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Application of environmental tracers to study groundwater recharge in a semi-arid area of Central Tunisia

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Abstract Groundwater of the Tertiary-Quaternary Formations in the Jeloula basin (Central Tunisia), together with rain and surface waters, were analysed to investigate the mineralization processes, the origin of the water and its recharge sources. The water samples present a large spatial variability of chemical facies which is related to their interaction with the geological formations. The main sources of the water mineralization are the dissolution of evaporitic and carbonate minerals and cation exchange reactions. Stable isotopes indicate that most groundwater samples originate from infiltration of modern precipitation. Surface water samples from small dam reservoirs show a $^{18}O/^{2}H$ enrichment, which is typical of water exposed to open-surface evaporation in a semi-arid region. Considerable data of ^{3}H and ^{14}C allow the qualitative identification of the present-day recharge that is probably supplied by infiltration of recent flood waters in the Wadi El Hamra valley, and by direct infiltration of meteoric water through the local carbonate outcrops.

Key words geochemistry; isotopes; groundwater; surface waters; recharge; Jeloula basin, Tunisia

Application des traceurs environnementaux à l'étude de la recharge des eaux souterraines dans une région semi-aride en Tunisie centrale

Résumé Les eaux souterraines des formations tertiaires et quaternaires du bassin de Jeloula (Tunisie centrale), ainsi que les eaux de pluie et les eaux de surface, ont été analysées afin d'étudier les processus de la minéralisation, l'origine des eaux et les sources de la recharge. Les échantillons d'eau présentent une grande variabilité spatiale des faciès chimiques, en lien avec les formations géologiques. Les principales causes de la minéralisation des eaux sont la dissolution des minéraux évaporitiques et carbonatés et les réactions d'échange cationique. Les isotopes stables ont indiqué que la majorité des eaux souterraines proviennent de l'infiltration de précipitations modernes. Les eaux des réservoirs collinaires montrent un enrichissement en ^{18}O et ^{2}H, typique d'une eau qui a subi une forte évaporation dans un contexte semi-aride. Un nombre considérable de données de ^{3}H et ^{14}C a permis l'identification qualitative de la recharge actuelle qui viendrait de l'infiltration récente des eaux de crue de l'Oued El Hamra, et de l'infiltration directe des eaux météoriques sur les affleurements carbonatés du bassin.

Mots clefs géochimie ; isotopes ; eaux souterraines ; eaux de surface ; recharge ; Bassin Jeloula, Tunisie

INTRODUCTION

Water scarcity is a perennial problem in semi-arid areas without permanent rivers. In the last century, global population expansion and actual climate change significantly increased the pressure on water resources and have required new approaches for water planning and management (Montoroi *et al.* 2002, Ma *et al.* 2009). To secure water supplies, water harvesting is used to counter the problems of drought and irregular precipitation. Thus, the technique of flood water harvesting (FWH) is widely developed in the semi-arid and arid parts of the world. When floodwater is harvested in the stream bed, the runoff water is dammed up and stored in permanent surface reservoirs (Montoroi *et al.* 2002, Grünberger *et al.* 2004). Rain-harvesting technology, such as hill reservoirs, can be used in the recharge of groundwater supplies, which acts as an efficient mechanism for preserving water resources. In Tunisia (North Africa), water harvesting plays an important role. Since the early 1990s, the Tunisian Government has undertaken implementation of the "National Strategy of Surface Runoff Mobilization", with the aim of building many large dams and small earth dams for irrigation and aquifer recharge (DGACTA 2005).

Several investigations, based on hydrogeological and geochemical information, have dealt with the impact of hill reservoir construction on groundwater flow and geochemistry in the Mediterranean basin (Marc *et al.* 1996, Stigter *et al.* 1998, Prinz 1999). However, only a few studies in Tunisia (Montoroi *et al.* 2002, Grünberger *et al.* 2004) have been carried out on this topic using isotope hydrology. In Jeloula basin (Central Tunisia), like many other semi-arid regions, water resources are limited. Since 1996, three hill reservoirs and three hill lakes have been constructed for groundwater recharge and irrigation (Fig. 1). In this case, the economic expansion of the agricultural areas in the basin requires improvement of the knowledge of the groundwater system. Using geochemistry, i.e. major elements and environmental isotopes (^{18}O, ^{2}H, ^{3}H, ^{13}C and ^{14}C), the present investigation concerns: (a) the processes of mineralization, (b) the origin of waters and (c) the recharge of the aquifer.

Isotope geochemistry techniques have been proven as valuable tools in investigating many problems in hydrology and evaluating hydrogeological and hydrochemical controlling mechanisms in aquifer systems (Clark and Fritz 1997). They provide valuable insights to recharge processes and are necessary for developing sustainable water resource management plans within the context of climate variability (Scanlon *et al.* 2006).

Environmental isotope techniques have been applied in several regional and local investigations to understand the origin of water, the flow paths, the residence time and the geochemical processes within aquifers (Edmunds and Smedley 2000). The stable isotopes of the water molecule (δ^{18}O and δ^{2}H) are generally considered to be transported conservatively in shallow aquifers. The use of these isotopes in hydrogeology provides information on the origin and movement of groundwater and can offer an evaluation of physical processes affecting water masses, such as evaporation and mixing (Geyh 2000). The tritium isotope (^{3}H) has been regarded as the simplest and most convenient tracer for determining the age of young groundwater. The occurrence of ^{3}H in groundwater indicates the extent of migration of modern post-1950s recharge, but its use is limited by its short half-life (12.3 years) (Edmunds and Smedley 2000). The ^{3}H content in groundwater depends primarily on the atmospheric concentration at the time of recharge and the radioactive decay that has occurred since infiltration (Maduabuchi *et al.* 2006). This requires that the initial precipitation ^{3}H input record be known in order to semi-quantitatively determine the groundwater age from the pattern of

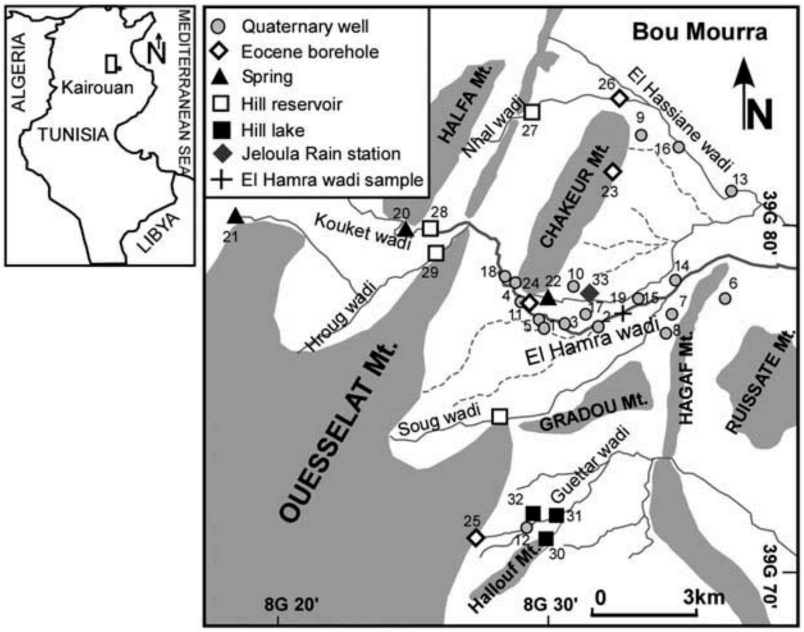

Fig. 1 Sample map of surface and groundwater in Jeloula basin (2009). Numbers indicate the sampling sites.

^{3}H concentrations along the groundwater flow path (Ma *et al.* 2009).

Radiocarbon (^{14}C) allows the determination of water residence time over time scales to 30 ka (Clark and Fritz 1997). As ^{14}C is involved in many geochemical reactions, a detailed understanding of the origin of dissolved inorganic carbon (DIC) is required to convert the measured ^{14}C activities into the ages (Clark and Fritz 1997). However, the interpretation of radiocarbon data in terms of groundwater absolute ages is seriously complicated by the potential for mixing with younger and older sources of carbon (^{14}C originating from widespread nuclear testing, or from the interaction of groundwater with carbonate minerals and with organic matter) (Clark and Fritz 1997). Therefore, knowledge of the carbonate hydrochemistry and understanding of the δ^{13}C evolution within the hydrological system are inevitably required (Clark and Fritz 1997, Edmunds and Smedley 2000).

STUDY AREA

The Jeloula basin is located 30 km northwest of Kairouan city in Central Tunisia (Fig. 1), between latitudes 39°70′ and 39°90′N and longitudes 8°20′ and 8°38′E. The basin is bounded in the west by the Ouesselat mountains, in the south by the Hallouf mountains, in the east by the Hagaf mountains and in the north by the Bou Mourra syncline.

The region's climate is semi-arid, with a mean annual precipitation of 328 mm year^{-1}, mean annual temperature of 19°C and potential evapotranspiration of 1712 mm year^{-1}. Jeloula basin is supplied by many intermittent rivers (locally named wadis), which discharge to the east. They are characterized by a seasonal flow and collect surface runoff mainly from the mountains (Fig. 1).

GEOLOGY AND HYDROGEOLOGY

Several physiographic features have been developed with northeast–southwest and north–south orientations (Rigane 1991, Abbes 2004). The most important are the Atlas structures and the major north–south structural feature of Central Tunisia.

The geological formations reflect the intense folding by Atlasian tectonic movements of Secondary, Tertiary and Quaternary sedimentary units, which has resulted in rock layers dipping steeply southwest to nearly vertical in the western part of the basin (Fig. 2). The Upper Cretaceous basement rocks consist of marine limestone that appears in the Halfa, Bou Dabbous and Ruissate mountains (Abbes 2004). The Palaeocene formation is represented mainly by sandy clays with some intercalations of sandy limestone, gypsum and glauconous clays (Boukadi 1994, Abbes 2004). This formation forms an outcrop of more than 390 m at the foot of the Bou Dabbous mountains in the western part of the basin (Burrolet 1956).

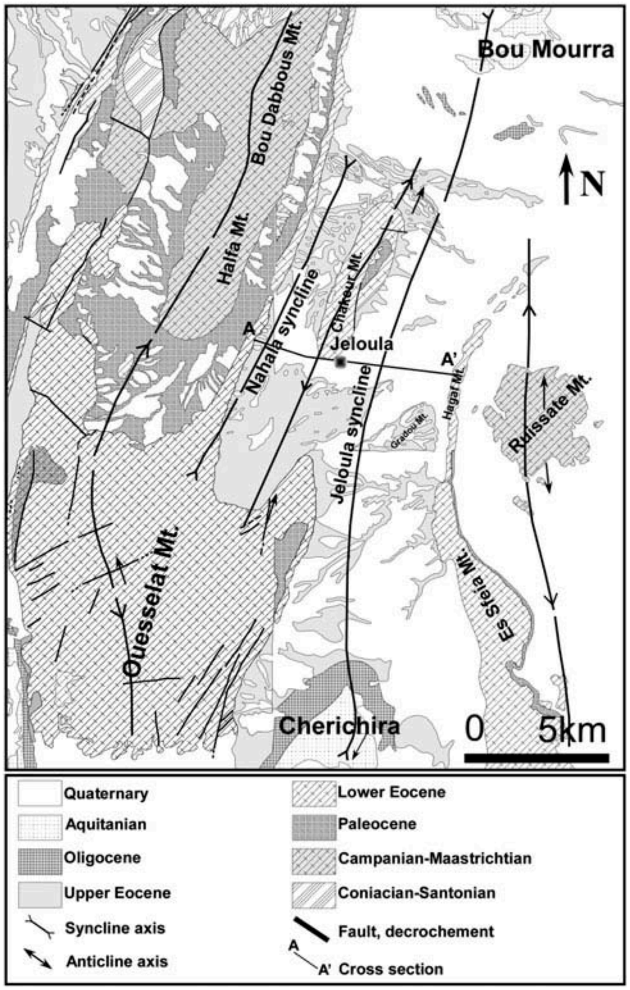

Fig. 2 Simplified geological and structural map of the Jeloula basin.

The Lower Eocene limestone formation outcrops widely in the study area, e.g. in the Es Sfeia, Chakeur and Ouesselat mountains, and shows significant variations of facies and thickness from north to south. This carbonate formation represents an important feature in the Atlas morphology of Central Tunisia (Rigane 1991). Upper Eocene deposits are found in the northern and the southern parts of the basin. This formation comprises marl series and grey clays and gypsum. Its thickness exceeds 800 m in the southern part of the basin (Abbes 2004). The Oligocene unit is principally made up of coarse- to medium-grained sandstone outcrops in the Bou Mourra and Cherichira synclines (Abbes 2004).

The surface geology of the basin is represented by recent Quaternary soil and terraces that partially cover the Eocene formations. The Jeloula basin has several syncline and anticline structures (Fig. 2), as shown by the representative west–east cross-section A–A′ (Fig. 3). Hydrogeologically, the Jeloula hydrogeological basin has two NNE–SSW asymmetric synclinal structures which are geometrically limited and crossed by the Chakeur anticline.

Figure 3 shows that the marl deposits of the Upper Eocene underlie the Quaternary sediments and overlay the Lower Eocene limestone. Hence, the Quaternary alluvium and Eocene carbonates are considered the most important aquifers in the Jeloula system (Borgi 1979, Farid 2007). They represent, respectively, the shallow and the deep aquifer. The hydrogeological structure confirms the absence of any hydraulic connection between these two hydrogeological units because the marl deposits of the Upper Eocene form an impermeable screen where the hydrogeological units are obviously separated.

The shallow aquifer is an unconfined aquifer hosted in the Quaternary continental sands, clayey sands, gravels, clays and conglomerates, with a thickness of 15–20 m. The hydraulic properties of this shallow aquifer reflect significant lateral variations due to the heterogeneity of the lithological facies. The transmissivity is relatively high in the vicinity of El Hamra and El Hassiane wadis (4.6×10^{-3} m^2 s^{-1}), whilst it is comparatively low in the other part of the basin (3.8×10^{-4} m^2 s^{-1}) (Hamza 1987). The storage coefficient is about 10^{-1}. The yields are low and range from approx. 0.1 to 6.5 L s^{-1}, and the specific capacity is about 0.04–2.6 L s^{-1} m^{-1}. Despite the high porosity of the Quaternary alluvium (20–30%) (Hamza 1987), this aquifer has been subject to strong exploitation which has exceeded the available resources (0.5×10^6 m^3 year^{-1}) in recent years. The number of shallow wells and total extraction increased during the period 1985–2010 from 70 to 115 wells and from 0.26 to 0.6×10^6 m^3 year^{-1}, respectively (DGRE 2010).

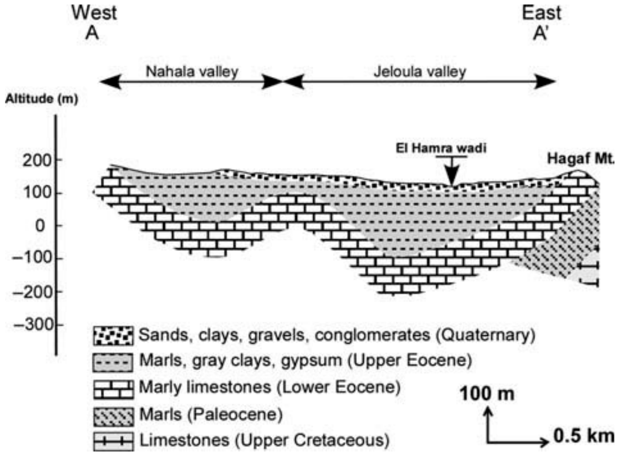

Fig. 3 Hydrogeological cross-section A–A′ showing the structure of the Jeloula basin and the distribution of the aquifers.

The deep aquifer is principally found in the fissured limestone of the Lower Eocene. This carbonate formation presents a confined and discontinuous aquifer at a depth of more than 250 m in the Nahala and Jeloula synclines (boreholes nos 24 and 26) (Fig. 1). However, it becomes unconfined and outcrops locally at the foot of the Chakeur and Ouesselat mountains (boreholes 23 and 25). The thickness ranges from 50 to 250 m (Hamza 1987). The carbonate formation has high porosity and permeability due to fissures and/or karstification (Rigane 1991, Maréchal and Etcheverry 2003). Moreover, this aquifer is tapped by many springs which are characterized by an artesian flow (Fig. 1). The hydrodynamic properties of the formation are variable. The mean transmissivity is about 1.5×10^{-2} m^2 s^{-1} (Hamza 1987). The storage coefficients are about 2.5×10^{-2} in the unconfined part and 3×10^{-2} in the confined area (Hamza 1987).

Data from pumping tests show that the water discharge from boreholes varies between approx. 10 and 43 L s^{-1} and the specific capacity is about 1.3–3.2 L s^{-1} m^{-1}. The dynamic resources are 0.8×10^6 m^3 year^{-1}. The infiltration coefficient is 26%, which allows a large amount of surface runoff in the piedmont fan to seep down and recharge the aquifer (Hamza 1987). Exploitation of groundwater from the deep Jeloula aquifer started in the 1970s. Despite the small number of boreholes drilled in this formation, the total extraction to meet agricultural and drinking supplies rose from 0.5×10^6 m^3 year^{-1} in 1979 to 0.9×10^6 m^3 year^{-1} in 2007 (DGRE 2007).

Piezometric data for the shallow aquifer show that the principal flow directions in the basin are NW–SE and SW–NE. Generally, the groundwater flow is from the edge of the mountains toward the east of the basin (Henchir Bou Halleb) which forms the natural discharge area (Fig. 4). In addition, the piezometric map reveals that the shallow aquifer is recharged by recent flood water infiltration in the

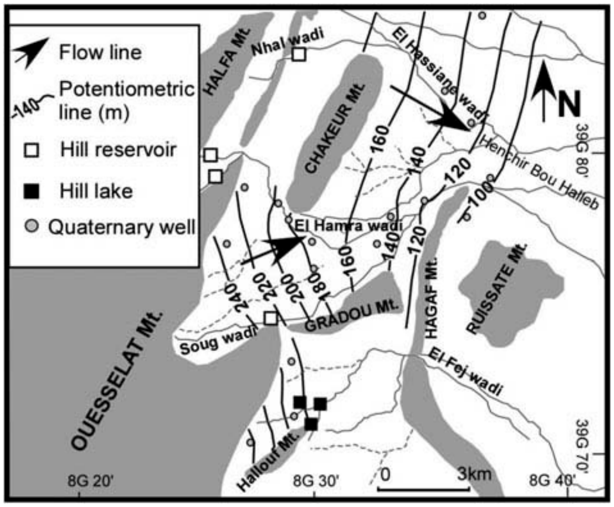

Fig. 4 Piezometric map of the Quaternary aquifer in Jeloula basin (2009).

valleys of the El Hamra and El Hossiane wadis, and by direct infiltration of rain water through the local carbonate outcrops of the basin. So these represent a preferential recharge area facilitated by host lithology. These hypotheses will be supported later in the isotopic study.

SAMPLING AND ANALYTICAL PROCEDURE

A sampling campaign for the geochemical and isotopic analyses was performed during March–April 2009. A total of 32 samples were collected from the Jeloula basin. Samples were specified according to the classification shown in the Table 1. Samples 1–18 were collected from the Quaternary aquifer, Sample 19 was taken from the valley of El Hamra wadi, samples 20–26 were collected from the Eocene aquifer at springs and boreholes, samples 27–29 were taken from the hill reservoirs and samples 30–32 were taken from the hill lakes (Fig. 1).

Measurements of pH, temperature and electrical conductivity (EC) were performed *in situ* (Table 1). Water samples were collected in 1000 mL polyethylene bottles with poly-seal caps for major elements analysis. Chemical analyses and isotopic measurements were determined in the Radio-Analysis and Environment Laboratory of the National School of Engineers of Sfax (Tunisia). Major elements (Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, Na^+, Mg^{2+}, K^+ and Ca^{2+}) were analysed by ion liquid chromatography. Stable isotope ratio ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) analyses were performed using laser absorption spectrometry (LGR DLT 100) (Penna *et al.* 2010). Analyses are reported in per mil (‰) *versus* Vienna-Standard Mean Oceanic Water (VSMOW).

Thirteen (13) groundwater samples were selected for analysis of ^{14}C activity for dating. Precipitation of $BaCO_3$ from groundwater samples was done in the field. The ^{14}C activity was determined by scintillation counting on C_6H_6 (Fontes 1971, Stuiver and Polach 1977). The $^{13}C/^{12}C$ ratios were determined by isotope ratio mass spectrometry at the Laboratory of Hydrogeology of Avignon, France. Values of $\delta^{13}C$ (δ) are expressed *versus* the Vienna Pee Dee Belemnite (VPDB) standard.

Eighteen (18) samples were selected for analysis of ^{3}H content using electrolytic enrichment and liquid scintillation spectrometry (Taylor 1976). Tritium concentration is expressed in Tritium Units (TU), where 1 TU is defined as the isotope ratio $^{3}H/^{1}H = 10^{-18}$.

Results of ^{14}C abundance are reported as percentage of modern Carbon (pmC). The precision of measurement for stable isotope and radioactive analysis is ±0.1‰ for $\delta^{18}O$, ±1‰ for $\delta^{2}H$, ±0.3 TU for ^{3}H and ±0.3‰ for ^{13}C.

RESULTS AND DISCUSSION

Physico-chemical data

The physico-chemical parameters (temperature, pH and EC) of the analysed water samples are presented in Table 1. Groundwater samples in the Jeloula basin show heterogeneous values of temperature, varying between 16.7 and 26.2°C. Generally, groundwater temperatures are influenced by the atmosphere and the season. The groundwater samples are almost neutral: pH values are very homogenous with an average of 7.4. However, pH in surface waters tends to be higher: ranging from 7.8 to 8.8 with an average of 8.3.

Most of Quaternary groundwater samples show values of EC similar to those of Wadi El Hamra (1700 $\mu S\ cm^{-1}$). The values vary between 1316 and 2560 $\mu S\ cm^{-1}$, suggesting recharge of the shallow aquifer by recent flood water in Wadi El Hamra. This recharge appears to be dominantly controlled by the dissolution of minerals within the lithological formations (Montoroi *et al.* 2002). The low EC of groundwater flowing in the recharge area is explained by the high permeability of the unsaturated zone which is formed by clayey sands, conglomerates, sands and gravel lenses. These hydrogeological characteristics allow rapid infiltration of surface water. However, the abundance of clay fractions in some

Table 1 *In situ* measurements, and geochemical and isotopic data of the analysed water samples.

No.	Sample type	T	pH	EC	TDS	Ca	Mg	Na	K	HCO_3	CO_3	Cl	SO_4	NO_3	^{18}O	^{2}H	^{3}H	^{14}C	^{13}C
		(°C)		(μS/cm)	(mg/L)										(‰ *vs* SMOW)		(TU)	(pmC)	(‰ VPDB)
1	Well (Quaternary aquifer)	17.5	6.9	4430	3729	427.1	204.1	434.0	0.0	267.0	0.0	408.0	1708.0	10.3	–4.4	–23.5		91.3	−12.4
2	Well (Quaternary aquifer)	17.8	7.3	1552	1045	144.7	45.3	99.4	7.2	329.4	0.0	97.8	278.4	3.3	–5.4	–33.8			
3	Well (Quaternary aquifer)		7.5	1316	858	122.7	28.2	90.9	8.0	292.8	0.0	81.6	216.9	5.9	–5.2	–31.1	3.1	92.3	−13.2
4	Well (Quaternary aquifer)	25.0	7.3	2300	1735	261.6	79.9	212.6	15.6	262.3	0.0	363.8	668.6	1.2	–3.3	–21.7		100.0	−11.4
5	Well (Quaternary aquifer)	21.0	7.3	2200	1600	250.0	74.0	144.0	14.6	262.0	0.0	236.2	640.0	17.2	–5.2	–27.4	2.9		
6	Well (Quaternary aquifer)	21.0	7.5	1500	1330	153.7	60.4	188.2	5.2	274.5	0.0	119.4	570.0	9.1	–4.5	–28.5		100.0	
7	Well (Quaternary aquifer)	26.2	8.0	1690	1370	129.7	51.6	134.8	0.0	225.7	0.0	159.6	395.6	12.0	–3.8	–28.9			
8	Well (Quaternary aquifer)	24.3	7.4	2560	1610	148.9	78.1	247.6	0.0	298.9	0.0	331.4	466.9	36.7	–4.6	–23.4			
9	Well (Quaternary aquifer)		7.7	2920	5076	493.8	268.9	712.3	14.4	329.4	0.0	1042.0	2046.7	0.0	–4.7	–28.4	2.0	65.6	−8.5
10	Well (Quaternary aquifer)	16.7	7.5	1610	1067	125.5	45.3	124.6	2.9	353.8	0.0	169.5	206.1	31.9	–5.6	–37.2			
11	Well (Quaternary aquifer)	15.9	7.9	1660	1249	134.1	53.7	121.8	3.4	237.9	0.0	143.7	440.2	10.2	–4.2	–24.1			
12	Well (Quaternary aquifer)	18.8	7.3	7180	6481	483.0	324.4	968.0	0.6	359.9	0.0	962.3	2923.6	10.6	–4.0	–28.6	2.9	65.0	−9.8
13	Well (Quaternary aquifer)	17.6	7.7	2300	1737	188.5	88.2	178.2	5.4	274.5	0.0	287.2	642.1	13.1	–5.3	–30.9	3.1	100.0	−9.7
14	Well (Quaternary aquifer)	19.5	7.2	1990	1432	197.8	64.0	138.9	4.1	366.0	0.0	245.8	416.1	20.8	–5.2	–29.2			
15	Well (Quaternary aquifer)	20.1	7.0	2220	1480	206.2	69.6	137.5	5.0	408.7	0.0	239.2	407.7	23.0	–5.4	–31.7	2.8	106.8	−12.7
16	Well (Quaternary aquifer)	16.9	7.5	2540	2061	248.3	98.6	175.5	5.2	286.7	0.0	306.1	702.3	30.8	–5.0	–32.8			
17	Well (Quaternary aquifer)	19.4	7.2	2230	1585	216.1	70.5	141.4	5.1	384.3	0.0	240.4	407.1	33.2	–4.2	–34.9			
18	Well (Quaternary aquifer)	19.3	7.4	1560	1187	128.6	47.2	167.8	6.0	237.9	0.0	144.1	450.2	1.3	–3.4	–22.6			
19	Wadi El Hamra water	16.6	8.2	1700	1214	146.1	52.9	111.1	3.7	274.5	0.0	161.1	390.2	12.9	–4.8	–29.0	2.8		
20	Spring (Lower Eocene aquifer)	23.2	7.3	803	572	100.7	11.6	41.0	1.2	262.3	0.0	74.1	41.8	9.5	–5.5	–32.0	2.1		
21	Spring (Lower Eocene aquifer)	22.7	7.6	960	610	114.3	20.4	35.8		286.7	0.0	49.7	99.6	36.8	–6.2	–33.7	4.8		
22	Spring (Lower Eocene aquifer)	22.4	7.5	651	442	71.7	16.8	25.4	2.0	200.7	0.0	45.1	55.6	23.2	–5.8	–33.1	2.9	78.2	−13.0
23	Borehole (Lower Eocene aquifer)	23.4	7.2	810	490	80.9	10.4	38.1	2.5	305.0	0.0	28.4	39.5	1.1	–5.1	–32.9		37.0	−12.4
24	Borehole (Lower Eocene aquifer)	22.3	7.6	730	552	82.4	17.2	30.5	1.4	237.9	0.0	46.7	69.9	21.9	–5.3	–33.1		67.3	−13.0
25	Borehole (Lower Eocene aquifer)	23.6	7.6	510	370	64.7	8.1	20.8	1.8	231.8	0.0	10.8	15.4	1.5	–5.5	–32.2		78.5	−12.7
26	Borehole (Lower Eocene aquifer)	22.8	7.3	1064	683	102.7	18.2	70.9	5.4	347.2	0.0	54.4	96.7	0.5	–5.3	–33.1	2.5	90.2	−13.0
27	Nhal hill reservoir (08/04/2009)	17.1	8.2	256	190	31.6	3.0	13.4	1.6	73.2	0.0	5.4	50.6	3.3	–4.1	–22.0	5.4		
28	Hroug hill reservoir (08/04/2009)	19.4	8.2	666	466	66.6	20.9	37.5	2.2	128.1	0.0	21.5	182.1	0.8	–2.6	–14.9	4.3		
29	Kouket hill reservoir (08/04/2009)	19.1	8.3	658	417	62.3	15.3	41.0	2.7	176.9	0.0	55.8	85.4	3.4	–3.2	–16.4	4.2		
30	Hallouf hill lake	24.3	8.0	2250	2128	479.4	46.4	104.3	7.7	73.2	0.0	135.4	1228.9	2.2	1.6	16.8	4.5		
31	Sidi Ali hill lake	24.1	8.8	1191	1020	157.0	35.4	110.2	3.5	36.6	0.0	101.7	549.3	0.9	–0.4	–8.5	4.9		
32	Masref hill lake	24.0	8.6	863	671	103.5	25.0	39.4	3.6	128.1	0.0	45.7	286.4	0.0	–2.2	–8.1	6.8		
33	Rain water (Jeloula station)					20.8	1.7	3.8	0.8	45.1	0.0	2.9	16.4	4.6	–5.2	–29.6	4.7		
34	Nhal hill reservoir (04/09/2008)				230	44.3	4.8	14.1	2.6	122	0.0	4.1	59.1	2.3	–5.3	–31.2	4.3		
35	Hroug hill reservoir (04/09/2008)	28.6	7.9		990	94.4	38.3	93.6	8.6	262.3	0.0	39.2	338.5	0.0	6.1	20.1	4.2		
36	Kouket hill reservoir (04/09/2008)	28.1	8.0		640	76.4	21.6	70.4	5.7	225.7	0.0	81.8	136.1	0.7	1.4	0.8	3.6		

parts of the basin will extend contact, leading to the longer periods of dissolution of minerals present in the detrital layers of the aquifer and so providing an additional input of chemical elements (Edmunds *et al.* 2002). Overall, the higher values are recorded in wells 1, 9 and 12 (Fig. 1) located near the evaporitic marls related to the Upper Eocene outcrops. However, the lower values of EC are found in the carbonate aquifer (springs and boreholes), with an average of 789.7 µS cm^{-1}.

The total dissolved solids (TDS) values of the surface water (hill reservoirs) are low and range from 190 mg L^{-1} (Sample 27 collected from Nhal hill reservoir) to 466 mg L^{-1} (Sample 28 collected from Hroug hill reservoir), suggesting significant recharge by rainfall water. The TDS values of the hill lake samples vary between 671 and 2120 mg L^{-1} (Table 1).

The chemical compositions of the analysed water samples are plotted on the Piper trilinear equivalence diagrams shown in Fig. 5. The surface and groundwaters present a large spatial variability of hydrochemical facies. Three groups of groundwater can be distinguished on the basis of major concentrations. The first type (Ca-HCO$_3$), weakly mineralized, is represented by four boreholes (nos 23, 24, 25 and 26) and three springs (nos 20, 21 and 22) located on the limestone outcrops of the Lower Eocene (Fig. 1). The second groundwater type (Ca-Na-SO$_4$-HCO$_3$) includes samples collected from the Quaternary wells (nos 2, 3, 4, 5, 6, 7, 10, 11, 14, 15 and 17) and located near the riverbed of Wadi El Hamra, which presents a water type similar to the Quaternary samples. The third type (SO$_4$-Ca) characterizes groundwaters with high TDS and SO$_4$, concentrations; it is represented by wells (nos 1, 9 and 12) located near the gypsiferous marls of Upper Eocene age.

The surface waters taken from the hill reservoirs (nos 27, 28 and 29) show an evolution between Ca-HCO$_3$ and Ca-SO$_4$ types, while those of hill lakes (nos 30, 31 and 32) present an SO$_4$-Ca type, which may reflect the influence of the Upper Eocene outcrops rich in SO$_4$ (Fig. 5).

To specify the likely origin of each major element participating in groundwater mineralization, plots of Na *versus* Cl, Ca *versus* SO$_4$ and Ca *versus* HCO$_3$ were prepared (Fig. 6). The Na–Cl relationship (Fig. 6 (a)) has often been used to identify mechanisms for acquiring salinity in arid and semi-arid regions (Dixon and Chiswell 1992). The relationship between these ions shows that the majority of points cluster along the halite dissolution line. However, if Na is only derived from the dissolution of evaporite minerals, then Na should balance Cl. The depletion in Cl^- content relative to Na^+ concentration, observed in some samples of the Quaternary aquifer (nos 1 and 12) is probably due to cation exchange reactions leading to Na^+ adsorption on clay minerals and simultaneous

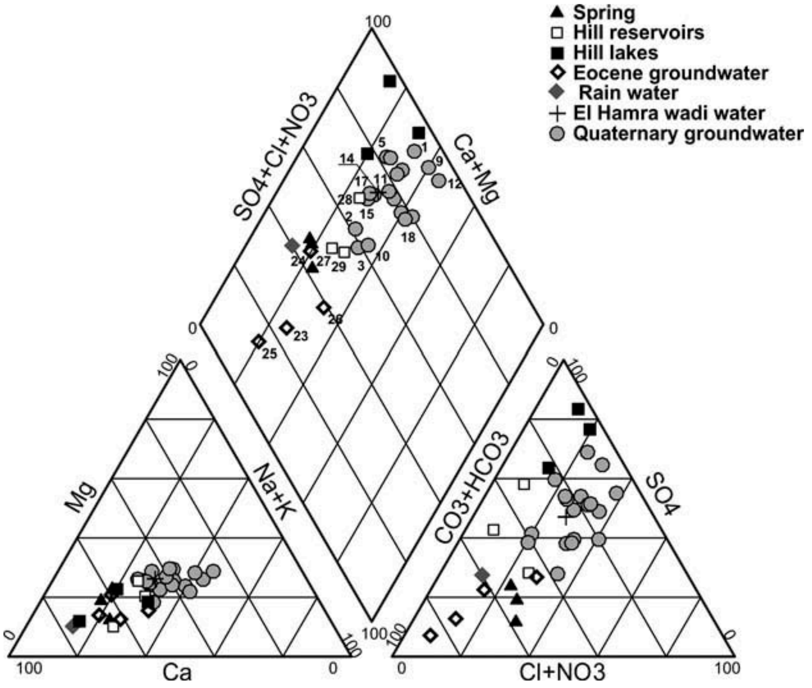

Fig. 5 Tri-linear diagram showing some major chemical compositions of the analysed water samples.

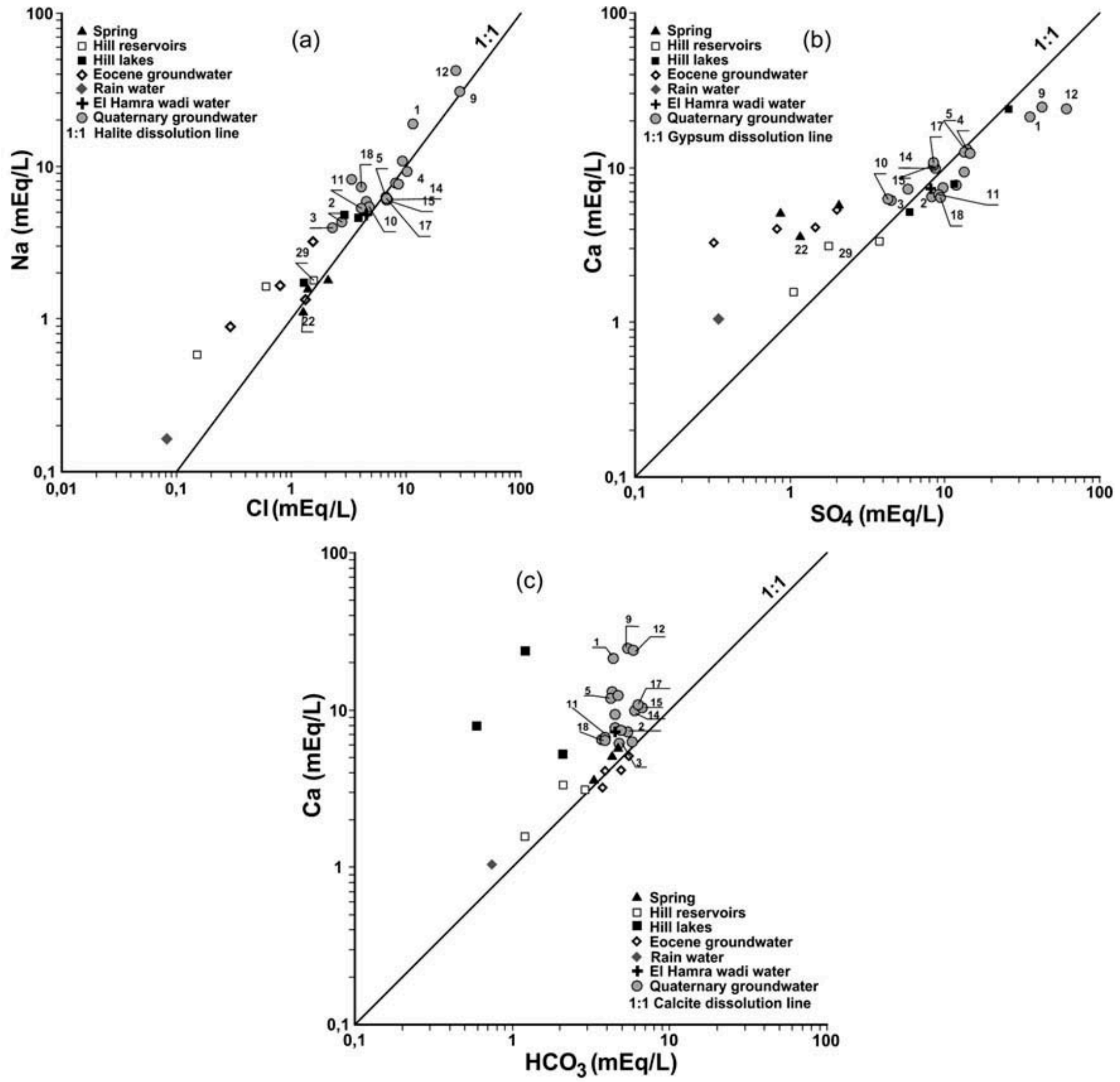

Fig. 6 Relationships between major elements in the analysed water samples: (a) Na/Cl, (b) Ca/SO_4 and (c) Ca/HCO_3.

release of Ca^{2+} ions. Those samples in which molar Na/Cl ratios are higher than one (Fig. 6(a)) also exhibit a deficit of Ca^{2+} with respect to SO_4^{2-}ions (Fig. 6(b)). This is in good agreement with a Ca–Na cation exchange process leading to a softening of the water (Hidalgo *et al.* 1995).

Some high Na^+/Cl^- molar ratios observed in Eocene groundwaters could be indicative of nahcolite ($NaHCO_3$) mineral dissolution, which may potentially add amounts of Na^+ to the groundwaters of the Eocene aquifer. The naturally occurring deposits of this carbonate mineral are found to be of Eocene-age (55.8–33.9 Ma) rocks (Sass and Scheuerman 1962). However, as SO_4^{2-} increases, a Ca^{2+} deficit appears (Fig. 6(b)), which suggests a process of calcite precipitation as a consequence of Ca^{2+} addition from gypsum dissolution. The plot of Ca^{2+} and HCO_3^{2-} illustrates an excess in calcium for points representing Eocene boreholes and hill reservoirs. This excess is probably due to the dissolution of carbonate minerals (probably the dolomite mineral). As shown in Fig. 6(c), the points representing the Eocene aquifer and hill reservoirs fall either on, or just above the 1:1 (calcite dissolution) line. All the other groundwater and surface water samples are above the line, indicating that another source of Ca must be present; this is possibly the weathering and erosion of gypsum and/or clay.

Isotope data

Isotope composition of rain water A total of 33 samples of rain water were collected from the Jeloula station (30 km from Kairouan city) and analysed between March 2009 and January 2012. In the diagram ($\delta^{18}O/\delta^{2}H$) (Fig. 7), all the meteoric waters fall either on, or just above/below the global meteoric water line (GMWL; Craig 1961). The meteoric line established within this study, $\delta^{2}H = 7.7\delta^{18}O + 9.4$, is in a good agreement with the West Mediterranean meteoric water line, $\delta^{2}H = 7.2\delta^{18}O + 6.1$, previously defined by Celle (2000) and Celle Jeanton *et al.* (2001) from 1968 to 1998 at the station of Tunis-Carthage, GNIP network (Global Network of Isotopes in Precipitation) (IAEA 2004).

This regional meteoric water line, obtained in thermodynamic equilibrium conditions (slope 8), is defined as $\delta^{2}H = 8\delta^{18}O + 11$ (Celle 2000, Celle Jeanton *et al.* 2001). In fact, the Tunisian climate is largely controlled by the influence of two major air mass trajectories: the cool North Atlantic air mass which circulates from the west over northern Africa and the warm Mediterranean air mass that circulates from the north (Celle 2000, Celle Jeanton *et al.* 2001, Gay 2004).

In addition, the contribution of Atlantic disturbances increases from May to September, with a deuterium excess of 10‰ in Tunis, whereas, from October to March, the influence of the Mediterranean disturbances is the cause of a deuterium excess of 11.4‰ (Celle 2000, Celle Jeanton *et al.* 2001, Gay 2004). Therefore, the local meteoric water line (LMWL) adopted in this study is $\delta^{2}H = 8\delta^{18}O + 11$.

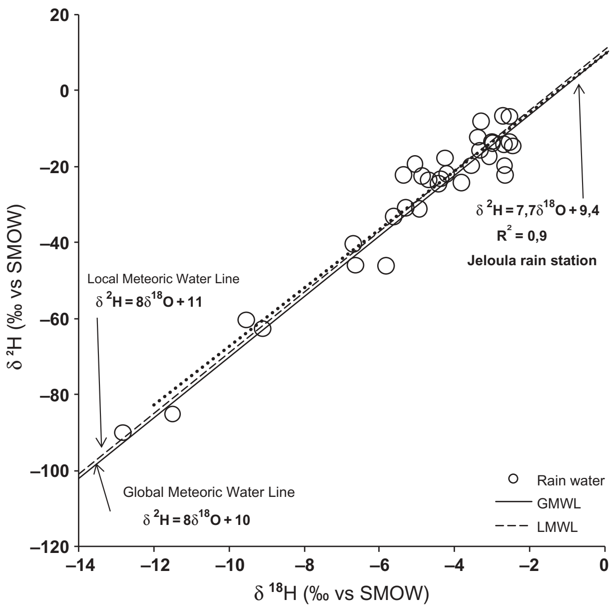

Fig. 7 $\delta^{18}O/^{2}H$ relationship (March 2009–January 2012) of rain water at Jeloula rain station.

Isotope composition of surfacewater and groundwater $\delta^{18}O$ and $\delta^{2}H$ values of the hill reservoirs range respectively from −2.6 to −4.1‰ and from −14.9 to −22.0‰. Data from the hill lakes are relatively more enriched and range from −2.2 to 1.6‰ for ^{18}O and from −8.1 to 16.8‰ for ^{2}H (Table 1).

Stable isotope compositions of samples representing the quaternary aquifer vary between −3.3‰ and −5.6‰ for oxygen-18 and between −21.7‰ and −37.2‰ for deuterium. The compositions of the Eocene aquifer range from −5.1‰ to −5.5‰ for oxygen-18, and from −32.2‰ to −33.1‰ for deuterium. The isotope composition of water from the artesian springs fluctuates between −5.5‰ and −6.2‰ for oxygen-18 and between −32.0‰ and −33.1‰ for deuterium (Table 1).

The composition of surface water and groundwater beneath the study area has a signature that is significantly similar to modern rainfall recorded at Jeloula station (−5.2 for $\delta^{18}O$/−29.6‰ for $\delta^{2}H$). Figure 8 shows all the water samples plotted together with the GMWL and LMWL). Most of

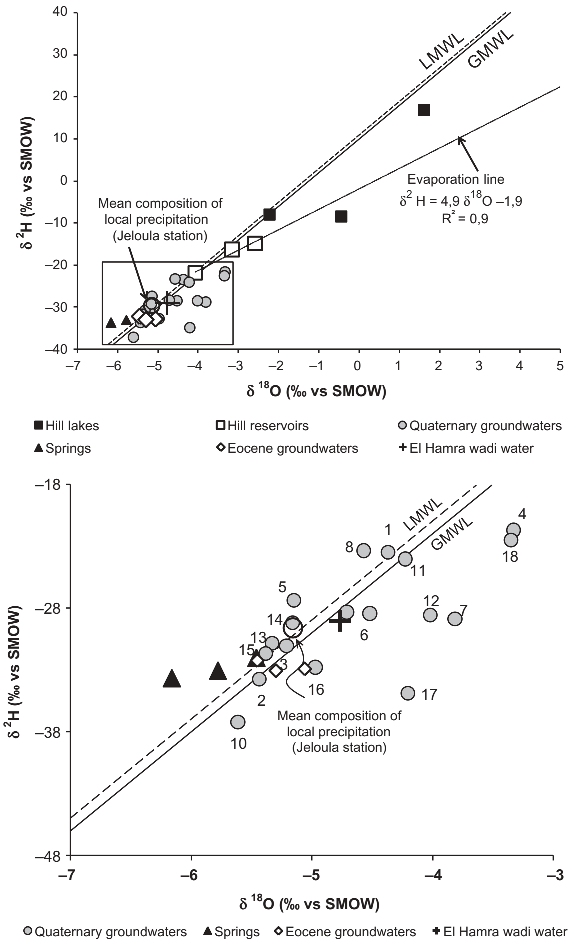

Fig. 8 $\delta^{18}O/\delta^{2}H$ relationship of the analysed water samples.

the groundwater samples fall on or near the GMWL or LMWL indicating that they originated from infiltrating modern precipitation that was not subject to surface or subsurface alteration of its isotopic composition (Grünberger *et al.* 2004). However, there are some Quaternary samples (nos 4, 7, 12, 17 and 18) that lie much below the GMWL and show an enriched isotopic composition that could be attributed to either the evaporation of meteoric water prior to groundwater recharge, and/or extensive water–rock interaction within the aquifer (Banner *et al.* 1989). These enriched values could be related to the evaporation process, which occurs possibly in the upper part of the unsaturated zone of the Quaternary aquifer where the total depth does not exceed 20 m.

Some data (samples 1 and 11) plot on, or close to the GMWL, indicating groundwater with slight evaporation. These groundwaters located in the vicinity of Wadi El Hamra are likely to receive surface water seepage in addition to rainwater infiltration.

Groundwaters sampled from limestone outcrops are less enriched in stable isotopes. This suggests rapid infiltration through the karstic and fissured Eocene limestone. The spring waters are more depleted and this indicates recharge at higher altitudes of the Eocene outcrops. In fact, as the altitude increases, the isotopic content becomes more depleted because the mean annual air temperature decreases (Maréchal and Etcheverry 2003). In Fig. 9, we plot the isotopic content according to the corresponding altitude of the sample points on the Eocene aquifer (springs and boreholes). The ^{18}O content was used to calculate the altitude of the recharge basin. The isotopic gradient defined in this study is $-0.4\delta^{18}O‰/100$ m.

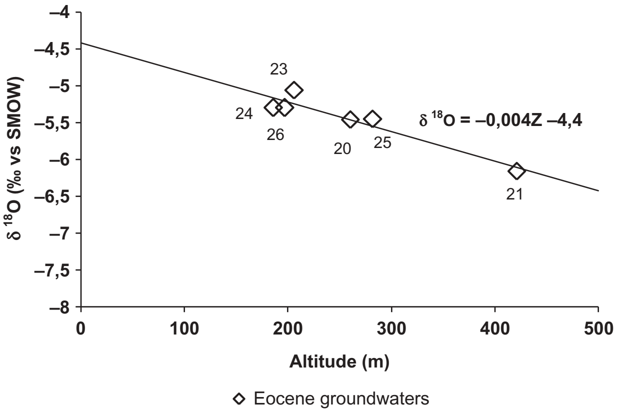

Fig. 9 Relationship between $\delta^{18}O$ and altitude (m) of Eocene groundwater (springs and boreholes).

Surface water samples reveal ^{18}O and ^{2}H enrichment, which is typical for water that has been subject to open surface evaporation under conditions of low relative humidity in a semi-arid region (Montoroi *et al.* 2002). The slope of the evaporation line characterizing hill reservoirs is nearly 4.9: $\delta^2H = 4.9\delta^{18}O - 1.9$ ($r^2 = 0.9$) (Fig. 8). The intersection between the evaporation line and the GMWL gives the initial composition of the water before evaporation (–4.2 to –24.1‰). Data from the hill lakes are strongly enriched in H and O isotopic composition.

To confirm the mechanism of mineralization in surface water and groundwater in Jeloula basin, we used TDS *versus* ^{18}O correlation. Figure 10 displays a well-defined relationship between the TDS and the ^{18}O values of surface reservoir waters (hill reservoirs and hill lakes). These reservoir waters have low TDS and are enriched in ^{18}O. These data have been interpreted as the evaporation process contributing to the salinization of the reservoir waters. However, no relationship can be observed between TDS and ^{18}O in Eocene groundwater and some samples of the Quaternary aquifer (nos 2, 3, 5, 10 and 14). This strongly supports the hypothesis that salinity is mainly controlled by a dissolution process, as shown previously in the chemical study. This indicates rapid infiltration of meteoric water and a short residence time in the unsaturated zone, except for the more mineralized groundwaters that are located near

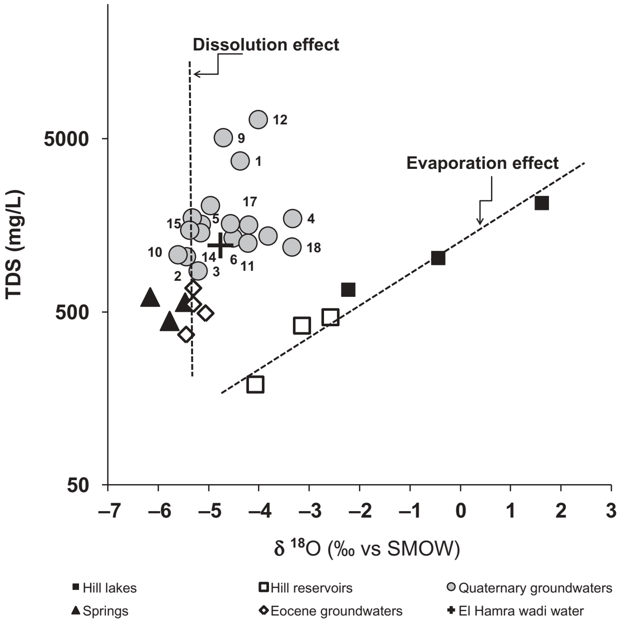

Fig. 10 Relationship between $\delta^{18}O$ and TDS (mg L^{-1}) of the analysed water samples.

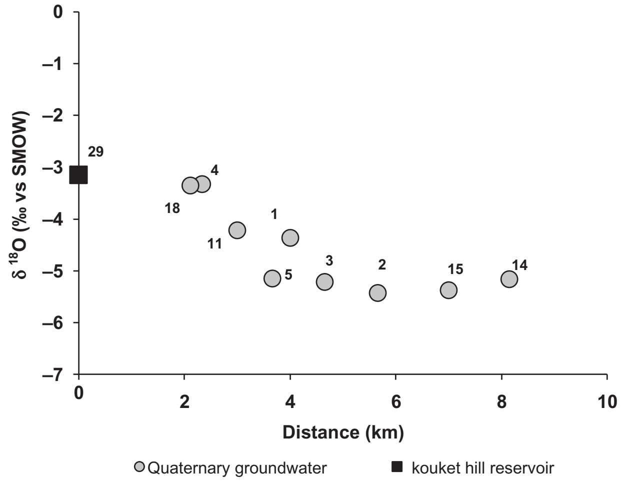

Fig. 11 Relationship between $\delta^{18}O$ and distance (km) of Quaternary groundwater from the Kouket hill reservoir.

gypsum outcrops (wells 1, 9 and 12). Others, of shallow depth, exhibit a weak relationship. This demonstrates that the mineralization of these groundwaters is controlled by both dissolution and a weak evaporation processes.

To infer the impact of the hill reservoirs on the recharge of the alluvial aquifer, we established the correlation between $\delta^{18}O$ content of the Quaternary samples located on/near the valley of Wadi El Hamra and distance to the Kouket hill reservoir (sample no. 29). Figure 11 reveals an enrichment trend that is noticeable up to a distance of more than 3 km. The decrease of the isotopic content of the samples (nos 1, 4, 11 and 18) that are close to the Kouket Reservoir does not suggest any implication for infiltration/re-infiltration of the reservoir water. These evaporated groundwaters are related to the low tapping depth, as confirmed by Fig. 12. The other non-evaporated samples (nos 2, 3, 5, 14 and 15) provide evidence of recent recharge which is assumed to occur by rapid infiltration of the meteoric water in the valley of Wadi El Hamra. This is facilitated by the good permeability of the alluvial deposits of the Quaternary aquifer.

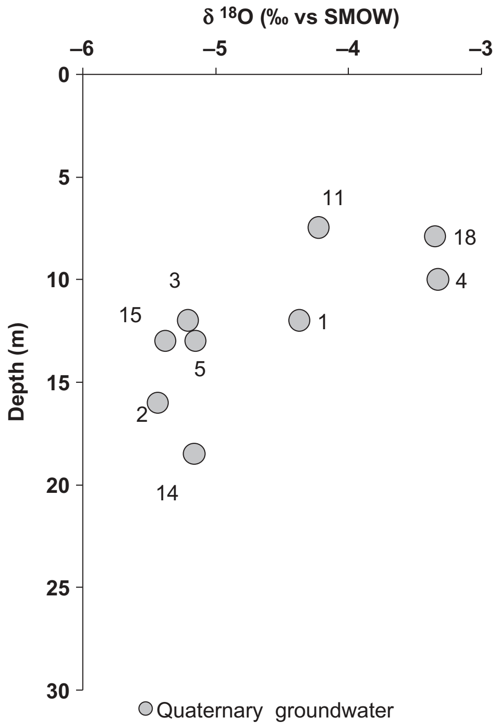

Fig. 12 Relationship between $\delta^{18}O$ and depth (m) of Quaternary groundwater in Jeloula basin.

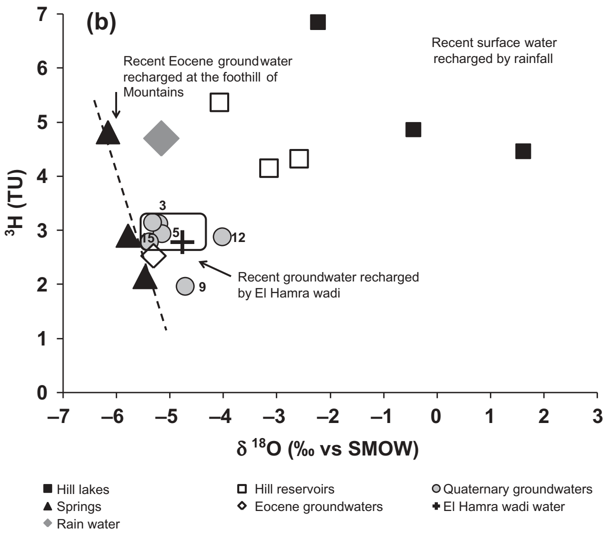

Fig. 13 (a) Relationship between ^{3}H (8 April 2009) and ^{3}H (4 September 2008) for hill reservoir water and (b) $\delta^{18}O/^{3}H$ relationship (April 2009) of the analysed water samples.

Tritium isotope The ^{3}H content of the hill reservoir waters were measured during two seasons (September 2008 and April 2009) (Fig. 13(a)). In fact, in September 2008, the ^{3}H content ranged from 3.6 (sample 36) to 4.3 TU (sample 34). During April 2009, the values varied between 4.2 (sample 29) and 5.4 TU (sample 27, Table 1). These concentrations were similar to those of local precipitations that were measured during April 2009 (4.7 TU) at Jeloula rain station (Fig. 13(b)). This suggests that these reservoirs are recharged directly by local rainfall and are subject to seasonal variations of ^{3}H activity (Fig. 13(a)). The same process is observed in the hill lakes. These waters show that the values of ^{3}H range between 4.5 (sample 30) and

6.8 TU (sample 32). This information provides evidence that surface flows which arrive at reservoirs have the same isotopic signal as local precipitation.

These data confirm that surface storage reservoirs show seasonal variations of tritium content. Hence, it is important to note here that the isotopic signature of the reservoir surface waters is largely controlled by the atmospheric processes (precipitations, evaporation) and the seasonal fluctuations of water level in the reservoirs (Gay 2004).

The $\delta^{18}O/^{3}H$ diagram (Fig. 13(b)), identifies the recharge sources of the waters in Jeloula basin. Most of the analysed samples exhibit values higher than 1 TU and suggest that recent recharge of the surface water and groundwater is occurring in the study area.

The measured ^{3}H concentration of samples representing the Quaternary aquifer is quite variable. The ^{3}H activity ranges from 2.0 to 3.1 TU (Table 1). All samples situated on/near the riverbed of Wadi El Hamra show homogenous contents, slightly higher than the wadi water's ^{3}H content (2.8 TU). This suggests that these groundwaters are recharged by recent flood water infiltration in the valley of Wadi El Hamra (Fig. 13(b)). Well no. 9, located close to the marl outcrops of Upper Eocene age, shows the lowest value (2.0 TU). This may be explained by the existence of clay lenses that constrain rapid infiltration of meteoric water in the unsaturated zone and prolong the groundwater residence time. Regarding the Eocene groundwater, the measured ^{3}H value in borehole no. 26 was 2.3 TU during April 2009. However, the ^{3}H activity in this borehole was 21.5 ± 1.5 TU in 1976 (Hamza 1987). This high value of ^{3}H in 1976 may indicate the presence of post-nuclear recharge. This suggests that this water has been recharged in recent time and that, in addition to Eocene water, it contains a large proportion of water infiltrated during these last years.

The spring waters also show high ^{3}H concentrations ranging from 2.1 to 4.8 TU, which indicates that Eocene groundwater (boreholes and springs) is recharged by the direct infiltration of meteoric water through the local carbonate outcrops (Chakeur and Ouesselat mountains) of the study area, which are highly porous.

Carbon data To support evidence of the recharge process inferred from the stable isotopes and tritium data, radiocarbon activity and $\delta^{13}C$ values in groundwater were used. The spatial distribution of the radiocarbon reveals that Quaternary groundwaters have high ^{14}C activity (more than 90% of modern C) for samples situated in the vicinity of Wadi El Hamra. This distribution confirms the dominant role of this wadi surface water in the recharge of the Quaternary alluvial aquifer. However, ^{14}C activity is comparatively low (65%) in wells 9 and 12, located close to the Upper Eocene outcrops. These values are justified by the existence of the clayey levels that contribute to the delay of the water infiltration in the unsaturated zone and to the increase in the residence time of groundwater.

The ^{14}C activity in Eocene samples ranges from 37 to 90.2 pmC (Table 1). The highest value is recorded in borehole 26 (90.2 pmC) and the lowest in borehole 23 (37 pmC). Both these boreholes are situated close to the limestone outcrops of Chakeur Mountain. The values confirm that the Eocene aquifer receives a modern and local recharge from the rapid infiltration of meteoric water into the carbonate outcrops of the region. However, the measured ^{14}C in borehole 26 was 44.2 ± 0.3 pmC in 1976 (Hamza 1987). This increase in the radiocarbon value explains that the relatively old groundwaters of the Eocene aquifer have been rejuvenated by mixing with recent water. The proportion of the mixture is variable and depends on the degree of fissuring and/or karstification of the Eocene limestone. The fracture porosity dominates over the karst in the carbonate aquifer, and can facilitate the groundwater flow and also interactions between the atmosphere and aquifer chemical components (Jirakova *et al.* 2010). This argument gives evidence for at least a significant present-day, direct infiltration towards the water table in the basin.

The $\delta^{13}C$ values in groundwaters (Table 1) range from –13.2 to –8.5 and from –12.4 to –13‰ for the Quaternary and Eocene aquifers, respectively, indicating domination of the soil-derived CO_2.

From comparison of the content of radiogenic tracers (^{14}C and ^{3}H) in borehole 26 between 1976 and 2009, it is noteworthy that the recent component dominates the old component. The system evidently receives strong recharge from recent rains (the rate of renewal is significant for the two periods).

CONCLUSIONS

Two hydrogeological aquifers within the Tertiary and the Quaternary deposits have been identified in Jeloula basin, located in Central Tunisia, which has semi-arid climate conditions. The combination of hydrochemical and isotopic tools significantly increases the possibility of understanding the hydrodynamic functioning, the processes controlling the groundwater chemistry and the identification of the recharge sources in this basin.

The spatial distribution of salinity indicates that the groundwater mineralization is in some way controlled by the different geological facies of the basin. The geochemical investigation shows the dominance of three water types (Ca-HCO_3, Ca-Na-SO_4-HCO_3 and SO_4-Ca) in the sampled waters, resulting essentially from water–rock interaction, such as the dissolution of evaporitic and carbonate minerals, and cation exchange reactions.

The stable isotope signatures indicate a similarity of isotopic signature of groundwater with the mean local precipitation of Jeloula station and provide evidence that most groundwater samples are of a meteoric origin. These tracers reveal the existence of non-evaporated groundwaters with relatively lower contents of $\delta^{18}O$ and $\delta^{2}H$, suggesting a recent recharge that is facilitated by the high permeability characterizing both the carbonate and alluvial aquifers, and evaporated waters with an enrichment in heavy isotopes highlighting the occurrence of an evaporation process from the surface prior to, or after infiltration from the unsaturated zone and from the water tables along the surface watercourses of the basin.

The investigated surface water samples collected from the hill reservoirs and hill lakes showed ^{18}O and ^{2}H enrichment. These data are significantly correlated with salinity and reveal distinct seasonal variability and, thus, provide evidence that water loss by evaporation is an important process in the open surface reservoirs. The ^{18}O content was used to calculate the altitude of recharge basin. The isotopic gradient defined in this study is $-0.4\delta^{18}O‰/100$ m.

The radiogenic (^{3}H, ^{14}C) isotope data and the piezometric map confirm the recent recharge and suggest that Wadi El Hamra forms the main axis from which the recharge of the alluvial aquifer can occur; it indicates the role of the limestone outcrops of Lower Eocene age in local infiltration to the deep aquifer. The radiotracers confirm that the relatively old groundwaters of the Eocene aquifer have been rejuvenated by mixing with modern infiltration water. The mixing proportions are variable and depend on the degree of fissuring and/or karstification of the Eocene limestone.

The scientific results of this study could be extended to focus the investigation on strategic areas such as fault zones, where exchanges between different aquifers along deep discontinuities still need to be clarified and quantified. As a future step, these considerations will help in water management of the area to sustainably develop exploitation of the resource, taking into account its dynamics and renewability.

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REFERENCES

Abbes, C., 2004. *Structurations et évolutions tectono–-sédimentaires Mésozoïques et Cénozoïques, associées aux accidents reghmatiques, à la jonction des marges téthysienne et Nord africaine (chaîne Nord–Sud – Tunisie Centrale)*. Thèse de Doctorat Es Sciences, Université Tunis El Manar.

Banner, J.L., *et al.*, 1989. Isotopic and trace-element constraints on the origin and evolution of saline groundwaters from central Missouri. *Geochimica et Cosmochimica Acta*, 53, 383–398. doi:10.1016/0016-7037(89)90390-6

Borgi, M., 1979. *Reconnaissance par prospection électrique de la plaine de Chougafiya.* Tunis: Direction Générale des Ressources en Eaux (DGRE).

Boukadi, N., 1994. *Structuration De l'Atlas De Tunisie : Signification Géométrique Et Cinématique Des Nœuds Et Des Zones D'interférences Structurales Au Contact De Grand Couloirs Tectoniques*. Thèse de Doctorat Es Sciences, Université Tunis II.

Burrolet, P.F., 1956. *Contribution à l'étude stratigraphique de la Tunisie Centrale*. Annales des mines et de la géologie, 345p.

Celle, H., 2000. *Caractérisation des précipitations sur le pourtour de la Méditerranée occidentale. Approche isotopique et chimique*. Thèse, Université d'Avignon et des Pays de Vaucluse, France, 222 p.

Celle-Jeanton, H., *et al.*, 2001. Caractérisation isotopique des pluies en Tunisie. Essai de typologie dans la région de Sfax. *C. R. Académie des Sciences,* Paris, série IIa, 33, 625–631.

Clark, I. and Fritz, P., 1997. *Environmental Isotopes in Hydrogeology.* New York: Lewis.

Craig, H., 1961. Isotopic variations in meteoric waters. *Science*, 133, 1702–1703. doi:10.1126/science.133.3465.1702

DGACTA (Direction Générale de l'Aménagement et de la Conservation des Terres Agricoles, Kairouan, Tunisie), 2005. *Etude d'impact des travaux de CES dans le gouvernement de Kairouan : Analyse des paramètres d'évaluation d'impact des travaux de CES et proposition de recommandations*. Rapport technique. Kairouan: DGACTA, 195p.

DGRE (Direction Générale des Ressources en Eau), 2007. *Annuaire de l'exploitation des nappes profondes de la Tunisie*. Tunis, Tunisie: DGRE.

DGRE (Direction Générale des Ressources en Eau), 2010. *Annuaire de l'exploitation des nappes phréatiques de la Tunisie.* Tunis, Tunisie: DGRE.

Dixon, W. and Chiswell, B., 1992. The use of hydrochemical sections to identify recharge areas and saline intrusions in alluvial aquifers, southeast Queensland, Australia. *Journal of Hydrology*, 130, 299–338.

Edmunds, W.M., Carrillo-Rivera, J.J., and Cardona, A., 2002. Geochemical evolution of groundwater beneath Mexico City. *Journal of Hydrology*, 258, 1–24. doi:10.1016/S0022-1694(01)00461-9

Edmunds, W.M. and Smedley, P.L., 2000. Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. *Applied Geochemistry*, 15, 737–752. doi:10.1016/S0883-2927(99)00079-7

Farid, I., 2007. *Contribution à l'étude Hydrogéologique, Géochimique et Isotopique du système aquifère de Chougafiya et ses relations avec les nappes limitrophes (Tunisie Centrale)*. Master, Ecole Nationale d'Ingénieurs de Sfax, p. 111.

Fontes, J.C., 1971. Un ensemble destiné à la mesure de l'activité du radiocarbone naturel par scintillation liquide. *Revue Geographie Physique Géologie Dynamique*, 13 (1), 67–86.

Gay, D., 2004. *Fonctionnement et bilan de retenues artificielles en Tunisie: Approche hydrochimique et isotopique*. Thèse de Doctorat, Université de Paris XI, France.

Geyh, M.A., 2000. An overview of ^{14}C analysis in the study of the groundwater. *Radiocarbon*, 42 (1), 99–114.

Grünberger, O., Montoroi, J.P., and Nasri, S., 2004. Quantification of water exchange between a hill reservoir and groundwater using hydrological and isotopic modelling (El Gouazine, Tunisia). *Comptes Rendus Geoscience*, 336, 1453–1462. doi:10.1016/j.crte.2004.08.006

Hamza, M., 1987. *Etude des formations hydrogéologiques du Bled Jeloula (Tunisie Centrale)*. Direction Générale des Ressources en Eaux (DGRE). Tunis, 119p.

Hidalgo, M.C., Cruz-Sanjulián, J., and Sanroma, A., 1995. Evolución geoquímica de las aguas subterráneas en una cuenca sedimentaria (acuífero de Baza-Caniles, Granada, España). *Tierra y Tecnol*, 20, 39–48.

IAEA, 2004. *Global network of isotopes in precipitation* [online]. Vienna: Isotope Hydrology Information System, International Atomic Energy Agency. Available from: http://isohis.iaea.org [Accessed 4 May 2004].

Jirakova, H., *et al.*, 2010. Carbon isotopes to constrain the origin and circulation pattern of groundwater in the north-western part of the Bohemian Cretaceous Basin (Czech Republic). *Applied Geochemistry*, 25, 1265–1279. doi:10.1016/j.apgeochem.2010.05.012

Ma, J., *et al.*, 2009. Limits to recharge of groundwater from Tibetan plateau to the Gobi desert, implications for water management in the mountain front. *Journal of Hydrology*, 364, 128–141. doi:10.1016/j.jhydrol.2008.10.010

Maduabuchi, C., Faye, S., and Maloszewski, P., 2006. Isotope evidence of palaeorecharge and palaeoclimate in the deep confined aquifers of the Chad Basin, NE Nigeria. *Science of the Total Environment*, 370, 467–479. doi:10.1016/j.scitotenv.2006.08.015

Marc, V., Travi, Y., and Pichon, A., 1996. Reconnaissance des mécanises hydrologiques sur un petit bassin versant méditerranéen. Approche par le traçage chimique et isotopique naturel de l'eau. *C.R. Académie des Sciences,* Paris, II a, 323, 57–64.

Maréchal, J.C. and Etcheverry, D., 2003. The use of 3H and 18O tracers to characterize water inflows in Alpine tunnels. *Applied Geochemistry*, 18, 339–351. doi:10.1016/S0883-2927(02)00101-4

Montoroi, J.P., Grünberger, O., and Nasri, S., 2002. Groundwater geochemistry of a small reservoir catchment in Central Tunisia. *Applied Geochemistry*, 17, 1047–1060. doi:10.1016/S0883-2927(02)00076-8

Penna, D., *et al.*, 2010. On the reproducibility and repeatability of laser absorption spectroscopy measurements for δ^2H and δ^{18}O isotopic analysis. *Hydrology and Earth System Sciences Discussions*, 7, 2975–3014. doi:10.5194/hessd-7-2975-2010

Prinz, D., 1999. Water harvesting techniques in the Mediterranean region. *In:* R. Berndtsson, ed. *Rain water harvesting and management if small reservoirs in arid and semi arid areas.* Lund, Sweden: ORSTOM/Hydromed-SAREC-NFR-Lund University. Report 3222, 151–163.

Rigane, A., 1991. *Les calcaires de l'Yprésien en Tunisie Centro-septentrionale : Cartographie, cinématique et dynamique des structures*. Thèse de Doctorat, Université de Franche Compte, France, 205p.

Sass, R.L. and Scheuerman, R.F., 1962. The crystal structure of sodium bicarbonate. *Acta Crystallographica*, 15, 77–81. doi:10.1107/S0365110X62000158

Scanlon, B.R., *et al.*, 2006. Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, 20, 3335–3370. doi:10.1002/hyp.6335

Stigter, T.Y., *et al.*, 1998. A hydrogeological and hydrochemical explanation of the groundwater composition under irrigated land in a Mediterranean environment, Algarve, Portugal. *Journal of Hydrology*, 208, 262–279. doi:10.1016/S0022-1694(98)00168-1

Stuiver, M. and Polach, H., 1977. Reporting of ^{14}C data. *Radiocarbon*, 19 (3), 355–363.

Taylor, C.B., 1976. *IAEA isotope hydrology laboratory.* Vienna: International Atomic Energy Agency. Technical procedure note no. 19.