Assessing seasonal variations and aquifer vulnerability in coastal aquifers of semi-arid regions using a multi-tracer isotopic approach: The case of Grombalia (Tunisia)

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Abstract

The Grombalia aquifer (NE Tunisia) is an example of an important source of water supply for regional and national development, where the weak controls over abstraction, fertilizers applications and waste disposal, coupled with limited knowledge of aquifer dynamics, is triggering aquifer over-exploitation and water quality degradation. Assessing the key role of groundwater to water resources security is therefore of paramount importance to support new actions targeted to preserve water quality and quantity in the long-run. This study hence presents one of the first investigations targeted to a complete assessment of aquifer dynamics in the Grombalia aquifer. A multi-tracer hydrogeochemical and isotopic (δ^2H, $\delta^{18}O$ and ^3H) approach permitted to study the influence of seasonal variations on piezometric levels, chemical and isotopic compositions and groundwater recharge. A total of 116 samples were collected from private wells and boreholes during a one year monitoring campaign (February-March 2014, September 2014 and February 2015). Results revealed the overall unsuitability of groundwater for drinking and irrigation purposes (NO_3 > 50 mg/L in 51% of the wells; EC > 1000 µS/cm in 99% of the wells). Isotopic balance coupled to piezometric investigation indicated the contribution of shallow aquifer to deep groundwater recharge. The study also revealed the weakness of business as usual management practices, highlighting possible solutions to tackle water related challenges in the Grombalia region where climate change coupled to population growth and intensive agricultural activities have generated a large gap between demand and available water reserves, hence becoming a possible driver for social insecurity.

Keywords: Quality assessment· Isotopes· Groundwater recharge· Mixing process· Tunisia

1. Introduction

Almost one-third of the total area of the world is arid land (FAO 1989). This means that, around 20% of the total population lives in regions where water scarcity is often associated to famine and severe poverty (UN 2017), highlighting how aridity can have impacts that spans out of the environmental domain to the social one. In the long-term, and especially if climate change will persist to increase droughts in these regions, aridity will more and more become the driver of environmental migrations and of the related widespread of climate refugees. In fact, when aridity endures, freshwater inevitably becomes a limiting factor for crops, livestock and domestic consumption, while food security, in some cases already representing a serious concern, will become even more challenging (Robins and Fergusson 2014). Although, populations are trying to adapt to this situation, for many this will imply a conscious move to another place to survive. Such moves may spark conflict with other communities, as an increasing number of people will compete for a decreasing amount of resources (UNHCR 2017). In this context, environmental migrants are defined as people who, “for reasons of sudden or progressive changes in the environment that adversely affect their lives or living conditions, are obliged to leave their habitual homes, or choose to do so, either temporarily or permanently, and who move either within their territory or abroad ” (IOC 2017). For example, Morocco, Tunisia and Libya each lose more than 1,000 Km^2 of productive land every year due to desertification (Prakash 2016) and residents on the edge of the Sahara Desert are forced to move to cities in the Maghreb (North Africa) and/or in Europe. Therefore, under these conditions it is fundamental to assess the role of renewable groundwater as the key to water resource security in semi-arid areas, and consequently to perform sound multidisciplinary investigations that can support new science-based management practices able to achieve its protection in the long-term. In fact, it is well known that in arid and semi-arid zones, like in the Middle East and North Africa (MENA region), groundwater often constitutes the main source of perennial water available for drinking, agricultural and industrial purposes (Zalidis et al. 2002; Re and Zuppi 2011; Bahir et al. 2012; Ouhamdouch et al. 2016), although the lack of adequate control over abstraction, fertilizers applications and waste disposal can lead respectively to aquifer over-exploitation (if withdrawal exceeds natural replenishment sates; Custodio 2002) and water quality degradation (Tropp and Jägerskog 2006; FAO 2011). Indeed, numerous studies revealed that major hydrological problems of arid or semi-arid rural zones in the MENA region are specifically associated to salinization, pollution and climate change. For example, the high salinity registered in the Souss basin (Southwest of Morocco) is explained by seawater intrusion and agricultural return flow, coupled with the decline of groundwater level. Together, these processes pose serious problems to the agricultural and domestic water supplies and hamper the future groundwater availability (Bouchaou et al. 2008). In the Mediterranean side of Morocco, the Bou-Areg coastal aquifer is characterized by a high salinization, due to both natural processes (namely water-rock interactions) and human impacts due to agricultural return flows, making water unsuitable for irrigation practices and implying that farmers have to resort to alternative water resources, often with higher costs (Re et al. 2013; Re and Sacchi, 2017). Similarly, the high groundwater mineralization of Chougafiya basin, situated in the central part of Tunisia, is controlled by water–rock interactions followed by ion exchange reactions and the mixing process with *Sebkha* (salt deposits), which consequent pressure on groundwater quality by becoming unsuitable for basic needs (Farid et al. 2013). In addition to natural and anthropogenic salinization and groundwater over-exploitation, climate change may exacerbate already existing water scarcity issues. For example, the El Daba'a shallow aquifer, located in north-west of Egypt, is currently facing a severe water crisis as a result of reported droughts affecting the Southern Mediterranean coast (Yousif et al. 2015). Consequently, as in many other countries of the MENA region, Tunisian authorities are becoming aware that water resources used to supply domestic and agricultural needs are limited (Gaaloul et al. 2014; Ayadi et al. 2016), and actions should be undertaken to prevent water crisis. The Grombalia coastal region, subject of the present study, is one of the most important agricultural areas in north-east Tunisia, which suffers from groundwater quality degradation and intensive exploitation. In fact, in this region, like in several developing countries, the water supply network is not available for all the households and hence most of the local inhabitants, especially in the rural areas, depend on groundwater for their basic needs. However, the often unregulated abstraction and widespread contamination often limits its suitability for drinking and irrigation purposes (Lachaal et al. 2016; Kammoun et al. 2018). This critical situation of water stress is the driver of several socio-economic issues, as discussed by Tringali et al. (2017): (i) decrease of crop production; (ii) farmers' migration from rural areas towards cities in search of new activities, and (iii) poverty increase due to loss of agricultural work. Therefore, a good knowledge of Grombalia aquifer system is the main challenge for the development of such an important agricultural district and can be the driver for a new socio-economic development that takes into account both the environmental issues and needs of local populations (Re 2015). In particular, to assure a suitable groundwater management in the long-run, besides assessing the drivers of groundwater contamination, it is fundamental to reach a better knowledge of the aquifer system as a whole, also taking into account its responses to seasonal variations. In fact, despite several studies have already been carried out within this basin, the majority were only targeting the shallow aquifer, which is the most exploited and most contaminated (e.g. Hamza et al. 2010; Ben Moussa and Zouari 2011; Charfi et al.

2013a; Tlili-Zrelli et al. 2013; Gaaloul et al. 2014). As a consequence, there is currently little knowledge on the deep aquifer and on the main processes regulating its chemistry and quality (Charfi et al. 2013b; Lachaal et al. 2016; Re et al. 2017). Indeed, a complete assessment would permit to gain further understanding on the overall groundwater availability and its potential to sustain human activities and natural ecosystems.

This work therefore aims at (i) performing a complete groundwater quality assessment of the multilayer aquifer system of Grombalia using multi-tracer hydrogeochemical approach, (ii) assess the effect of seasonal variations on groundwater quality, and (iii) present a preliminary evaluation of the interactions between the shallow and deep aquifers. Overall this investigation can demonstrate the fundamental role of multidisciplinary hydrogeological assessment to support sustainable development in arid and semi-arid regions, highlighting the crucial role that adequate groundwater management can play to reduce poverty and environmental migrations.

2. Site description

Grombalia Basin is a part of the Cap Bon peninsula located in the north-eastern part of Tunisia (Fig. 1). It extends between latitudes 36°29'00"- 36°42'00"N and longitudes 10°27'00"- 10°47'00"E and covers a surface of 719 Km^2. It belongs to Northern hemisphere and according to specific weather conditions, the year is divided into four meteorological seasons: summer (June, July, August), fall (autumn: September, October, November), winter (December, January, February) and spring (March, April, May). The studied area is characterized by a semi-arid climate with an alternation of dry (summer and spring) and rainy (winter and fall) seasons, influenced by humid air masses coming from the Mediterranean Sea. The average annual precipitation in the region is approximately 506 mm/year, 60% of which occur from November to March, while it hardly rains in summer and early autumn seasons (CRDA; calculated over a period of 1954-2015). As concerns the period object of the present investigation, the mean precipitation recorded between 2014 and 2015 was about 458 mm (with monthly precipitation of 61 mm in February-March 2014, 13 in September 2014 and 106 mm in February 2015).The atmospheric temperature (T) is very low in winter (T = 7 °C) and very high in summer (T = 32 °C; CRDA 2015). The mean potential evapotranspiration is about 920 mm/year, varying in time and space depending on climatic parameters and surface occupation (i.e. vegetation cover, lake, river, bare soil, buildings; Bahir et al. 2012), therefore higher potential evapotranspiration is generally registered in July and August (CRDA 2015).

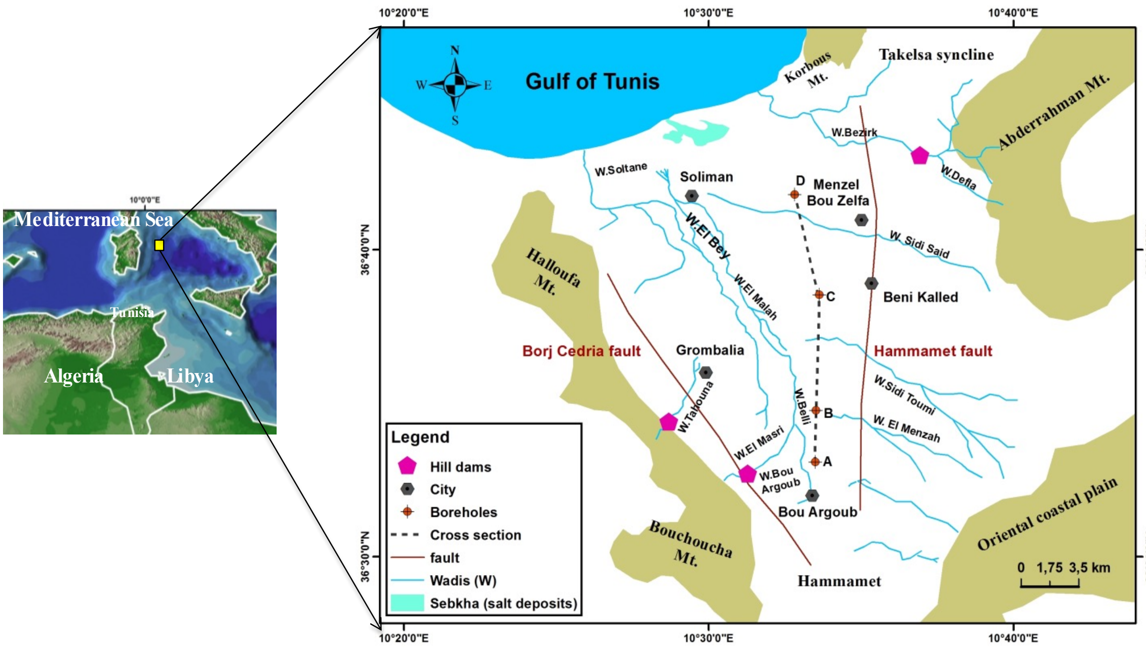

Fig.1 Localisation of the study region: Grombalia basin (North-east of Tunisia)

From a geological point of view, Grombalia plain is defined as a graben characterized by NW-SE direction (Castany 1948). The graben structure was related to two normal faults, Borj Cedria (NNW–SSE) and Hammamet (NE–SW), that appeared during the Middle Miocene (Hadj Sassi et al. 2006).

The groundwater system of Grombalia is composed by shallow and deep aquifers which are separated by a thick clay layer (Ben Moussa and Zouari2011). The shallow aquifer is filled by Quaternary sediments (alluvium, sands, and sandy clays) reaching to 50 m depth, whereas the deep aquifer is composed by Miocene series (Beglia Formation), i.e. essentially by sandstone deposits (Fig. 2). These two aquifers are often communicating via sandy clay semi-permeable layers (Ennabli 1980; Hadj Sassi et al. 2006; Charfi et al. 2013b; Lachaal et al. 2016). Hydraulic conductivity values range from 5.4×10^{-6} (north and west of the plain) to 6.5×10^{-3} m/s (in the south and east part of the plain) according to Charfi et al. (2013). The aquifer transmissivity varies between 25×10^{-4} and 2×10^{-2} m²/s and the storage coefficient is equal to 5.5×10^{-3} (Tlil-Zrelli et al. 2013).

The hydrographical network in this region is well developed and composed of several rivers (*wadis*) with permanent or ephemeral regime. The most important river is Wadi El Bey, which constitutes the main water supply in this region. Given the relatively large amount of water provided by Wadi El Bey, two dams (Masri and Tahouna) were built to ensure a better management of surface water resources.

In terms of economic activities, the studied region is primarily known for its intense agricultural activities. The latter include viticulture, arboriculture, cereals and livestock. Secondly, it is also characterized by its industrial activities, such as agro-food industries, textiles and dairy products. All activities are highly water-dependent, and can possible cause water deficit in the region. Therefore, the Medjerda-Cap Bon canal was set up to ensure the transfer of surface water from the north, i.e. from several dams built on the country's longest river, the Medjerda, to Grombalia region. The transferred water has been used for irrigation and for artificial recharge in some wells since 1992. Despite artificial recharge and irrigation by the Medjerda-canal water, the piezometric state of the whole aquifer system is currently continuing to decline. This basin is being exploited by wells from 20 to 40 m of depth. The exploitation of shallow aquifer was estimated at 106.0 Mm^3 in 2015, which exceeds (of almost the double) renewable resources estimated at 51 Mm^3/year (DGRE 2015). For the deep aquifer, the exploitation has passed from 2.16 Mm^3 in 1990 to 21.62 Mm^3 in 2014, due to the increasing construction of deep boreholes (more than 500 along the Grombalia plain) whose depths could reach to 160 m, while the renewable resources are estimated to 9.5 Mm^3/year (DGRE 2015). Therefore, both aquifers suffer from an over-exploitation of water resources.

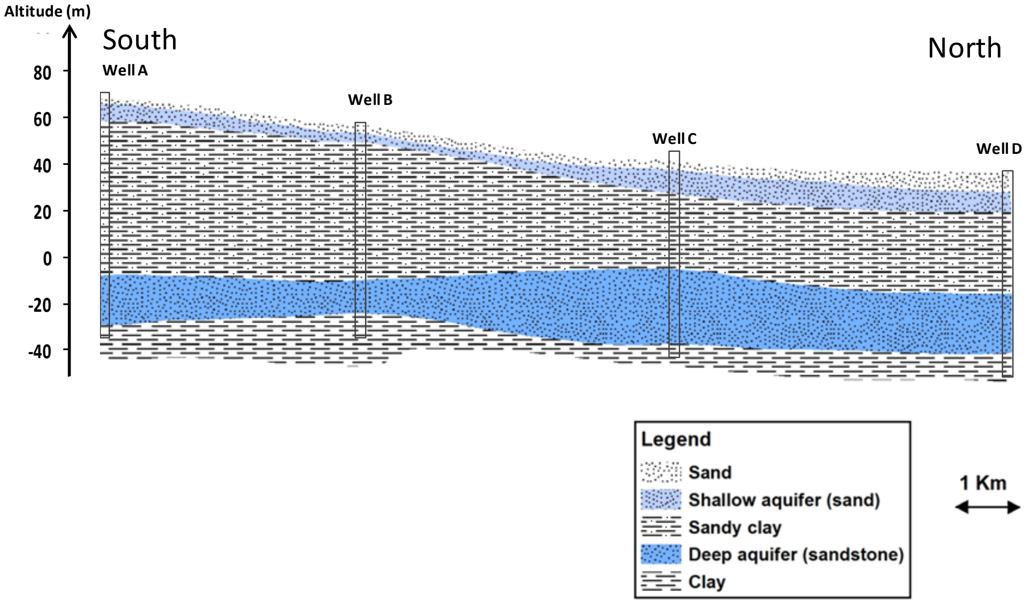

Fig.2 Hydrogeological cross section (Data source: CRDA 2015)

3. Materials and methods: data acquisition and methodology used

Sampling of groundwater within the Grombalia region was carried out on a six-month basis during three campaigns. A total of 116 samples were collected from the existing wells and boreholes (Fig. 3) at several periods: (i) between February and March 2014 (spring 2014), (ii) in September 2014 (fall 2014) and (iii) in February 2015 (spring 2015). The second and third sampling campaigns were targeted to assess the occurrence of chemical and isotopic content evolution following seasonal variations. The spatial distribution maps of the sampling points were performed using the software package of Arc GIS (Ver. 9). Chemical analyses and isotopic measurements were conducted at the Radio-Analysis and Environment Laboratory of the National Engineering School of Sfax (Tunisia). Major elements (Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, SO_4^{2-} and NO_3^-) were analysed by means of high performance ion liquid chromatography (HPLC). Carbonate and bicarbonate concentrations were analysed by titration using HCl acids (0.1N) and phenolphthalein and methyl red as colour indicators. The ionic balance for all samples was within ± 5%. Stable isotope ratio ($^{18}O/^{16}O$ and $^2H/^1H$) analyses were performed using the Laser Absorption Spectrometer LGR DLT 100 (Penna et al. 2010). Results are reported in ‰ vs. SMOW (Standard Mean Oceanic Water) with an analytical error ± 1 for δ^2H and ± 0.1 for $\delta^{18}O$. Tritium analyses were performed using electrolytic enrichment and liquid scintillation counting (Taylor 1976). Tritium concentration is expressed in tritium unit (TU), according to isotope ratio $^3H/^1H = 10^{-18}$, with an analytical error equal to 0.3.

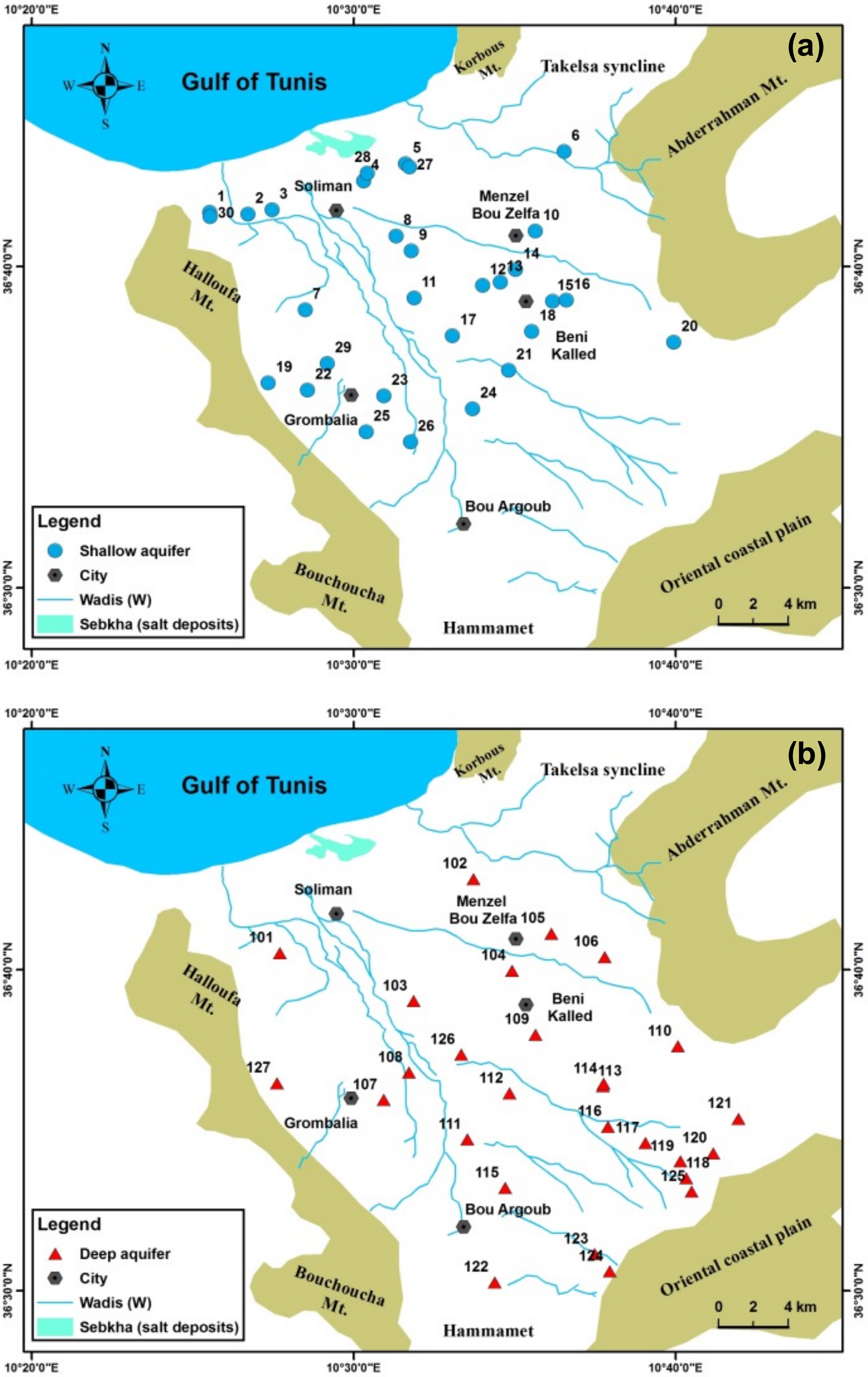

Fig. 3 Sampling map in the Grombalia basin for: **a** shallow aquifer; **b** deep aquifer

4. Results and discussions

4.1. Water table monitoring

Water table monitoring and piezometric studies were established based on available data for the year 2014 provided by the Regional Commissariat for Agricultural Development of Nabeul -Tunisia (CRDA 2015). The piezometric study aims to determine water level depth and to temporarily and spatially monitor its evolution.

Figure 4 shows that water level depth is season-dependent, increasing in rainy season (in April) and decreasing in dry one (in September), for both aquifer layers, except for wells S8 and D4 from shallow and deep aquifers respectively. These two samples, located close to artificial recharge sites, recorded a slight water level rise with less than one meter. For the shallow groundwater, the average fluctuation is about 1.2 m with the maximum decrease (4.3 m) observed in well S11 and the maximum increase reach to 3.8 m in well S8. Whereas for the deep aquifer, the maximum decrease is about 2.9 m (well D4) and the maximum increase reach to 2.3 m (well D3) with an average fluctuation of about 0.7 m. Therefore, seasonal fluctuations of water level depths are higher in shallow aquifer rather than in the deep one. This could be related to the variability of precipitations, recharge and exploitation rate.

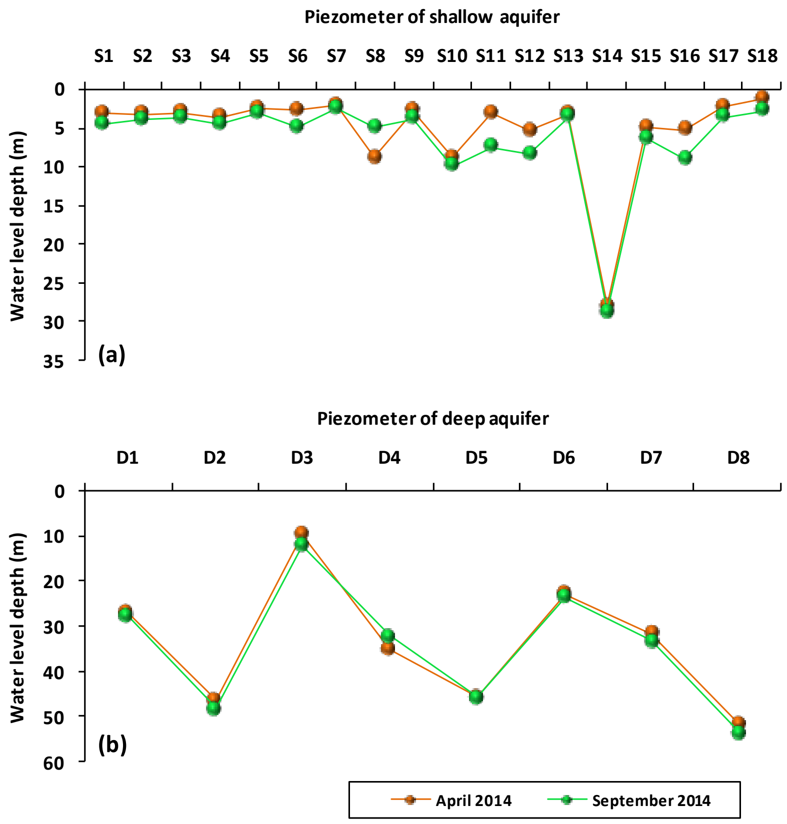

Fig. 4 Seasonal fluctuation of water levels depths in 2014 for: **a** shallow aquifer; **b** deep aquifer (CRDA 2015)

The study of the groundwater piezometry in Grombalia basin, for shallow and deep aquifers, permitted to identify groundwater flow direction, recharge zones and the interconnection between these two aquifer layers. For both aquifers, piezometric levels decrease from the south towards the north of the plain, passing from 60 to 10 m for the shallow aquifer and from 140 to 20 m for the deep one (Fig. 5). Two main recharge zones can be identified: one is located in the east of the plain, corresponding to foothills of Abderrahman Mountain, and one in the south-east part, close to the Bou Argoub region, resulting in a main SE-NW groundwater flow direction, hence from upstream towards downstream of the basin (the depression of Sebkha El Malah and the Gulf of Tunis). In Beni Kalled and Menzel Bou Zelfa regions, the piezometric curves are tighter, reflecting a strong hydraulic gradient which can be explained by high groundwater abstraction rates in these areas. Furthermore, downstream of the basin, the piezometric curves become more spaced with a low hydraulic gradient due to the decrease in exploitation of the deep aquifer. In addition, the piezometric map (Fig. 5) highlights the possible recharge of the deep aquifer by shallow groundwater, driven by the lithology and the structure of the intermediate formations, and/or in presence of existing micro faults contributing to this direct recharge.

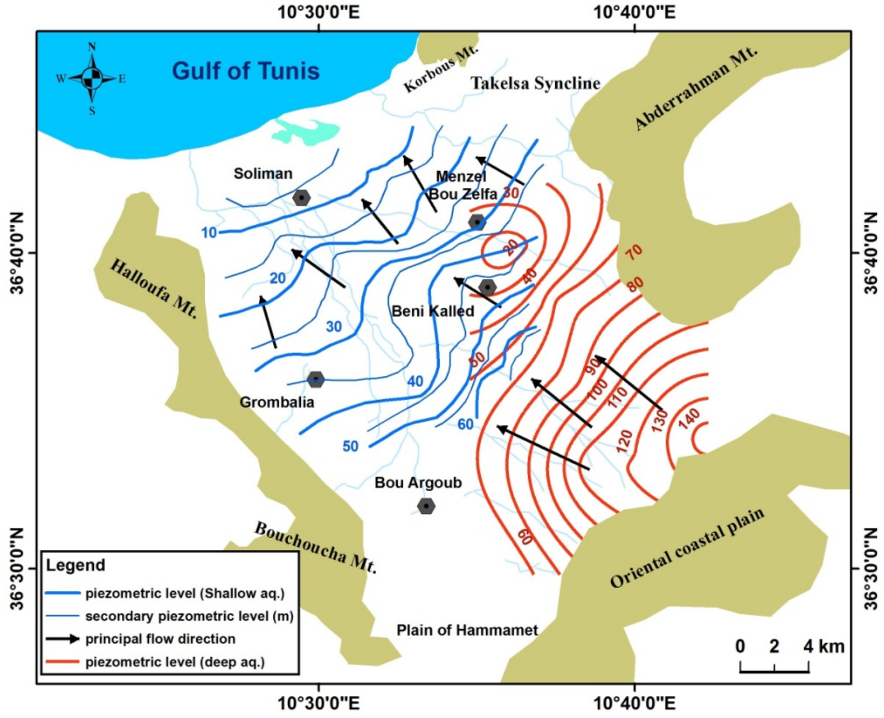

Fig. 5 Piezometric map of shallow aquifer (*blue lin*es) and deep aquifer (*red lines*) in 2014 (Data source: CRDA 2015)

4.2. Mineralization origin and quality assessment

The physico-chemical data of the analysed groundwater samples (Table 1 and 1S in Electronic supplementary material) show a relatively wide range of temperature values. For the first campaign of spring 2014, temperature values range from 15.7 to 21.3 °C (mean 18.2 °C) in the shallow aquifer and from 15.8 to 23.7 °C (mean 20.4 °C) in the deep aquifer. For the second and third sampling campaigns, temperature values decreased slightly in spring and increased in fall season. This variation is related to the water level depths and the influence of atmospheric temperature. The pH values are generally neutral for all samples collected from both aquifers during all campaigns. The average electrical conductivity (EC) for the shallow groundwater samples, collected in spring 2014, is about 3867.7 µS/cm varying within a wide range of values, from 1039 µS/cm (well 23, located in the south-western part of the plain) to 9180 µS/cm (well 1, the nearest well to the Mediterranean Sea). For the deep aquifer, EC values range from 1042 (well 122) to 14020 µS/cm (well 108), with an average value equal to 2640.1 µS/cm. These values confirm the high mineralization of groundwater in Grombalia basin. Variation of water quality is a function of physico-chemical parameters and chemical composition that are greatly influenced by both the geological nature of the reservoir and anthropogenic activities (Subramani et al. 2005).

Table 1 Descriptive statistics of chemical and isotopic parameters. Concentrations of major ions are expressed in mg/L; water hardness is expressed as milligrams of calcium carbonate equivalent per litre (mg/L of $CaCO_3$); isotopic values as ‰ vs. SMOW and tritium values are expressed in TU.

		T	**pH**	**EC**	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**CO_3^{2-}**	**HCO_3^-**	**Na^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**TDS**	**Hardness**	**δ^2H**	**$\delta^{18}O$**	**Tritium**
		°C		**µS/cm**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**‰ vs. SMOW**	**‰ vs. SMOW**	**TU**
Shallow Spring 2014	Min.	15.7	6.9	1039.0	112.4	0.0	145.3	0.0	164.7	111.1	0.0	26.1	69.0	715.4	280.0	-37.1	-5.4	0.6
	Max.	21.3	7.8	9180.0	2932.4	514.7	759.6	0.0	481.9	1193.7	40.3	292.3	775.2	6357.5	3140.0	-20.8	-3.5	5.6
	Mean	18.2	7.2	3867.7	838.8	148.0	434.1	0.0	332.5	397.5	16.8	99.9	349.5	2617.0	1283.0	-28.4	-4.6	2.4
	Std. dev	1.4	0.2	1538.1	534.1	140.9	165.0	0.0	75.8	220.0	10.7	54.2	156.8	1110.9	569.0	3.2	0.5	1.2
Shallow Fall 2014	Min.	20.0	6.7	1872.0	290.0	2.2	216.5	0.0	195.2	143.4	3.8	46.5	151.6	1197.9	570.0	-32.1	-5.2	1.3
	Max.	25.8	7.4	7400.0	2101.9	444.8	847.7	12.0	486.7	864.9	37.4	221.2	610.3	4556.8	2150.0	-17.5	-2.1	2
	Mean	22.8	6.9	3871.4	796.3	137.5	464.0	0.7	319.8	373.7	16.4	111.5	338.2	2558.0	1303.0	-27.9	-4.5	2.8
	Std. dev	1.7	0.2	1517.5	464.0	141.9	193.0	3.0	86.8	203.1	9.5	53.7	138.7	963.7	491.0	3.5	0.7	0.7
Shallow Spring 2015	Min.	13	6.57	714	57.59	0.0	82.125	0.0	164.7	68.15	4.9	17.185	50.035	524.925	200.0	-35.3	-5.8	-
	Max.	21.2	7.7	9560.0	2889.3	430.5	695.5	0.0	445.3	1201.9	40.5	257.1	621.7	5967.5	2610.0	-25.0	-3.7	-
	Mean	17.0	7.0	3818.6	876.8	114.7	423.5	0.0	312.4	425.8	14.4	98.9	304.0	2570.4	1166.0	-28.7	-4.8	-
	Std. dev	2.3	0.3	2013.5	623.4	141.8	174.1	0.0	74.3	264.0	9.3	57.5	152.7	1268.4	571.0	2.4	0.5	-
Deep Spring 2014	Min.	15.8	7.0	1042.0	107.3	2.0	23.8	0.0	128.1	72.8	4.2	12.7	31.6	727.2	230.0	-34.8	-6.1	0
	Max.	23.7	7.7	14020.0	3436.0	230.6	3105.0	42.0	688.0	1888.4	63.6	557.3	696.5	10177.4	4030.0	-28.7	-4.5	2.4
	Mean	20.4	7.2	2640.1	473.3	55.7	383.0	4.8	321.3	275.9	16.1	89.7	181.8	1801.5	823.0	-31.8	-5.4	1.0
	Std. dev	1.4	0.2	2587.8	650.6	62.1	777.1	11.1	99.9	359.0	15.0	114.0	157.6	1938.0	840.0	1.7	0.4	1.0
Deep Fall 2014	Min.	22.0	6.7	1089.0	106.0	1.0	9.8	0.0	244.0	73.8	3.5	15.8	34.7	628.8	200.0	-34.3	-6.2	1
	Max.	27.7	7.4	5310.0	1214.8	148.1	640.1	36.0	396.5	511.3	22.4	160.9	269.7	3145.5	1330.0	-28.2	-4.6	1.1
	Mean	23.9	7.0	2156.3	358.5	30.6	201.1	11.3	316.9	202.6	11.6	68.0	134.5	1335.0	615.0	-31.0	-5.5	1.2
	Std. dev	1.5	0.2	1100.3	289.4	38.4	174.0	14.7	46.3	118.7	6.0	40.4	78.2	676.2	344.0	1.4	0.4	0.1
Deep Spring 2015	Min.	11.4	6.9	1077.0	112.5	0.0	30.1	0.0	140.3	83.7	3.1	11.4	65.2	755.8	350.0	-33.4	-5.9	-
	Max.	21.1	7.5	5120.0	1230.7	217.8	580.2	0.0	457.5	647.3	23.4	161.7	345.7	3263.0	1330.0	-28.5	-4.5	-
	Mean	17.1	7.1	2299.2	424.9	46.2	200.7	0.0	342.0	212.4	9.4	66.0	161.8	1463.4	677.0	-31.2	-5.4	-
	Std. dev	3.4	0.2	1045.9	285.9	59.1	155.8	0.0	83.1	143.2	5.1	35.6	82.2	651.6	292.0	1.6	0.4	-

The chemical compositions of analysed samples were plotted on Piper diagram in order to specify the different groundwater types for both the shallow and the deep aquifers, and to assess their seasonal evolution (Fig. 6). The majority of the samples collected in the shallow aquifer belong to the mixed pole in the triangle of cations, whereas some groundwater samples present a slight dominance either of calcium or sodium. In the triangle of anions, the same variability can be highlighted, with predominance either of chloride, bicarbonate or sulphate. Therefore, based on the distribution of samples in the Piper diagram and the calculated percentage of each ion, it emerges that for the shallow aquifer, there is an absence of dominant *facies*. For the shallow aquifer, groundwater can be classified as mixed water type (76%), Ca(Na)-Cl (17%) and Na(Ca)-Cl (7%). On the other hand, for the deep aquifer, the mixed water type constitutes 86% of the samples, although some samples display either a Ca(Na)-Cl (5%) or Na(Mg)-Cl (4%) water type. Additionally, for some samples located in proximity of the recharge zone (i.e. the foothills of Abderrahman Mountain), sodium and bicarbonate are the dominant ions Na-HCO_3 (5%).

The difference of water type from one region to another could be explained by an evolution according to transit time and/or the transition of formations' lithology, passing from continental deposits (in the south) to marine deposits close to Gulf of Tunis (Charfi et al.2013b). The similarities of chemical *facies* for some samples collected from shallow and deep aquifers suggest a possible groundwater mixing (Re et al. 2017). The Piper diagram also highlights the absence of significant influence on groundwater types of seasonal variations. The latter may affect ion concentration, but without changing the overall water type.

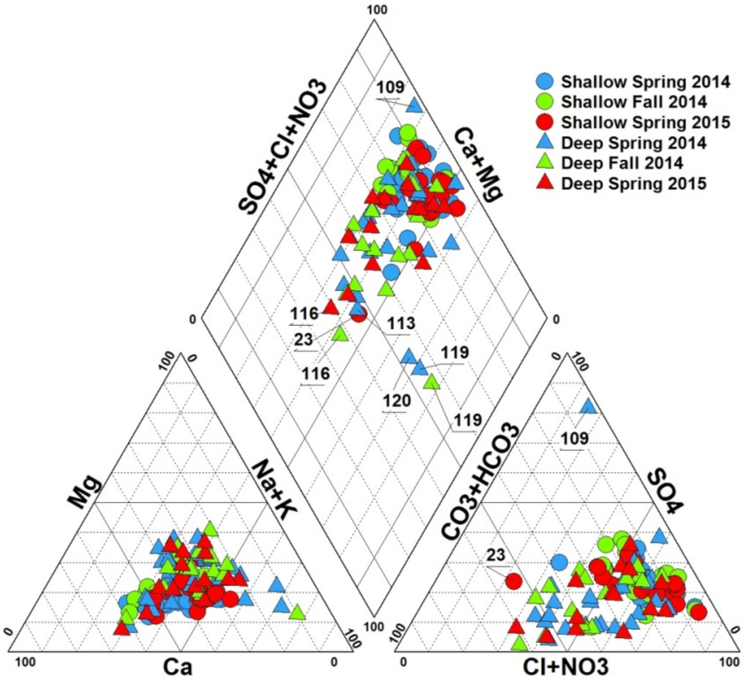

Fig. 6 Piper diagram of the Grombalia aquifer system

In fact, the evolution of groundwater chemical composition for some samples from both shallow and deep aquifers, (Fig. 7 and Fig. 8) highlights the variability of major elements concentrations from one season to another, that mainly depends on atmospheric temperature, controlling evaporation process, aquifer recharge and return flow of irrigation water (Ben Moussa et al. 2011).

The principal process contributing to aquifer mineralization, as discussed by several authors (Ben Moussa and Zouari 2011; Charfi et al. 2013; Lachaal et al. 2016; Re et al. 2017; Kammoun et al. 2018) and also confirmed by the present survey, is the dissolution of evaporates (such as halite: NaCl, gypsum: $CaSO_4$, $2H_2O$ and anhydrite: $CaSO_4$) generally existing in sedimentary deposits. These dissolution processes can be highlighted by both the strong correlation between sodium *versus* chloride (Figs 7a, 8a) and calcium *versus* sulphate (Figs 7b, 8b), and also by the under-saturation state for most of samples with respect to halite, gypsum and anhydrite. Figures 7c and 8c show a poor correlation between calcium and bicarbonate indicating the inability of water to dissolve carbonate minerals.

Thus, calcium excess and sodium deficiency characterizing some samples suggest that other mineralization processes should be considered, such as the ion exchange reactions that significantly affect water chemical composition, by which the Na^+ minerals are adsorbed on the surface of clay minerals against the release of Ca^{2+}. The ion exchange process was confirmed by the relation between $[(Ca^{2+}+ Mg^{2+}) - (HCO_3^- + SO_4^{2-})]$ and $[Na^+ + K^+ - Cl^-]$, as reported by Garcia et al. (2001), (Figs 7d, 8d).

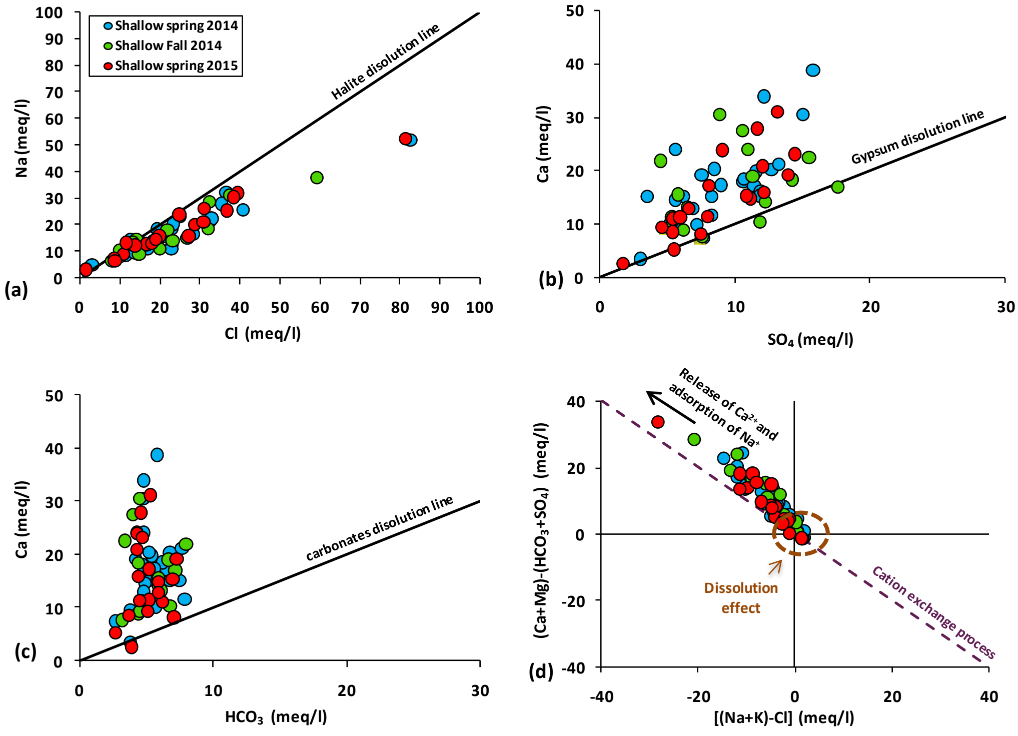

Fig. 7 Relationship between major elements for shallow aquifer samples: **a** Na *versus* Cl; **b** Ca *versus* SO_4; **c** Ca *versus* HCO_3; **d** (Na + K) – Cl *versus* (Ca + Mg) - (SO_4 + HCO_3)

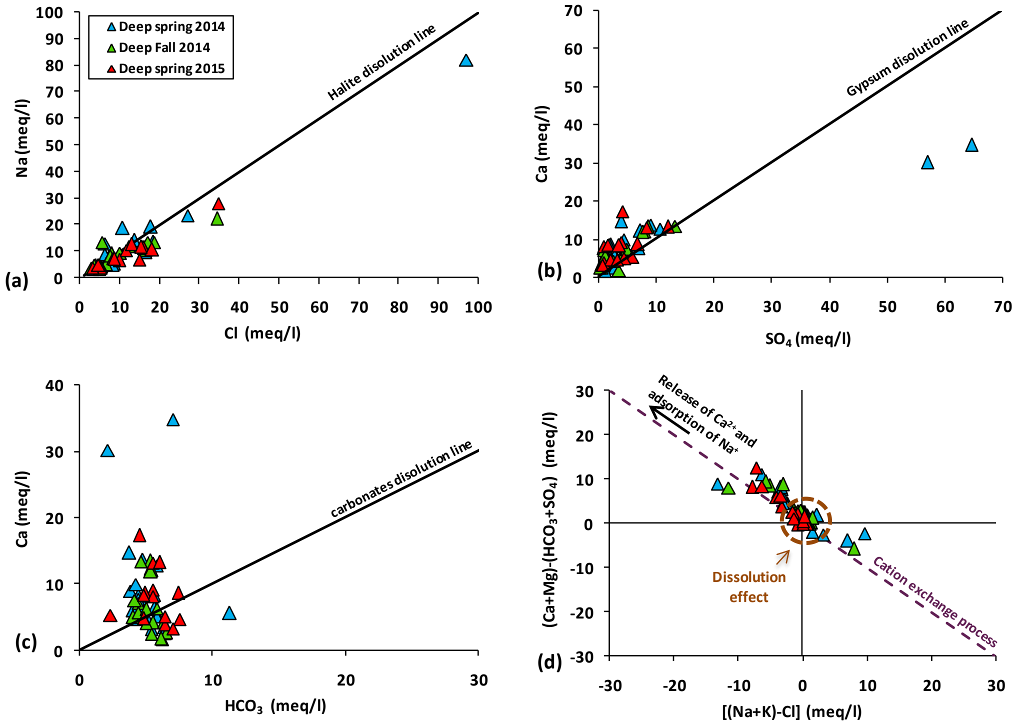

Fig. 8 Relationship between major elementsfor deep aquifer samples: **a** Na *versus* Cl; **b** Ca *versus* SO_4; **c** Ca *versus* HCO_3; **d** (Na + K) – Cl *versus* (Ca + Mg) - (SO_4 + HCO_3)

In addition, previous studies focusing on nitrate pollution (Hamza et al. 2010; Chenini et al. 2015; Re et al. 2017; Ben Moussa and Zouari 2011; Charfi et al. 2013a) highlighted their significant influence on groundwater salinization and quality degradation. As concerns the spring 2014 campaign, results shows that there are about 70% of the shallow aquifer's samples and 41% from the deep one that exceed the statutory limit for drinking (50 mg/L; WHO 2011). The highest nitrate concentrations are especially found in regions where agricultural activities are dominant, hence associated to the high potential for contamination due to agricultural return flow (Kammoun et al. 2018). On the other hand, relatively low nitrate concentrations are observed in the deeper wells which can be explained by denitrification process that occurred in anaerobic condition. Several studies have shown the agricultural source of contamination in this region (Chenini et al. 2015; Lachaal et al. 2016) whereas, Zouari et al. (2015) and Re et al. (2017) revealed that besides agricultural activities (fertilizers and manure application), nitrates are also generated by urban/domestic activities, due to the lack of adequate sanitation systems in some parts of the plain.

In addition to nitrate pollution, high values of electrical conductivity make this water in doubtful suitability for irrigation use. Analytical data for the three sampling campaigns show that 67% of the total samples collected from shallow aquifer and 20% from the deep one are characterized by EC > 3000 µS/cm, therefore they are considered as unsuitable for irrigation use. Also, the high values of calcium that characterise most of samples, can affect water hardness and water suitability to both human consumption and irrigation. For example, the calculated hardness values of samples collected in spring 2014 are very high, ranging from 280 (well 23) to 3140 mg/L (well 1) for shallow aquifer and from 230 (well 120) to 4030 mg/L (well 108) for the deep one. This could be explained by water-rock interaction processes, as water flowing through aquifer formations' may dissolve calcium and magnesium minerals. In addition, the excessive use of $Ca(NO_3)_2$ and $MgSO_4$ fertilizers may increase water hardness, highlights the indirect role of nitrate fertilizers, inducing an acidic perturbation of the solution which is buffered by carbonate dissolution, leading to an increase in water hardness (Spruill et al. 2002). According to these high levels, the consumption of this water can have negative consequences for human health.

Since groundwater resources are mainly used for irrigation in the study area, monitoring of water suitability for irrigation is crucial. Therefore, the different irrigation parameters: sodium percentage (%Na), permeability index (PI), magnesium adsorption ratio (MAR), and sodium adsorption ratio (SAR) are calculated according to the following equations (1, 2, 3 and 4):

$$\%Na = \frac{(Na+K)}{(Ca+Mg+Na+K)} * 100 \qquad (1)$$

$$PI = \frac{(Na+\sqrt{HCO3})}{Ca+Mg+Na} * 100 \qquad (2)$$

$$MAR = \frac{Mg}{Ca+Mg} * 100 \qquad (3)$$

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \qquad (4)$$

Where, all ion concentrations are expressed in meq/L (Table 1S in Electronic supplementary material and Table 2).

Regarding sodium percentage values, all groundwater samples are permissible for irrigation except two samples (wells 119, 120) with %Na falling between 60 and 80%. Concerning the permeability index, all water samples with PI ranging between 0 and 75 are considered to be good and suitable for irrigation (Doneen 1964). Analytical data show that just two groundwater samples from deep aquifer (wells 119, 120) were not suitable for irrigation based on permeability index, whereas the rest of samples were good. In the study region, MAR values were found within a wide range. One groundwater sample (well 29) from shallow aquifer and ten samples from the deep one (wells 103, 108, 111, 113, 115, 116, 117, 119, 120, and 124), exceed the admissible limit of 50, that is considered harmful and unsuitable for irrigation purpose (Subramani 2005). It is important to evaluate soil exchange reactions and the probability of accumulation of sodium in the soil. For this purpose, Sodium Adsorption Ratio (SAR) is used to classify sodium hazards in irrigation water (Richards 1954).

The calculated SAR values of groundwater samples from the shallow aquifer, collected in spring 2014, range from 2.8 to 9.3. Some groundwater samples are characterized by low SAR values (wells 10, 16, 19, 20 and 23) but after taking into account their high electrical conductivity, these samples are considered as unsuitable for irrigation, especially in soils with restricted drainage (Subramani et al. 2005) and harmful for plants and crops, as the perennial woody species in Grombalia (e.g. orange, lemon, grapes), that have low to moderate salt tolerance. The majority of samples show very high water salinity with average values of SAR. This type of water can be used, under favourable drainage conditions, just for irrigation of semi-tolerant and tolerant salt cultures. Only three samples represent waters with very high salinity and high SAR (wells 1, 3 and 8). These samples are considered to be poor water quality and therefore unsuitable for irrigation, particularly on clay soils. For the deep aquifer, SAR varies between 1.6 and 12.9 of which a single sample (well 108) is greater than ten. The spatial distribution of SAR parameter (Fig 9), produced by ordinary kriging technique, shows that the higher values characterized samples located in the north of the plain (Soliman region), towards the sea, for both aquifers. For the deep aquifer, high SAR values also occur in Grombalia and Beni Kalled regions.

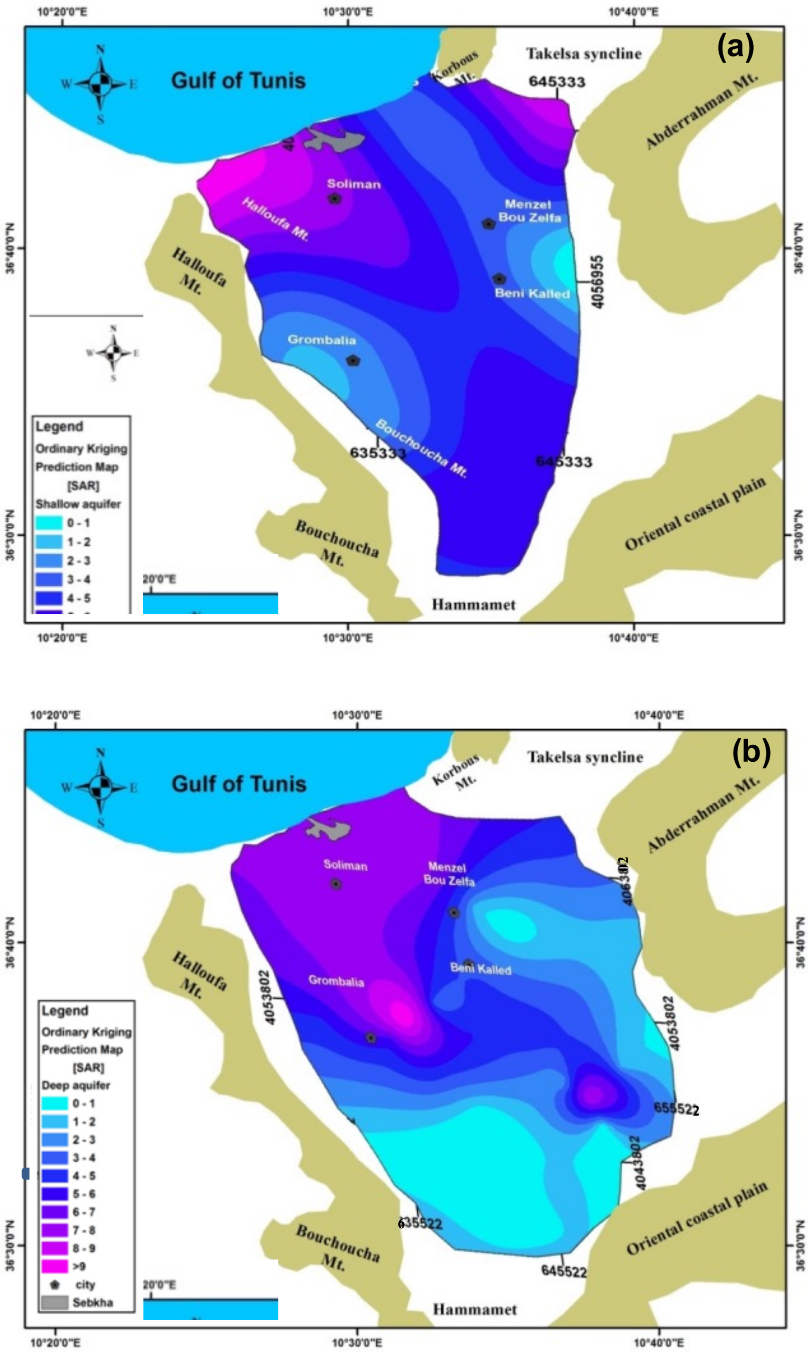

Fig. 9 Spatial distribution map of sodium adsorption ratio (*SAR*) produced by *ordinary kriging* method for: **a** shallow aquifer (spring 2014); **b** deep aquifer (spring 2014)

Table 2 Classification of irrigation water based on sodium adsorption ratio (SAR), magnesium adsorption ratio (MAR), sodium percentage (%Na) and permeability index (PI) and their variation under seasons

		SAR	MAR	%Na	PI
Shallow Spring 2014	Min.	2.8	18.0	26.3	31.5
	Max.	9.3	44.1	53.0	65.1

	Mean	4.7	32.2	40.6	46.3
Shallow Fall 2014	Min.	2.4	18.4	28.1	32.6
	Max.	8.1	49.0	49.6	56.2
	Mean	4.4	35.1	38.3	44.0
Shallow Spring 2015	Min.	2.1	18.8	33.3	37.7
	Max.	10.2	52.1	55.6	71.8
	Mean	5.2	34.9	43.9	50.8
Deep Spring 2014	Min.	1.6	12.0	26.3	26.6
	Max.	12.9	66.0	71.6	84.7
	Mean	3.9	43.3	41.1	52.4
Deep Fall 2014	Min.	1.6	15.5	28.5	37.7
	Max.	9.5	65.4	77.4	91.5
	Mean	3.6	46.0	42.2	54.7
Deep Spring 2015	Min.	1.7	10.4	29.2	39.9
	Max.	7.7	59.7	55.0	65.1
	Mean	3.4	40.9	39.7	51.4

4.3. Isotope composition of groundwater and recharge process

Stable isotopes of water molecule ($\delta^{2}H$,$\delta^{18}O$) are indicators of local conditions present at the moment of groundwater recharge (Faure 1986), and used to evaluate the physical processes affecting water masses, such as mixing and evaporation processes (Geyh 2000). The isotopic compositions of groundwater samples collected from the shallow aquifer range from -5.4 to -3.5‰ vs. SMOW for $\delta^{18}O$ and from -37.1 to -20.8‰ vs. SMOW for $\delta^{2}H$ (spring 2014). Isotopic signatures of the majority of groundwater sample are comparable to those of the local precipitation,–4.3 for $\delta^{18}O$ and –24.8‰ vs. SMOW for $\delta^{2}H$, in Tunis-Carthage meteoric station (N°6071500) according to the global network of isotopes in precipitation (GNIP 2007). This similarity indicates the aquifer recharge through rapid infiltration of rainwater. In the deep aquifer, isotopic values range from -6.1 to -4.5‰ vs. SMOW for $\delta^{18}O$ and from -34.3 to -28.2‰ vs. SMOW for $\delta^{2}H$ (spring 2014). It is seen from Fig.10 that most samples from both shallow and deep aquifers fall around the GWML (Global Water Meteoric Line) reported by Rozanski et al. (1993) according to the equation $\delta^{2}H= 8.17\ \delta^{18}O +10.35$ and the Local Meteoric Water Line of Tunis-Carthage (LMWL) with $\delta^{2}H = 8\ \delta^{18}O + 12.4$ reported by Zouari et al. (1985). This indicates that they originated from modern precipitation infiltration. According to the position of the points on the $^{18}O/^{2}H$ diagram three groups of groundwater have been identified. The first group (G1 in Fig.10) is characterized by the most enriched samples collected from shallow aquifer highlighting the significance of surface water input in the evolution of the observed isotopic composition, and/or the return flow of irrigation water affected by evaporation process. These samples generally present relatively high tritium values (> 2 TU) and high nitrate contents (> 50 mg/L).The second group (G2) represents the most depleted water samples, mainly from the deep aquifer, characterized by a different isotopic composition than present day precipitation.. This could be explained by the presence of old water recharged in a different period in the past. This hypothesis is supported by the very low tritium values characterizing these samples (Table 3).

Finally, a third group (G3) can be representative of mixing process occurring between recent and old groundwater. This explains the position of some points between the depleted and the relatively enriched stable isotopes, respectively representing the old and present day recharge water. Stable isotopes of the water molecule are related to the isotopic signature of the precipitation from which they derive, taking into account the atmospheric circulation which causes these masses of air that dominate well-defined seasons. In fact, rain is more depleted in winter and more enriched in summer. In addition, the fact that these two aquifer layers display similar signatures of δ^2H and δ^{18}O, especially for the third group, is a sign of water exchange between these two aquifers especially in the eastern part of Grombalia region (wells 8, 16, 104, 105, 110, 113, 114, 122, 126).

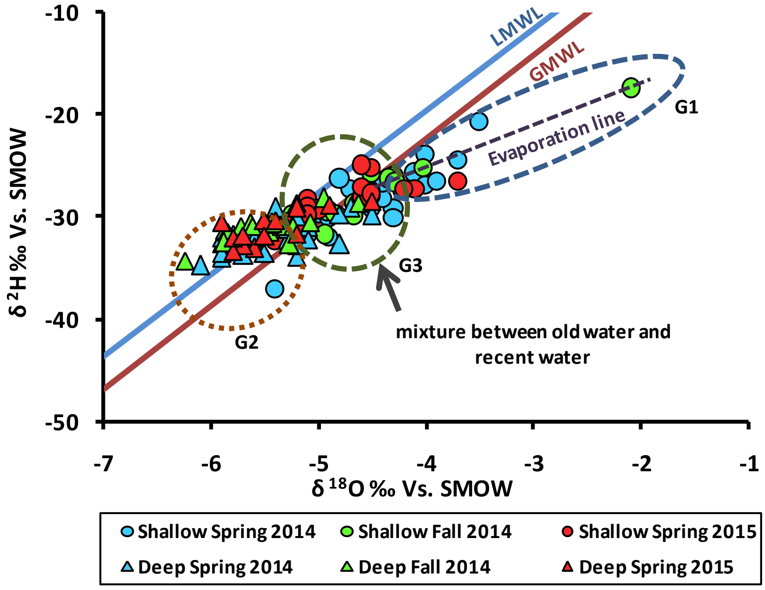

Fig. 10 Plot of δ^2H *versus* δ^{18}O of the shallow and deep groundwater samples during three campaigns, with *GWML* corresponds to Global Water Meteoric Line reported by Rozanski et al. (1993) according to the equation $\delta\ ^2H= 8.17\ \delta^{18}O +10.35$ and *LMWL* corresponds to Local Meteoric Water Line of Tunis-Carthage reported by Zouari et al. (1985) according to the equation $\delta^2H = 8\ \delta^{18}O + 12.4$.G1, G2 and G3 correspond to group 1, group 2 and group 3, respectively

The comparison of the isotopic composition (δ^{18}O, δ^2H) of groundwater between the different sampling campaigns is useful to assess the recharge evolution and the occurrence of seasonal variations. Analytical errors of isotopic measurements were considered with ± 0.1‰ vs. SMOW for $\delta^{18}O$ and ± 1‰ vs. SMOW for $\delta^{2}H$. The observed difference in isotopic composition is considered as not significant if variation values belong to the margin of analytical error. Figures 11 and 12 show a small variation in isotopic signatures for all sampling campaigns for both the shallow and the deep aquifer, except for two samples from the shallow one which are characterized by extreme values (wells 11 and 23). For the shallow aquifer, seasonal variation of isotopic composition is significant for samples 3, 11, 19, 23 and 26 for both $\delta^{18}O$ and for $\delta^{2}H$ contents (Fig. 11). In the deep aquifer (Fig. 12), stable isotopes variation is significant for wells n° 103, 104, 112, 113, 114, 116 and 117. These variations could be related to the change of climatic parameters from one season to another. These results reveal the relationship between isotopic composition and wells' depth. In fact, the most depleted samples represent the deeper wells whereas the most enriched samples characterize the nearest points to earth surface (i.e. situated at depths varying between 15 and 40 m). These points are more exposed to the phenomenon of evaporation, which depends on both atmospheric temperature and the degree of sunlight. Therefore, stable isotope compositions of the groundwater samples vary with the depth: going deeper into the aquifer the isotopic composition will be more depleted.

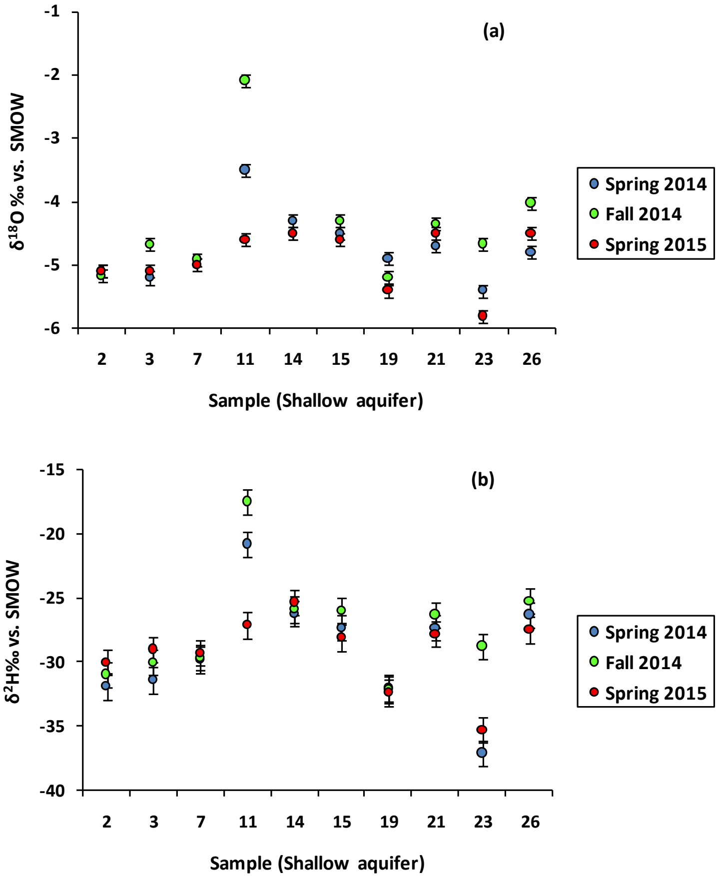

Fig.11 Seasonal variation of isotopic composition for shallow aquifer taking into account analytical error with: **a** δ^{18}O values with error rate of ± 0.1‰ vs. SMOW; **b** δ^{2}H contents with error rate of± 1‰ vs. SMOW

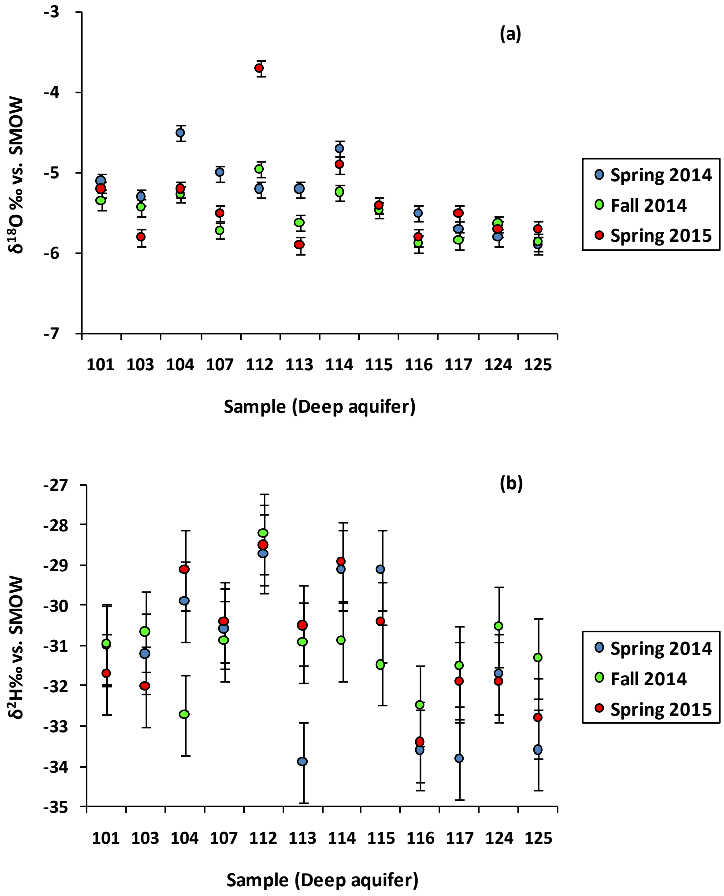

Fig.12 Seasonal variation of isotopic composition for deep aquifer taking into account analytical error with: **a**δ^{18}O values with error rate of ± 0.1‰ vs. SMOW; **b** δ^{2}H contents with error of ± 1‰ vs. SMOW

In fact, water temperature increased in dry season (fall 2014) for both aquifers, with temperature values ranging from 20 to 25.8 °C and from 22 to 27.7 °C for shallow and deep aquifers, respectively. As shown in Fig. 13, samples collected in fall 2014 in the deep aquifer are present the more depleted for δ^{18}O values, compared with the other campaigns. On the other hand, samples collected in the same period in the shallow aquifer are more enriched, meaning that this water is more affected by evaporative process than the one collected in spring season. This could be due to the semi-arid climate, characterizing the study area, with high variation of temperature and precipitation intensity. Therefore, for the shallow aquifer, temporal variations of water temperature are accompanied by a variation of δ^{18}Ocontents (same order of colour for the temperature and δ^{18}O). However, for the deep water, the temperature does not follow the same trend as δ^{18}Ocontents which mean that there are other processes that intervene other than evaporation (e.g. mixing processes and/or the variability of wells depths).

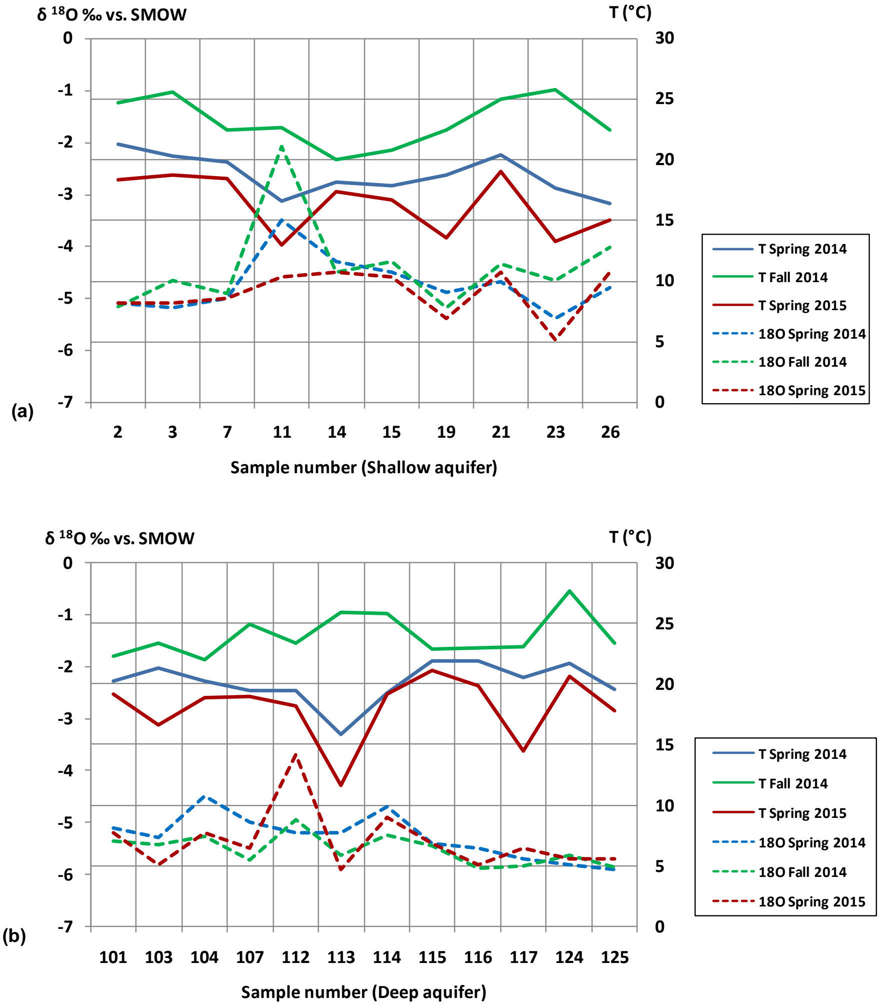

Fig. 13 Seasonal variation of isotopic composition (*$\delta^{18}O$*) and groundwater temperature (*T*) for: **a** shallow aquifer; **b** deep aquifer. *Continuous line* represented temperature line and *discontinuous line* represented δ^{18}O values

Tritium (^{3}H) analysis is very useful providing an indication of young water ages (Dulinski et al. 2003). Its short half-life is about 12.32± 0.02 years (Lucas and Unterweger 2000) allowing it to be used for identifying recent water recharge (< 50 years) according to Mann et al. (1982). Tritium contents in shallow aquifer samples vary between 0.6 and 5.6 ± 0.3 TU (Tritium Unit). Those of deep groundwater range from 0 to 2.4 ± 0.3 TU for spring 2014 period. More than 70% of water samples from deep aquifer present significant tritium values. As most samples from both shallow and deep aquifers are characterized by values greater than 0.65 TU, it means that most waters are post-nuclear recharged waters, i.e. groundwater recharged after the period of 1960 (Clark and Fritz 1997). These high values of tritium are found almost in the south-east of the basin. This means that direct infiltration of recent rain water, characterizing by tritium content around 5.9 TU (GNIP 2007), contributes to the groundwater recharge especially at the foothills of Abderrahman Mountain. Tritium variation may be due to the elevation effect and/or the recharge during the depleted winter period as there are depleted samples in $\delta^{18}O$ (equal to -6 ‰ vs. SMOW) with significant tritium levels.

Few water samples display low values of tritium, less than 0.65 TU. Such the absence of tritium in some samples (Wells 103, 115, 121, 122 and 124) could be explained by either an old origin of water or the existence of mixed groundwater in the studied basin system (Fig. 14). It means that aquifer recharge was likely occurred during a cooler climate in the past. These observations are agreeing with the previous results found by Charfi et al. (2013b), which proved that recharge of deep aquifer, in some sites of the basin, was occurred during the late Pleistocene and early Holocene periods based on carbon-14 analyses. The few samples taken during fall 2014 are characterized by lower values in tritium highlighting the limited recharge at the end of summer season.

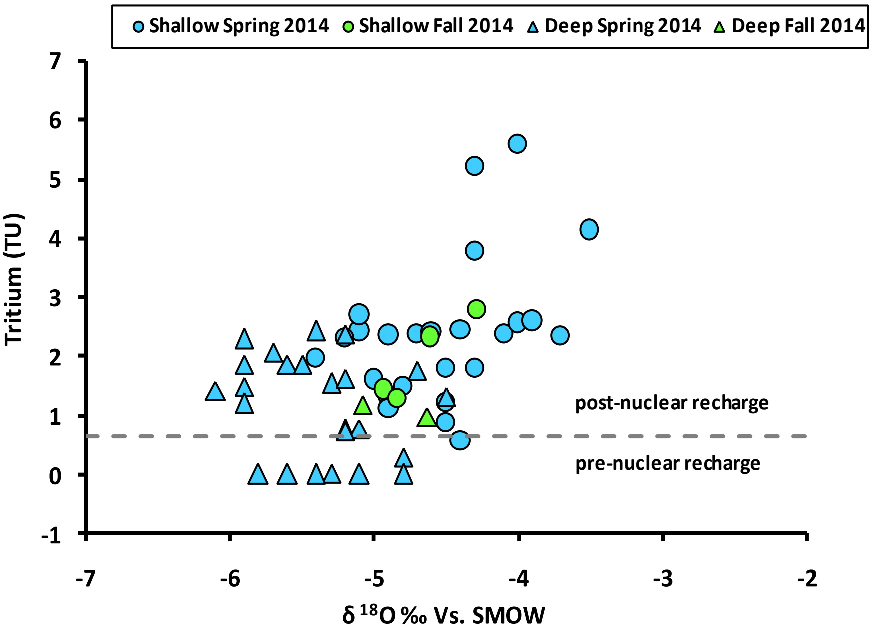

Fig. 14 Plot of tritium *versus* $\delta^{18}O$

4.4. Mixing process and quantifying groundwater flow exchange

Isotopic composition of shallow and deep aquifers may result from a contribution of shallow aquifer to the deep groundwater recharge. The variability of hydraulic head between these two aquifers, as shown in the piezometric map (Fig. 5), has increased by the over-exploitation of the shallow aquifer.

Thus, the deep aquifer would represent a mixing between old water and descending shallow groundwater, as suggested previously by the piezometric investigation. The mixing rate between shallow and deep groundwater, could be estimated using the isotopic mass balance (Trabelsi et al. 2009; Carreira et al. 2014; Ayadi et al. 2016) according to the equation (5) reported by Clark and Fritz (1997):

$$(X_1+X_2)\ \delta E_{sample} = X_1 \delta E_s + X_2 \delta\ E_d \quad (5)$$

With

X_1: fraction of shallow aquifer; X_2: fraction of deep aquifer with $X1+X_2=1$; and δE_{sample}, δE_s and δE_d representing the isotopic composition ($\delta^{18}O$ or $\delta^{2}H$) of the sample, shallow aquifer and deep groundwater respectively.

The mixing rates were calculated by isotope mass balance using both $\delta^{18}O$ and $\delta^{2}H$ for all samples during three campaigns. To study the contribution of shallow groundwater to the deep aquifer recharge, the mean values of isotopic composition adopted for the shallow aquifer are -4.6 ± 0.2‰ vs. SMOW for $\delta^{18}O$ and -28.5 ± 1‰ vs. SMOW for $\delta^{2}H$. The mean values of $\delta^{18}O$ and $\delta^{2}H$ used for the deep aquifer are -5.3 ± 0.2 and -31.6 ± 1‰ vs. SMOW, respectively. The results of the mixing rates are presented in Table 3. The 0% value means that there is no contribution, whereas 100% (well 104, campaign spring 2014) represent the maximum of contribution. Fifty-four percent of the total groundwater samples, collected during spring season in 2014, present no contribution of shallow aquifer to deep aquifer recharge, 27% have isotopic balance (IB) rates ranging between 1 and 50% and only 19% of samples present a high mixture rates varying between 51 and 100%. Computed values of the mixing proportion indicate that the descending vertical leakage of the Grombalia aquifer is significant in some region especially in north-east part of the basin where the contribution can reach 100%. According to isotope balance, as shown in Table 3, the mixture rate is most important in spring season. This is already highlighted by both $\delta^{18}O$ and $\delta^{2}H$ isotope balances except for some samples (e.g. 103, 124 and 125).

Table 3 Groundwater tritium contents and mixing rate (%) for the deep aquifer

Well	^{3}H (TU) Spring 2014	^{18}O IB (%) Spring 2014	^{2}H IB (%) Spring 2014	^{18}O IB (%) Fall 2014	^{2}H IB (%) Fall 2014	^{18}O IB (%) Spring 2015	^{2}H IB (%) Spring 2015
101	0	29	19	0	21	14	0
102	1.5	0	0	ND	ND	ND	ND
103	0	0	13	0	30	0	0
104	1.3	100	55	4	0	14	81
105	0.3	71	0	ND	ND	ND	ND
106	1.9	0	0	ND	ND	ND	ND
107	0	ND	ND	0	24	0	39

108	0.7	14	52	ND	ND	ND	ND
109	1.4	0	0	ND	ND	ND	ND
110	0.8	29	0	ND	ND	ND	ND
111	2.4	0	32	0	28	ND	ND
112	1.6	14	94	50	100	100	100
113	0.7	14	0	0	22	0	35
114	1.8	86	81	9	23	57	87
115	0	0	81	0	4	0	39
116	1.9	0	0	0	0	0	0
117	2.0	0	0	0	3	0	0
118	2.4	14	0	ND	ND	ND	ND
119	1.5	0	0	0	0	ND	ND
120	2.3	0	0	ND	ND	ND	ND
121	0	0	0	ND	ND	ND	ND
122	0	71	58	ND	ND	ND	ND
123	1.8	0	0	ND	ND	ND	ND
124	0	0	0	0	35	0	0
125	1.2	0	0	0	9	0	0
126	1.0	96	96	96	96	0	0
127	1.2	31	35	31	35	0	0

IB: isotopic balance, corresponds to the contribution of shallow aquifer to the recharge of deep groundwater, negative values are represented by 0% which means no contribution, whereas values equal to 100% expressed the maximum of contribution; *ND* expressed no data

The estimated values of the shallow groundwater contribution to the deep aquifer recharge, based on the $\delta^{18}O$ balance, appear to be the most reliable confirming findings of piezometric study as discussed previously. Figure 15 shows the spatial distribution of groundwater flow exchange (%) between shallow and deep aquifer systems of Grombalia basin using $\delta^{18}O$ mass balance. The contribution of the shallow aquifer is very limited spatially, as just a few samples show significant values. The most important mixing rates seem to occur in the north-east and the centre of the plain (south of Beni Kalled and Menzel Bou Zelfa), whereas in the south of the plain the contribution of shallow aquifer to deep aquifer recharge is very low.

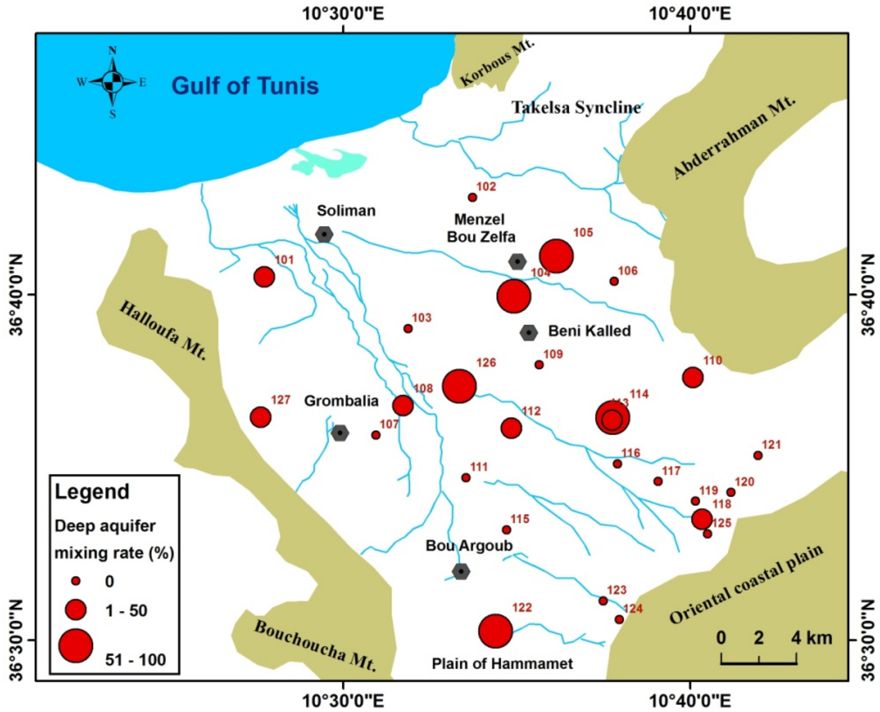

Fig. 15 Spatial distribution of groundwater flow exchange (%) between shallow and deep aquifers showing the contribution of shallow aquifer to deep aquifer recharge using $\delta^{18}O$ mass balance for spring season in 2014

5. Management implications

Hydrogeochemical and isotopic findings of the present study highlight the critical state of groundwater resources in the Grombalia region and provide relevant information on groundwater quantity and quality: a fundamental requisite for the implementation of sustainable management strategies. The obtained chemical data and the associated socio-economic assessment (Re et al. 2017; Tringali et al. 2017) reveal that the uncontrolled use of fertilizers and lack of environmental awareness are the main drivers for the increase of contaminants leaching from surface sources to groundwater reservoirs, threatening both groundwater quality and the long-term water supply capacity of the region. On the other hand, groundwater over-exploitation, due to the arbitrary proliferation of pumping-wells, is the main cause of piezometric levels' decrease, as some farmers tend to dig deeper wells when existing ones run dry.

The studied basin shows an example of two connected aquifer layers, where nitrate pollution affecting the shallow aquifer continue to pollute the deeper one. Consequently, if nitrate contamination, salinization and over-exploitation will continue with current trends, the deep aquifer would stop being considered as a strategic groundwater reservoir for future groundwater development. Therefore, groundwater resources, and especially the area where mixing processes are dominant, have to be protected against anthropogenic pollution and salinization, by limiting groundwater abstraction and increasing artificial recharge. In fact, the adoption of preventative measures is still the most appropriate approach to protect natural water resources.

With regard to nitrate contents in groundwater, the best suggestion to avoid nitrate pollution is to reduce the nitrogen fertilizers application, hence collaborating with farmers and local stakeholders (Re et al. 2017; Tringali et al. 2017), and to implement a drainage system to collect irrigated water, instead of allowing it draining into a the *wadis* or leaching to groundwater.

During the last decades, water shortage become an increasing problem derived from several causes such as land use change, climate variability, pollution and diversion of surface water (Pereira et al. 2009). As consequence, water deficit caused a significant deterioration of agricultural activities, resulting in land abandonment, particularly in coastal areas. This led the public authorities in Grombalia region to implement three dams, namely the Bezigh (built in 1954, with capacity of 6.5 Mm^3/year) situated upstream of Menzel Bou Zelfa region, the El Masri (built in 1968, with capacity of 6.9 Mm^3/year) and Tahouna dams (built in 1967, with capacity of 0.96 Mm^3/year) situated upstream of Bou Argoub region (Lachaal et al. 2016). Also, since the end of the 1980s and onwards, a vast program of water resources mobilization was implemented targeted to the safeguard of irrigated agriculture and the supply of drinking water to urban areas in the region. Thus, the Medjerda-Cap Bon canal was set up to ensure the transfer of water from the north collected by several dams built on the country's longest river Medjerda to several irrigated perimeters in the Grombalia region. The transferred water, characterized by an average salinity of 1000 mg/L (DGRE 2015), is used for irrigation and for artificial groundwater recharge in some sites since 1992. Indeed, despite of the fact that many management plans have been applied in Grombalia region since 1974, such as adopting artificial recharge by water injection in shallow wells and infiltration basins building, water supply stress is still the main concern faced by this agricultural coastal area. In addition, recent climate change coupled to population growth and the associated rise in water and food demand, are contributing increasing the gap between demand and available water resources, and may harm groundwater resources availability in the long-run (especially when the drawdown affects the deep aquifer system).

Results of the present investigation hence reveal the weakness of current groundwater management in the region, due to (i) a poor control and regulation on private wells and their abstraction; (ii) an often inequitable access to water resources; and (iii) the lack of sewage treatment network. In addition, as a consequence of the scarce availability of water resources, the agricultural base in this region fails to provide employment to the entire population located in the rural areas. This generates an internal migration from rural to urban areas, which not only contributes hampering the issue of land abandonment, but also generates overcrowding of cities by non-skilled labour force seeking jobs in different areas of employment (e.g. trade, industry, transport and services). This situation, common to many arid and semi-arid regions worldwide, including the MENA countries, is increasingly becoming source of social instability and often the driver for riots and conflicts at both local and regional level (Robins and Fergusson 2014; Miletto et al. 2017). Therefore, since business as usual management actions, focused on dams and reservoirs constructions, did not prove to be effective in mitigating the effects of piezometric level decrease, it will be of paramount importance to seek for alternative strategies to bridge the supply-demand gap, by focusing on both scientific innovation and participative actions (Kinzelbach et al. 2003). This means to increase the investigations and associated investments on managed aquifer recharge, irrigation and crops' yield optimization, but also to collaborate with local population and water regulators in order to promote the implementation of effective water conservation strategies and contamination source control. The latter could be fostered by hydrogeologists, as providers of sound information on groundwater status that can also be actively engaged in public participation of local stakeholders and bottom-up investigations targeted to rural development, according to the socio-hydrogeological approach proposed by Re (2015). Indeed, sustainable groundwater management cannot be achieved in the long-term without a sound knowledge of the hydrogeochemical properties of water resources and this study also reveals the fundamental role of multidisciplinary investigations to support the sustainable development in arid and semi-arid regions with the potential to reduce poverty in rural areas.

Conclusion

Hydrochemical and isotopic investigations performed in Grombalia aquifer system (NE Tunisia) permitted to better define groundwater chemical composition and to preliminary assess the evolution of groundwater quality according to seasonal variations. Chemical data showed high salinity of the analysed groundwater samples with significant variation in time and space. Several factors are controlling the groundwater quality traducing the complexity and the interference of several geochemical processes. The first process expresses the phenomenon of water-rock interactions which is enhanced with longer residence time, the second represents the evaporation process affecting mainly the shallow groundwater and return flow of evaporated irrigation water, the third process represents cation exchange reactions with clay minerals and the fourth one is expressed by mixture process between shallow and deep aquifers. The present study reveals also that anthropogenic factor contributes effectively to groundwater mineralization. Nitrate concentrations achieved in many places already alerting levels exceeding the drinking water limit (50 mg/L). Determination of agricultural parameters coupled with high total hardness and electrical conductivity values indicate the unsuitability of most groundwater samples for drinking and irrigation purposes. The spatial distribution of SAR values, using ordinary kriging technique reveals that high values occurred most in the north of the region near the coast. Concerning isotopic composition, groundwater displays large range of variation. The stable isotope composition of groundwater samples and tritium contents proved the existence of three groundwater groups. The first one is characterized by a strong contribution of modern precipitation to aquifer recharge, confirming the recent recharge by rapid infiltration of rain water indicate either recent origin or the existence of mixing process. However, the second group corresponds to the most enriched samples dominated by an evaporation effect. The third group represents the most depleted groundwater samples from deep aquifer that is probably recharged during cooler climate. Therefore, the fact that these two aquifers are characterized by a similar isotopic signature represents a sign of water exchange between these two aquifers. The comparison of groundwater isotopic composition under seasons, taken into account the analytical errors, reveals that seasonal variations affect stable isotope compositions especially for the shallower wells. Isotopic mass balance, using both δ^2H and δ^{18}O isotopes, has confirmed the mixture between shallow and deep aquifers in some sites of the basin and allowed to quantify the mixing percent as a preliminary synthesis of mixing rates between the different aquifers of Grombalia. The over-exploitation state of groundwater resources needs to be properly managed as part of integrated plans for the basin's future supplies. The scientific results of this study have important implications for groundwater management in the Grombalia basin and represent an important contribution to the overall assessment of groundwater quality in the MENA region. This work highlights the need for implementing new measures to bridge the gap between water supply and demand, with concerted efforts by various agencies and local (private and public) stakeholders. In addition, as concerns the role of hydrogeology and hydrogeochemistry in supporting aquifer protection, special attention should be dedicated to the realization of a permanent monitoring network, targeted to the control and mitigation of aquifer salinization and over-exploitation. Seasonal monitoring data would be an asset for the development of numerical groundwater flow models, useful to predict aquifer behaviours under different climatic and recharge scenarios.

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