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Recharge and paleorecharge of the deep groundwater aquifer system in the Zeroud Basin (Kairouan plain, Central Tunisia)

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ABSTRACT

The multilayered aquifer of Zeroud basin is characterized by the hydrodynamic complexity due to natural (geology) and anthropogenic (management) features. Stable and radioactive isotope data have been used to investigate the origin of the groundwater and its recharge area and to understand the deep groundwater system within the southern Kairouan sedimentary basin. Most of the stable isotopic data indicate that most deep groundwater samples derived either from meteoric water or from the Zeroud River, and were not affected by any significant degree of evaporation during recharge. Current tritium concentration in the groundwater is very low. However, it proved useful in the qualitative identification of modern recharge and mixing of recent and old groundwater. Radiocarbon-deduced ages range from more than 30,000 years to modern. A modern recharge characterizes the deep aquifer upstream of the basin. The groundwater with ages range from more than 30,000 years and depleted of heavy isotopes are found in the deeper aquifer (aquifer B), downstream of the basin, and could be inherited from paleorecharge.

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1. Introduction

The drainage network in the Kairouan Plain (center of Tunisia, Fig. 1), although important, is characterized by non-perennial discharge. Thus, domestic and agricultural water supply depends on groundwater resources. Their sustainability is threatened by an increasing population, drought periods and probably by the anthropic actions (management), especially in the southern area of the plain where groundwater quality is originally poor.

In this area, known as the hydrogeologic Zeroud basin (Fig. 1), the groundwater system is characterized by high heterogeneity and by complex recharge mechanisms especially after the management of the Zeroud wadi by construction of the Sidi Saad dam (Fig. 1). Early studies, mainly those of Besbes (1975, 1978), have estimated that recharge of deeper aquifers is strongly influenced by the Zeroud wadi, the most significant hydrographic network. In this paper, isotopic techniques (stable and radioactive isotopes) are used to characterize the deep groundwater systems in the Zeroud basin and to discuss recharge processes and period in the area.

2. Regional setting

The study area (35°10′–35°40′N, 9°45′–10°40′E) is in the center of Tunisia, in the southern part of the Kairouan Plain basin. It covers a region limited in the north by the Drâa Affane hill and the basin of Merguellil wadi, in the east and south by a set of endorheic depressions (Sebkhet Sidi El Heni, Chrita and Mechertat), and by the Siouf – Cherahil Mountains in the west (Fig. 1).

The selected area corresponds to the downstream portion of the Zeroud wadi watershed (1000 km^2). This wadi is to the west of Kairouan Plain and drains a total basin of 8650 km^2 (34°45′–35°49′N, 8°19′–9°45′E) from the Tunisia–Algeria border.

The Kairouan Plain basin is covered by Neogene and Quaternary deposits. The Mio-Pliocene formations mainly consist of sands, silts, clays, marls, and conglomerate strata which derived from the erosion of secondary and tertiary age deposits surrounding the basin.

Rainfall recorded in Kairouan since 1950 (National Meteorology database of Tunisia) shows an average value of 310 mm/y. Most rainfall occurs during the rainy season (September–May) and is limited to individual and torrential events. Under this regime, the majority of the wadis, including the Zeroud, are characterized by high peak flow discharge (several hundreds of m^3 in a quarter to a half an hour). The endorheic depression, Sebkhet El Kalbia, is the natural discharge zone of the Zeroud wadi. To protect the city of Kairouan against flooding of this wadi and for a better mobilization

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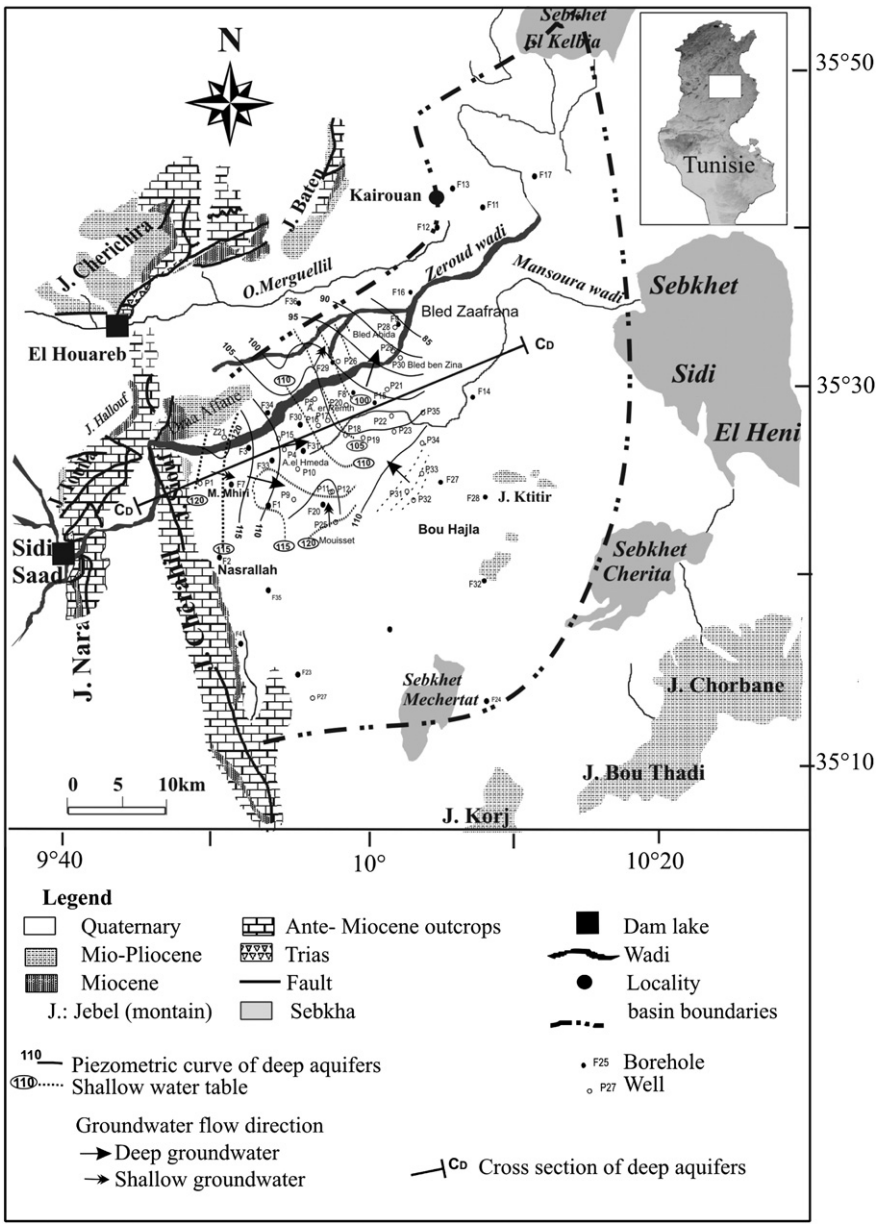

Fig. 1. Simplified geologic map of Zeroud area showing equipotential lines based on piezometric measurements in the deep aquifer in the central part of the area.

of surface waters, the Sidi Saad dam was constructed in 1982, 20 km upstream in the Kairouan Plain. This dam has obviously disturbed the natural flow regime and has strongly influenced the relationships between the wadi and the groundwater system. Water released from the Sidi Saad dam has occasionally been used to artificially recharge the aquifer when piezometric levels were extensively low.

The Mio-Plio-Quaternary deposits are up to 700 m thick in the central area of the Kairouan Plain basin, along the Zeroud wadi and host one shallow and two deep aquifers (Fig. 2). The thickness of the deep aquifer formations varies from 50 to 100 m. Its depth below the surface varies from 100 to 700 m. The upper aquifer (aquifer A) is formed by fine-grained sands and disappears southward, near Nasrallah and Bou Hajla, and toward the east of the basin, beyond Bled Zaafrana. The lower aquifer (aquifer B) consists of coarse sand and is exploited only in the south and in the east of the hydrogeologic Zeroud basin where it is accessible. The leaky-confining body which separates the two aquifers (aquifer A and aquifer B) is formed essentially by clay and alternating clay and sand. The water table of the shallow groundwater is deeper than 60 m below the ground. The groundwater in both the shallow and the deep aquifers drain from the western boundary highlands towards the depressions in the east (sebkhas El Kelbia, Sidi El Hani, Cherita and Mechertate) which constitute the natural discharge area of the aquifers.

The superposition of the piezometric maps of the two aquifers reveals leakage and percolation through the argillaceous formation. Thus on the upstream area, the deep aquifer is recharged from the shallow aquifer, where the piezometric levels in aquifer A is 5 m lower than the shallow aquifer. This is in contrast to the downstream area, where the shallow groundwater is recharged by water from the deep aquifers. The hydraulic head difference exceeds 10 m north of Kairouan town where the piezometric head of the deep groundwater is above the ground surface. In the middle zone, the piezometric level of the two aquifers is the same (Besbes, 1975). Overall, in this aquifer system upward flow from the deep layers dominates.

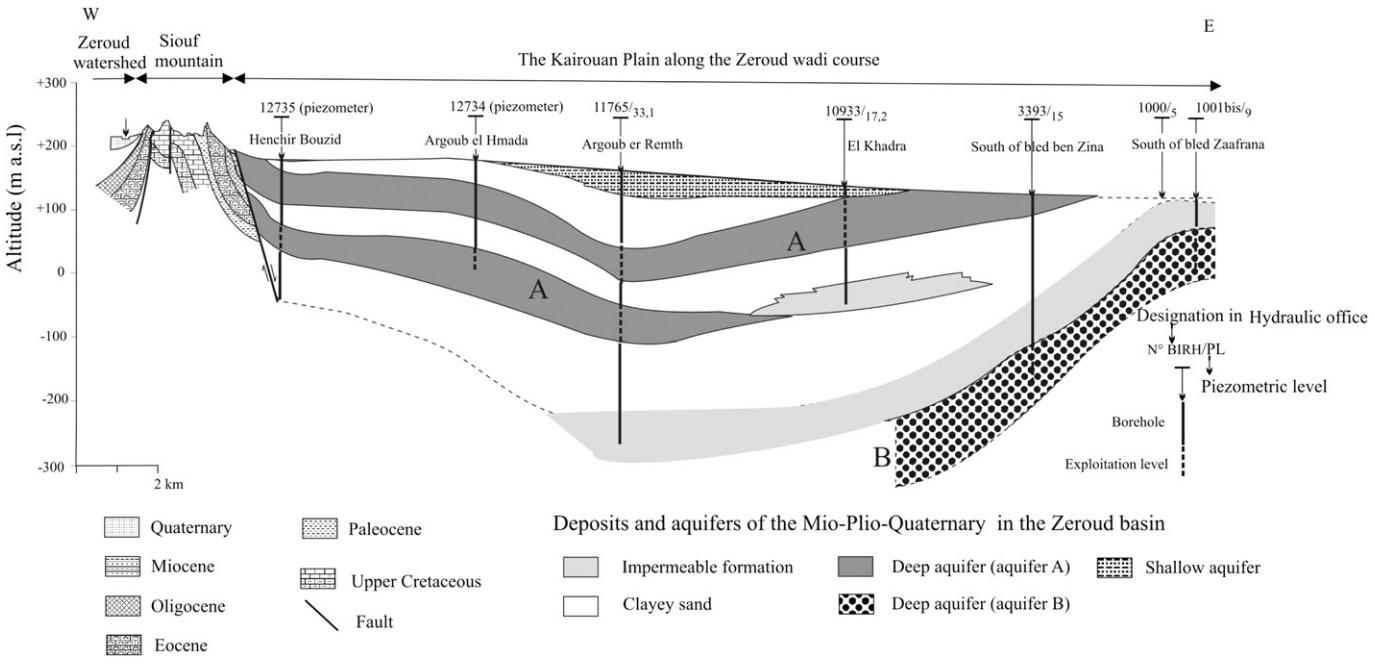

Fig. 2. Schematic cross section of the deep aquifers along the Zeroud course (modified from SEREQ 1973).

3. Materials and methods

Surface water and groundwater samples were collected from reservoir lakes and deep aquifers, exploited on both sides of the Zeroud bed but especially in the southern bank, during the rainy season (November, 1997 and February, 1998) and at the end of the dry season (September, 1998). The samples from the confined aquifer were collected from boreholes equipped with electrical pumps.

Physical and chemical parameters (temperature, pH, and alkalinity) were measured in situ (Table 1). Total dissolved inorganic carbon (TDIC) is calculated from temperature, pH and alkalinity using the equilibrium equations between the different carbon species in solution (Stumm and Morgan, 1981) as shown in Table 1.

Thirty-six deep groundwater and 16 surface water samples were selected for oxygen-18/deuterium content analyses, while 29 deep groundwater samples have been analyzed for TDIC carbon-13 and carbon-14 content. Twenty-seven deep groundwater and 10 surface water samples were analyzed for tritium. For more information, five samples from piezometers upstream of the study area, at the proximity of the wadi course, were analyzed for oxygen-18/deuterium and tritium.

In addition, 49 rainwater samples were also collected from late 1987 to late 2000 in some stations in the Zeroud basin watershed, on an event basis, for oxygen-18/deuterium content.

Isotopic contents ($\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$) were measured using the usual protocols (Fontes, 1971, 1983), applied in the Laboratory of "Orsay Terre" in Orsay (France). Samples for carbon-14 analysis were taken by precipitating $BaCO_3$ with the addition of excess $BaCl_2$ to a certain volume of water previously brought to pH 12 by addition of NaOH. The carbon-14 activities for groundwater were determined by liquid scintillation counting on benzene synthesized from CO_2 (Fontes, 1971) at the Laboratory of Radio-Analyses and Environment of ENIS (Tunisia). Tritium contents were measured by counting after electrolytic enrichment, at the Laboratories of the Hydrology Section of the International Atomic Energy Agency (IAEA).

The ^{18}O, ^{2}H and ^{13}C contents are reported in ‰ versus SMOW (Standard Mean Ocean Water) and ‰ versus PDB (Pee Dee Belemnite), respectively, with an uncertainty of 0.2 ‰ for ^{18}O and ^{13}C and of 2 ‰ for ^{2}H. The tritium contents and the carbon-14 activities are reported respectively in tritium units (TU) and in percentage of modern carbon (pmc). The precision of the latter measurements depends on the amount of carbon recovered for analysis (Le Gal La Salle et al., 2001) and typically varies between 3 and 0.4 pmc. Tritium counting with electrolytic enrichment of ^{3}H provides a precision better than 0.8TU (Clark and Fritz, 1997).

4. Results and discussion

4.1. Stable isotopes ^{18}O and ^{2}H

4.1.1. Surface and Sidi Saad water signature

The Sidi Saad lake samples have the isotopic composition (Table 2) strongly affected by evaporation. They lie, as do the other lakes situated in the Kairouan region (el Houareb (Fig. 1), Fidh Ali, Bou Arfa, El Midhi, Ain el Haj, El Morra, Cherichira, El Fej and El Haroug), on an evaporation line with the equation $\delta^{2}H = 5.2\ \delta^{18}O - 9.6$ (Fig. 4) (Jeribi, 2004). The intersection of this evaporation line with the GMWL (Global Mean Water Line) gives values of −6.8‰ and −44‰ for the respective $\delta^{18}O$ and $\delta^{2}H$ content of the non evaporated rain water which contribute to surface run-off. This original depleted composition of rainfall is attributed to the altitude effect in the western part of the Zeroud basin in which a coefficient of 0.52‰ of $\delta^{18}O$ for 100 m is estimated (Jeribi, 2004).

4.1.2. Groundwater signature

$\delta^{18}O$ values of the deep groundwater samples range from −6.36 to −4.57‰, with a mean of −5.54‰, and $\delta^{2}H$ values vary from −43.9 to −24.8‰ with a mean of −34.9‰ (Table 2). In Figs. 3 and 4, the $\delta^{18}O$ and $\delta^{2}H$ data of the groundwater samples plotted together with the Global Meteoric Water Line (GMWL) (Craig, 1961), the Regional Meteoric Water Line (RMWL) (Celle-Jeanton et al., 2001) and Surface Water Line (SWL) show a set of the deep groundwater wells (aquifer B) in the depleted end member which offsets slightly the GMWL. This group indicates that these waters were presumably recharged in humid periods during the late Pleistocene and the early Holocene recognised in south and central Tunisia (Causse et al., 1989, 1991,

Table 1
Physico-chemical parameters of groundwater, C-14 activities and $\delta^{13}C$ of the TDIC and $\delta^{13}C$ in equilibrium with gas.

N°	Site	Aquifer	pH	T (°C)	Alcalinity (meq l^{-1})	TDIC (mmol l^{-1})	C-14 (%) activity	$\delta^{13}C$ (‰ *vs* PDB)	$\delta^{13}C$eq. gas (‰ *vs* PDB)
		February 1998							
F1	Bir el Hadj Sadok	Deep	7.47	~17,4	2.70	2.92	37.0 ± 1.04	−7.69	−15.2
F2	Nasrallah commune	Deep	7.81	23.1	3.98	4.12	3.3 ± 0.9	−9.37	−17.2
F3	Henchir Mestiri	Deep	7.81	~16	2.68	2.77	48.4 ± 0.96	−9.36	−17.9
F7	Pavillier 3 (Apr-99)	Deep	7.79	22.3	2.54	2.63	51.7 ± 10	−10.37	−18.3
F8	Henchir frazier	Deep	7.88	17.7	3.28	3.38	30.4 ± 1.11	−9.34	−17.8
F9	CFPA Barrouta (Sep-98)	Deep	6.93	21.2	3.60	5.65	23.2 ± 0.60		
F11	Draa el Karouia	Deep	6.65	23.1	4.86	7.35	Nil	−7.84	−12.9
F12	RNTA	Deep	7.67	20.6	3.96	4.15	4.0 ± 0.78	−9.32	−17.3
F13	SOBOCO bis	Deep	7.44	~22.7	5.85	6.33	2.0 ± 0.78	−7.47	−14.9
F14	Zaafrana 6 bis (Sep 98)	Deep	7.4	22.0	4.45	4.86	14.8 ± 0.40	−8.88	−16.4
F15	Henchir Bechaux 2	Deep	7.8	20.0	3.02	3.13	36.5 ± 1.30	−8.53	−16.7
F17	El Ghabet	Deep	7.78	22.7	4.24	4.39	Nil	−8.51	−16.4
F20	Bir Djedid bis	Deep	7.58	21.9	4.86	5.15	23.0 ± 0.82	−8.95	−16.7
F20	Bir Djedid bis (Nov-00)	Deep	8.26	21.6	4.86	4.88	24.4 ± 1.30	−8.56	−16.7
F21	Bir Djedid 1 (Nov-00)	Deep	7.98	~21.6	4.86	4.96	30.8 ± 1.30	−8.54	−16.6
F23	Fidh el Behira	Deep	6.96	25.8	4.04	5.02	Nil	−9.9	−16.0
F24	Mechertat	Deep	7.61	27.9	3.10	3.26	Nil	−10.57	−17.8
F25	Chrarda 2 (Sep 98)	Deep	7.28	26.6	3.94	4.39	4.7 ± 0.70	−8.56	−15.4
F27	Ahmed Abdessamiaa	Deep	7.38	22.9	3.96	7.78	20.1 ± 0.90	−8.55	−16.0
F28	Gassat	Deep	7.5	21.2	3.36	3.63	Nil	−9.72	−17.9
F29	Bir el Kilani	Deep	6.64	23.3	4.78	4.87	21.5 ± 0.92	−8.91	−16.9
F30	Argoub Remth 2	Deep	7.7	20.5	4.14	4.33	48.0 ± 1.06	−10.64	−18.6
F31	El Aouja 3	Deep	7.78	21.7	3.58	3.71	45.0 ± 1.01	−10.05	−18.0
F32	Noualia	Deep	7.51	25.0	4.50	4.80	Nil	−9.51	−16.9
F33	Argoub el Hamada	Deep	7.41	22.5	2.75	2.99	47.0 ± 1.70	−10.1	−17.5
F34	Amor Jellouli	Deep	6.64	23.3	5.14	7.83	11.6 ± 1.40	−7.19	−12.2
F35	Garaat Bledet 1	Deep	8.03	24.1	3.78	3.84	4.5 ± 0.95	−13.38	−21.2
F36	Melelsa	Deep	7.58	18.8	3.90	4.14	35.4 ± 2.64	−9.69	−17.7
F16	Raggada (Dassi, 1999)	Deep	7.37	19.5	3.20	3.53	14.7 ± 0.50	−8.32	−16.0

2003; Fontes and Gasse, 1989; Ouda, 2000; Zouari et al., 1998). This hypothesis must be confirmed by carbon-14 results.

Besides this old water end member, two groups are distinguishable. The first group shows a cluster of some deep groundwater samples along the SWL with a slope of 5.2. This group indicates groundwater affected by significant evaporation. This groundwater located at the vicinity of the Zeroud wadi course is likely to receive the mixture of surface water seepage with significant (low flood) or slight evaporation (high flood). Conversely, the majority of deep groundwaters shows another cluster distinctive from the evaporation line. This trend is likely to represent the mixing between waters of different ages or mixing between the Zeroud water flood and local rain water infiltration. Although definite conclusions on mixing process and age determination cannot be made from the stable isotopes alone, differences in cluster layouts and trends support the idea that distinctive water types are clearly identified.

4.2. Radioactive isotope ^3H

Both natural and anthropogenic tritium enters the hydrological cycle via precipitation. Its presence in groundwater provides evidence for active recharge. As it is part of the water molecule, it is the only direct water dating method available. The most important use of tritium in groundwater is in distinguishing between water that entered an aquifer prior to 1952 (pre-bomb water) and water that was in contact with the atmosphere after 1952. Because of the variable source of tritium and uncertainties due to possible mixing, tritium is not used for age dating in the conventional way but it is useful in studies of mixing processes.

^3H concentration measured on 1998 in Kairouan precipitation (*only one sample of* September rain*)* is around 7 TU. Before 1990 measurements in precipitation exceed 10 TU (Fig. 5) (Zouari, 1988; GNIP, 1999). In surface reservoir lakes measurements fluctuate between 4.8 and 6.0 TU. All of deep groundwater samples exhibit ^3H contents less than 0.5 TU. The low ^3H contents display that groundwater may be recharged prior 1952 or there is mixing with a high contribution of the non tritiated old groundwater, thus decreasing the groundwater ^3H content.

4.3. Carbon isotopes and carbon-14 dating of groundwater

4.3.1. Carbon-13 contents and origin of the TDIC in the deep aquifers

The deep groundwater carbon-13 contents (Table 1) range between −13.4‰ to −7.5‰. Broadly these values are relatively depleted and show that the main source of inorganic dissolved carbon in this system is probably soil gas CO_2. The plots of carbon-13 contents versus pH in Fig. 6 show that most groundwater samples lie between the theoretical curves representing the carbon-13 content of TDIC in isotopic equilibrium with soil CO_2 with $\delta^{13}C$ CO_2 ranging between −20‰ and −13‰ (Deines et al., 1974; Le Gal La Salle et al., 2001). Those $\delta^{13}C$ CO_2 values are in good agreement with those found in the literature in subtropical dry grassland and prairie areas (Taupin, 1990) where typical carbon-13 contents of soil gaseous CO_2 range from −19‰ to −13‰ versus PDB (Le Gal La Salle et al., 2001). The depleted $\delta^{13}C$ CO_2 are measured under the area dominated by native vegetation in which carbon-13 content of biogenic CO_2 is −19.2‰ and −20‰ (values measured in Niger by Ousmane, 1988; Taupin, 1990). The soil gas enriched in carbon-13 is related to cultivated plants essentially pepper and olive-tree (−10‰ to −13‰, values measured in Niger by Taupin, 1990). The variations observed for carbon-13 contents of TDIC are thus related to different proportions of biogenic CO_2 produced under cultivated and/or native vegetation.

4.3.2. Carbon-14 activity

The ^{14}C concentration (Table 1) of groundwater samples ranges from 0 to 51.7(±1 pmc) in the deep aquifers. The relatively high ^{14}C

Table 2
^{18}O, ^{2}H and ^{3}H contents of groundwater and surface waters.

N°	Site	Aquifer	$\delta^{18}O$ (‰ *vs* SMOW)	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	Tritium (UT)	
			November 1997		September 1998		Nov-97	Sep-97
F1	Bir el Hadj Sadok	Deep	−5.14	−33.9			0.28 ± 0.24	
F2	Nasrallah commune	Deep	−5.50	−33.1			0.00 ± 0.23	
F3	Henchir Mestiri	Deep	−5.44	−35.7	−5.82	−33.8	0.01 ± 0.24	
F4	Ajebna	Deep	−5.37	−36.5			0.18 ± 0.23	
F7	Pavillier 3 (April 99)	Deep	−5.83	−34.3			0.19 ± 0.24	
F8	Henchir frazier	Deep	−5.77	−36.2	−5.70	−36.7	0.07 ± 0.24	
F9	CFPA Barrouta	Deep	−5.11	−29.3			0.10 ± 0.24	
F11	Draa el Karouia	Deep	−5.48	−30.4			0.18 ± 0.24	
F12	RNTA	Deep	−5.10	−30.7			0.31 ± 0.23	
F13	SOBOCO bis	Deep	−5.62	−34.3			0.06 ± 0.23	
F14	Zaafrana 6 bis (Sep 98)	Deep	−5.44	−34.3			0.06 ± 0.23	
F15	Henchir Bechaux 2	Deep	−5.94	−37	−5.79	−33.8	0.15 ± 0.27	
F17	El Ghabet (Feb 98[a])	Deep	[a]−5.96	[a]−41.2			[a]0.00 ± 0.31	
F20	Bir Djedid bis	Deep	−4.96	−25.9	−5.96	−38.3	0.00 ± 0.31	0.31 ± 0.16
	Bir Djedid bis (2000)	Deep	−5.16	−35.7				
F22	Boussari	Deep			−5.44	−34.9		
F23	Fidh el Behira	Deep	−6.40	−40.1			0.00 ± 0.31	
F24	Mechertat	Deep	−5.90	−33			0.01 ± 0.31	
F25	Chrarda 2	Deep	−5.60	−38.1			0.00 ± 0.31	
F27	Ahmed Abdessamiaa	Deep	−5.52	−35.3	−5.53	−32.5	0.00 ± 0.31	
F28	Gassat	Deep	−6.36	−41.5			0.00 ± 0.31	
F29	Bir el Kilani	Deep	−4.95	−24.8			0.00 ± 0.31	
F30	Argoub Remth 2	Deep	−4.57	−29.9			0.00 ± 0.31	0.00 ± 0.15
F31	El Aouja 3	Deep	−6.00	−35.7	−5.83	−37.8	0.01 ± 0.31	
F32	Noualia	Deep	−6.34	−43.9			0.00 ± 0.30	
F33	Argoub el Hamada	Deep	−5.76	−33.7	−4.99	−34.3	0.00 ± 0.30	
F34	Amor Jellouli	Deep	−5.29	−34.5			0.16 ± 0.32	
F35	Garaat Bledet 1	Deep	−5.04	−35.5				
F36	Melelsa ([a]Feb 98)	Deep	[a]−5.83	[a]−35.0				
PZ3	Z21 19184/4 (Jan-98)	Deep	−1.17	−10.6			5.17 ± 0.29	
PZ4	K 12836/4 (Jan-98)	Deep	−5.51	−38.6			0.13 ± 0.14	
PZ5	P bis 18097/4 (Jan-98)	Deep	−5.46	−35.8			12.58 ± 0.55	
R1	Barraga Sidi Saad	Lake	−1.13	−13.5	0.09	−7.2	5.62 ± 0.43	
R2	Barrage El Houareb	Lake	−3.87	−29.6	7.41	27.9	5.33 ± 0.43	
R3	Lac collinaire Bou Arfa	Lake	−4.47	−40.5			5.26 ± 0.36	
R4	Lac collinaire el Midhi	Lake	−1.49	−15.6			5.77 ± 0.36	
R5	Lac collinaire Fidh Ali	Lake	−2.9	−26.2			5.02 ± 0.34	
R6	Lac collinaire Ain el Hadj	Lake	−3.68	−31.4			4.84 ± 0.34	
R7	Barrage collinaire el Morra	Lake	−0.84	−13.7	2.63	2.1	6.01 ± 0.43	
R8	Barrage collinaire Cherichira	Lake	−0.97	−12.4	5.73	23	5.40 ± 0.42	
R9	Barrage collinaire el Fedj	Lake	−3.49	−23.8	1.3	−1.4	5.35 ± 0.42	
R10	Barrage collinaire el Haroug	Lake	−3.78	−27.7	9.48	36	5.15 ± 0.42	

[a] Dassi (1999).

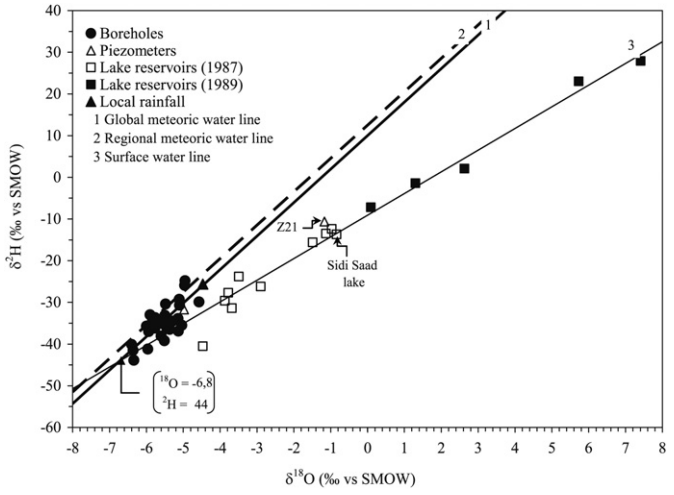

Fig. 3. Oxygen-18 and deuterium diagram of surface and groundwater. [1] Global meteoric water line (GMWL), [2] Tunis Carthage water line, [3] Surface water line.

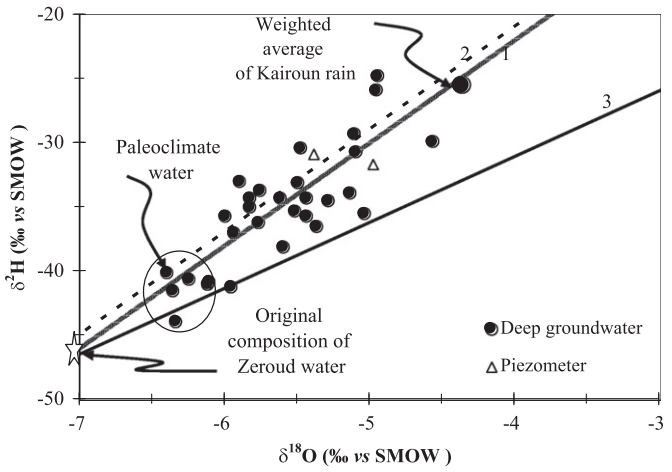

Fig. 4. Oxygen-18 and deuterium diagram of groundwater. [1] Global meteoric water line (GMWL), [2] Tunis Carthage water line, [3] Surface water line.

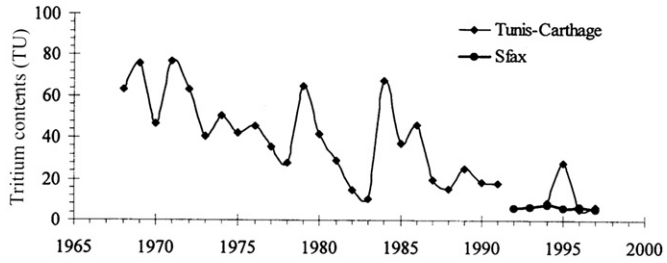

Fig. 5. Evolution of the weighted average annual tritium contents of the rain water in the stations of Tunis Carthage and Sfax.

activities observed in some samples of the deep aquifer suggest a recent recharge from a source of water upstream of the basin, near the Zeroud wadi course in the Menzel Mhiri area (Fig. 1). Towards the east and the south, activities decrease progressively. At the basin boundaries, ^{14}C activities decrease suddenly to reach very weak or nil values, revealing an isolated and closed reserve. Those groundwaters corresponding to the deeper aquifer (aquifer B) are characterized by depleted $\delta^{18}O$ and $\delta^{2}H$ contents (Fig. 4) and related to recharge in the Holocene and late Pleistocene humid phases.

4.3.3. Correction models and groundwater residence time

Models are necessary to assess the initial activity A_0 (Fontes, 1992) for waters with a ^{13}C signature resulting from carbonate rock dissolution (middle and terminal Pleistocene) and dissolution soil CO_2 gas (Fig. 7). These models are based on different mixing processes: pure models of chemical (Tamers, 1975) and isotopic (Ingerson and Pearson, 1964) mixing, and models of chemical mixing with isotopic exchange (Evans et al., 1979; Fontes and Garnier, 1979; Mook, 1980; Salem et al., 1980; Eichinger, 1983). The carbon introduced in these calculations has the following isotopic contents:

(1) Due to lack of local measurements of biogenic carbon in soil CO_2 gas, a $\delta^{13}C = -22‰$ value was used, referring to the average of values measured in Niger (Joseph, 1990; Taupin, 1990) and in northern Atlas (Guendouz, 1985) (similar ecosystem) and $A^{14}C = 100\%$.

(2) For marine carbonates, $\delta^{13}C = 0‰$, average calculated in the south of Tunisia on Holocene carbonates (Gargouri-Ben Ayed et al., 2007) and $A^{14}C = 0\%$.

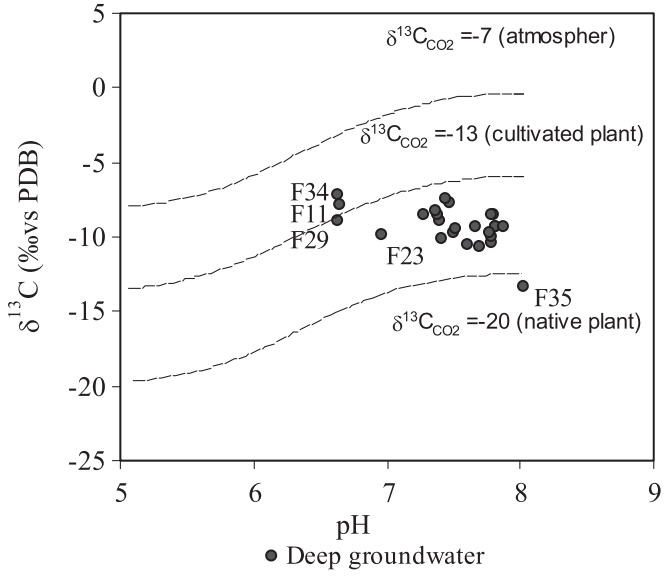

Fig. 6. Carbon-13 of the TDIC versus pH. The three curves represent the theoretical groundwater compositions in ^{13}C resulting from an isotopic equilibrium with gaseous CO_2 with different carbon-13 content ($\delta^{13}C_{CO_2}$ of **−7**, −13 and −20‰ versus PDB).

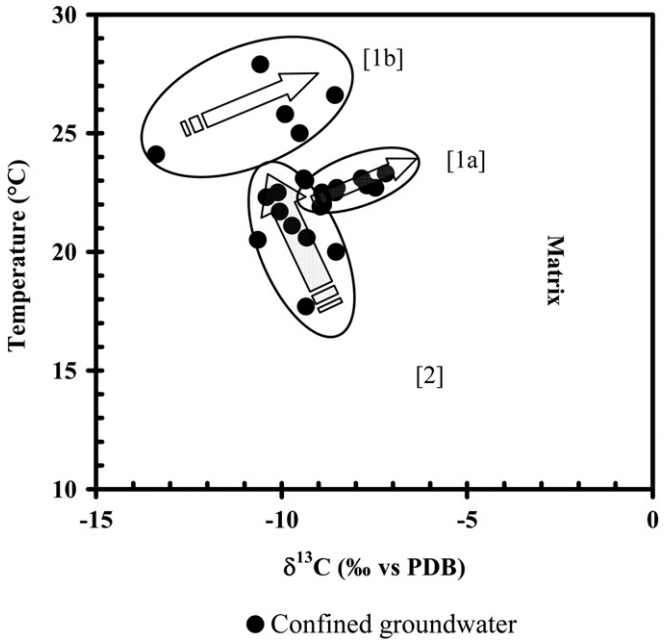

Fig. 7. Temperature versus TDIC $\delta^{13}C$ diagram. $\delta^{13}C$ evolution against the temperature show a mixing between biogenic CO_2 and mineral carbonate along groundwater flow [1] and from the surface water reserves [2].

The calculated A_0 falls within a wide range of values (Table 3). Some of the models (Ingerson and Pearson, 1964; Evans et al., 1979; Fontes and Garnier, 1979; Eichinger, 1983) give similar values (Fig. 8). Higher values are given by the IAEA (Salem et al., 1980) or the Tamers models (Tamers, 1975). The Mook (1980) model does not apply at all, as it gives negative initial activities. All of these models take into account chemical and isotopic mixtures with isotopic exchange in carbon between soil CO_2 and carbonates. The chemical model of Tamers cannot be used, as $\delta^{13}C$ varies with ^{14}C activities, which suggests an isotopic exchange with the carbonated matrix through time (Fig. 7), an exchange process which is not taken into account in the Tamers approach (Le Gal La Salle et al., 1996). The activities given by the Pearson model agree with results obtained with tritium contents.

After the correction of the initial activities, the calculated ages can be discussed according to ^{18}O contents, which relates to the paleoclimatic variations. Groundwater Pearson ages (Ingerson and Pearson, 1964), which show a large variation from old to modern in the deep groundwater aquifers, can be summarized, as in Fig. 9, into 3 categories:

(1) From present to 8500 BP, with a wide variation in ^{18}O contents and characterizing a belt of 12 km from the wadi bed. Recent recharge (F30, F1, F3) shows now homogenous ^{18}O contents, between −6.0 and −4.5‰ vs. SMOW, due or not to infiltration of the enriched water from Sidi Saad lake, of local rainfall and of depleted Zeroud wadi floods. The groundwater in which ^{18}O varies from −5.80 to −5.29‰ *vs* SMOW (F8, F34, F14) may

Table 3
Calculated values of initial activities and corresponding ages.

N°	14C (pmc)	Ao							Ages						
		Tamers	Pearson	Mook	F. & G.	AIEA	Evans	Eichinger	With $A_o = 100\%$	Tamers	Pearson	F. & G.	AIEA	Evans	Eichinger
F1	37.0	53.8	35.0	-19.4	34.3	55.7	32.5	32.9	8200	3100	Negative	Negative	3400	Negative	Negative
F2	3.3	51.9	42.7	16.5	42.4	67.8	40.5	40.8	28,200	22,800	21,150	21,100	25,000	20,750	20,800
F3	48.4	51.7	42.5	2.8	42.3	71.6	41.3	40.6	6000	550	Negative	Negative	3250	Negative	Negative
F7	51.7	51.8	47.3	33.8	47.1	75.5	45.3	45.1	5500	18	Negative	Negative	3150	Negative	Negative
F8	30.4	51.6	42.5	7.1	42.2	70.4	41.0	40.6	9850	4400	2750	2700	6950	2450	2400
F9	23.2								12,100						
F11	0.0	67.0	35.6	-53.6	34.4	56.6	32.2	26.9	Dead	Dead	Dead	Dead	Dead	Dead	Dead
F12	4.0	52.4	42.4	9.6	42.0	68.6	40.5	40.4	26,600	21,300	19,500	19,500	23,500	19,150	19,100
F13	2.0	53.9	34.0	-24.0	33.2	54.1	31.5	31.8	32,350	27,200	23,400	23,250	27,250	22,800	22,900
F14	14.8	54.2	40.4	-1.5	39.9	64.6	38.2	38	15,800	10,750	8300	8200	12,200	7850	7800
F15	36.5	51.8	38.8	-5.3	38.4	63.1	36.9	37.1	8350	2900	500	400	4500	83	126
F16	14.7	54.7	37.8	-20.7	37.3	61.8	36.0	35.3	15,850	10,850	7800	7700	11,850	7400	7250
F17	0.0	51.8	38.7	0.4	38.2	61.6	36.4	37	Dead	Dead	Dead	Dead	Dead	Dead	Dead
F20	23.0	52.9	40.7	3.6	40.2	65.2	38.6	38.6	12,150	6900	4700	4650	8600	4250	4300
F20	24.4	50.6	38.9	2.7	38.5	62.5	36.8	37.4	11,650	6050	3850	3750	7800	3400	3550
F21	29.5	51.2	38.8	0.6	38.4	62.4	36.7	37.2	10,100	4550	2250	2200	6200	1800	1950
F23	0.0	59.8	35.0	8.2	44.3	70.0	42.5	41.1	Dead	Dead	Dead	Dead	Dead	Dead	Dead
F24	0.0	52.5	48.0	37.9	47.8	73.6	45.5	45.8	Dead	Dead	Dead	Dead	Dead	Dead	Dead
F25	4.7	55.2	38.9	-0.1	38.2	60.1	36.1	36.3	25,300	20,350	17,450	17,300	21,050	16,850	16,900
F27	20.1	74.4	38.9	-65.7	37.5	62.0	36.6	25.3	13,250	10,800	5450	5150	9300	4950	1850
F28	0.0	53.7	44.2	3.4	44.0	74.3	43.0	41.8	Dead	Dead	Dead	Dead	Dead	Dead	Dead
F29	21.5	51.1	40.5	9.2	40.1	64.6	38.3	38.8	12,700	7150	5250	5150	9100	4750	4900
F30	48.0	52.3	48.4	35.6	48.2	78.4	46.7	46.1	6050	700	62	41	4050	Negative	Negative
F31	45.0	51.9	45.7	26.7	45.5	73.3	43.8	43.6	6600	1150	124	85	4050	Negative	Negative
F32	0.0	53.2	43.2	17.3	42.8	67.6	40.8	41	Dead	Dead	Dead	Dead	Dead	Dead	Dead
F33	47.0	54.1	45.9	21.7	45.6	73.2	43.9	43.5	6250	1150	Negative	Negative	3650	Negative	Negative
F34	11.6	67.2	32.7	-64.7	31.3	51.8	30.1	23.4	17,800	14,520	8550	8200	12,350	7850	5800
F35	4.5	51.0	60.8	87.3	66.4	95.8	59.2	57.9	25,650	20,100	21,550	22,250	25,300	21,300	21,100
F36	35.4	53.0	44.0	11.6	43.8	72.4	42.5	41.8	8600	3350	1800	1750	5900	1500	1400

result from recharge during the humid phases of the Holocene (2000–4000 and 7000–10,000 BP) recognized in the Center of Tunisia (Ouda et al., 1998; Ouda, 2000) and in the South-East surroundings of Sakhet Sidi el Heni (Ben Jmaa, 2001) and confirmed by climatic events of the last deglaciation recorded in the $\delta^{13}C$ profiles of stalagmite from the La Mine cave (36.03°N, 9.68°E, 975 m asl) at the north west of Kairouan (Genty et al., 2006). The water with more enriched $\delta^{18}O$ suggests a mixing of Holocene and recent waters.

(2) The period between 17,500 and 24,000 BP corresponds to waters in which $\delta^{18}O$ ranges from −5.60 to −5.04‰ *vs* SMOW (F2, F13, F12, F25 and F35). Groundwater may results from recharge during the humid pulses recognized between 18 and 34 ka identified in the Great Chotts Area of Southern Tunisia (Causse et al., 2003).

(3) Groundwater with carbon-14 activities equal or close to 0 (no exact dating) and depleted in heavy isotopes ($\delta^{18}O$ range from −6.40 to −5.48‰ *vs* SMOW) (F11, F17, F23, F24, F28, F32) exploited at the boundaries of the study area and corresponding to the deeper aquifer (aquifer B). The groundwater probably results from recharge during the humid phases of the late Pleistocene recognized around 30, 95–100, 130–150, or 180–200 ka (Causse et al., 1989, 1991, 2003; Fontes and Gasse, 1989; Zouari et al., 1998, Ouda et al., 1998; Ouda, 2000; Bedoui et al., 2002; Genty et al., 2002).

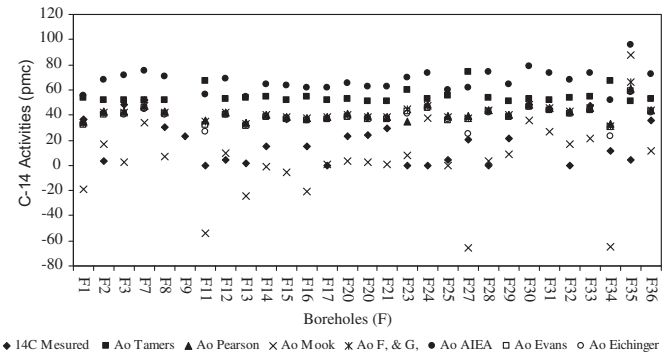

Fig. 8. Measured and calculated activities (pmc) by different models for each borehole (F).

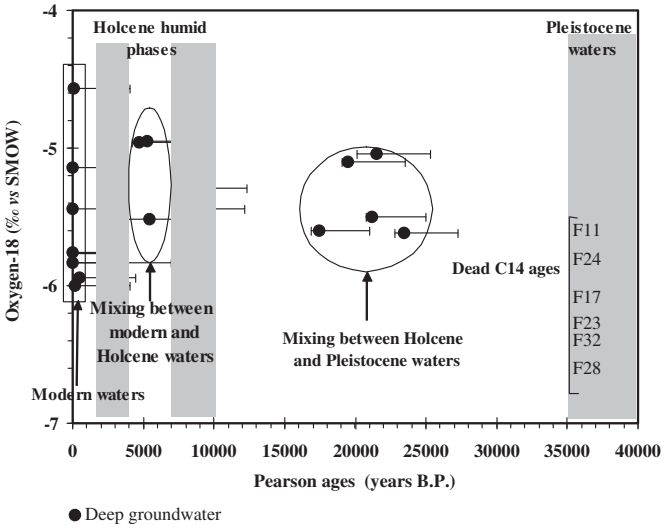

Fig. 9. $\delta^{18}O$ versus radiocarbon ages relationship for deep groundwater. The span length is calculated from the max and the min corrected age given by each model.

5. Conclusions

The deep groundwater aquifer system of the southern Kairouan Plain basin is widely heterogeneous and complex. The variations of the carbon-13 signature show the relative influence of native vegetation and cultivated plants on the geochemical signature of soil carbon dioxide. Radiocarbon, tritium, oxygen-18 and deuterium measurements of groundwater in this area have been made to provide a framework for a better understanding of recharge sources of the deep aquifers. The tritium concentrations, although very low in most of the groundwaters, suggest a mixture of recent and pre-1950 groundwater. The oxygen-18 and radiocarbon results show that recharge may have taken place during a long period, including the humid phases of the late Pleistocene when the environmental conditions were different. The upper deep groundwaters (aquifer A) are representative of recharge under Holocene climatic conditions at a distance of about 12 km from the Zeroud wadi course. Isolated and closed resources are identified in the basin boundaries and could be inherited from paleorecharge. Isotopic evidence indicates that recharge is due to rainfall infiltration as well as Zeroud wadi floods in the vicinity of the wadi within a 12 km wide area. The actual isotopic signature in the Menzel Mhiri and Bled ben Zina zones show the effect of artificial recharge from the Sidi Saad lake.

Finally, a general recharge schema of the aquifer system in the study area is proposed, mostly dominated by the Zeroud wadi. Indeed, the Zeroud flood overflows the minor bed, inundate the southern bank and recharge deep aquifer upstream the area. In falling stage period or during artificial recharge of the aquifers, the volume of water released in the river is relatively low and enriched in heavy isotopes. This signature is only detected in the vicinity immediate of the wadi course.

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References

Bedoui, Ch., Ben Ouezdou, H., Zouari, K., 2002. Géomorphologie et phases humides quaternaires dans la cuvette de Meknassy (Tunisie centrale). Séminaire international: Eau et environnement, Tunisie (Sousse). Volume des abstracts, p. 38.

Ben Jmaa, H., 2001. Analyse et cartographie des formes et des formations quaternaires des abords sud-est de Sakhit Sidi al Heni. DEA en géomorphologie. Fac. Des Sc. Humaines et Sociales, Univ. Tunis I.

Besbes, M., 1975. Etude hydrogéologique de la plaine de Kairouan sur modèles mathématiques. Ecole National Sup. des Mines de Paris. 121pp.

Besbes, M., 1978. L'estimation des apports aux nappes souterraines. Un modèle régional d'infiltration efficace. Thèse doct. Es Sciences, Univ. Paris VI.

Causse, C., Coque, R., Fontes, J.Ch., Gasse, F., Gibert, E., Ben Ouezdou, H., Zouari, K., 1989. Two high levels of continental waters in the southern Tunisian chotts at about 90 and 150 ka. Geology 17, 922–925.

Causse, C., Coque, R., Fontes, J.Ch., Gasse, F., Gibert, E., Ben Ouezdou, H., Zouari, K., 1991. Two high levels of continental waters in the southern Tunisian chotts at about 90 and 150 ka. Geology 19, 95–96.

Causse, Ch., Ghaleb, B., Chkir, N., Zouari, K., Ben Ouezdou, H., Mamou, A., 2003. Humidity changes in Southern Tunisia during the Late Pleistocene inferred from U-TH dating of mollusc shells. Applied Geochemistry 18, 1691–1703.

Celle-Jeanton, H., Zouari, K., Travi, Y., Daoud, A., 2001. Caractérisation isotopique des pluies en Tunisie. Essai de typologie dans la région de Sfax. Comptes Rendus de l'Académie des Sciences Paris, Sciences de la Terre et des Planètes 333, 625–631.

Clark, I.D., Fritz, P., 1997. Environmental Isotopes in Hydrogeology. Lewis Publishers, New York. 307pp.

Craig, H., 1961. Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. Science 133, 1833–1834.

Dassi, L., 1999. Contribution à l'étude hydrogéologique, hydrochimique et isotopique du système aquifère du bassin d'oued Merguellil (Plaine de Kairouan) DEA, Fac. Sc. Université Tunis II, 93pp.

Deines, P., Langmuir, D., Harmon, R.S., 1974. Stable carbon isotope ratios and the existence of a gas phase in the evolution of carbonate ground waters. Geocchimica et Cosmochimica Acta 38, 1147–1164.

Eichinger, E., 1983. A contribution to the interpretation of ^{14}C groundwater ages considering the example of a partially confined sandstone aquifer. Radiocarbon 25, 347–356.

Evans, G.V., Otlet, R.L., Downing, A., Monkhouse, R.A., Rae, G., 1979. Some problems in the interpretation of isotope measurements in United-Kingdom aquifers. In: Proceedings of a Symposium, Neuherberg, 19–23 June 1978. IAEA-SM 228/34. Isotope Hydrology, vol. 2, pp. 639–708.

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

Fontes, J.Ch., 1983. Environmental isotopes in groundwater hydrology. In: Fritz, P., Fontes, JCh (Eds.), Environmental Isotope Geochemistry, vol. I. Elsevier, New York, pp. 75–140.

Fontes, J.Ch., 1992. Chemical and isotopic contraints on ^{14}C dating of groundwater. In: Taylor, R.E., Long, A., Kra, R.S. (Eds.), Radiocarbon after Four Decades. An Interdisciplinary Perspective. Springer, Berlin, pp. 242–261.

Fontes, J.Ch., Garnier, J.M., 1979. Determination of the initial ^{14}C activity of the total dissolved carbon: a review of the existing models and a new approach. Water Resources Research 15, 399–413.

Fontes, J.C., Gasse, F., 1989. On the ages of humid Holocene and late Pleistocene phases in north Africa – remarks on "Late Quaternary climatic reconstruction for the Maghreb (North Africa)" by P Rognon. Palaeogeography, Palaeoclimatology, Palaeoecology 70, 393–398.

Gargouri-Ben Ayed, Z., Abichou, A., Oueslati, A., Zouari, K., 2007. Sedimentation and Paleoenvironnements of paralic system of Skhira-Gabes costal: Sebkha Gattiate (The Gulf of Gabes), Tunisia. Book of Abstracts of the 2nd International Conference on Coastal Conservation and Management in the Atlantic and Mediterranean.

Genty, D., Baker, A., Bakalowicz, M., Balamart, D., Causse, Ch., Ouhadi, R., Gilmour, M., Plangnes, V., Chkir, N., 2002. Abrupt climate changes of the last 80 ka from stalagmite stable isotopes: examples of Villars (Dordogne, Fr), Chauvet (Adreche, Fr) and La Mine (Tunisie) caves. Séminaire international: Eau et environnement, Tunisie (Sousse). Volume des abstracts, p36.

Genty, D., Blamart, D., Ghaleb, B., Plangnes, V., Causse, Ch., Bakalowicz, M., Zouari, K., Chkir, N., Hellstrom, J., Wainer, K., Bourges, F., 2006. Timing and dynamics of the last deglatiation from European and North African $\delta^{13}C$ stalagmite profiles-comparison with Chinese and south Hemisphere stalagmites. Quaternary Science Reviews 25, 2118–2142.

G.N.I.P., 1999. Global Network for Isotopes in Precipitation. The GNIP Database. Release 3, October 1999. URL: http://www.iaea.org/programs/ri/gnip/gnipmain.htm.

Guendouz, A., 1985. Contribution à l'étude géochimique et isotopique des nappes profondes du Sahara Nord-Est septentrionale, Algérie. Thèse de Doctorat de 3ème cycle en sciences, Univ. Paris Sud, centre d'Orsay.

Ingerson, E., Pearson, F.J., 1964. Estimation of the age and rate of motion of groundwater by the ^{14}C method. In: Recent Researches in the Fields of Hydrosphere. Atmosphere and Nuclear Geochemistry, Sugarawa Festival, Vol Maruzen, Tokyo, pp. 263–283.

Jeribi, L., 2004. Caractérisation hydrochimique et isotopique du système aquifère du bassin de Zeroud (plaine de Kairouan, Tunisie centrale); Thèse Doctorat. Fac. Sc. Tunis en cotutelle avec l'Univ. de Paris Sud, Orsay.

Joseph, A., 1990. Recharges and paléorecharges des nappes en régions subdesertiques au Niger. Thèse de Docteur en sciences, Univ. Paris XI.

Le Gal La Salle, C., Marlin, C., Savoye, S., Fontes, J.C., 1996. Geochemistry and ^{14}C dating of groundwaters from Jurassic aquifers of North Aquitaine Basin (France). Applied Geochemistry 11, 433–445.

Le Gal La Salle, C., Marlin, C., Leduc, C., Taupin, J.D., Massault, M., Favreau, G., 2001. Renewal rate estimation of groundwater based on radioactive tracers (^{3}H, ^{14}C) in an unconfined aquifer in a semi-arid area, Iullemeden basin, Niger. Journal of Hydrology 254, 145–156.

Mook, W.G., 1980. Carbon-14 in hydrogeological studies. In: Fritz, P., Fontes, J.Ch (Eds.), Handbook of Environmental Isotopes Geochemistry. The Terrestrial Environment, vol. 1. Elsevier, pp. 49–74.

Ouda, B., Zouari, K., Ben Ouezdou, H., Chkir, N., Causse, C., 1998. New paleoenvironmental data for the Late Quaternary of Maknassy Basin (central Tunisia). Académie des Sciences 326, 855–861.

Ouda, B., 2000. Paléohydrologie isotopique du basin de Maknassy (Tunisie centrale) pendant le Quaternaire recent. Thèse 3ème cycle, Fac. Sci. De Tunis el Manar.

Ousmane, B., 1988. Etude géochimique et isotopique des aquifers du socle de la bande sahélienne du Niger Liptako, Sud Maradi et Zinder-est). Thèse de Doctorat en Sciences. Université de Niamey.

Salem, O., Visser, J.H., Dray, M., Gonfiantini, R., 1980. Groundwater flow patterns in the western Lybian Arab Jamahirya. In: Arid-Zone Hydrology: Investigations with Isotopes Techniques. IAEA, Vienna, pp. 165–179.

Stumm, W., Morgan, J., 1981. Aquatic Chemistry. Wiley-Inter-Science, New York.

Tamers, M.A., 1975. Validity of radiocarbon dates on groundwater. Geophysical Surveying 2, 217–239.

Taupin, J.D., 1990. Evaluation isotopique de l'évaporation en zone non saturée sous climat sahélien, et évolution géochimique des solutions du sols (vallée du moyen Niger). Thèse de Docteur en Sciences, Univ. Paris XI.

Zouari, K., 1988. Géochimie et sédimentologie des dépôts continentaux d'origine aquatique du Quaternaire supérieur du Sud tunisien: Interprétation paléohydrologique et paléoclimatologique (Geochemistry and sedimentology of aquatic origin late quaternary continental deposits in the South of Tunisia: Palaeohydrological and palaeoclimatic interpretation). PhD thesis University of Paris-Sud, Orsay, France.

Zouari, K., Gibert, E., Causse, C., 1998. Chronologie (14C et Th/U) des épisodes humides majeurs du Quaternaire récent au Sahara: sites choisis du programme PALHYDAF. In: Causse, C., Gasse, F. (Eds.), Hydrologie et Géochimie Isotopique. Orstom, Paris, pp. 177–195.