation water and the total number of groundwater samples of the study area representing the boron classes are presented in Table 9. Based on this classification, it is observed that all of groundwater samples collected from the CI groundwater and 14 samples (34.15 %) of those collected from the Djeffara aquifers are found to be excellent for tolerant and semi-tolerant crops based on boron concentration. However, 15 samples (36.6 %) and 12 samples (29.25 %) were found to be permissible and unsuitable for semi-sensitive crops. Three samples from CI groundwater and 14 samples (34.41 %) were found to be excellent for tolerant and semi-tolerant crops based on boron concentration.

from Djefara aquifers were found to be excellent for semi-sensitive and tolerant crops. The remaining samples reveal that 17 samples (41.5 %) were found to be good, and 6 samples (14.7 %) belongs to the permissible category, and 4 samples (9.70 %) fall in the doubtful category for semi-sensitive and tolerant crops.

#### *Permeability index (PI)*

The permeability index also indicates whether groundwater is suitable for irrigation. The soil permeability is affected by the long-term use of irrigation water as influenced by  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{HCO}_3^-$  contents of the soil. Doneen (1964) and Ragunath (1987) used a criterion for assessing the suitability of water for irrigation based on permeability index and accordingly, water can be classified as class I, II and III. Class I and II water are categorized as good for irrigation with 75 % or more of maximum permeability. Class III water is unsuitable with 25 % of maximum permeability.

The PI of CI groundwater ranges from 47.72 to 73.94 % with an average value of 57.55 % and the corresponding values (Table 5b) in Djefara aquifers ranged from 38.57 to 73.94 % with an average of 48.20 % (Table 5b; Fig. 14e). According to the permeability index values, all of groundwater samples comes under class II (Table 9), suggesting the suitability of groundwater for irrigation. The calculated values reveal that all the sampling sites are good for irrigation purpose.

#### **Conclusion**

The Djefara aquifer system is one of the most important groundwater resources in Tunisia. It is the main water source for the local population and agriculture needs. Therefore, deciphering the mechanisms responsible for observed chemistry and assessing the water quality in this system, pursued in the framework of this study, are of great practical importance. Simultaneous analysis of both major and trace elements allowed better understanding of the hydrodynamic functioning and assessing the water quality in the Djefara aquifer system. The Piezometric map (Fig. 4) and the geochemical data (Tables 1, 2) point to the significant role of carbonate and sandy outcrops of the Cretaceous and Miocene, respectively, located in the southern and northern parts of study area in local recharge of this aquifer system. Stratigraphic, tectonic and hydraulic conditions seem to be important factors controlling the geochemical evolution of groundwater in the study area. The principal changes in chemical composition of Djefara aquifer system result from mixing with CI water of deeper circulation. Closer analysis of available chemical data

reveals the importance of dissolution/precipitation processes as well as cation exchange reactions in evolution of groundwater chemistry. In general, mineralization of groundwater increases along the flow path from El Hamma region toward the sabkhas and Mediterranean Sea. The  $\text{Na}^+/\text{Cl}^-$  molar ratio suggests that the dissolution of halite in evaporites within the Miocene and Cretaceous sequences is the main source of these ions in groundwater. The values of this ratio,  $>1$ , observed in some of the wells may indicate the occurrence of cation exchange reaction releasing  $\text{Na}^+$  into the water with simultaneous removal of  $\text{Ca}^{2+}$ . The existence of such exchange is confirmed by the balance between the excess of  $(\text{Na}^+ + \text{K}^+)$  over the  $\text{Cl}^-$  ions and excess of  $(\text{Ca}^{2+} + \text{Mg}^{2+})$  over the  $(\text{HCO}_3^- + \text{SO}_4^{2-})$  anions (Fig. 10e). Chemical data indicate also the importance of gypsum dissolution as a factor controlling groundwater chemistry. The source of the salinity as shown from the  $\text{Sr}^{2+}/\text{Ca}^{2+}$  ratios is mainly derived from evaporitic formations of Cretaceous, except in the Ouedref Metouia/El Meïda graben where the influence of both the salt water from sabkhas and water leaching evaporitic formations of Cretaceous is evident. What is more, the molar ratio  $\text{Sr}^{2+}/\text{Ca}^{2+}$  allows the distinguishing of the different evaporitic influences in this region.

The spatial distribution of fluoride and boron shows that highest concentration of these elements characterizes the waters of the northern part of study area, with a reduction in the flow direction. Fluorine and boron may essentially come from a natural origin. Limestone, marly formations and gypsum can contain significant quantities of fluorine and boron which can be released by water–rock interaction.

With limited supply by the recent infiltration waters, the increased exploitation of wells can lead to further deterioration of the quality of groundwater resources available for the population in this area.

Assessment of water samples according to exceeding the permissible limits prescribed by WHO for drinking purposes indicated that groundwater in study area is chemically unsuitable for drinking uses. High TH and TDS at a number of subareas clearly indicate the unsuitability of groundwater for drinking and irrigation purposes. Therefore, the water of these wells must be desalinated before use for drinking.

The suitability of groundwater for irrigation was evaluated based on the irrigation quality parameters like boron, SAR, %Na, RSC, RSBC, and permeability index. Among these parameters, boron and SAR imply that the water samples fall in excellent to permissible, excellent to doubtful, excellent to good for irrigation purpose. RSC and RSBC values specify that water samples belong to good classes. The high EC value and percentage of Na in most of the groundwater indicate its unsuitability for irrigation. However, permeability index recommends that the water

samples from the Djefara aquifers, belonging to class 2, are suitable for irrigation. According to the US Salinity Classification, in deep Djefara aquifers of the northern Gabes, 56.52 % fall in the C4–S2 category, 32.61 % fall in the C4–S3 category and 10.87 % fall in the C4–S4 category, indicating high salinity/high sodium and medium salinity/high sodium type and there is a need for better drainage to overcome salinity problems. From this classification, it is clear that the groundwater in the Djefara aquifers is unfit for irrigation. Water that is not suitable based on the above classification may be suitable in well-drained soils.

The following remedial measures can be helpful (Subba Rao 2003) in the Gabes-north region: (1) drip irrigation should be preferred over traditional irrigation practices, such as flooding to prevent weathering and leaching and also to reduce water consumption and evaporation; (2) application of calcium chlorite, gypsum and organic manures to cause de-alkalization and deflocculation, and to produce more permeable soil supporting plant expansion; (3) cultivation of sodium salt-tolerant crops and (4) using judicious fertilizers to obtain higher crop yields should be based on crop requirements and soil characteristics.

Groundwater quality in the study area reaches alarming situation so that stringent monitoring and control measures are necessary to ensure sustainable safe use for the resource. In this strategy, Tunisia is involved in a series of geological, hydrogeological and hydrochemical investigations that will provide technical support for developing policies to help preserve groundwater availability and protect water quality, also, assess the origins and the evolution of salinity in the water.

Finally, based on this studies, recommendations have been made to the local authorities to adopt conjunctive use of surface water with groundwater to stringently monitor and control low groundwater quality regions to ensure sustainable safe use of the resource.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

## References

- Abdès C, Abdeljouad S, Ben Oueddou H, Zargouni F (1986) Carte géologique d'El Hamma à 1:100 000. Feuille n°74, Office National des Mines, Tunis
- Abdeljaouad S (1983) Etude sédimentologique et structure de la partie est de la chaîne nord des Chotts. Thèse de Doctorat. Univ. de Tunis El Manar, Tunisie
- Abid K, Trabelsi R, Zouari K, Abidi B (2010) Caractérisation hydrogéochimique de la nappe du Continental Intercalaire (sud tunisien). *Hydrol Sci J* 54(3):526–536
- Abid K, Zouari K, Dulinski M, Chkir N, Abidi B (2011) Hydrologic and geologic factors controlling groundwater geochemistry in the Turonian aquifer (southern Tunisia). *Hydrogeol J* 19:415–427
- Abidi B (2004) Caractéristiques hydrodynamiques et géochimiques de la Djefara de Gabés. DGRE 2004
- ACF (Action Contre la Faim) (1996) La qualité et les analyses d'eau. ACF, France
- Adams S, Titus R, Pietersen K, Tredoux G, Harris C (2001) Hydrochemical characteristics of aquifers near Sutherland in the Western Karoo, South Africa. *Hydrogeol J* 241:91–103
- Aghazadeh N, Mogaddam AA (2011) Investigation of hydrochemical characteristics of groundwater in the Harzandat aquifer, Northwest of Iran. *Environ Monit Assess* 176:183–195
- Al-Bassam AM, Al-Rumikhani YA (2003) Integrated hydrochemical method of water quality assessment for irrigation in arid areas: application to the Jilh aquifer, Saudi Arabia. *J Afr Earth Sc* 36:345–356
- Al-Shaibani AM (2008) Hydrogeology and hydrochemistry of a shallow alluvial aquifer, western Saudi Arabia. *Hydrogeol J* 16:155–165
- Anku YS, Banoeng-Yakubo AEB, Daniel AE, Asiedu K, Sandow A, Yidana EM (2009) Water quality analysis of groundwater in crystalline basement rocks, Northern Ghana. *Environ Geol* 58(5):989–997
- Arumugam K, Elangovan K (2009) Hydrochemical characteristics and groundwater quality assessment in Tirupur Region, Coimbatore District, Tamil Nadu, India. *Environ Geol* 58:1509–1520
- Ayewew T, Demlie M, Wöhlisch S (2008) Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. *J Afr Earth Sc* 52(3):97–113
- Bahar MM, Reza MS (2009) Hydrochemical characteristics and quality assessment of shallow groundwater in a coastal area of Southwest Bangladesh. *Environ Earth Sci*. doi:10.1007/s12665-009-0427-4
- Bardsen A, Bjorvatn K, Selvig KA (1996) Variability in fluoride content of subsurface water reservoirs. *Acta Odontol Scand* 54:343–347
- Benton MJ, Bouaziz S, Buffetaut E, Martill D, Ouaja M, Soussi M, Trueman C (2000) Dinosaurs and other fossil vertebrates from fluvial deposits in the lower cretaceous of Southern Tunisia. *Palaeogeogr Palaeoclimatol Palaeoecol* 157:227–246
- Bouaziz S (1995) Etude de la tectonique cassante dans la plateforme et l'Atlas Sahariens (Tunisie Meridionale): évolution des paleochamps de contraintes et implications géodynamiques. Thèse de Doctorat. Univ. de Tunis El Manar, Tunisie
- Boughriba M, Melloul A, Zarhloule Y, Ouardi A (2006) Extension spatiale de la salinisation des ressources en eau et modèle conceptuel des sources salées dans la plaine des Triffa (Maroc nord-oriental). *CR Geosci* 338(11):768–744
- Brondi M, Fidelibus MD, Gagnani R, Tulipano L (1983) Hydrochemical study and distribution of some trace elements in the most important coastal springs and groundwater of the Apulian Region (Southern Italy). *Geol Appl Idrogeol XVII(II):65–80*
- Busson G (1970) Le Mésozoïque saharien, tomes 1 et 2. Centre National de Recherche Scientifique, Paris
- Custodio E, Bruggeman GA (1987) Groundwater problems in coastal areas. UNESCO. Studies and reports in hydrology
- Castany G (1954) L'accident sud tunisien et ses relations avec l'accident sud-atlasique. *C R Acad Sci* 238:1–184
- Castany G (1982) Bassin sédimentaire du Sahara septentrional (Algérie-Tunisie)-Aquifères du Continental intercalaire et du Complexe Terminal. Bulletin Bureau Recherches Géologiques Minières (BRGM). Série 2.3. 127–147
- Catroll D (1962) Rain water as a chemical agent of geological process: a view. USGS Water Supply 1533:18–20



- Ceron JC, Jimenez-Espinosa R, Pulido-Bosch A (2000) Numerical analysis of hydrogeochemical data: a case study (Alto Guadalupe, southeast Spain). *Appl Geochem* 15:1053–1067
- Chan HJ (2001) Effect of land use and urbanization on hydrochemistry and contamination of groundwater from Taejon area, Korea. *J Hydrol (Amsterdam)* 253:194–210. doi:10.1016/S00221694(01)00481-4
- Coetsiers M, Kilonzo F, Walraevens K (2008) Hydrochemistry and source of high fluoride in groundwater of the Nairobi area, Kenya. *Hydrol Sci J* 53(6):1230–1240
- Collins R, Jenkins A (1996) The impact of agricultural land use on stream chemistry in the middle Hills of Himalaya, Nepal. *J Hydrol* 185(71):86
- Dassi L (2010) Use of chloride mass balance and tritium data for estimation of groundwater recharge and renewal rate in an unconfined aquifer from North Africa: a case study from Tunisia. *Environ Earth Sci* 60(4):861–871
- Dassi L, Zouari K, Peter Seiler K, Faye S, Kamel S (2005) Flow exchange between the deep and shallow groundwaters in the Sbeitla synclinal basin (Tunisia): An isotopic approach. *Environ Geol* 47(4):501–511
- Davis SN, DeWiest RJ (1966) *Hydrogeology*. Wiley, New York
- Desbarats AJ (2009) On elevated fluoride and boron concentrations in groundwaters associated with the Lake Saint-Martin Impact Structure, Manitoba. *Appl Geochem* 24:915–927. doi:10.1016/j.apgeochem.2009.02.016
- DGRE (Direction Générale des Ressources en Eau) (2008). *Annuaire d'exploitation de la nappe profonde 1950–2008*. Ministère de l'Agriculture, Tunis
- Dixon W, Chiswell B (1992) The use of hydrochemical sections to identify recharge areas and saline intrusions in alluvial aquifers, southeast Queensland, Australia. *Hydrogeol J* 130:299–338
- Djabri L, Rouabhia A, Hani A, Lamouroux Ch, Pulido-Bosch A (2007) Origin of water salinity in a lake and coastal aquifer system. *Environ Geol* 54(3):565–573
- Domenico PA, Schwartz FW (1990) *Physical and chemical hydrogeology*. Wiley, New York, pp 410–420
- Doneen LD (1964) Notes on water quality in agriculture. Published as a water science and engineering paper, 4001, Department of water science and engineering, University of California
- Eaton FM (1950) Significance of carbonates in irrigation waters. *Soil Sci* 39:123–133
- Edmunds WM, Guendouz A, Mamou A, Moulla A, Shand P, Zouari K (2003) Groundwater evolution in the Continental Intercalaire aquifer of southern Algeria and Tunisia: trace element and isotopic indicators. *Appl Geochem* 18:805–822
- Elango L, Kannan R, Senthil K (2003) Major ion chemistry and identification of hydrogeochemical processes of groundwater in a part of Kancheepuram District, Tamil Nadu, India. *Environ Geol* 10(4):157–166
- ERESS (1972) *Etude des ressources en eau du Sahara Septentrional*. UNESCO, Paris
- Fehdi Ch, Aek Rouabhia, Baali F, Boudoukha A (2009) The hydrogeochemical characterization of Morsott-El Aouinet aquifer, Northeastern Algeria. *Environ Geol* 58(7):1611–1620
- Freeze RA, Cherry JA (1979) *Groundwater*. Prentice-Hall, New Jersey
- Garcia MG, Del Hidalgo M, Blesa MA (2001) Geochemistry of groundwater in the alluvial plain of Tucumán province Argentina. *Hydrogeol J* 9(6):597–610
- Garrels RM (1976) A survey of low temperature water mineral relations. In: *Interpretation of environmental isotope and hydrogeochemical data in groundwater hydrology*: Vienna, International Atomic Energy Agency, pp 65–84
- Ghanmi M, Potfaj M, Ben Youssef M, Zargouni F (1984) Carte géologique d'Oglet Mertaba à 1:100 000. Feuille no. 82. Office nationale des mines. Tunisie
- Giménez E, Morell I (1992) Utilisació del boro como indicador de contaminación en la Plana de Castellón. *Hidrogeologica y Recursos Hidráulicos XVI(IV)*:285–292
- Giridharan L, Venugopal T, Jayaprakash M (2008) Evaluation of the seasonal variation on the geochemical parameters and quality assessment of the groundwater in the proximity of River Cooum, Chennai, India. *Environ Monit Assess* 143:161–178
- Graniel CE, Morris LB, Carrillo Rivera JJ (1999) Effect of urbanization on groundwater resources of Merida, Yucatan, Mexico. *Environ Geol* 37(4):303–312. doi:10.1007/s002540050388
- Guendouz A, Moulla AS, Edmunds WM, Zouari K, Shand P, Mamou A (2002) Hydrogeochemical and isotopic evolution of water in the Complex Terminal aquifer in the Algerian Sahara. *Engineering Sciences Faculty, Blida, Algeria*, pp 483–495
- Guler C, Thyne GD (2004) Hydrologic and geologic factors controlling surface and groundwater chemistry in Indian Wells—Owens Valley area, southeastern California, USA. *Hydrogeol J* 285:177–198
- Guler C, Thyne GD, McCray JE, Turner AK (2002) Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeol J* 10:455–474
- Gupta SK, Gupta IC (1987) *Management of saline soils and water*. Oxford and IBM Publ. Co, New Delhi
- Hamzaoui-Azaza F, Ketata M, Bouhlila R, Gueddari M, Ribeiro L (2011) Hydrogeochemical characteristics and assessment of drinking water quality in Zeus–Koutine aquifer, southeastern Tunisia. *Environ Monit Assess* 174:283–298
- Hamzaoui-Azaza F, Ameer M, Bouhlila R, Gueddari M (2012) Geochemical characterization of groundwater in a Miocene Aquifer, Southeastern Tunisia. *Environ Eng Geosci* 18(2):159–174
- Han D, Liang X, Jin M, Currell MJ, Han Y, Song X (2009) Hydrogeochemical indicators of groundwater flow systems in the Yangwu River Alluvial Fan, Xinzhou Basin, Shanxi, China. *Environ Manage* 44:243–255
- Handa BK (1975) Geochemistry and genesis of fluoride containing groundwater in India. *Groundwater* 13(3):275–281
- Haritash AK, Kaushik CP, Kaushik A, Kansal A, Kumar YA (2008) Suitability assessment of groundwater for drinking, irrigation and industrial use in some North Indian villages. *Environ Monit Assess* 145:397–406
- Hatira A, Baccar L, Grira M, Gallali T (2007) Analyse de sensibilité du système oasien et mesures de sauvegarde de l'oasis de Métouia (Tunisie). *Rev Sci Eau* 20(1):59–69
- Hébrard O, Pistre S, Cheynet N, Dazy J, Batiot-Guilhe C, Seidel JL (2006) Origine des eaux des émergences karstiques chlorurées du Languedoc-Roussillon. *C R Geosci* 338(2006):703–710
- Hem JD (1985) *Study and interpretation of the chemical characteristics of natural water*. USGS, Water Supply paper no. 2254, pp 117–120, 264
- Hidalgo MC, Cruz-Sanjulián J, Sanroma A (1995) Evolución geoquímica de las aguas subterráneas en una cuenca sedimentaria (acuífero de Baza-Caniles, Granada, España). *Tierra Tecnol* 20:39–48
- Hitchon B (1995) Fluoride in formation waters. Alberta Basin, Canada. *Appl Geochem* 10:357–367
- Hounslow AW (1995) *Water quality data: analysis and interpretation*. CRC/Lewis, Washington
- Hsissou Y, Chauve P, Mania J, Mangin A, Bakalowicz M, Gaiz A (1996) Caractérisation des eaux de l'aquifère turonien du bassin du Tadla (Maroc) par le rapport des concentrations molaires  $Sr^{2+}/Ca^{2+}$ . *Hydrogeol J* 183:445–451
- Jalali M (2007) Salinization of groundwater in arid and semiarid zones: An example from Tajarak, western Iran. *Environ Geol* 52(6):1133–1149
- Jalali M (2009) Geochemistry characterization of groundwater in an agricultural area of Razan, Hamadan, Iran. *Environ Geol* 56:1479–1488

- Jeevanandam M, Kannan R, Srinivasalu S, Rammohan V (2006) Hydrogeochemistry and groundwater quality assessment of lower part of the Ponnaiyar River Basin, Cuddalore district, South India. *Environ Monit Assess* 132(1):263–274. doi:10.1007/s10661-006-9532-y
- Kallel R (2003) Hydrologie de la Jeffara tunisienne. Rapport interne. CRDA de Gabes
- Kamel S, Younes H, Chkir N, Zouari K (2008) Geochemical and isotopic investigation of the aquifer system in the Djerid–Nefzoua basin, southern Tunisia. *Environ Geol* 49:59–170
- Kelley WP (1951) Alkali soils: their formation properties and reclamations. Reinhold, New York
- Ketata M, Hamzaoui F, Gueddari M, Bouhlila R, Ribeiro L (2011) Hydrochemical and statistical study of groundwaters in Gabes south deep aquifer (southeastern Tunisia). *J Phys Chem Earth* 36:187–196
- Khazaei E, Stednick JD, Sanford WE, Warner JW (2006) Hydrochemical changes over time in the Zahedan aquifer, Iran. *Environ Monit Assess* 114:123–143
- Krishna Kumar S, Rammohan V, Dajkumar Sahayam J, Jeevanandam M (2009) Assessment of groundwater quality and hydrogeochemistry of Manimuktha River basin, Tamil Nadu, India. *Environ Monit Assess* 159:341–351
- Krishnakumar S (2004) Quality characterization and geochemical characteristics of lower Gadilum River Basin, Tamil Nadu, India. Dissertation, University of Madras
- Kumar M, Ramanathan AL, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. *Environ Geol* 50:1025–1039
- Kumar M, Kumari K, Ramanathan AL, Saxena R (2007) A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India. *Environ Geol* 5(553):574
- Kumar M, Kumari K, Singh UK, Ramanathan AL (2009) Hydrogeochemical processes in the groundwater environment of Muktsar, Punjab: conventional graphical and multivariate statistical approach. *Environ Geol* 57:873–884
- Kurumbin WC, Graybill FA (1965) An introduction to statistical models in geology. McGraw-Hill, New York
- Magaritz M, Nadler A, Koyumdjisky H, Dan N (1981) The use of Na/Cl ratio to trace solute sources in a semiarid zone. *Water Resour Res* 17:602–608
- Mamou A (1990) Caractéristiques, Evaluation, Gestion des ressources en eau du Sud Tunisien. PhD thesis, University of Paris South, Paris
- Mandel S, Shiftan ZL (1981) Groundwater resources investigation and development. Academic Press Inc, New York
- McCarthy TS, Ellery WN (1994) The effect of vegetation on soil and ground water chemistry and hydrology of islands in the seasonal swamps of the Okavango Fan, Botswana, Botswana. *Hydrogeol J* 154:169–193
- McLean W, Jankowski J, Lavitt N et al (2000) Groundwater quality and sustainability in an alluvial aquifer, Australia. In: Sililo O (ed) Groundwater, past achievement and future challenges. Balkema, Rotterdam, pp 567–573
- Mekrazi AF (1975) Contribution à l'étude géologique et hydrogéologique de la région de Gabes Nord. PhD thesis, University of Bordeaux, France
- Meybeck M (1984) Les fleuves et le cycle géochimique des éléments. Etat Thesis, Univ Paris VI
- Morgan-Jones M, Eggboro MD (1981) The hydrogeochemical of the Jurassic limestones in Gloucestershire, England. *Q J Eng Geol (London)* 14:25–29
- OSS (Observatoire Sahara et Sahel) (2003) Système aquifère du Sahara septentrional: gestion commune d'un bassin transfrontière. Review article. OSS, Tunisia
- Piper AM (1944) A graphical interpretation of water analysis. *Trans Am Geophys Union* 25:914–928
- Plummer LN, Jones BF, Truesdell AH (1976) WATEQF, a Fortran IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters. *US Geol Surv Water Resour Invest* 76:13
- Qiyam F, Baoping H (2002) Hydrogeochemical simulation of water-rock interaction under water flood recovery in Renqiu Oilfield, Hebei Province, China. *Chin J Geochem* 21:156–162
- Ragunath HM (1987) Groundwater, 2nd edn. Wiley Eastern Ltd., New Delhi
- Raju NJ (2007) Hydrogeochemical parameters for assessment of groundwater quality in the upper Gunjanaeru River basin, Cuddapah District, Andhra Pradesh, South India. *Environ Geol* 52:1067–1074
- Ravikumar P, Venkatesharaju K, Somashekar RK (2009) Major ion chemistry and hydrochemical studies of groundwater of Bangalore South Taluk, India. *Environ Monit Assess* 163:643–653
- Ravikumar P, Somashekar RK, Angami M (2010) Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River basin, Belgaum District, Karnataka State, India. *Environ Monit Assess* 173(1–4):459–487
- Richards LA (1954) Diagnostics and improvement of saline and alkaline soils. U.S. Dept. of Agriculture hand book no. 60. U.S. Salinity Laboratory, Washington, DC
- Risacher F, Alonso H, Salazar C (2003) The origin of brines and salts in Chilean salars: a hydrochemical review. *Earth Sci Rev* 63:249–293
- Robbins J (2010) Irrigation water for greenhouses and nurseries. U.S. Dept. of Agriculture, and County Governments Cooperating no. 6061. Agriculture and Natural Resources, University of Arkansas, Division of Agriculture
- Rose EF, Chaussidon M, France-Lanord C (2000) Fractionation of boron isotopes during erosion processes: the example of Himalayan rivers. *Geochim Cosmochim Acta* 64:397–408
- Rosset R, Douville S, Ben Amor M, Walha K (1999) L'inhibition de l'entartrage par les eaux géothermales du sud tunisien. *Étude sur site. Rev Sci Eau* 12(4):753–764
- Rouabhia A, Baali F, Fehdi Ch, Kherici N, Djabri L (2009) Hydrochemical and isotopic investigation of a sandstone aquifer groundwater in a semiarid region, El Ma El Abiod, Algeria. *Environ Geol* 57(8):1699–1705
- Rouatbi R (1967) Contribution à l'étude hydrogéologique du Karst en terre de Gabès Sud. PhD thesis, Montpellier
- Salesh A, Al-Ruwaih F, Shehata M (1999) Hydrogeochemical processes operating within the main aquifers of Kuwait. *J Arid Environ* 42:195–209
- Sami K (1992) Recharge mechanisms and geochemical processes in a semi-arid sedimentary basin, Eastern Cape, South Africa. *Hydrogeol J* 139:27–48
- Sánchez-Martos F, Pulido-Bosch A, Molina-Sánchez L, Vallejos-Izquierdo A (2002) Identification of the origin of salinization in groundwater using minor ions (lower Andarax, southeast Spain). *Sci Total Environ* 297:43–58
- Sawyer GN, McCarty DL (1967) Chemistry of sanitary engineers, 2nd edn. McGraw Hill, New York
- Schroeder HA (1960) Relations between hardness of water and death rates from certain chronic and degenerative diseases in the United States. *J Chronic Dis* 12:586–591
- Scofield CS (1936). The salinity of irrigation water. Annual Report, Smithsonian Institute, pp 275–287
- Srinivasa Gowd S (2005) Assessment of groundwater quality for drinking and irrigation purpose: a case study of Peddavanka watershed, Anantapur District, Andhra Pradesh, India. *Environ Geol* 48:702–712

- Stuyfzand PJ (1989) Nonpoint source of trace element in potable groundwater in Netherland. In: Proceedings of the 18th TWSA Water Working, Testing and Research Institute. KIWA, Nieuwegein
- Subba Rao N (2003) Groundwater quality: focus on fluoride concentration in rural parts of Guntur District, Andhra Pradesh, India. *Hydrol Sci J* 48:835–847
- Subba Rao N (2006) Seasonal variation of groundwater quality in a part of Guntur district, Andhra Pradesh, India. *Environ Geol* 49:413–429
- Subba Rao N, Gurunadha Rao VVS, Gupta CP (1998) Groundwater pollution due to discharge of industrial effluents in Venkatapuram area, Visakhapatnam, Andhra Pradesh, India. *Environ Geol* 33(4):289–294
- Subramani T, Elango L, Damodarasamy SR (2005) Groundwater quality and its suitability for drinking and agricultural use Chithar River Basin, Tamil Nadu, India. *Environ Geol* 47:1099–1110
- Tank DK, Chandel CPS (2009) A hydrochemical elucidation of the groundwater composition under domestic and irrigated land in Jaipur city. *Environ Monit Assess*. doi:10.1007/s10661-009-0985-7
- Tayfur G, Kirer T, Baba A (2008) Groundwater quality and hydrogeochemical properties of Torbali Region, Izmir, Turkey. *Environ Monit Assess* 146:157–169
- Todd DK (1980) *Groundwater hydrology*, 2nd edn. Wiley, New York
- Todd DK, Mays LW (2005) *Groundwater hydrology*, 3rd edn. Wiley, New York
- Trabelsi R, Zaïri M, Smida H, Ben Dhia H (2005) Salinisation des nappes côtières: cas de la nappe nord du Sahel de Sfax, Tunisie. *C R Acad Sci* 337(5):515–524
- Trabelsi R, Zairi Z, Ben Dhia H (2007) Groundwater salinization of the Sfax superficial aquifer, Tunisia. *Hydrogeol J* 15(7):1341–1355
- Trabelsi R, Kacem A, Zouari K, Rozanski K (2009) Quantifying regional groundwater flow between Continental Intercalaire and Djefara aquifers in southern Tunisia using isotope methods. *Environ Geol* 58(1):171–183
- Trabelsi R, Abid K, Zouari K (2011) Geochemistry processes of the Djefara palaeogroundwater (Southeastern Tunisia). *Quat Int* 3:1–13
- Travi Y, Faye A (1992) Fluoride in Paleocene aquifers in Sengal. An example of the contamination of a confined aquifer by its roof zone, aggravated by intensive exploitation. In: Proceedings of XXIII IAH Congress on Aquifer Overexploitation of Canary Islands and Spain, pp 171–174
- Umar R, Sami Ahmad M (2000) Groundwater quality in part of Central Ganga Basin, India. *Environ Geol* 39(6):673–678. doi:10.1007/s002540050480
- Vengosh A, Kloppmann W, Marie A, Livshitz Y, Gutierrez A, Banna M, Guerrot C, Pankratov I, Ranan H (2005) Sources of salinity and boron in the Gaza Strip: natural contaminant flow in the southern Mediterranean Coastal aquifer. *Water Resour Res* 41:W01013. doi:10.1029/2004WR003344
- Wen XH, Wu AEY, Andwu AEJ (2008) Hydrochemical characteristics of groundwater in the Zhangye Basin, northwestern China. *Environ Geol* 55(8):1713–1724
- Wenzel WW, Blum WEH (1992) Fluoride speciation and mobility in fluoride contaminated soil and minerals. *J Soil Sci* 153:357–364
- WHO (1993) *Guidelines for drinking water quality, recommendations*, vol 1, 2nd edn. WHO, Geneva
- WHO (1996) *Water quality monitoring: a practical guide to the design and implementation of freshwater quality studies and monitoring programmes*. E&FN Spon, London
- WHO (2004) *Guidelines for drinking water quality: training pack*. WHO, Geneva
- Wilcox LV (1948) *The quality of water for irrigation uses*. U.S. Dept. Agri. Tech. Bull. 962. USDA, Washington, DC
- Wilcox LV (1955) *Classification and use of irrigation waters*. USDA, Circular 969, Washington, DC
- World Health Organization (WHO) (1996) *Guidelines for drinking water quality. Health criteria and other supporting information*, vol 2, 2nd edn. WHO, Geneva
- Yaouti FEL, Mandour AEL, Khattach D, Benavente J, Kaufmann O (2009) Salinization processes in the unconfined aquifer of Bou-Areg (NE Morocco): a geostatistical, geochemical, and tomographic study. *Appl Geochem* 24:16–31
- Zhaoli S, Mi Z, Mingao T (1989) The characteristics of fluoride in groundwater of north China and significance of fluorite–water interaction to fluorine transportation. In: Proceedings of 6th international symposium on water rock interaction, Malvern (UK Balkema), pp 801–804