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Origin and residence time of groundwater in the Tadla basin (Morocco) using multiple isotopic and geochemical tools

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SUMMARY

Groundwater resources in the Tadla basin stem from surface water recharge and different groundwater inflows, forming a multilayered aquifer system, which hosts one of Morocco's most important groundwater reservoirs. The hydrodynamic infrastructure; i.e. the relationship between all regional aquifers, recharge, and the residence time of waters poses a serious challenge for current water management and future exploitation in aiming for a long-term sustainable utilization. A combined hydrogeologic and isotopic investigation using hydrochemical and isotopic tracers such as ^{18}O, ^{2}H, ^{3}H, ^{13}C and ^{14}C was carried out in order to determine the sources of water recharge to the aquifers, the groundwater flow system, and the residence time of these waters. More than one hundred point measurements throughout the study area in varying wells, boreholes, springs and rivers were investigated. Chemical compositions of the groundwater indicate an important influence by the host carbonate rocks from each of the Tadla aquifers. Stable isotope results indicate the existence of two groups of groundwater corresponding to the unconfined aquifer in the north and the confined aquifer in the south. The $\delta^{18}O$, $\delta^{2}H$, ^{3}H, and ^{14}C data indicate that the High Atlas Mountains in the south and east of the basin, which are characterized by high rainfall and low $\delta^{18}O$ and $\delta^{2}H$ values, are currently the major source of recharge for the Tadla aquifers. A significant recharge zone lies in the northern part of the basin where all the aquifers outcrop. The confined zones show depleted ^{18}O values, corresponding to the signature of recharge water from the Atlas Mountains. Moreover, all isotope data demonstrated clearly that the Tassaout springs, which are located in the southwest of the basin and were previously interpreted as representing natural outlet of the deep aquifers, are comprised of young waters with depleted ^{18}O and ^{2}H signatures, suggesting a high altitude recharge from the Atlas Mountain. In contrast, the unconfined parts of the aquifers show higher values of $\delta^{18}O$, indicating an evaporation phenomenon, which occurs during infiltration or recharge from irrigation. The mixing process of old and recent waters is confirmed by ^{14}C and ^{3}H. The isotopic data also indicates probable interaction and flow between the different aquifers. The isotopic and hydrochemical data is therefore essential in confirming possible mixing relationships between aquifers whereas traditional hydraulic data is not capable to provide a quantitative assessment of these relationships. The data generated in this study will certainly encourage the revision and improvement of the current hydrological water resources model for the Tadla basin. The results provide a framework for development of a comprehensive management plan in which water exploitation shifts towards areas with modern recharge and where young and high quality groundwater is found.

Introduction and objectives

Inadequate management of water resources, such as high exploitation rates that exceeding natural replenishment, result in a severe decline in groundwater levels and degradation of water

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quality, as demonstrated in several aquifers in Morocco (Agoussine and Bouchaou, 2004; Bouchaou et al., 2008). In the Tadla basin in the centre of Morocco (Fig. 1), the demand for water has increased over the last 20 years due to population expansion, and the growth of agricultural and industrial activities. To satisfy the increasing need for water, several wells have been drilled at various locations in the basin, and abstraction from all groundwater sources has increased beyond the acceptable perennial yield of the Tadla basin. This high demand and exploitation of groundwater in the Tadla basin has coincided with an increasing reoccurrence of drought conditions over the last 40 years, exacerbating the already fragile water deficit in the region. Sustainable use of water resources with sufficient understanding of groundwater recharge and flow is therefore essential for future management of this basin.

The Tadla basin is located in a semi-arid area, between the Atlantic coastal plain in the northwest and the Atlas Mountains in the southeast (Fig. 1). The annual average temperature is about 19 °C; seasonal variations are significant and daily amplitude can reach 20 °C. Annual precipitation varies from 400 mm/year in the north of the basin to 600 mm/year in the Atlas Mountains in the south of the basin. The major aquifer systems of the Tadla basin are the Liassic in the mountains area and multilayered aquifers in the plain (Fig. 2). The Liassic and Turonian aquifers constitute the main water resources for the area and are among the most important aquifer sources in Morocco. Groundwater and surface water (via dams) from the basin are used mainly for agriculture and domestic supplies. The main river (called "oued" in Morocco) in this basin is the Oum Er-Rbia (OER) River, which has an average inter-annual discharge rate of 30 $m^3 s^{-1}$. Its major tributaries are derived from the High Atlas Mountains, and include the Oued Laabid (OA), Derna, and Tassaout rivers (Fig. 1).

In order to develop an effective water use system, it is first necessary to scientifically understand the behavior of groundwater. However, only a few studies have been conducted to evaluate the groundwater resources in the basin. Evaluating the recharge, discharge, and relationships between different aquifers within the basin has been the focus of water regulatory institutions in the region such as the Hydraulic Basin Agency (ABH) and the National Office of Water Drinking (ONEP) of Morocco.

One of the critical questions always posed to decision-makers is whether a water resource is sustainable based on current and future use projections. In the Tadla Basin, this refers to the renewable degree of groundwater that is tapped from deep and confined aquifers, which constitutes the major drinking water resource of the main cities in the area (Beni Mellal, Khouribga). The sustainability question is especially critical for the confined Turonian aquifer, which is the most productive aquifer system in the basin, with high production rates up to 1300 $l s^{-1}$. The evaluation of recharge–discharge relationships of these aquifer systems has been based solely on hydraulic head gradients and a few chemical and stable isotope studies (Marcé, 1975; Kabbaj et al., 1978; Bouchaou et al., 1995, 1996, 1997; Bouchaou et al., 2002; Hsissou et al., 1996).

In this study we provide a comprehensive analysis of water resources in the Tadla basin through use of several geochemical and isotopic tracers (oxygen, hydrogen, tritium, and carbon isotopes). The multi-tracer approach, using isotopes and solute concentrations in water, has been used for elucidating the origin and residence time of groundwater and the interaction between groundwater and river water in semi-arid and arid regions (Bouchaou et al., 1995; Edmunds et al., 2003; Vengosh, 2003; Farber et al., 2004; Guendouz et al., 2006; Mahlknecht et al., 2006; Bajjali, 2006; Palmer et al., 2007; Bouchaou et al., 2008). While traditional hydraulic data is important for evaluating the safe yield of the groundwater basin (e.g., Weyenmeyer et al., 2002; Grassi and Cortecci, 2005), we demonstrate in this study that geochemical and isotope data provide important supplemental information for studying groundwater recharge and discharge processes, hydraulic connections between aquifers, and residence time for a system that is complex as the Tadla basin.

Geological and hydrogeological settings

The Tadla basin, with an area of over 10,000 km^2, is located in the centre of Morocco (Fig. 1). It consists of two main zones; the

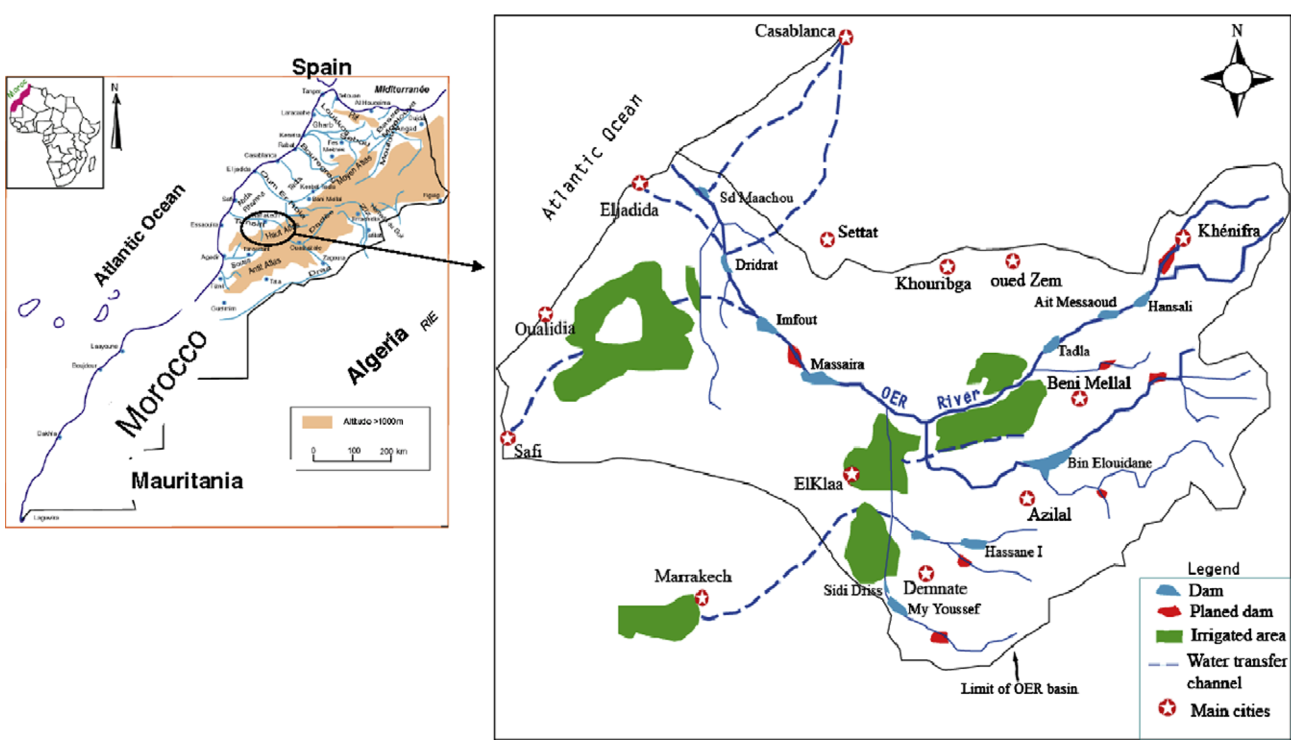

Fig. 1. General and detailed maps of the Oum Er Bia (ORB) river and Tadla basins in the central part of Morocco.

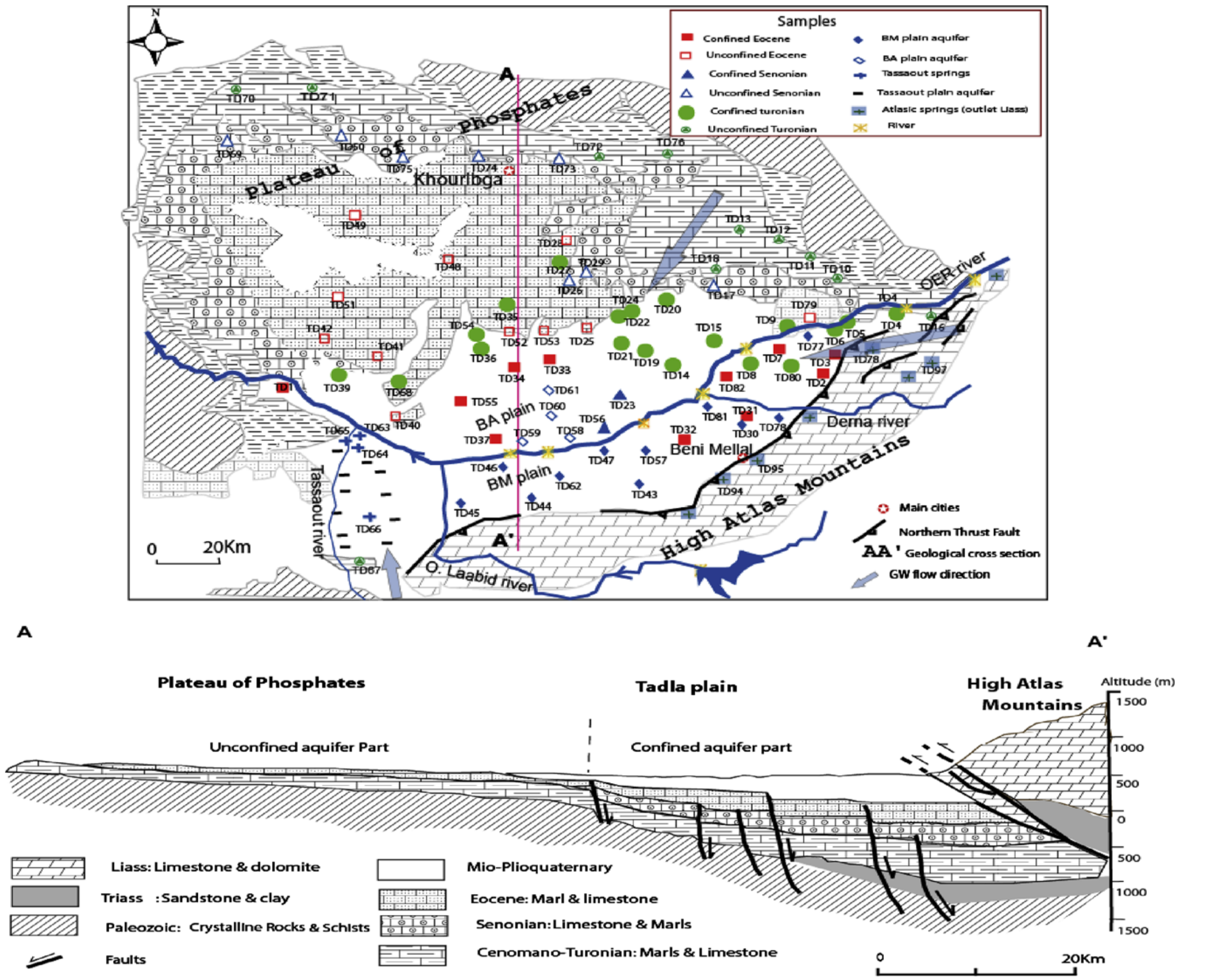

Fig. 2. A: simplified geological map of the Tadla basin. Sampling points of wells and surface water in Tadla basin, sorted by their geographical distribution (defined as water groups, see Table 1). The general groundwater flow directions in the basin are also included. B: geological cross-section in the studied area (position marked in (A)).

Tadla plain in the south and the Plateau of Phosphates in the north (Figs. 1 and 2). The Tadla region located on the northern edge of the Atlas Mountains of Beni Mellal is a complex zone where two important domains meet (the Atlas Mountains and the Tadla plain) through piedmont formations and the north Atlas faults. The Tadla plain is demarcated in the northeast by the Plateau of Phosphates, in the southeast by the Atlas of Beni Mellal and in the west by the Tassaout area. The geological formations are mainly composed of limestone, marls and sandstone. Their ages range from Palaeozoic to Quaternary. The water resources are derived from two system types: (i) the karst aquifer of the Atlas Mountains and (ii) the superficial and deep aquifers of the Tadla plains, the so-called "multilayered system". The latter is composed of four aquifers: (1) Mio-Plio-Quaternary, (2) Eocen e, (3) Senonian, and (4) Turonian (Liass), which is the main productive aquifer in the region, and is separated by impermeable or semi-permeable horizons that allow large hydraulic intercommunications (Fig. 2). Thus, the Turonian aquifer, which is the most important aquifer in the Tadla plain is formed in the north by karstic limestone and dolomite, and is characterized mostly by dolomite in the south, with occurrences of anhydrites and marls in the neighborhood of the Atlas Mountains. It is underlain by the impermeable marl formation with some evaporate incursions of Cenomanian. The two formations are regrouped generally in terms of marine Cenomano–Turonian. Its thickness varies from 50 m in the outcrop zone, reaching 200 m hedging the Atlas Mountains. The thickness of limestone–dolomite forming the Turonian aquifer ranges from 50 m (in the north) to 100 m (in the south). The second major system, the Senonian aquifer is made of limestone and marls with anhydrites intercalation. Its thickness varies from between 40 and 60 m in the north, reaching more than 200 m in the piedmont of the Atlas Mountains. The third system, the Eocene aquifer, is relatively more important than the Senonian, and is composed of limestone and phosphate marls with bituminous marls, which constitute its impermeable substratum. Its thickness reaches 100 m. Finally, the Mio-Plio-Quaternary aquifer constitutes the replenishment of the basin. It corresponds to heterogeneous fluvio-lacustrine sediments composed essentially of alternating silts, clays, limestone and conglomerates. We distinguish between several units (Fig. 2): (1) the Beni Amir (BA) aquifer that is situated in the right bank of the Oum Er-Ribia River (OER); (2) the Beni Moussa aquifer in the left bank of the river, which extends west up to the Oued Laabid River; and (3) the Tassaout aquifer, located between the Oued Laabid and Tassaout rivers. The Eocene, Senonian and Turonian aquifers are unconfined in the north at the phosphate plateau and confined in the south toward the Atlas Mountains (Fig. 2). Lithological and geophysical studies have shown an alternation between permeable and impermeable formations within the Tadla plain. Some layers contain evaporate minerals (gypsum in Cretaceous, and halite in Triassic formations). The whole of these formations constitute a large syncline of Tadla plain which lies uncorfomably on Triass or Palaeozoic formations (cross-section in Fig. 2). In addition to the direct and local recharge to the multilayered system in the Tadla plain, the region receives considerable water contribution from the adjacent Atlas aquifer, formed mainly by Liassic karstic limestone. This causes multiple springs in the piedmont, the most important being Ain Asserdoune spring with an average discharge of $1000\,l\,s^{-1}$. This spring contributes $200\,l\,s^{-1}$ as drinking water to Beni Mellal city.

The geological structure of the basin infers a continuation of the north Atlas thrust fault toward the Tadla plain (Monbaron, 1981, 1982; Bouchaou et al., 1996). Liassic overlapping of the Piedmont formations is observed along the 2–6 km section, which allows for a very wide contact between these regional formations (Fig. 2). The contact between the Turonian and Liassic along the thrust fault near the Beni Mellal area does not exist, but is observed in the northeast (Fig. 2). The faulted structure (Fig. 2) of different formations also allows for hydrodynamic relations between different aquifers in the area.

The plain hosts a large number of wells and boreholes with depths varying from a few metres to more than 1000 m. A piezometric survey of deep aquifers, mostly in the Turonian aquifer, shows a flow direction from northeast and northwest to west, towards the centre of the basin (Fig. 2). The main supposed outlet of these deep aquifers is pumping from boreholes and possibly contributing to the Tassaout springs at a slow flow rate (Fig. 2). This hypothesis was tested in this study. The general drainage of the Plio-quaternary aquifer takes place from northeast toward the southwest along the Oum Er-Ribia River. Some vertical hydraulic exchanges were identified in the complex multilayered aquifer of the Tadla (DRPE, 1993, 2005).

Groundwater sampling and analytical methods

More than 100 water samples were collected during 1999–2001 and analyzed for their chemical and isotopic compositions. The sources of samples from various aquifers were as follows: Eocene aquifer (22), Senonian aquifer (10), Turonian aquifer (30), Mio-Plio-Quaternary system of Beni Amir and Ben Moussa (23), Plio-Quaternary of Tassaout (21), springs in the Tassaout area (5), and springs alongside the Atlas Mountains (Liassic aquifer; 5). In addition, eight samples were taken from local rivers in the basin.

Temperature, electrical conductivity (EC), pH and Alkalinity (HCO_3^-) were measured in the field. Water sampling and in situ measurements were done after a certain amount of pumping in order to obtain representative groundwater circulating at deep levels.

Chemical analysis was conducted at the Laboratory of the Hydraulic Basin Agency of Beni Mellal using classic methods of volumetric dosage for HCO_3, Ca, Mg and Cl, flame photometer for Na and K, and spectrophotometer for SO_4.

Stable isotopes of oxygen and hydrogen as well as tritium were analyzed at isotope laboratories in the "Centre National des Sciences and Technologies Nucléaires (CNESTEN), Rabat, Morocco" and at the IAEA (Vienna, Austria). The results for stable isotopes are expressed in the conventional δ notation in ‰ versus V-SMOW with a reproducibility of ±0.1‰ for $\delta^{18}O$ and ±1‰ for δ^2H. The ^3H contents were measured using liquid scintillation after electrolytic enrichment; results are expressed in Unity Tritium (TU). The ^{14}C activity and $\delta^{13}C$ versus ‰ (versus V-PDB) were measured at the University of Groningen, Netherlands by accelerator mass spectrometry. Uncertainty for $\delta^{13}C$ is 0.15‰ and that for ^{14}C is 1% of the measured activity and expressed in percent of modern Carbon (pmc).

Results and discussion

Table 1 presents chemical and isotopic data from sampling campaigns for measured aquifers. The data and following discussion are presented according to geographical distribution of sampling points in the basin (Fig. 2). Overall, results are considered in relation to the conceptual cross-section and the regional map with all sampled sites from different aquifers in the studied area (Fig. 2).

Chemical characterization

Isotope and chemical data for this study are listed in Table 1. Groundwater salinity is based on chloride concentrations and electrical conductivity (EC), which represents overall dissolved salts.

Different groundwater components show that salinity of confined and unconfined groundwater from the Eocene, Senonian, and Turonian aquifers is usually low, mostly <300 mg Cl/L. In contrast, shallow superficial aquifers are characterized by significantly higher salinity, particularly the Beni Amir (BA) and Beni Moussa (BM) aquifers (Fig. 3). The relationship between chloride and EC shows a similar correlation for all water groups, except for the Tassaout aquifer and some groundwater from the confined Turonian aquifer with conspicuously lower chloride/EC ratio (Fig. 3). Surface water salinity in the Tadla basin exhibits a wide range, from very low concentrations in the Oued Laabid and Derna rivers of (less than $200\,\mu s\,cm^{-1}$) to high salinities, ranging from 2000 to $3550\,\mu s\,cm^{-1}$, in the main river Oum Er-Rbia. The river's high salinity may be derived from dissolution of upstream triassic evaporites. Temperature values (Table 1) in groundwater sampled from unconfined areas are less than those measured in confined parts of the aquifers. The groundwater temperature of unconfined aquifers ranges from 15.6 to 25 °C, reflecting mean annual temperature, while confined groundwater temperatures are higher than 27 °C and reach 42.7 °C in the confined Senonian aquifer (TD23) at a depth of 600 m. Water from the Tadla basin is generally characterized by a neutral pH except for surface water, which has basic values (>8).

To better illustrate different water types, we plotted all chemical data in a Piper diagram (Fig. 4); bicarbonate (HCO_3^-) greatly dominates the water composition, followed by chloride and sulfate (SO_4) in terms of dissolved anions, whereas calcium (Ca) followed by magnesium (Mg) dominates cations (Fig. 4). The Ca–Mg–HCO_3 water type is dominant, while Ca–Cl–SO_4 composition appears in the more saline water. This indicates that mineralization of groundwater through interaction with limestone formations in the basin is a major process that affects overall water chemistry. In addition, sulphate and chloride concentrations are relatively significant in Tadla groundwater. Our data show that for high Ca–SO_4 groundwater, particularly from the confined Turonian and Senonian, the Ca/SO_4 ratio is close to unity, which suggests dissolution of Cretaceous gypsum (Fig. 5). In contrast, for Ca–Mg–HCO_3 water, the Ca/SO_4 ratio is higher than 1, which reflects dissolution of carbonate minerals. In the superficial aquifer of BA, Ca/SO_4 ratios are largely deviate from a slope of 1 (Fig. 5), ruling out the possibility of gypsum dissolution. The Na/Cl ratios of all water types are lower than 1, particularly for Cl-rich water from the confined Senonian and surficial BA with typically low Na/Cl ratios (Fig. 6). This can be explained by dissolution of evaporites (Senonian, Turonian) followed by ion exchange, which replaces Na^+ with Ca^{2+} and Mg^{2+}. Most waters show saturation with carbonate minerals (calcite,

Table 1
Chemical and isotope (stable isotopes of oxygen and hydrogen and tritium) data in the Tadla basin (results from 1999 to 2001 sampling campaigns).

Code	Nature	Date	Depth (m)	*T* (°C)	EC (μs. cm^{-1})	pH (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Saturation index				$\delta^{18}O$ (‰)	δ^2H (‰)	^3H (TU)	^3H error (TU)	$A^{14}C$ (pmc)	$A^{14}C$ error (pmc)	$\delta^{13}C$ (‰)
														Cal.	Dol.	Gyp.	An.							
Confined Eocene aquifer (Group 1)																								
TD1	Borehole	1999/3/18	nd	28	1302	7.37	66	52	<0.4	129	281	213	20	0.2	0.1	−2.3	−2.5	−6.67	−40.7	0.4	0.28	1.88	0.06	−10.65
TD2	Borehole	1999/3/18	295	25.9	634	7.33	94	34	<0.4	7	317	21	8	0.4	0.1	−2.5	−2.7	−6.57	−39.4	−0.12	0.27	7.36	0.09	−10.99
TD3	Borehole	1999/3/18	325	25.2	545	7.31	32	34	<0.4	2	262	7	3	−0.2	−0.5	−3.3	−3.5	−6.47	−39.6	0.29	0.28	1.79	0.06	−10.6
TD7	Borehole	1999/3/18	130	21.5	658	7.24	60	41	<0.4	18	317	35	1	0.0	−0.4	−3.4	−3.6	−6.34	−35.9	3.58	0.31	73.24	0.38	−9.83
TD31	Borehole	1999/4/19	400	31.8	1053	7.1	48	46	<0.4	87	287	32	13	−0.1	−0.4	−2.6	−2.7	−6.55	−39.9	0.64	0.23	26.57	0.19	−10.29
TD32	Borehole	1999/4/19	368	31.5	1016	7.18	60	36	<0.4	74	311	142	29	0.1	−0.2	−2.1	−2.3	−6.57	−40.7	0.04	0.23	1.44	0.07	−10.73
TD33	Borehole	1999/4/20	110	25.9	1503	7.19	114	86	<0.4	159	268	305	39	0.2	0.0	−1.8	−2.1	−5.57	−37.2	1.05	0.24	42.67	0.26	−10.64
TD34	Borehole	1999/4/20	94	25.2	1025	7.1	76	54	<0.4	64	293	128	47	0.0	−0.4	−1.9	−2.1	−5.47	−37.2	0.38	0.23	27.13	0.19	−10.11
TD37	Borehole	1999/4/21	172	27.1	1017	7.82	80	56	<0.4	37	275	71	130	0.7	1.1	−1.4	−1.6	−6.29	−40.1	0.1	0.22	9.11	0.11	−9.35
TD55	Borehole	1999/4/28	109	25	877	7.18	86	48	<0.4	46	293	85	18	0.1	−0.2	−2.2	−2.4	−5.21	−36.9	0.05	0.21	21.35	0.16	−10.14
TD82	Borehole	1999/6/9	250	26.3	554	7.79	66	41	<0.4	2	329	7	3	0.7	1.0	−3.1	−3.3	−6.48	−39.1	0.24	0.17	28.67	0.2	−10.68
Unconfined Eocene aquifer (Group 2)																								
TD25	Borehole	1999/4/15	105	24.8	1394	7.07	90	72	<0.4	145	275	262	21	−0.1	−0.4	−2.2	−2.4	−5.7	−37.7	1.73	0.28	31.88	0.2	−9.85
TD28	Well	1999/4/16	31.9	21.5	654	7.68	56	33	<0.4	28	287	50	7	0.4	0.3	−2.7	−3	−5.05	−34	0.38	0.22	33.3	0.22	−10.52
TD40	Well	1999/4/21	14	19.5	2820	8.12	86	137	<0.4	359	409	603	134	1.0	1.9	−1.5	−1.8	−4.6	−32.8	1.11	0.23	78.88	0.43	−9.37
TD41	Well	1999/4/21	10	22.7	1667	7.68	60	97	<0.4	152	464	248	65	0.6	1.1	−1.9	−2.1	−4.62	−30.7	1.49	0.23	68.52	0.39	−10.97
TD42	Well	1999/4/21	20.4	22.5	1067	7.51	24	56	<0.4	69	372	113	16	−0.1	0.0	−2.8	−3.0	−4.63	−31.2	0.46	0.22	50.56	0.3	−11.56
TD48	Well	1999/4/27	18.5	22.3	550	7.76	32	39	<0.4	14	177	28	7	0.1	−0.1	−3.0	−3.2	−4.99	−31.8	2.66	0.25	25.78	0.18	−10.1
TD49	Well	1999/4/27	20	21.9	1139	7.91	98	52	<0.4	67	323	113	5	0.9	1.2	−2.7	−3.0	−5.07	−32.8	3.34	0.28	49.08	0.29	−10.84
TD51	Well	1999/4/27	12	20.1	712	7.22	40	34	<0.4	21	250	43	7	−0.3	−0.9	−2.9	−3.1	−4.63	−30.5	0.74	0.21	29.02	0.2	−10.95
TD52	Well	1999/4/28	45	24	926	7.74	50	46	<0.4	74	177	128	4	0.2	0.2	−3.1	−3.3	−4.9	−33.4	0.08	0.2	33.23	0.22	−10.61
TD53	Well	1999/4/28	47	24.3	865	7.64	54	50	<0.4	48	214	92	3	0.2	0.2	−3.2	−3.4	−4.49	−32.6	0.34	0.21	30.18	0.2	−10.04
TD79	Well	1999/5/11	32.4	22.7	1446	8.29	68	56	<0.4	99	336	177	3	1.1	1.9	−3.1	−3.4	−6.42	−38.3	2.4	0.22	81.94	0.48	−11.31
Confined Senonian aquifer (Group 3)																								
TD23	Borehole	1999/4/14	604	42.7	1652	7.12	114	47	<0.4	152	275	255	179	0.4	0.3	−1.1	−1.2	−6.93	−41.3	0.74	0.27	13.06	0.11	−7.78
TD56	Borehole	1999/4/28	480	35.6	836	7.14	74	48	<0.4	30	275	57	47	0.1	0.0	−1.8	−2.0	−6.55	−38.6	0.1	0.2	3.7	0.08	−10.29
Unconfined Senonian aquifer (Group 4)																								
TD17	Well	1999/4/1	56.1	23.5	530	7.27	58	37	<0.4	9	238	21	8	−0.1	−0.5	−2.7	−3.0	−5.29	−33.1	8.87	0.42	92.97	0.47	−12.15
TD26	Well	1999/4/15	41.2	25	670	7.18	98	38	<0.4	145	262	248	7	0.1	−0.4	−2.6	−3.0	−4.78	−34	0.33	0.22	20.18	0.15	−9.42
TD29	Well	1999/4/16	58.6	25.5	1476	7.15	86	64	<0.4	149	372	248	50	0.1	0.0	−1.8	−2.0	−5.04	−35.9	0.46	0.23	8.12	0.1	−12.23
TD50	Well	1999/4/27	16.6	20.6	1625	7.66	82	98	<0.4	67	122	142	35	0.1	0.0	−2.0	−2.2	−4.33	−29.1	9.04	0.46	90.12	0.49	−11.44
TD69	Well	1999/4/28	21.2	21.9	860	7.45	74	40	<0.4	30	305	71	4	0.3	0.1	−2.9	−3.1	−4.49	−29.0	1.44	0.21	39.36	0.26	−9.7
TD73	Well	1999/5/4	23	21.5	741	7.75	56	34	<0.4	41	238	85	2	0.4	0.4	−3.2	−3.5	−4.93	−31.8	0.01	0.18	35.17	0.23	−9.74
TD74	Well	1999/5/5	59	21.5	778	7.53	84	41	<0.4	9	391	21	1	0.5	0.5	−3.5	−3.7	−5.0	−31.5	0.2	0.13			
TD75	Well	1999/5/5	43.2	22.4	1757	7.35	88	68	<0.4	152	323	277	22	0.2	0.1	−2.2	−2.4	−5.6	−34.7	1.77	0.21	88.93	0.51	−9.66
Confined Turonian aquifer (Group 5)																								
TD4	Borehole	1999/3/18	136	20.1	1843	7.38	50	33	<0.4	207	226	397	22	−0.2	−0.8	−2.4	−2.6	−7.32	−45.0	0.83	0.29	84.42	0.54	−9.82
TD5	Borehole	1999/3/18	150	21.6	587	7.54	64	39	<0.4	11	336	28	4	0.4	0.3	−2.9	−3.1	−6.37	−34.4	7.58	0.42	20.0	0.14	−10.63
TD6	Borehole	1999/3/18		22	1055	7.22	66	46	<0.4	67	311	149	6	0.0	−0.4	−2.8	−3.0	−6.31	−36.5	1.72	0.31	58.21	0.32	−10.82
TD8	Borehole	1999/3/19	328	28.1	859	7.53	62	35	<0.4	51	317	92	9	0.4	0.4	−2.6	−2.8	−6.92	−40.8	0.58	0.26	42.53	0.25	−10.06
TD9	Borehole	1999/3/19	236	23.7	1018	7.32	60	38	<0.4	76	293	128	8	0.1	−0.3	−2.7	−2.9	−6.48	−38.8	1.16	0.28	66.15	0.35	−10.71
TD14	Borehole	1999/4/1	425	37.5	1120	7.44	54	40	<0.4	122	293	206	22	0.3	0.5	−2.3	−2.5	−6.86	−41.7	0.03	0.26	44.08	0.26	−9.77
TD15	Borehole	1999/4/1	393	28.5	894	7.0	56	46	<0.4	60	354	92	8	−0.1	−0.5	−2.7	−2.9	−6.6	−40.4	0.55	0.27	60.92	0.37	−10.32
TD19	Borehole	1999/4/14	331	32.5	1122	7.06	86	37	<0.4	69	305	106	50	0.1	−0.2	−1.7	−1.9	−6.73	−40.8	0.33	0.26	57.65	0.31	−10.27
TD20	Borehole	1999/4/14	180	25.9	1017	7.58	84	58	<0.4	34	268	71	118	0.5	0.6	−1.4	−1.6	−5.39	−34.9	1.58	0.28	82.87	0.42	−11.57
TD21	Borehole	1999/4/14	303	28.6	902	7.86	40	47	<0.4	55	336	92	20	0.6	1.1	−2.5	−2.7	−6.34	−39.9	−0.02	0.25	62.87	0.34	−10.78
TD22	Borehole	1999/4/14	228	28.4	1140	7.42	72	71	<0.4	53	293	113	117	0.3	0.4	−1.5	−1.7	−5.52	−35.4	1.26	0.28	76.0	0.39	−11.09
TD24	Borehole	1999/4/15	240	25.3	920	7.03	66	60	<0.4	25	220	85	40	−0.3	−0.8	−2.0	−2.2	−5.61	−35.8	0.45	0.25	59.36	0.32	−10.74
TD27	Borehole	1999/4/16	200	30.7	1123	7.45	70	45	<0.4	71	268	128	46	0.3	0.4	−1.9	−2.1	−6.2	−39.6	0.06	0.22	34.12	0.22	−9.89
TD35	Borehole	1999/4/19	339	35.7	1182	7.12	68	27	<0.4	83	299	142	50	0.1	−0.2	−1.8	−2.0	−6.3	−40.5	−0.02	0.21	46.35	0.28	−8.93

(*continued on next page*)

Table 1 (*continued*)

Code	Nature	Date	Depth (m)	*T* (°C)	EC (µs. cm^{-1})	pH (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	SO4 (mg/l)	Saturation index				$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	^{3}H error (TU)	$A^{14}C$ (pmc)	$A^{14}C$ error (pmc)	$\delta^{13}C$ (‰)
														Cal.	Dol.	Gyp.	An.							
TD36	Borehole	1999/4/20	326	31	3220	7.18	491	149	<0.4	99	207	163	1383	0.6	0.6	0.1	−0.1	−6.91	−43.4	−0.15	0.22	2.74	0.08	−2.18
TD39	Borehole	1999/4/21	110	29.1	1132	7.14	60	52	<0.4	71	354	128	26	0.1	−0.1	−2.2	−2.4	−5.2	−34.8	0.29	0.22	21.39	0.16	−10.47
TD54	Borehole	1999/4/28	325	27.4	816	7.61	86	38	<0.4	44	311	71	15	0.6	0.7	−2.3	−2.5	−6.05	−38.1	−0.09	0.2	56.88	0.33	−10.62
TD68	Borehole	1999/4/29	198	27.6	2300	7.42	377	111	<0.4	21	275	50	754	0.9	1.0	−0.2	−0.4	−5.82	−38.1	0.28	0.19	4.04	0.06	−5.36
TD80	Borehole	1999/5/11	467	23.6	1122	7.38	52	44	<0.4	53	311	92	16	0.1	−0.1	−2.4	−2.7	−6.8	−41.0	1.33	0.2	67.48	0.4	−10.84
Unconfined Turonian aquifer (Group 6)																								
TD10	Borehole	1999/3/31	100	25.1	539	7.6	60	32	<0.4	9	262	21	4	0.4	0.3	−2.9	−3.1	−5.4	−31.9	11.72	0.49	92.57	0.47	−11.91
TD11	Well	1999/3/31	34	22.8	590	7.52					262							−5.43	−33.2	9.8	0.45	103.71	0.52	−11.94
TD12	Well	1999/3/31	14.6	23	593	7.39	46	48	<0.4	9	201	11	7	−0.1	−0.4	−2.8	−3.1	−5.49	−33.8	7.48	0.39	92.61	0.5	−12.2
TD13	Well	1999/3/31	36.5	19	993	8.46	48	55	<0.4	30	250	78	36	1.0	1.7	−2.14	−2.4	−4.58	−29.2	7.18	0.39	100.87	0.5	−8.46
TD16	Borehole	1999/4/1	150	23.5	1473	7.06	108	81	<0.4	115	268	156	206	0.0	−0.4	−1.14	−1.4	−5.13	−32.9	6.83	0.38	94.05	0.47	−11.28
TD18	Borehole	1999/4/1	85	23.9	1268	7.09	66	71	<0.4	57	329	99	146	−0.1	−0.4	−1.5	−1.7	−4.99	−32.1	8.77	0.42	99.99	0.5	−11.86
TD67	Well	1999/4/30	38.68	24.3	1570	7.27	130	76	<0.4	103	275	234	148	0.3	0.11	−1.2	−1.4	−6.45	−41.8	1.27	0.2	72.55	0.43	−8.39
TD70	Well	1999/4/29	14.5	21.1	1360	7.9	82	38	<0.4	44	262	106	4	0.7	0.8	−2.9	−3.1	−4.45	−24.7	4.04	0.28	71.16	0.44	−8.2
TD71	Borehole	1999/4/29	90	21.3	990	7.9	86	45	<0.4	159	226	248	127	0.6	0.7	−1.4	−1.7	−4.49	−26.1	2.29	0.23	55.04	0.35	−9.29
TD72	Well	1999/5/4	40.6	21.2	1240	7.95	68	65	<0.4	87	336	177	4	0.8	1.2	−3.0	−3.2	−4.8	−31.9	0.00	0.18	62.01	0.38	−10.55
TD76	Well	1999/5/10	5.6	18.5	770	7.4	60	50	<0.4	18	275	57	8	0.1	−0.3	−2.7	−3.0	−5.06	−30.9	8.59	0.43	95.95	0.57	−11.7
Superficial aquifer Beni Moussa (Group 7)																								
TD30	Well	1999/4/19	45.5	23.7	947	7.1	60	70	<0.4	23	287	113	29	−0.2	−0.5	−2.2	−2.4	−6.3	−37.6	2.09	0.26	62.39	0.36	−11.26
TD43	Well	1999/4/27	7.5	20.1	1086	7.46	70	60	<0.4	46	281	113	49	0.2	0.0	−1.9	−2.1	−6.6	−41.6	8.4	0.43	86.82	0.47	−11.66
TD44	Well	1999/4/27	18	21.8	2410	7.24	100	143	<0.4	115	397	447	198	0.2	0.3	−1.3	−1.5	−5.9	−36.2	6.05	0.36	75.23	0.42	−11.37
TD45	Well	1999/4/27	12.5	21.7	9110	7.06	595	383	<0.4	699	214	2074	1532	0.3	0.2	0.1	−0.2	−5.5	−37.0	6.06	0.36	73.53	0.4	−10.67
TD46	Well	1999/4/27	8	21.8	5090	7.17	196	338	<0.4	396	287	1471	234	0.2	0.4	−1.1	−1.3	−5.9	−39.4	6.06	0.35	91.55	0.55	−12.02
TD47	Well	1999/04/27	80	25	775	7.21	56	63	<0.4	23	336	43	43	0.0	−0.1	−2.0	−2.2	−6.7	−38.7	0.64	0.21	41.71	0.25	−10.74
TD57	Spring	1999/4/28		21.1	1128.1	7.62	74	82	<0.4	80	403	156	132	0.5	0.8	−1.5	−1.7	−6.4	−42.7	9.84	0.49	95.29	0.52	−11.25
TD62	Well	1999/4/29	14	24.8	1439	7.29	76	107	<0.4	101	476	170	2	0.3	0.6	−3.3	−3.5	−6.22	−38.7	2.95	0.26	80.52	0.45	−12.37
TD77	Well	1999/5/10	32.2	21.1	682	7.1	46	30	<0.4	nd	293	21	2	−0.3	−1.0	−3.4	−3.6	−5.94	−34.4	5.8	0.33	88.95	0.52	−6.22
TD78	Well	1999/5/10	40	20.8	581	7.46	40	27	<0.4	nd	281	7	2	0.03	−0.4	−3.4	−3.6	−6.04	−33.1	8.48	0.42	86.19	0.5	−10.16
TD81	Well	1999/5/11	38.8	21.2	652	7.8	52	32	<0.4	nd	232	28	16	0.4	0.3	−2.4	−2.6	−6.69	−39.4	5.58	0.32	73.92	0.44	−9.75
Superficial aquifer Beni Amir(Group 8)																								
TD58	Well	1999/4/29	17	22.6	4290	7.5	220	234	<0.4	246	220	1301	974	0.5	0.7	−0.4	−0.7	−5.63	−38.2	3.69	0.28	62.22	0.37	−10.59
TD59	Well	1999/4/29	13.2	21.7	1858	7.46	114	128	<0.4	161	262	411	660	0.3	0.4	−0.7	−1	−4.89	−34.2	4.2	0.3	61.62	0.37	−9.31
TD60	Well	1999/4/29	12.5	22.2	8510	7.22	615	363	<0.4	391	183	2677	14	0.5	0.5	−1.9	−2.1	−5.14	−35.4	4.58	0.3	58.87	0.36	−9.69
TD61	Well	1999/4/29	11.5	23.7	9420	7.37	441	285	<0.4	117	275	3053	30	0.7	1.0	−1.7	−1.9	−5.62	−38.2	4.94	0.32	65.9	0.4	−9.57
Tassaout springs (Group 9)																								
TD63	Spring	1999/4/30		23.5	1619	7.48	122	47	<0.4	115	268	248	164	0.4	0.3	−1.3	−1.4	−7.48	−48.3	5.78	0.34	72.6	0.41	−8.91
TD64	Spring	1999/4/30		24.4	1639	7.37	108	59	<0.4	113	244	269	134	0.3	0.1	−1.3	−1.5	−7.37	−48.8	5.88	0.34	71.67	0.41	−8.59
TD65	Spring	1999/4/30		25.2	1604	7.5	110	50	<0.4	103	244	255	145	0.4	0.3	−1.3	−1.5	−7.45	−48.8	2.81	0.25	65.17	0.39	−8.43
TD66	Spring	1999/4/30		22.6	1612	7.08	100	71	<0.4	94	287	199	158	−0.0	−0.4	−1.3	−1.5	−7.25	−47.3	9.8	0.47	88.54	0.51	−10.3
TD63	Spring	2000/05/16		26	1670	6.92					110							−7.45	−47.1	4.9	0.36			
TD64	Spring	2000/05/16		24.3	1655	7.23					256							−7.55	−49.4	5.59	0.38			
TD65	Spring	2000/05/16		25.6	1622	7.29					250							−7.47	−47.8	2.74	0.29			
TD66	Spring	2000/05/16		22.2	1636	7.05					348							−7.2	−47.0	8.51	0.43			
TD22	Spring	2000/05/16		28.8	1745	7.38					250							−7.02	−46.1	0.09	0.22			
Atlas springs: outlet GW Atlas Mountains (Group 10)																								
TD95	Spring	2000/05/24		15.9	580	7.2					287							−7.34	−42.7	4.78	0.29			
TD94	Spring	2000/05/23		19.9	643	7.21					360							−6.5	−37	8.21	0.47			
TD96	Spring	2000/05/25		17.5	520	7.33					336							−6.44	−37.4	6.47	0.35			
TD97	Spring	2000/05/26		18.4	590	7.32					378							−7.14	41	6.02	0.39			
7	Spring	2001/10/09		19.1	544	8.31					299							−6.23	−35.5	4.89	0.28			
10	Spring	2001/10/22		16.1	591	7.01					287							−6.26	−34.5	4.36	0.26			
11	Spring	2001/10/22		18	537	8.17					281							−6.66	−37.2	4.57	0.29			
1795/37	Spring	2001/10/22		19.5	645	8.25					372							−6.6	−36.9	4.83	0.3			
TD98	Borehole	2000/05/27	130	20.1	888	7.06					378							−6.73	−39.4	6.9	0.37			

Rivers from Atlas Mountains(Group 11)										
9	River	2001/10/24	17	2910	8.36	262	−8.13	−50.4	2.33	0.19
11	River	2001/10/24	21.4	3270	8.27	244	−7.07	−44.5	2.91	0.21
12	River	2001/10/24	20.4	3550	8.64	262	−7.9	−49.1	2.46	0.2
13	River	2001/10/25	20.4	3240	8.4	201	−7.04	−44.8	3.39	0.23
14	River	2001/10/25	25.6	2220	8.6	201	−4.04	−31.3	4.77	0.28
15	River	2001/10/25	24.8	3150	8.24	214	−3.97	−30.4	4.32	0.26
16	River	2001/10/26	21.7	1050	8.63	177	−5.485	−39.0	5.88	0.32
17	River	2001/12/07		2010	8.5	305	−5.855	−39.2		
18	River	2001/12/07		2750	8.45	201	−5.82	−38.9		
19	River	2001/12/07		2100	8.43	207	−5.885	−39.1		
TD137	River	2002/04/06	15.6	483	7.67	220	−7.89	−49.7		
Tassaout aquifer(Group 12)										
T1	well	2000/05/04	24.2	1661	7.92	329	−7.44	−48.2	4.57	0.26
T2	Spring	2000/05/04	22.1	2510	8.1	360	−5.96	−40.8	5.34	0.29
T3	well	2000/05/04	25.1	1768	8.12	317	−7.58	−47.8	4.07	0.24
T4	well	2000/05/04	24.9	1962	7.92	329	−6.49	−41.8	1.13	0.15
T5	well	2000/05/04	19.8	2240	8.16	390	−6.26	−40.9	5.48	0.38
T6	well	2000/05/04	25.5	1286	7.96	378	−7.87	−48.3	3.48	0.31
T7	well	2000/05/04	21.6	2260	8.14	390	−6.65	−43.2	5.61	0.38
T8	well	2000/05/04	22.1	2260	8.21	415	−7.51	−48.1	2.64	0.28
T9	well	2000/05/11	20.6	1981	7.3	348	−7.11	−46.3	6.83	0.42
T10	well	2000/05/11	20.4	1680	7.4	305	−7.1	−46.4	6.54	0.41
T11	well	2000/05/11	21.3	2530	7.52	348	−7.3	−46.6	2.09	0.27
T12	well	2000/05/11	21.7	2380	7.54	360	−6.81	−42.5	4.99	0.3
T13	well	2000/05/11	21.5	2150	7.22	311	−6.91	−43.3	6.4	0.35
T14	well	2000/05/11	21	1105	7.33	372	−7.67	−47.0	6.3	0.34
T15	well	2000/05/11	21.9	1433	7.94	256	−7.33	−46.2	7.12	0.37
T16	well	2000/05/16	22.4	1240	7.26	323	−7.59	−48.3	5.98	0.39
T17	well	2000/05/16	21.8	1300	7.28	342	−7.44	−47.4	9.55	0.46
T18	well	2000/05/16	22	1642	7.09	354	−7.34	−47.1	8.46	0.48
T19	well	2000/05/16	22.3	1665	7.02	384	−7.24	−46.7	8.94	0.5
T20	well	2000/05/16	24	2140	7.24	360	−6.84	−44.1	9.16	0.45
T21	well	2000/05/16	23	1661	7.39	250	−7.39	−47.6	2.58	0.28

N.B.: Empty box = non measured value.

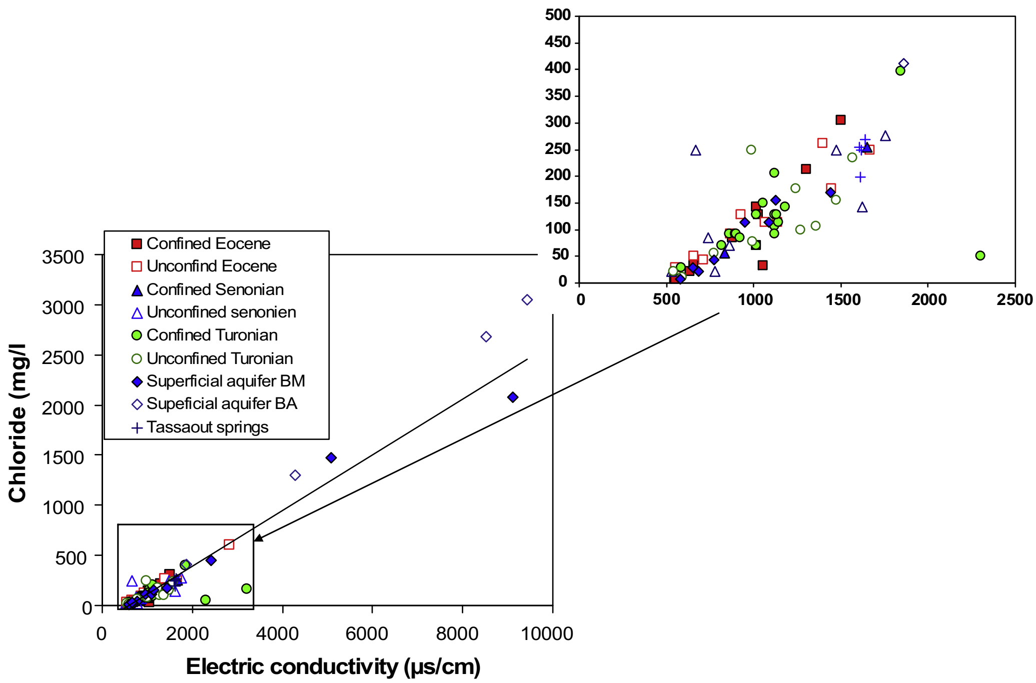

Fig. 3. Relationship between chloride and electric conductivity.

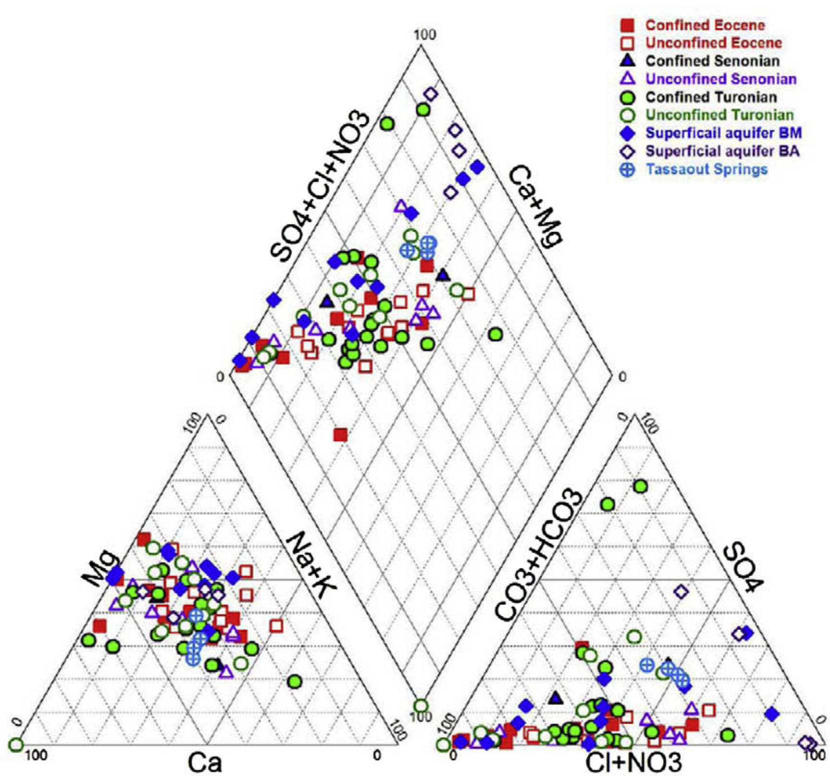

Fig. 4. Trilinear diagram of the groundwater samples.

dolomite) confirming the carbonate character of the host aquifers, however all waters present an under-saturation state with respect to gypsum and halite minerals (Table 1).

Overall, the results presented here show that each aquifer unit has a unique geochemical characterization, mainly due to intensive water–rock interaction with the host aquifer rocks. Nonetheless, similarities in geological formations (e.g., carbonate as the major rock unit) makes specific distinction more difficult as the overall carbonate predominance masks the geochemical fingerprints. This hydraulic relation between the Liassic Karst

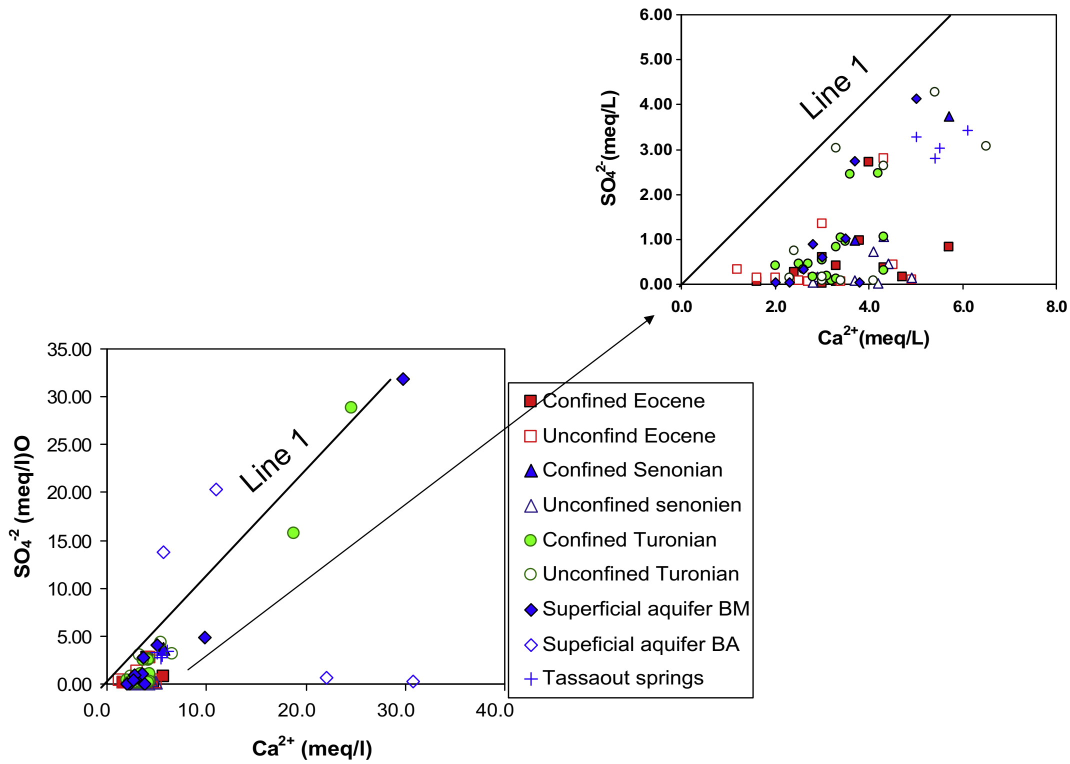

Fig. 5. Relationship between sulfate and calcium.

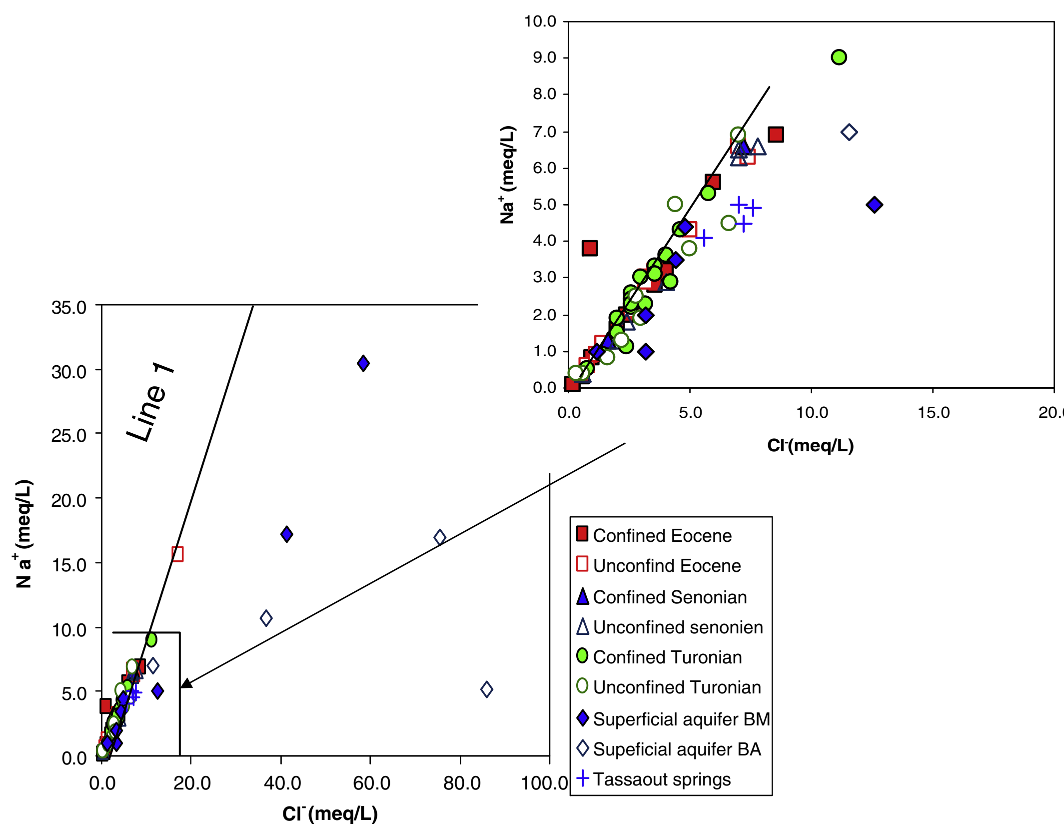

Fig. 6. Relationship between chloride and sodium.

aquifer of the Atlas Mountains and individual aquifers in the Tadla basins has been the focus of investigation in previous studies (Bouchaou et al., 1995, 1996), and will also be addressed later in this paper.

Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$)

According to a study conducted by Ouda et al. (2004) on the daily measurement of isotopes in precipitation at Beni Mellal station

(Piedmont of High Atlas, 500 m.a.s.l.), the $\delta^{18}O$ values vary from −0.09‰ to −11‰. Monthly $\delta^{18}O$ values in regional rainfall are −4‰ to −7.5‰ and +10‰ to −87‰ for $\delta^{18}O$ and ^2H, respectively. The local meteoric line, which is representative of the southern part of the Tadla basin, is defined by the following equation: $\delta^2H = 8 \times \delta^{18}O + 13$. As air masses originate mainly from the Atlantic Ocean and occidental Mediterranean Sea, the relatively high deuterium excess suggests the importance of recycled water vapor in contributing to rainfall (Clark and Fritz, 1997).

The $\delta^{18}O$ and δ^2H values of water from wells, boreholes, surface water and springs sampled in this study are plotted and compared to Local and Global Meteoric Water Lines (GMWL) in Fig. 7. The isotopic values show high variability; between −3.95‰ and −7.93‰ for $\delta^{18}O$ and between −24.7‰ and −50.2‰ for δ^2H. Two groups of groundwater can clearly be distinguished: (1) groundwater with heavy isotope composition, corresponding to wells tapping unconfined areas of aquifers (Eocene, Senonian, Turonian, Ben Amir plain) in the north, where the formation constituting the aquifers outcrop (Phosphates Plateau) and (2) groundwater with depleted isotope composition corresponding to confined areas of aquifers in the south, close to the Atlas Mountains.

The deuterium excess ($d = \delta^2H - 8\delta^{18}O$) for the first group is significantly lower than of the second group, which is similar to that of precipitation at the Beni Mellal station. The difference in the isotopic composition of the two groups is attributed to the difference in average elevation of recharge areas between northern (400 m a.s.l.) and southern (Atlas Mountains >700 m a.s.l.) parts of the basin. The ^{18}O and ^2H contents depleted toward to the high altitude. For the first group, recharge occurs locally from formation outcrops (altitude of about 400 m) whereas for the second group with lower $\delta^{18}O$ and δ^2H values the recharge occurs from higher elevation.

Groundwater from the first group has $\delta^{18}O$ values of more than −5.5‰, and includes groundwater from the unconfined Eocene, Senonian, Turonian, and Ben Amir plain aquifers and several river samples. This group shows a deviation of $\delta^{18}O$ and δ^2H values from the meteoric line (i.e., slope <8), which suggests surface evaporation. However, several samples from the confined Turonian aquifer (TD20, TD22, TD24 and TD39) and the confined Eocene (TD33, TD34 and TD55) aquifers also show $\delta^{18}O$ and δ^2H offset from the meteoric line. These boreholes were sampled in the north middle section of the Tadla plain up to the boundary between unconfined and confined parts (Fig. 2). According to the placement of these points and their isotopic signature, they can be recharged from the Plateau of Phosphates in the north of the basin. This could explain contribution from aquifer outcrops towards the middle of the Tadla multilayered aquifer, which was suggested previously (Bouchaou et al., 1995). Moreover, association of these samples suggests significant water exchange between unconfined and confined units of these aquifers in that location. One has to take into account that during water sampling from wells can present a blend originating from different aquifers. We attribute values measured in unconfined Turonian water to isotopic signature input from the Phosphate Plateau (average $\delta^{18}O = -5.5$‰). In contrast, the Turonian aquifer shows significantly lower stable isotopes values ($\delta^{18}O = -6.5$‰, $\delta^2H = -41.8$‰) in TD67, a well situated on the southwestern outcrop of the aquifer (Tassaout). These isotopic values are similar to the isotopic data of groundwater sampled in the middle basin, where the Turonian aquifer is confined and pressurized. TD67 well has a relatively low $\delta^{18}O$ and δ^2H signatures and seems to overlap with the composition of water generated in the Atlas Mountains. Overall, the Plio-Quaternary, Eocene and Senonian formations have a low infiltration rate and water can evaporate during its travels through the unsaturated zone.

The second group, which includes groundwater from confined aquifers; Atlasic springs (Atlas Mountains outlet), the Tassaout plain aquifer and Tassaout springs, exhibits low $\delta^{18}O$ (−5.5‰ to −8‰) and δ^2H (−33‰ to −50‰) values. The lowest values are measured in Tassaout (springs and wells) situated in the southwest of the basin, in the Beni Mellal region Atlasic springs, and in the upstream section of the OER river. The Tassaout springs (TD63, TD64, TD65 and TD66) emerge from Plio-quaternary formations, and are supposed to be the natural outlet of the Tadla Turonian aquifer at the southern part of the basin (Fig. 1). The much depleted isotopic signatures of both these springs and the Tassaout plain aquifer suggests a common origin. In contrast, discharge of groundwater from the other aquifer units is unlikely, given the depleted isotopic signature of the Tassaout springs. Thus, our data rule out the possibility of hydrological connection between confined and unconfined units to the Tassaout aquifer, which receives its water from highly depleted water originating at high altitude in the High Atlas Mountains. Two of these springs were analyzed for ^{18}O in June 1989 (Hsissou et al., 1996): TD63 and TD66. The measured values were

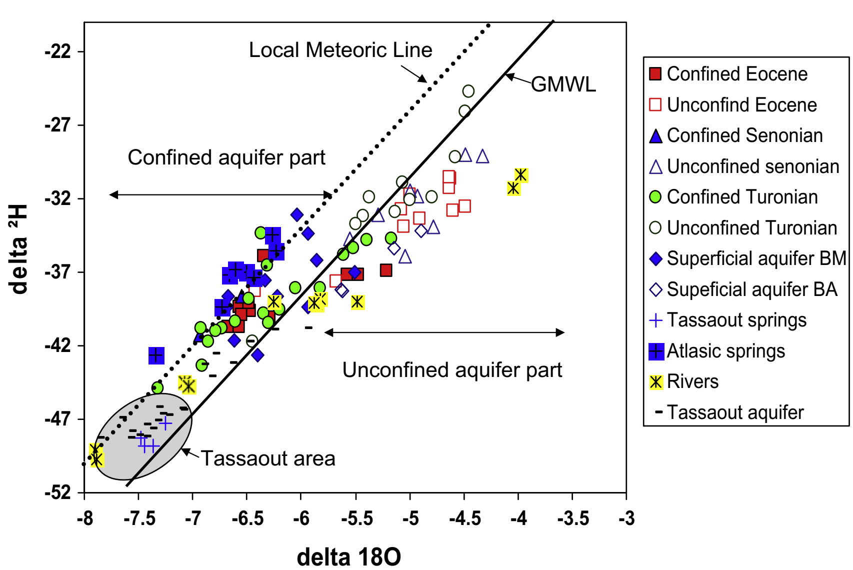

Fig. 7. δ^2H versus $\delta^{18}O$ values of groundwater and surface water investigated in this study as compared to the Global Meteoric Water Line (GMWL; Rozanski et al., 1993). Samples are sorted according by geographical distributions in Fig. 2.

respectively −7.84‰ and −7.60‰. Low variations noted between June 1989 and April 1999 eliminates the possibility of Turonian groundwater contribution to these springs. The conclusion can thus be drawn that pumped water is the main source of discharge from the Turonian aquifer. Based on the good quality of Turonian water, the pumping rate from this reservoir is evaluated to be 1.5 $m^3 s^{-1}$. The relatively high tritium content of the Tassaout aquifer (see below) rules out the possibility of fossil water with a depleted isotopic signature.

On the other hand, we notice the same isotopic signature for samples from the Atlasic springs, rivers, the Beni Moussa aquifer, and the Tadla confined aquifers. The Turonian aquifer, a deep aquifer in the Tadla plain of productive importance, presents a similar isotopic signature to the Atlasic springs. This result indicates a significant recharge rate from the Atlas Mountains to the deep aquifers in the Tadla plain, notably from the eastern part. The Beni Moussa aquifer is recharged by: (1) direct rainfall in the plain; (2) surface water from the Atlas Mountains (river) which used for irrigation; and (3) underflow from the Atlasic aquifer through piedmont materials. Samples from the Atlas springs and confined aquifers plotted above the GMWL (Fig. 7) seem to originate from different sources, altitudes and recycling of air masses.

The relationship between EC and $\delta^{18}O$ values (Fig. 8) shows that $\delta^{18}O$ values are not associated with an increase in salinity in most of the investigated samples. We identify this correlation in just a few river samples, where evaporation causes a concurrent increase in EC and $\delta^{18}O$. In contrast, the highly saline waters of the BM and BA surface aquifers have relatively low $\delta^{18}O$ values, which confirm our assumption of evaporate dissolution by meteoric water. Moreover, these saline waters have high ^{14}C activities (60–80 pmc), indicating modern water recharge from the Atlas Mountains and a direct hydraulic connection between Atlas outflows and BM and BA superficial aquifers (Fig. 2).

Based on isotopic variation, we hypothesize that groundwater recharge into the Tadla basin is composed of: (1) direct rainfall within the plain; (2) surface water flowing from the Atlas Mountains and used for irrigation; and (3) subsurface flow from the Atlasic Liassic aquifer through piedmont materials. While local recharge has a relative enriched $\delta^{18}O$ value (−5.5‰), the latter two-recharge components have a lower isotopic value (−6.5‰ to −7.3‰). We used a mass-balance mixing model to calculate the relative contribution of recharge components to the confined Turonian aquifer in order to quantify the relative contribution of Atlas groundwater (end-member 3) and local recharge (end-member 1).

$$\delta^{18}O_{mix} = \delta^{18}O_{R3}(f) + \delta^{18}O_{R1}(1-f) \quad (1)$$

where $\delta^{18}O_{Mix}$ (=−6.3‰), $\delta^{18}O_{R3}$ (=−5‰) and $\delta^{18}O_{R1}$(=−6.66‰) are $\delta^{18}O$ values of confined Turonian groundwater, the Atlas outlet and Turonian Outcrops (recharge 3), and local recharge (recharge 1), respectively. Our calculation suggests a predominant contribution of about 80% of input that is derived from subsurface recharge originated from the Atlas Mountains. A similar contribution of 90% was previously highlighted (Bouchaou et al., 1995). This result is in concordance with the flow direction of the two-end members and annual rainfall values of 400 and 700 mm in the Plateau of Phosphates and Atlas Mountains, respectively. Direct contact between Turonian and Liassic limestone in the southeast allows hydraulic circulation from the Liassic to the Turonian aquifer. We note also that the OER River circulates on Turonian limestone along a 20 km stretch, where it can be recharged from surface water.

Water mean residence time (MRT)

To better evaluate the water resource management program for the multilayered system aquifer of the Tadla basin, the residence time of the water (i.e., modern versus old water; Salomon and Mook, 1986; Geyh, 2005; Plummer, 2005) is quantified in this paper. Relative ages of investigated waters in the Tadla basin can also be the key to defining their origins. Carbon isotopes of dissolved inorganic carbon, tritium and water stable isotopes have been used frequently as age tracers in groundwater systems (e.g. Pearson and White, 1967; Rozanski, 1985; Rose et al., 1996; Clark et al., 1998).

Tritium

Tritium data from the Tadla basin vary from 0 to 11.7 TU (Table 1 and Fig. 9). The lowest values were found in the confined aquifers (except TD7 in the confined Eocene with 3.6 TU and TD5 in the confined Turonian aquifer with 7.6 TU), while relatively high values were found in the unconfined aquifers; Tassaout springs, Atlasic springs, and rivers. Higher values are observed in the unconfined Turonian (TD10 = 11.7 TU; TD11 = 9.8 TU; TD18 = 8.8 TU), the unconfined Senonian (TD17 = 8.9 TU), Tassaout springs (TD66 = 9.8 TU), and the Tassaout aquifer (T17 = 9.9 TU;

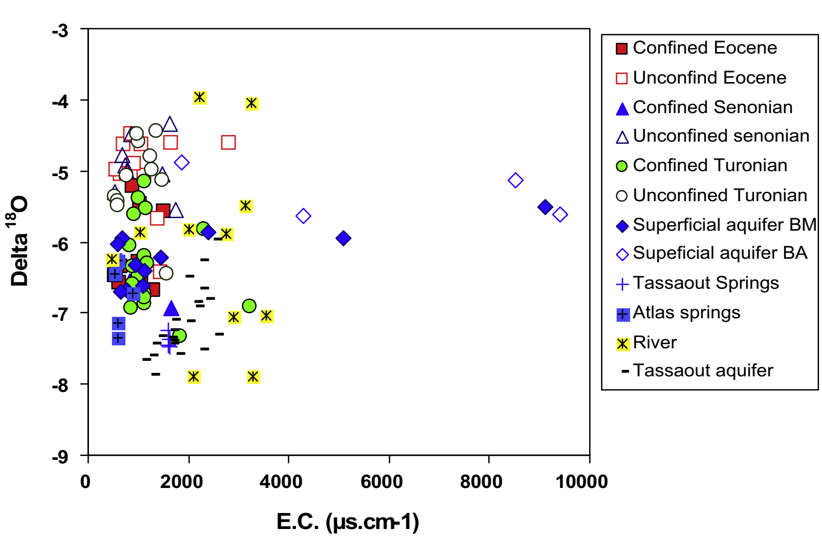

Fig. 8. Variations of $\delta^{18}O$ values (‰) versus electrical conductivity of groundwater and surface water investigated in this study. Samples are sorted according by geographical distributions.

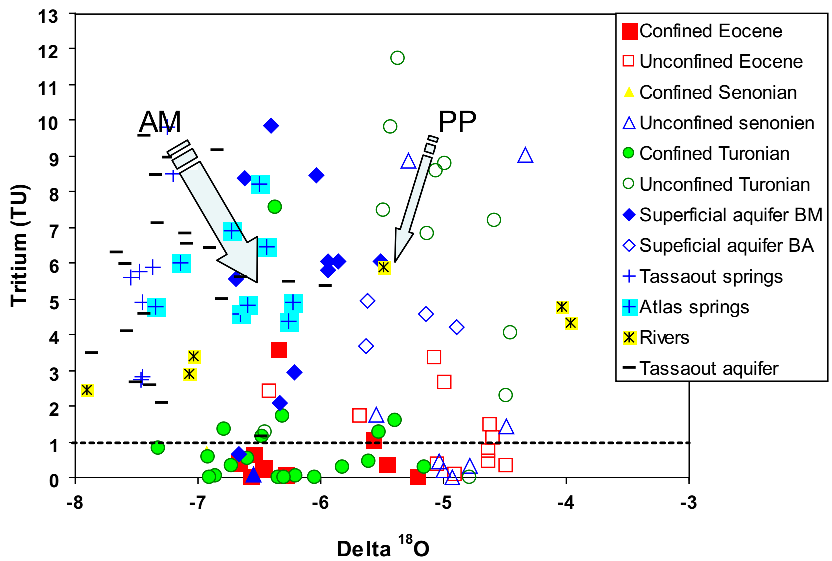

Fig. 9. Variations of tritium (TU) versus $\delta^{18}O$ values (‰) in groundwater and surface water investigated in this study. Samples are sorted according by geographical distributions.

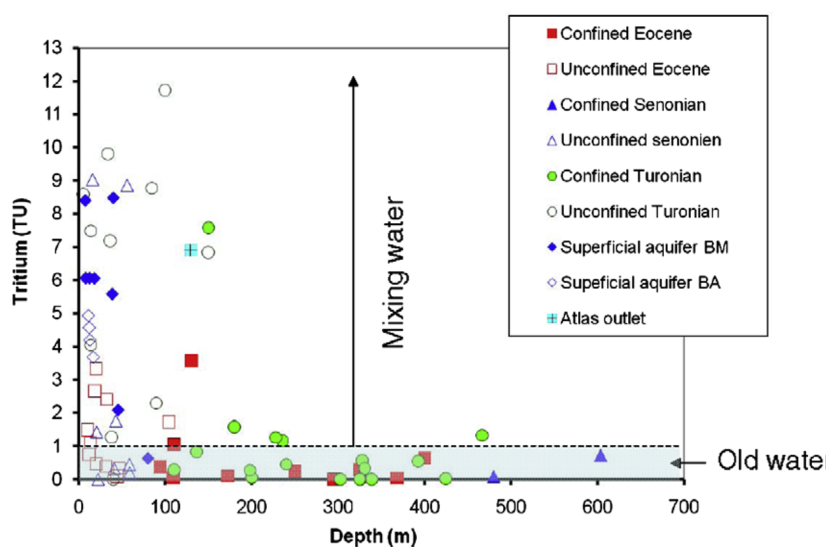

Fig. 10. Variations of tritium (TU) versus depth of wells investigated in this study. Samples are sorted according by geographical distributions.

T18 = 8.46 TU; T19 = 8.94 TU; and T20 = 9.16 TU). We assume that waters showing values of less than 1 UT were recharged before the 1950s, whereas waters presenting values of more than 1 UT are recent or mixed with old recharge (Figs. 9 and 10). Since tritium activities data in precipitation in the basin are not available, we used 5–10 TU range to represent the modern meteoric signal (IAEA/WMO, 2004). Similar values of 5.5 TU were measured in High Atlas Mountains surface water in the Souss basin (Bouchaou et al., 2008). OER River values show a variation from upstream to the Tadla basin. Low values of 2.3–2.91 TU were measured in the upstream part (Kénifra in Middle Atlas Mountains) where the river originates from the OER springs. Upon its entry to the Tadla basin, tritium values increase and vary from 3.39 to 5.88 TU. As water recharges vertically within the plain and laterally from the recharge zone adjacent to the aquifer basins, tritium activities are expected to decrease with time. In Fig. 9, we observe a non-correlation between tritium and $\delta^{18}O$ values. This lack of correlation might reflect a mixture between ^{18}O-depleted water and modern water with high tritium derived from recharge in the Atlas Mountains (marked as AM in Fig. 9) and deep older groundwater with lower tritium activities as well as low $\delta^{18}O$ values. On the other hand, local recharge on the Plateau of Phosphates (marked as PP in Fig. 9) is characterized by relatively high tritium and ^{18}O-enriched values, reflecting surface evaporation of water. The relationship between tritium and well depth (Fig. 10) shows clearly the difference in ^{3}H contents between unconfined and confined areas of the basin. Deeper boreholes are associated with lower tritium activities except for TD5 in the confined Turonian and TD7 in the confined Eocene. These two boreholes are located in the eastern part of the basin (Fig. 2), and may be influenced by recent water recharge from the Atlas Mountains with relatively high tritium amounts of 4.36–8.21 TU in the Atlas springs.

Groundwater with tritium higher than 1 UT measured in the confined Turonian aquifer (TD6, TD9, TD20 and TD22), suggests a mixing between recent and old waters. The only unconfined Eocene sample with low tritium activity is TD25 (1.7 TU), which is located in the centre of the basin. This can be explained by old groundwater contribution, probably from the underlying confined unit. We notice that this well is drilled in a zone where underlying groundwater is pressurized and thus we expect the rising up of older groundwater. In contrast, three samples from the unconfined Turonian (TD67, TD71 and TD72) show very low tritium values of between 0 and 1.3 TU. TD67 represents the outcropped Turonian in the Tassaout area while TD71 and TD72 are situated in the northern part. Lower tritium activities suggest the contribution of old water in these wells indicating long water MRT in this part of the aquifer. This result is consistent with our ^{18}O mass-balance calculation for low contribution of local recharge and significant contribution of deep old groundwater with low $\delta^{18}O$ values derived from a long flow path within the basin.

It is interesting to note that both lateral recharge processes from the Atlas Mountains and the Plateau of Phosphates take longer than 30 years. The absence of high tritium activities in groundwater suggests that the 1960s tritium peak has already diminished in that groundwater system (Michel, 2005; Plummer, 2005). Consequently, low values measured in the Tadla multilayered system reflect relatively increasing water age from the recharge area towards the centre of the basin.

Tritium and Carbon-14

Combining the ^3H and ^{14}C results, we identify three water groups (Fig. 11) in the Tadla basin: (1) Groundwater with high ^3H (5–11 TU) and high ^{14}C activity (90–100 pmc): this groundwater type probably corresponds to recharge of modern water post

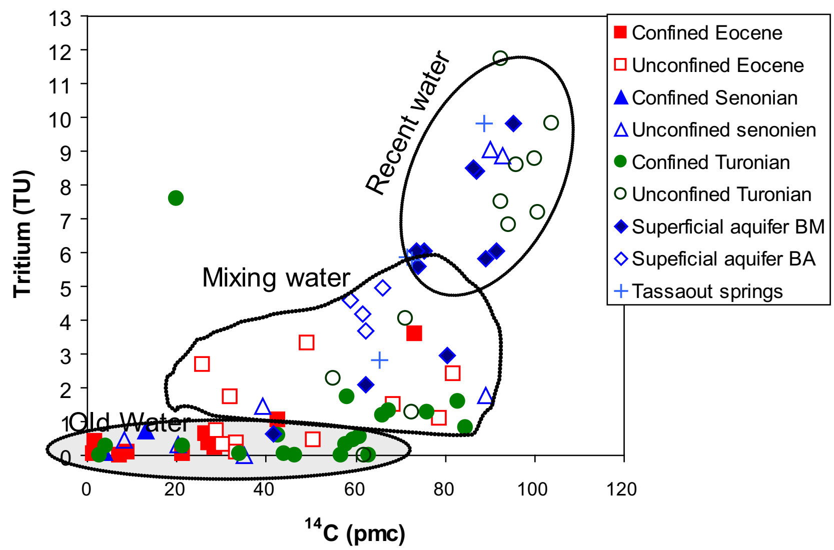

Fig. 11. Relationship between ^{14}C activity and tritium in groundwater of Tadla basin: Tree groups are distinguished: recent, old and mixing waters.

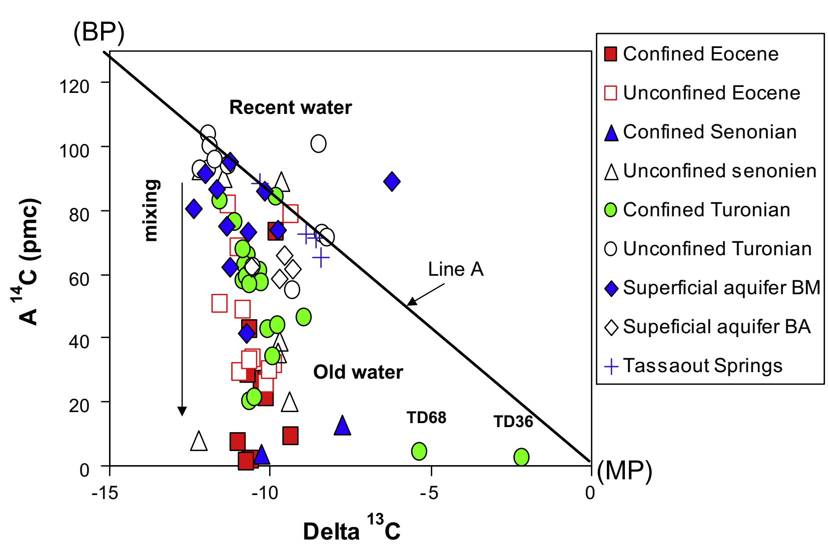

Fig. 12. $A^{14}C$ (activity of ^{14}C normalized to percent modern carbon; pmc) versus $\delta^{13}C$ values (‰) in groundwater investigated in this study. Samples are sorted according by geographical distributions. Line A represents a theoretical closed-system mixing between modern DIC (derived from soil CO_2 with $A^{14}C \sim 130$ pmc and $\delta^{13}C \sim -15$‰) and marine carbonate rock DIC ($A^{14}C \sim 0$ pmc and $\delta^{13}C \sim 0$‰). Groundwater samples with $A^{14}C$ and $\delta^{13}C$ values along this line are hypothesized to reflect mixing between soil-derived DIC and carbonate rock dissolution under a closed system and thus are modern, whereas deviation from that mixing line is modeled to ^{14}C decay and thus residence time of the groundwater.

to atmospheric nuclear tests (i.e., high ^{14}C activities) with an apparent water age of less of than 50 years. This group contains samples mainly from the unconfined Turonian aquifer, the Plio-quaternary aquifer of Beni Amir (BA) and the main Tassaout springs (TD63, TD64 and TD66). (2) Samples showing low ^3H content ($\leqslant$1 TU) and low ^{14}C activity ($\leqslant$60 pmc): this groundwater appears to originate from old water with an apparent age before the first nuclear atmospheric tests in the 1950s. This group of samples comes particularly from the confined Eocene, with the lowest $A^{14}C$, the Senonian and the confined Turonian aquifers. Some waters from the unconfined Eocene and Senonian aquifers are associated with this group. Their composition is attributed to radioactive decay indicating a long residence time of water. (3) An intermediate group with ^{14}C values of 60–85 pmc and tritium values of 1–5 TU, principally representing waters from the Turonian aquifer, superficial aquifers and Tassaout springs. This composition suggests mixing between old and recent waters in the Tadla basin. The measured value of 60 pmc (sample TD15) and the relatively high transmissivity of the Turonian aquifer indicated by high pumping rates (0.5 m^3/s) are consistent with a rapid renewal of water in this part of the aquifer.

Groundwater from the Eocene and Senonian aquifers seem to be "older" than the underlying Turonian groundwater. This could be related to the nature of geological formations hosting these water resources. The Eocene and Senonian aquifers are composed of marl whereas the Turonian aquifer is characterized by karstic limestone with higher permeability, allowing significant water lateral renewal from the recharge uptake areas in the Atlas Mountain. The composition of the Tassaout springs suggest that the springs are separated from confined aquifers, which reinforces our earlier argument that the outlet is not the main discharge for deep Tadla aquifers.

Dissolved inorganic carbon ($\delta^{13}C$ and $A^{14}C$)

The $\delta^{13}C$ values vary between −12.4‰ and −2.2‰ PDB (Table 1) with an average of −10.2 ± 1.1‰ PDB. This range suggests that DIC in the Tadla basin is derived from the mixing of two components: (1) dissolution of limestone/dolomite in the basin ($\delta^{13}C$ = 0‰); and (2) conversion of soil CO_2 ($\delta^{13}C$ = −23‰ to −25‰) to bicarbonate. During the dissociation of carbonic acid to bicarbonate, the residual DIC would be enriched in ^{13}C and thus generated DIC would have a $\delta^{13}C$ value of −15‰ (Salomon and Mook, 1986; Clark and Fritz, 1997). We use $\delta^{13}C$–$A^{14}C$ relationships as an indicator for tracing sources of DIC and for the degree of carbon dilution induced by water–rock interactions associated with dissolution of old carbon from host aquifer rocks.

In Fig. 12 we show the $\delta^{13}C$ and $A^{14}C$ relationships. Based on our earlier assumption, we use a mixing line of two proposed end members: (1) a biogenic end member (BP) with a $\delta^{13}C$ of −15‰ and $A^{14}C$ of 130 pmc; and (2) a mineral end member (MP) with a $\delta^{13}C$ value of 0‰ and $A^{14}C$ of 0 pmc. Several groundwater samples (with high $A^{14}C$) from unconfined and Plio-Quaternary aquifers are located along this line. In this case, we attribute these water figures to modern age recharge. Samples (TD13, TD77) located above the mixing line show isotopic signatures that can probably be attributed to equilibrium with atmospheric CO_2 (between gas and aqueous phases), thus their water age is also recent. Most samples, however, are located below the mixing line, indicating radioactive decay and thus a long residence time. Larger ^{14}C offset and apparent older ages are found in groundwater from the confined Eocene, Senonian and Turonian aquifers. Two water samples from the confined Turonian aquifer (TD36 and TD68) have the lowest $\delta^{13}C$ and $A^{14}C$ values (Fig. 12). These low values seem not to be derived from radioactive decay but rather from extensive water–rock interactions with the carbonate aquifer.

To express this variability in ^{14}C activities in terms of water age, we selected samples with low tritium values (e.g. <1 TU) to calculate age, using carbon activities and the Pearson Model (Table 2, Fig. 12). We believe those waters are not influenced by recent recharge. Older ages are found in waters of the confined Eocene, Senonian and some parts of the confined Turonian (TD36, 39 and TD69) aquifers. The oldest water samples from the Turonian show low $\delta^{13}C$ and $A^{14}C$ values, and can be explained by their geographical placement in the northwest of the basin, which has a low recharge rate from the Atlas Mountains where the recent recharge is very significant. Water in confined parts of the Turonian aquifer has different water ages without a discernable pattern due to groundwater flow. This is not consistent with the apparent high permeability of 10^{-3} m/s, suggested by the mathematical model for the Turonian aquifer (DRPE, 1993). Given the isotopic data, this apparent high permeability appears to be highly overestimated. In order to verify these values, we used ages determined by carbon-14 to calculate hydraulic permeability in some areas, mainly for the Turonian aquifer, taking account of the flow direction from east to west. With a porosity of 20%, results show permeability values of around 10^{-6}–10^{-5} m s^{-1}, which is in agreement with the 10^{-5} m s^{-1} value predicted by pumping test (Hsissou et al., 1996). These new values seem to be consistent with the lithology that characterizes this aquifer system. On the other hand, the relationship between calculated ages and depths of wells in Fig. 13 indicates that the oldest waters correspond to the deepest wells

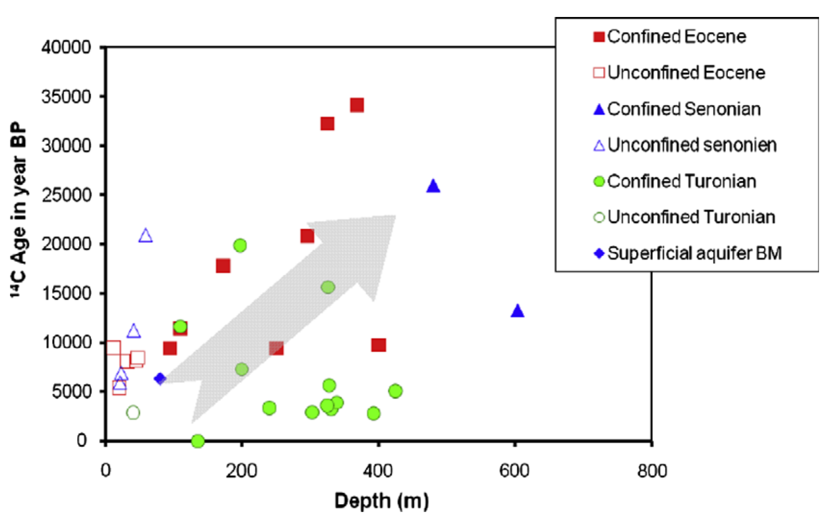

Fig. 13. Variation of calculated water ages according to depth of boreholes. A correlation is shown in Eocene and Senonian confined aquifers.

Table 2
Age water using the Pearson model.

Code	Nature	Depth (m)	^{3}H (TU)	^{3}H error (TU)	A^{14}C (pmc)	A^{14}C error (pmc)	d^{13}C (‰)	A0 (pmc) Pearson	Age (y BP)
Confined Eocene aquifer (Group 1)									
TD1	Borehole		0.4	0.28	1.88	0.06	−10.65	88.6	31864
TD2	Borehole	295	−0.12	0.27	7.36	0.09	−10.99	91.6	20841
TD3	Borehole	325	0.29	0.28	1.79	0.06	−10.6	88.3	32230
TD31	Borehole	400	0.64	0.23	26.57	0.19	−10.29	85.8	9685
TD32	Borehole	368	0.04	0.23	1.44	0.07	−10.73	89.4	34130
TD34	Borehole	94	0.38	0.23	27.13	0.19	−10.11	84.3	9367
TD37	Borehole	172	0.1	0.22	9.11	0.11	−9.35	77.9	17742
TD55	Borehole	109	0.05	0.21	21.35	0.16	−10.14	84.5	11372
TD82	Borehole	250	0.24	0.17	28.67	0.2	−10.68	89	9364
Unconfined Eocene aquifer (Group 2)									
TD28	Well	31.9	0.38	0.22	33.3	0.22	−10.52	87.7	8001
TD42	Well	20.4	0.46	0.22	50.56	0.3	−11.56	96.3	5329
TD51	Well	12	0.74	0.21	29.02	0.2	−10.95	91.3	9470
TD52	Well	45	0.08	0.2	33.23	0.22	−10.61	88.4	8089
TD53	Well	47	0.34	0.21	30.18	0.2	−10.04	83.7	8429
Confined Senonian aquifer (Group 3)									
TD23	Borehole	604	0.74	0.27	13.06	0.11	−7.78	64.8	13245
TD56	Borehole	480	0.1	0.2	3.7	0.08	−10.29	85.8	25982
Unconfined Senonian aquifer (Group 4)									
TD26	Well	41.2	0.33	0.22	20.18	0.15	−9.42	78.5	11229
TD29	Well	58.6	0.46	0.23	8.12	0.1	−12.23	101.9	20913
TD69	Well	21.2	1.44	0.21	39.36	0.26	−9.7	80.8	5949
TD73	Well	23	0.01	0.18	35.17	0.23	−9.74	81.2	6913
Confined Turonian aquifer (Group 5)									
TD4	Borehole	136	0.83	0.29	84.42	0.54	−9.82	81.8	0
TD8	Borehole	328	0.58	0.26	42.53	0.25	−10.06	83.8	5609
TD14	Borehole	425	0.03	0.26	44.08	0.26	−9.77	81.4	5072
TD15	Borehole	393	0.55	0.27	60.92	0.37	−10.32	86	2850
TD19	Borehole	331	0.33	0.26	57.65	0.31	−10.27	85.6	3266
TD21	Borehole	303	−0.02	0.25	62.87	0.34	−10.78	89.8	2950
TD24	Borehole	240	0.45	0.25	59.36	0.32	−10.74	89.5	3394
TD27	Borehole	200	0.06	0.22	34.12	0.22	−9.89	82.4	7290
TD35	Borehole	339	−0.02	0.21	46.35	0.28	−8.93	74.4	3913
TD36	Borehole	326	−0.15	0.22	2.74	0.08	−2.18	18.2	15637
TD39	Borehole	110	0.29	0.22	21.39	0.16	−10.47	87.3	11621
TD54	Borehole	325	−0.09	0.2	56.88	0.33	−10.62	88.5	3654
TD68	Borehole	198	0.28	0.19	4.04	0.06	−5.36	44.7	19864
Unconfined Turonian aquifer (Group 6)									
TD72	Well	40.6	0.00	0.18	62.01	0.38	−10.55	87.9	2885
Superficial aquifer Beni Moussa (Group 7)									
TD47	Well	80	0.64	0.21	41.71	0.25	−10.74	89.5	6311

and boreholes. This result confirms the low rate of water renewal according to geographical situation.

Conclusion

The multilayered aquifer of the Tadla plain in central Morocco constitutes a complex hydrogeological system. Increasing exploitation of these aquifer systems is a major concern for local and national water authorities given the draw down in piezometric levels and the apparent unsustainability of this basin. This study presents results of stable isotope and age-dating isotopic tools in an attempt to clarify the origin of recharge water, the residence time of groundwater resources and hydraulic connections between different aquifers in the Tadla basin. Geochemical data mainly indicate low mineralization of the groundwater (EC $\leqslant 1100\ \mu s\ cm^{-1}$), except for a few wells in the Senonian and Turonian aquifers, which are influenced by dissolution of evaporite rocks (gypsum and halite) in these formations, and some samples from Plio-Quaternary aquifers, which are subject to surface evaporation. The water composition is predominated by a Ca–Mg–HCO_3 water type, reflecting the calcareous and dolomite nature of the formations hosting the aquifers.

Stable isotopes data indicate that the Tadla confined aquifer is highly influenced by the contribution of water recharge from the Atlas Mountains, particularly in southeast part of the basin. The Atlas Mountains, which receive high rainfall, also constitute the main recharge area for the Beni Moussa and Tassaout Plio-Quaternary aquifers. For the deeper aquifers (Eocene and Turonian), two water sources have to be considered: (1) the Atlas Mountains and (2) the Plateau of Phosphates. Water from northern outcrops in the Plateau of Phosphates contributes to recharge mainly in unconfined parts of aquifers but seems to have negligible influence on the confined parts. An evaporation effect on the stable isotopes is only observed for some groundwater, mainly in unconfined parts of the aquifers, probably due to significant water retention in the unsaturated zone. Isotopic tracing clearly revealed that the Tassaout springs do not constitute an outlet for the Turonian aquifer. These springs are characterized by depleted isotope composition, which is similar to the high altitude signature of precipitation in the Atlas Mountains.

The results of age dating using ^{3}H and ^{14}C data confirm that most of the investigated groundwater is derived from mixing old waters and recently recharged (tritiated) waters. The mixing process is clear for the important Turonian aquifer, indicating that a significant modern recharge of groundwater occurs only along the northeast, southeast and south sections of the Tadla basin. This result confirms a lateral flow and a continuing water resources renewal of the Turonian aquifer.

The Mio-Plio-Quaternary aquifers receive local recharge through precipitation and Atlasic recharge via the surface network and shallow piedmont discharge. All tools used in this study (geology, chemistry and isotopes) indicate probable interconnections between the Tadla aquifers. Factors affecting multiple recharge areas, including geological, climatic and hydrological contexts, suggest that the Tadla aquifers are vulnerable to climate change, as well as to contamination in this populated and agricultural region.

In sum, this study demonstrates the importance of using isotopic tracers in hydrological studies. The results of this study, including information about recharge areas and residence time, should not only be used to conceptualize, but also to calibrate future groundwater flow models carried out by water authorities, in order to develop and refine groundwater management plans for adequate exploitation of this fragile water resource.

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