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A conceptual framework of groundwater flowpath and recharge in Ziban aquifer: south of Algeria

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Abstract

The Zyban aquifers (southern Algeria) are an important source of groundwater and are mainly found in limestone and dolomite from the Senono-Eocene. To be able to assess the effects of overuse of the Zeban groundwater, it is necessary to understand the origin of the recharge and determine its path out of the recharge zones. This study aims to better understand the flow path and replenishment areas using hydrology. For this purpose, 145 water samples were collected and analyzed for the determination of major ions and isotopes (^{18}O, ^2H and ^3H). The isotope analysis of hydrogen, oxygen and tritium allowed a certain distinction between the origin and the mixture of water. The study area is located in the fault corridor of the South Atlas, a network of migration and folding defects that leads to a complex structure characterized by the subdivision of the formations and the variety of facies. The regional flow pattern is mainly influenced by the topography, and this is through the distribution of supply and flow, which is produced by transport at many depths and levels of distribution (local or regional). The rocky nature and the severe fractures are responsible for the division of the hydrogeological units and play an important role in the dynamics and transport of the groundwater. The hydrodynamic analysis shows the dominance of regional hydrogeology in terms of geological nature and structure. This is supported by a hydrochemical signal showing the distribution and evolution of the elements according to the structural and geological scheme (evolution from calcium bicarbonate facies to calcium sulphate medium facies).

Keywords Aurès · Leakage · Oxygene-18 · Recharge · Saharian Atlas and tritium

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Introduction

The area of Biskra hydrologic basin appears as the transition and the transfer zone of groundwater between aurésiens hydrosystem and those of the Eastern Saharan Atlas (Hodna region) and the northeastern borders of the Lower Sahara. These regions contain sometimes huge water reservoirs and consist of a series of aquifers of different ages and lithologies. The aquifers of Zibans belong to regional aquifer systems of great extension: aquifer of the Complexe Terminal (CT) in relation with the confined Continental Intercalaire (CI) (UNESCO 1983; OSS 2003). The potentialities of the limestone aquifers of Zibans, mainly those in the region of Tolga and El Outaya contained in the carbonate formations of Cretaceous and Eocene, cannot be justified by direct infiltration due to the low rainfall (isohyet 100–150) (Chabour 2006). It is agreed that the availability of local groundwater is a function of regionals processes as well as the local processes (Dennehy et al. 2015). The large-scale exploitation of

groundwater in the Ziban region has led to an uninterrupted reduction in source flow and piezometric level.

Moreover, the response time from recharge areas of regional groundwater systems are very slow and the over exploitation consequences are only detected once they become an irreversible situation (Rushton et al. 2020; Afonso et al. 2019; Bredehoeft and Durbin 2009). The aquifer of Ziban (Tolga region) which is sometimes located more than 200 m deep, includes a large area where the aquifer is artesian. Hydrogeological knowledge of these areas inside the transition zone (Saharan Atlas—Platform Saharan) made difficult due to the structural and tectonic complexity of the formations. This transition zone is a major hydrogeological boundary that influences the flows of groundwater at regional scale (Chabour 2012). For this reason, it is imperative to extend the perimeter of investigation to surrounding areas (Aurès, Hodna). Despite their location in semi-arid area, the Aurès massif represents for the surrounding areas and especially those of the South, the main reservoir supplying both rivers and groundwater. This characteristic in relation with precipitation, also originates from the snow from mountains.

The regional existence of different types of springs (cold and thermal waters), karst phenomena and wetlands dampens a regional gravity flow of groundwater (Mádl-Szőnyi and Tóth 2015). The gravity as being the dominant driving power of groundwater flow (Toth 1999), the essential of the direct recharge from precipitation occurring in massifs is transported laterally to the southern aquifers of Zibans. Besides the porous aquifers of the Neogene cover, fractured and karstic aquifers divided in hydrogeological blocks more or less interconnected which taking place in relay flow from the massif of the Aurès and the northern part of the Saharan Atlas. The boundaries between these hydrogeological units materialized either by faults or evaporites rise or impervious materials (Aurès-El Outaya limit) or by lines of groundwater watershed (Hodna–Zibans basins). The faults limiting these compartments may act as barriers, limiting the horizontal flows and allowing the ascent of the groundwater to the ground surface (appearance of springs along faults) or on the contrary, as drains by putting different pervious formations in the same level (Bhagwat et al. 2020; Bouteraa et al. 2019; Mailloux et al. 1999; Melchiorre and Criss 1999). Thermal anomalies (hot springs) appear in those areas clearly indicating the preferential flow along faults (Bouaicha et al. 2020; Foued et al. 2017; Curewitz and Karson 1997; Bense et al. 2008).

Isotopic geochemistry is a technique that uses stable isotopes and radioactive isotopes of the environment to trace the movements of water in the hydrological cycle. In this case, it is possible to know the origin, the directions and the velocities of the water flows, the mixtures between the different types of water, the transit time and the residence time of the waters. Stable isotopes make it possible to characterize a water relative to meteoric waters (Poage and Chamberlain 2001) and can provide elements of response in determining the areas and conditions of recharge of the aquifers and their relationships. This involves comparing the heavy isotope content of precipitation with that of groundwater. The meteoric lines (relationship of the ^{18}O contents with those of ^{2}H) are, therefore, references for groundwater (Wirmvem et al. 2020; Craig 1961; Fontes and Edmunds 1989). In the study area, some isotopic studies in the beginning of the 1970s were initiated by FAO (1969) and followed by other studies (Bellion 1973; Gonfiantini and Dincer 1974); UNESCO 1983 ERESS project (Study of the water resources of the Northern Sahara); Guendouz (1985); Edmunds 1997; Guendouz et al. 2003; Moulla and Guendouz 2003; Edmunds 2003). The types of isotopic analyzes performed are generally composed of stable isotopes (oxygen 18 and deuterium), tritium and carbon 14 and 13.

The main objective of this work is to better understand the flowpath and recharge areas using hydrogeology, chemical and isotopic characteristics gathered from various sources helping to provide information about recharge, groundwater origin and conceptual flow model in the Atlas Saharan and Ziban.

Study area

The study area is located in northeastern Algeria between longitude 04.5° E–06.5° E east and latitude 34.5° N–35.5 N north (Fig. 1). The perennial streams originate and circulate in the higher areas of the Aurès; they infiltrate in the plains or join the most southern streams. The study area are characterized by gradual transition climate, ranging from Mediterranean type to semi-arid in the North to the hyper-arid type in the South. If the transition between climatic conditions of the Saharan Atlas in the West and those of the Sahara is gradual, it is, however, faster between the high altitudes of the Aurès and Lower Sahara. Climate areas seem, therefore, to be superimposed on major morphostructural sets; the last mountains of the Saharan Atlas mark the limit of the arid climate. The climate of the Ziban region characterized by large annual and interannual variability, with large dry periods. Irregular rainfalls occurring usually between October and April, they gather, often for a few days or hours characterize the rainfall that governs the regime of groundwater and surface water. The annual rainfall does not exceed to 150 mm/year. The temperatures are quite high (average maximum between 36 and 40 °C), evapotranspiration is very large and exceed the average of precipitations. In the Northern part, the Aurès region influenced by the Mediterranean climate (Hamel 2009) with rainfall of around 450 mm and the periods of snow are about 25 days per year.
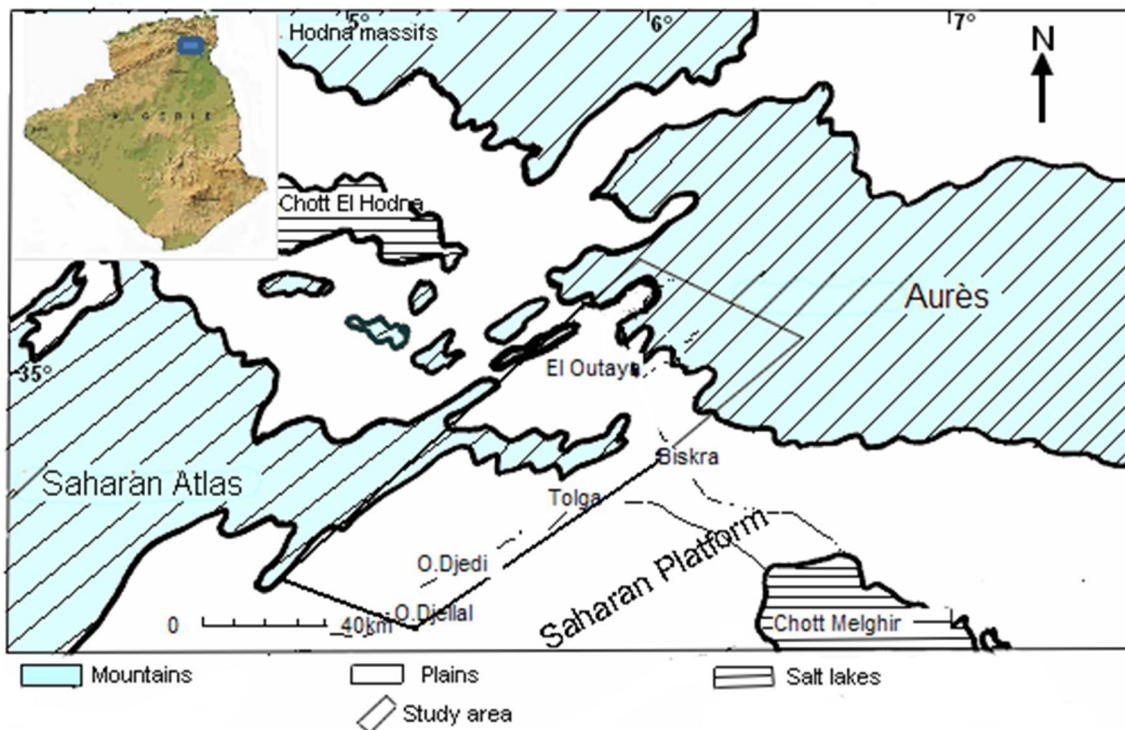
Fig. 1 Location map

Regional hydrogeology

The southern part of the Saharan Atlas, the influence of the Alpine range does not stop specifically at the flexure, but is continued further south, deep in the foothills initiating Platform Saharan Africa. In this region, the groundwater basins are by far more important than the sub watersheds. Some aquifer systems, by their extension, become the junction, relay, between several hydrogeological units. This is the case of limestone layer of Zibans which is part of the TC (Fig. 2) defined in the Saharan Platform (OSS 2003) and that is found at the southern foot of the Aurès and the southern Saharan Atlas (Chabour 2006). The classification of hydrogeological entities according to their lithostratigraphic character may sometimes be biased (deformed) because of the importance of tectonics which puts different aquifer units at the same level. Except for the aquifer of the CI which seems to confine in the Saharan Platform and is studied as such, the CT, however, belongs to the two geographic entities (Saharan Atlas and Saharan Platform).

However, some aquifers of CT, specially the complex karst formations overlaying from the Turonian until the middle Eocene considered as a regional aquifer system (sometimes multilayer) overflowing on several sectors. Large hydrogeological units (Aurès, Hodna, El Outaya, Zibans) are hydraulically interconnected (we can differentiate them only by their geological structure, facies, relief of land and water quality). The stratigraphic and structural contexts control the flow and water quality. In addition, faults that can considered as drain or barrier, thick layers of impermeable or semi-permeable formations classified as aquitards enable large exchange of water between the different formations and control very well the regional flow systems groundwater (Eaton et al, 2007), so the deeper formations (CI) are not isolated from other surface formations (CT).

Hydrogeology of the Southern Saharan Atlas and the Southwestern part of Aurès

The area between the plains of East Hodna and Aurés, bounded to the south by the mountains of the Zab is formed by aquifers belonging to formations overlaying from Jurassic to Quaternary (Fig. 2). This is a very folded structure with NE-SW direction, dominated by the anticline of Djebel El Azreg, limited by the syncline of Ghassira in the south and Bouzina in the North. These series consist essentially of carbonates and detrital elements (Guiraud 1990). Jurassic has a summital position on a reservoir essentially carbonate. Lower Cretaceous of this unite in continuity with the lower cretaceous of Saharan Platform, and formed of sandstone (Southern Chott el Hodna). In the region of Aurès, the lower Cretaceous (Albian aquifer) consists mainly of limestone and fractured sandy limestone (Abchiche et al. 1999). However, the Cenomanian–Turonian (marl and clay) constituting
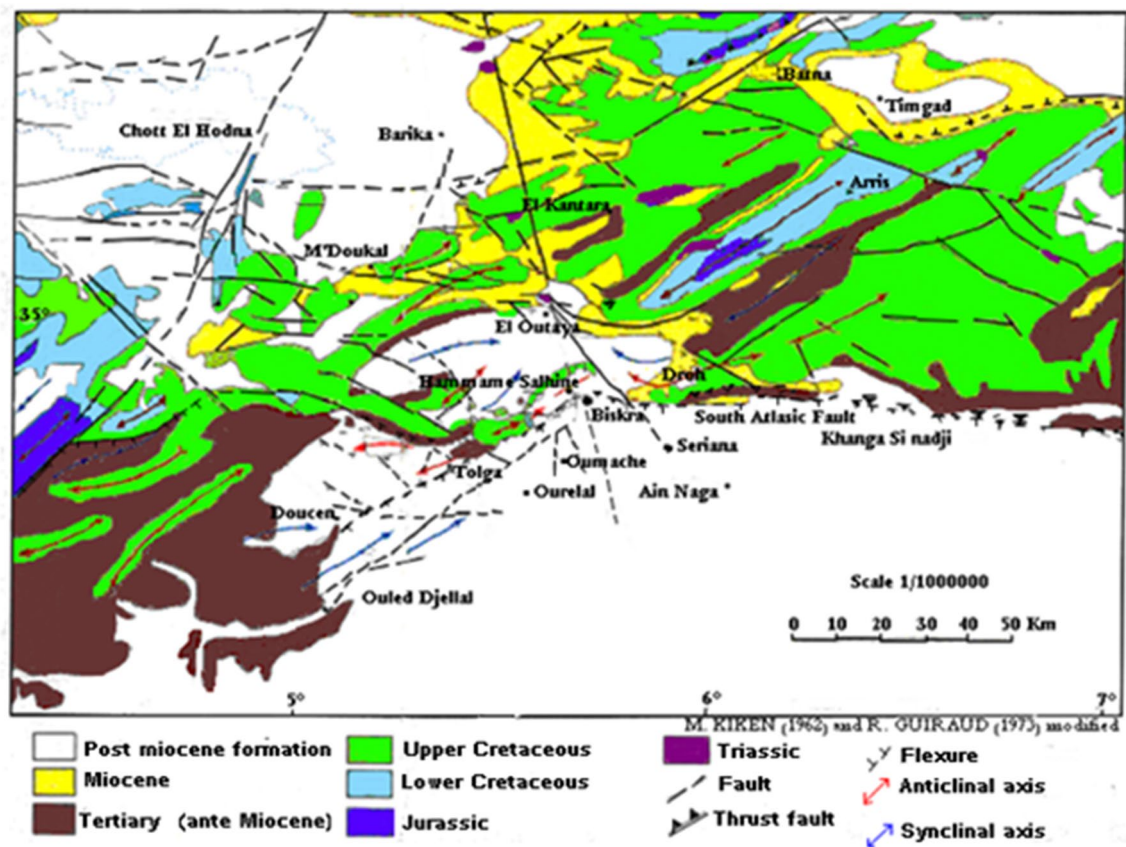
Fig. 2 Geological and tectonic map (extracted from the hydrogeological map of Biskra ANRH Report, 1980)

the substratum of CT in Sahara. A very large aquifer allows the transfer of large masses of water from aquifers in mountains of Bellezma to aquifer system of Hodna in the West and aquifers of Zibans in the South. In this region, the Cenomanian–Turonian, the upper Senonian, and the lower Eocene (multilayer carbonate) aquifer, which represents the main, recharge area. Due to the tectonic and low thicknesses of the impervious intercalary layers, the exchange of water, by leakage are very important. The Neogene and the Quaternary formed essentially by conglomerates and sandstone formations.

Aurès sub-system

The geological structure of the Aurès consists of a series of anticlines and synclines, oriented NE-SW, with a strong slope towards the Southwest. The surface waters of the Bouzina valley drained by the river Abdi flow towards the plain of El Outaya (Hamel 2009) to reach Wadi Biskra. The aquifers consist mainly of carbonated intercalations of the Eocene, the Maastrichtian, the Turonian, the Albo-Aptian and the Neocomian. However, the main reservoir matches the powerful carbonate formation of the Maastrichtian. The

Albian formations that form the CI in the Sahara are here consisted by levels of calcareous to calcareous sandstone (Abchiche et al. 1999) laying over a series of sandstone belonging to the Neocomian. The formations between the units of the Eocene and Turonian form a multilayer aquifer system consisting of limestone layers separated by clay and marl layers.

Zibans sub-system (Tolga Aquifer)

This aquifer is more perspective in the Tolga area; it is often called the limestone aquifer of Ziban. This type of aquifers is of considerable importance in terms of resources, because of their high productivity and chemical water quality. It is an artesian aquifer (Fig. 3); even though, due to overexploitation, this artesianism has decreased enormously. However, towards the south-west, in the region of Ouled Djellal and Sidi Khaled, the limestone sheet is located at a greater depth, in addition to a transition to formations with poor hydrodynamic characteristics. This southern part surmounted by the aquifer of the middle Eocene and constituted by dolomitic limestone intercalated with clay and gypsum formations. The limestone aquifer is not productive in its
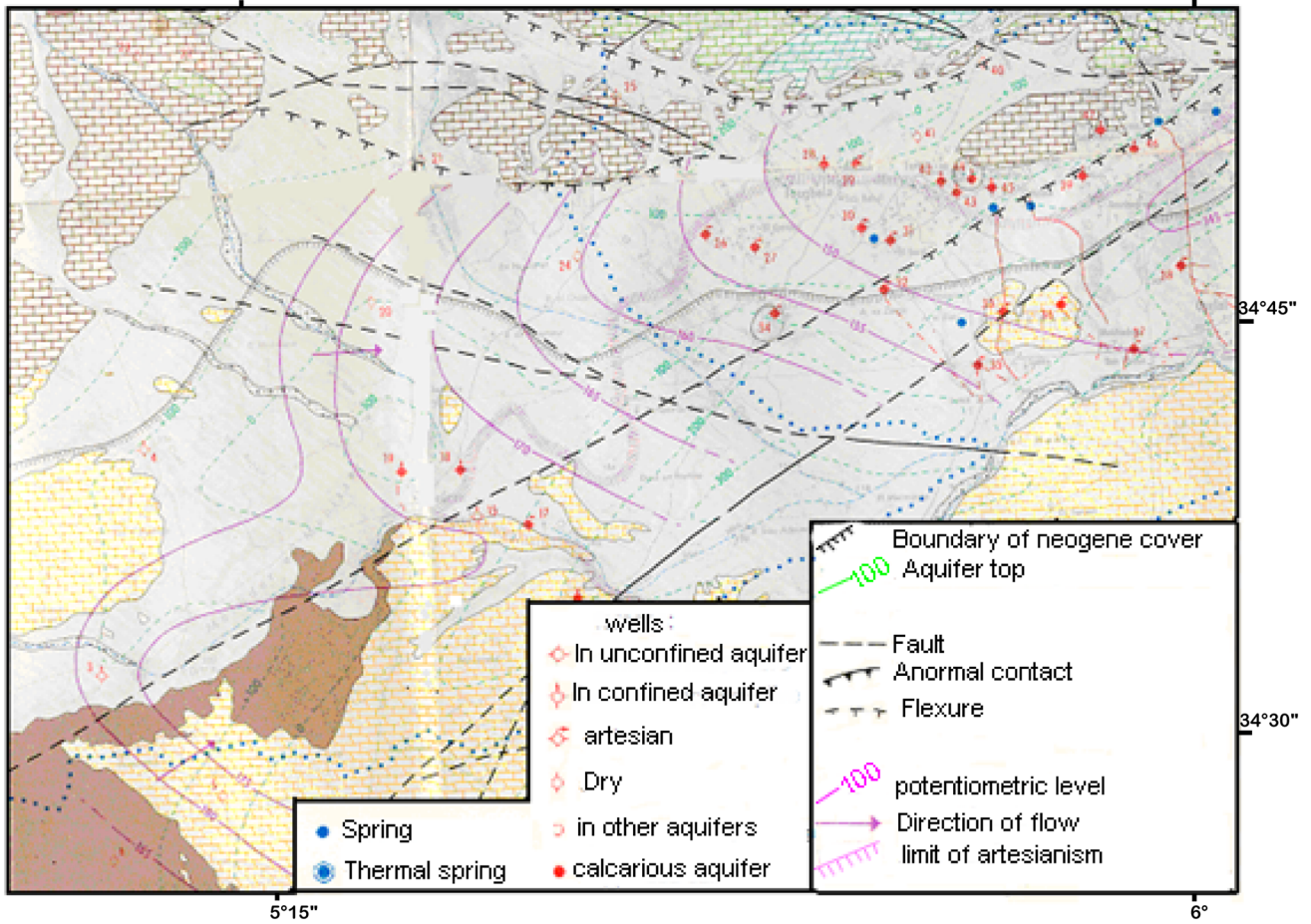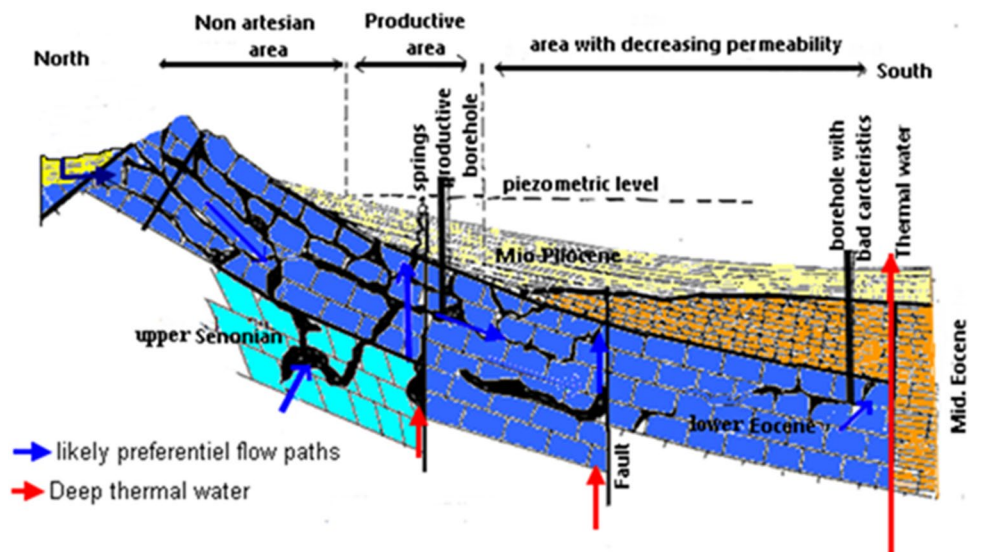
Fig. 3 Hydrogeological map of the Ziban - western part (extracted from the hydrogeological map of Biskra, ANRH, data 1971)

Fig. 4 Schematic hydrogeological cross-section based on N-S, through the Tolga area

full extent (Fig. 4), the structure favoring karstification due partly to cracks that are located especially on the flanks of anticline or the arch bend. The cover, where the alignments of folds of relatively high anticline are the most susceptible to erosion, which puts them in contact with meteoric water containing CO_2.

The productive zone starts from the northern border of the middle Eocene and is limited according to the piezometric level; 3) facies changes (the permeability reduction towards West and South of the lower Eocene can also be explained by the lithology). The fractured limestone of Ziban pass in Ouled Djellal to grey limestone with multiple intercalations of anhydrite. The pumping test in the Tolga area indicates good transmissivity values for the lower Eocene. These vary between $2\ 10^{-1}$ and $5\ 10^{-2}$ m^2/s, but can decrease to 1.10^{-3} m^2/s. However, we note that this transmissivity decreases towards the West and the South, so that in Ouled Djellal it is very low, of the order of 5 to 10^{-4} m^2/s. At El Outaya, the transmissivity is of the order $1.9\ 10^{-2}$ m^2/s.

Methodology

To understand the conceptual model of the water flow path at the regional level by adopting a continuous change in volume (Fig. 5), in this study, we used several geological approaches and methods that allow the characterization of individual hydrogeological units due to the nature of tectonic or sedimentary nature. This approach require to integrate various available data sets such as hydrogeological, hydrochemical and environmental tracer data (Lauber and Goldscheider

2014; Pavlovskiy and Selle 2015). This study is focused on the compilation and analysis of data taken essentially from recognition campaigns by drilling and geophysical studies that are, for the most part, the work of petroleum researchers. Geological and hydrogeological maps at different scales in the region were carried out, especially by Brive (1924), Cornet et al (1959), Laffite (1939), Busson (1971, 1989); Caratini (1972); Bellion (1973); A.N.R.H. (1980); Guiraud (1990); Bouchiba (1992) and Abchiche et al (1999). However, most of these regional studies, on a small scale, do not enable us to draw a conceptual geological model, taking into account the heterogeneity and the role of fracturing. Since the hydrodynamic approach alone cannot explain the flow system and the transfer of water bodies, environmental tracers are combined with these techniques and consist in the use of environmental isotopes and chemical elements. Sampling water chemistry analyzes were conducted at the regional level and for different periods (Bellion 1973; Gonfiantini et al. 1975; GTZ 2009). These hydrochemical investigations cover the regions of the Aurès, the plain of the Hodna, the Zibans and South Atlasic foothills.

A representative collection of groundwater samples was carried out during two periods first on 2004 and the second on 2005. A total of 145 samples was collected from borehole and springs (Fig. 6). All water samples were filtered through 0.45 μm membranes on site it was carried out after a short pumping period (boreholes) in polyethylene bottles and stored in an icebox at a temperature < 4 °C (APHA 2005). At each sampling point, three bottles of water samples were collected, and reagent-grade HNO_3 was added to one of them to get the pH below 1 for cation analysis. Hydrogen
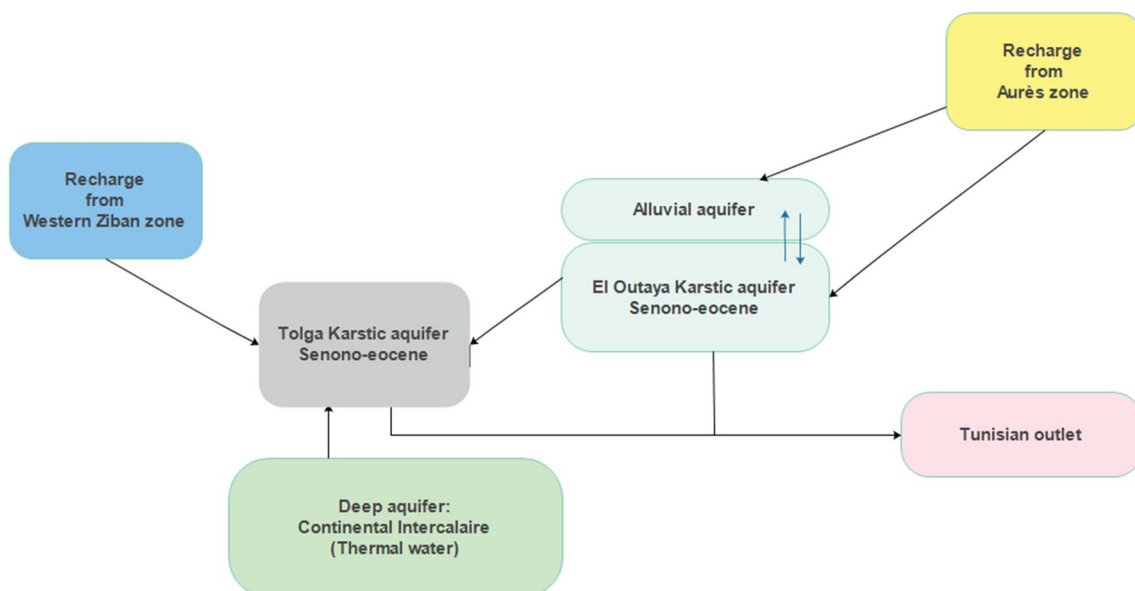

Fig. 5 Diagram of regional flow pattern and lateral recharge. Arrows show the direction of flow of groundwater
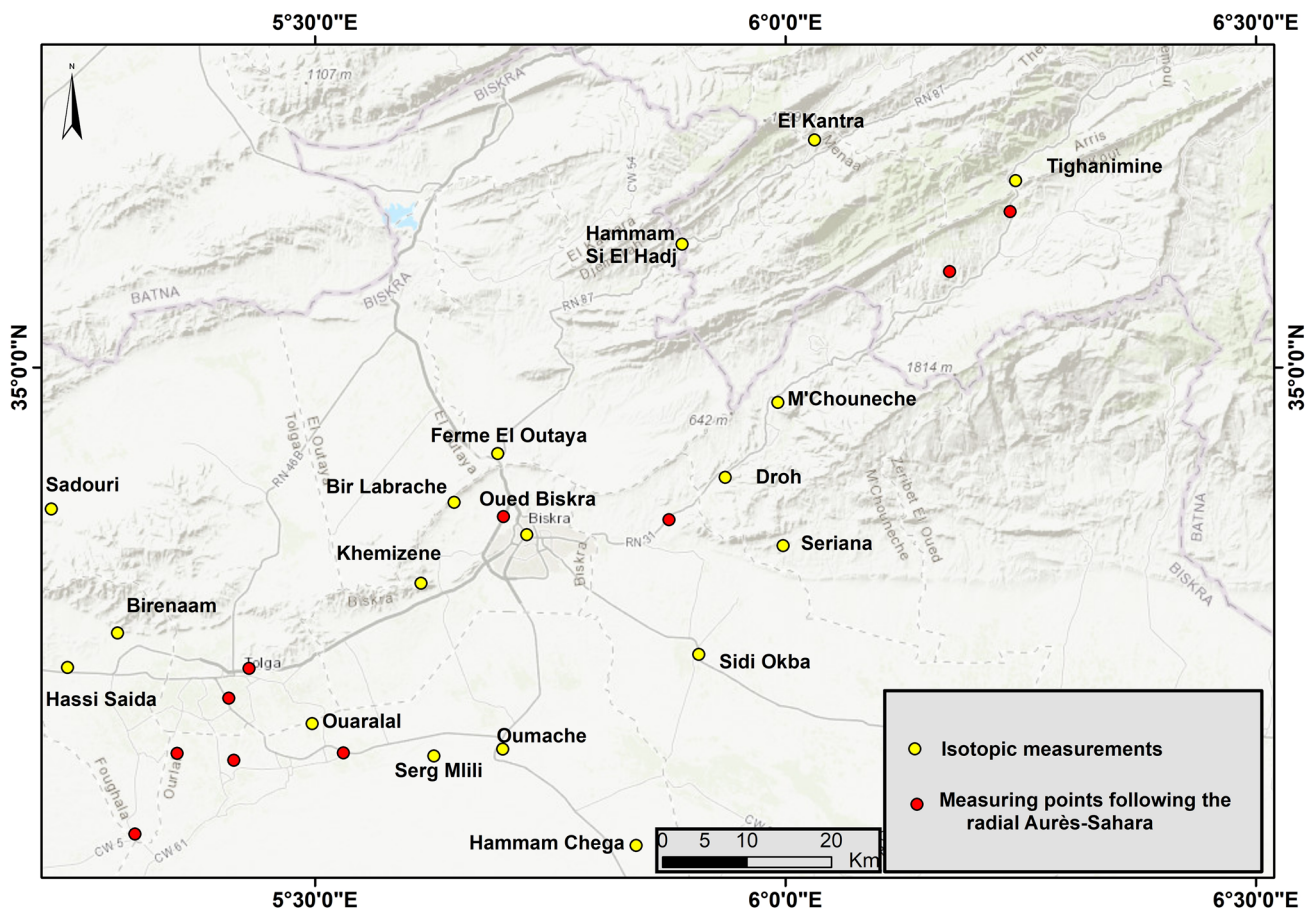
Fig. 6 Location of measurement points (in yellow, isotopic data and in orange, hydrochemical data following the Aurès-Saharan platform radial)

potential (pH), electrical conductivity (EC), and temperature (T°C) were measured immediately after field sampling using a HANNA Hi-9813–6 multi-parameter. Subsequently, the samples were transported to the laboratory (Faculté des sciences de la terre, Université frères Mentouri—Constantine 1), and analyzed for their major chemical constituents (Ca, Mg, Na, K, Cl, SO₄, HCO₃). The methods of analysis are those recommended by the American Public Health Association (Eaton et al. 2005). The concentrations of calcium (Ca) and magnesium (Mg) were measured by the volumetric method in the presence of an aqueous EDTA solution; this method was also used for titration of bicarbonates (HCO_3). The chlorides (Cl) are determined in the neutral medium by a titrated solution of silver nitrate in the presence of potassium chromate. Sulfate (SO4) was measured by a spectrophotometric method, sodium (Na) and potassium (K) were determined using flame photometer. Sr was measured by Graphite Furnace Atomic Absorption Spectrophotometer (Perkin-Elmer AAnalyst 700). The precision of the chemical analysis was confirmed by calculating ion balance errors, where the errors were generally 10%. In the context of Algerian-German Technical Cooperation (GTZ

2009), hydrogeological studies were carried out to determine the rate of renewal groundwater, between the southern Aurès and the piedmont of the Atlas Mountains, they include isotopic analyzes carried out in German laboratories.

The analysis of isotopic data (tritium, 18O and deuterium) (Table 1) presents different groups of groundwater, reflecting various origins: (i) recent water depleted in stable isotopic contents, recharged at altitude, (ii) deep old water free of evaporation (mixture with old waters of the CI), (iii) recent waters evaporated and located at the south piedmont.

Results and discussion

Hydrochemistry

Groundwater mineralization in arid and semi-arid areas influenced by lithology, residence and transit time, evaporation and low recharge. The regional scale of flows (long transit time) and mixing with waters of deep origin (CI) are partly responsible for the high mineralization. However, dominance of evaporates formations (including intercalary

Table 1 Concentrations of stable isotopes and tritium in the Aurès Zibans region (analysis carried out in December 2008)

N°	Site name	Hydrogeological unit	Altitude m	$\delta^{18}O$ ‰	δ^2H ‰	^3H TU
1	Tihmamine	Albien	1240	− 8.75	− 56.7	2.2 ± 0.6
2	Hammam Salhine	Albo- Barrémien	137	− 9.6	− 67.7	< 0.6
3	Hassi Saida	Eocène Inf	273	− 7.93	− 50.1	0.9 ± 0.6
4	Bir Naam	Sénono- Eocène	281	− 7.88	− 50.9	< 0.6
5	Hammam Chegga	Sénono- Eocène	6	− 8.24	− 55.2	< 0.6
6	Khemizene	Sénono- Eocène	181	− 7.32	− 48.3	< 0.6
7	Ourelal	Sénono- Eocène	89	− 8.39	− 57.9	< 0.6
8	Bir Labrache	Eocène Inf	181	− 7.43	− 49.3	< 0.6
9	M'Chouneche	Maestrichtien	369	− 7.86	− 51.2	< 0.6
10	Droh	Maestrichtien	203	− 7.58	− 50.5	< 0.6
11	Sériana	Mio-Plio-Q	115	− 4.4	− 30.9	3.6 ± 0.7
12	Chicha	Mio-Plio-Q	218	− 7.7	− 52	7.2 ± 1.1
13	Sidi Okba	Mio-Pliocène	40	− 8.34	− 58	< 0.6
14	ferme Amor	Mio-Pliocène	204	− 7.37	− 49.1	< 0.6
15	Serg M'lili	Mio-Pliocène	66	− 5.84	− 40.6	< 0.6
16	O. Biskra 2	Quarenaire	135	− 7.7	− 51.3	< 0.6
17	Sadouri	Turonien	456	− 8.34	− 57.9	< 0.6
18	ITDAS	Turonien	133	− 7.95	− 48.5	< 0.6
19	El Kantara	Turonien	631	− 9.05	− 58.6	1 ± 0.5
20	Hammam S. Hadj	Turonien/ CI	407	− 9.07	− 61.7	< 0.6

TU tritium unit (1 TU = 1 ^3H atoms per 10^{18} H atoms = 1.100 10^{-19} mol/$g_{pure\ water}$)

layers and salt domes) traversed by lateral flows, which is responsible for the generalization of the sulphated facies at the expense of the initial bicarbonate facies inherited in the Aurès massif. In this region, hydrochemical data are very rare and total mineralization or total dissolved solids generally define water quality. The latter is between 1.1 and 2.5 mg/L. The highest values are observed in the East and South-East sector, with a second evolution from the North to the South. The lowest values (1.1 mg/L) are observed in the El Amri sector. The Foughala, Tolga, Lichana axis has a total dissolved solids value 2 mg/l. The highest values are found in the Southeast and are greater than 2 mg/l (2.5 mg/l at Ourelal).

The groundwater temperature varies between 21 and 25 °C; these relatively hot waters, characteristic of moderately deep waters (between 200 and 500 m) are in conformity with the geothermal gradient. These anomalies are usually manifested by the resurgence of thermal springs of very deep origin, such as the thermal springs in the Biskra region (Hammam Essalhine and Ain Taba), which can reach temperatures of 45 °C. These thermal waters of deep origin (CI) and generally very mineralized, rise to the surface through faults and mix with the waters of the Senono-Eocene aquifer. Similar cases observed further south in Ouled Djellal and Doucen where lower Senonian waters have given temperatures between 30 and 31 °C (Bouchiba 1992). All samples characterized by pH ranged from 6.7 to 8, generally greater than 7.

Table 2 Statistical summary of the physical and chemical parameters of groundwater samples in the study area

Variable	Min	Max	Mean	SD	Cv
K	6.6	12	8.3	1.88	48.0
Mg	29	245.0	118.31	49.59	73.0
Ca	162	618.0	366.57	95.81	59.0
Na	105.0	687.0	184.84	125.79	82.0
Cl	113.0	408.0	187.05	81.50	72.0
SO4	576.0	2830.0	1306.421	438.12	69.0
HCO3	16.0	410.0	224.947	133.25	96.0
Sr	4.2	13.5	6.9	2.37	49.0
T°	21.0	25	24.316	0.92	16.0
pH	6.7	8	7.6	0.34	16.0

Min minimum, *Max* maximum, *SD* standard deviation, *Cv* coefficient of variation

All values are in mg/l except pH and EC (µ.Siemens/cm)

The statistical investigation of the spatial distribution of chemical elements (90 samples were taken between September and November 2004, 55 between April and May 2005) (Table 2). For all values only the pH, the temperature and the potassium have values of less than 50%, which indicates a heterogeneity of the origin of the chemical elements and a significant spatial development of chemistry. Calcium with 59% has a relatively homogeneous origin with an average of 366.5 mg/L. Ca $^{2+}$ originate mainly

from rocks that are rich in carbonates such as limestone, which corresponds to a facies of calcium bicarbonate (Shan et al 2020). These values are found in Tolga and the El Outaya regions. The magnesium content averages 118.31 mg/L. The main source of Mg^{2+} was the exchange of mineral ions in rocks (dolomite limestone) (Abdennour et al 2020). Chlorides and sodium follow the same trend from north to south with a high value with an average value of 184.84 mg/L, which corresponds to a evaporate facies. Sulphates follow roughly the same development as the hydraulic gradient, the high frequencies observed downstream of the aquifer system with high values of 1306.42 mg/l (Abdennour et al 2020), elevated values associated with the washout of gypsum by water. On the other hand, bicarbonates show a multimodal frequency change, their spatial distribution is quite heterogeneous.

Chemical facies

The mineralized waters of the region found in the limestone formation in relation to the fractured and karstic system. The presence of the strong mineralization explained by the leaching of the saline formations (halite) of the Djebel El Mellah massif located near El Outaya. It also comes from the exchange with the rock constituted of evaporite layers intercalated between the carbonate layers. The origin of calcium and magnesium is thus mixed: from limestones and gypsum formations. The values relatively high of magnesium (a maximum of 245 mg/L) indicate a very long residence time of the water in contact with the rock (Walter et al. 2017; Chabour 2006; Laidlaw et Smart 1980). Sulphates generally related to the presence of gypsum (Shan et al. 2020). Sodium indicating triassic formations (Belhai et al. 2016) with chlorides attributed to meteoric waters are present
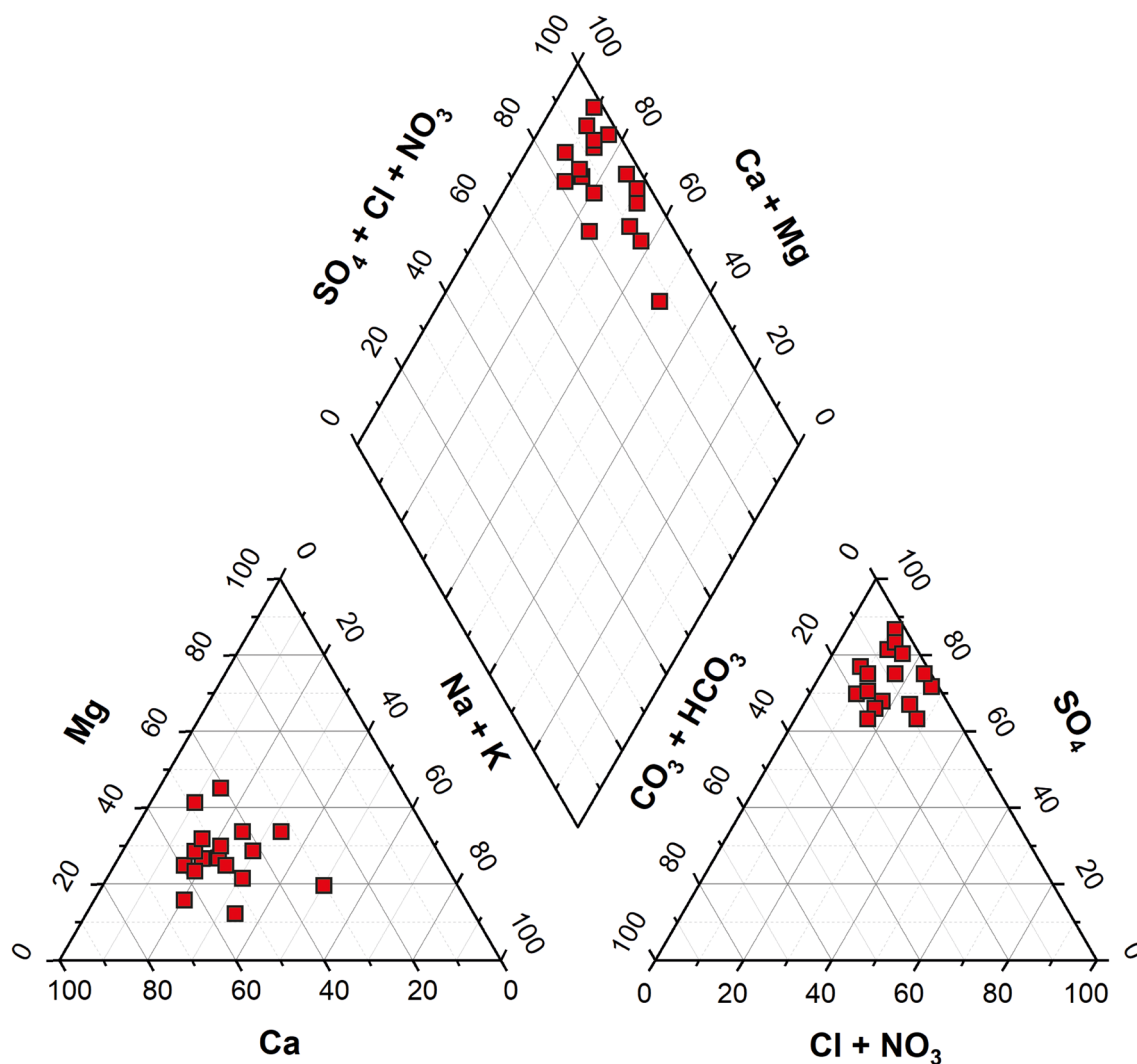

Fig. 7 Piper diagram

in large quantities (maximum 408 mg/L) as a result of the leaching of saline formations (halite) (Benmoussa et al. 2020). The hydro-chemical facies deduced from the piper diagram (Fig. 7) are grouped in the sulphate and chloride and sulphated- calcium and magnesium poles. The 70% of the samples have a sulphated calcic facies and 30% a sulphated sodium facies.

The approach involves analyzing the evolution of chemical elements from the recharge areas located in the Aurès massif (carbonate, karstic and fractured formations) which is the main reservoir for the supply of aquifers located further south. We selected the results of 12 samples made at the same time (May 2005) and concerning the same chemical elements (Fig. 7). As it travels through the different provinces, groundwater acquires its chemical composition and undergoes modifications. Monitoring is carried out on four elements: Cl, SO4, Ca and HCO3. Chlorides are the most conservative elements of aquifer systems, the enrichment in this element is acquired during the initial phase from the meteoric waters or by leaching of the salts (halite), following the transit through the salt deposits located in El Outaya. In the Aurès, samples show fairly high levels (> 350 mg/L) inherited in these regions. After enrichment in the El Outaya region (Fig. 8), contents decreased in areas south of the Atlasic Fault. The evolution of the Cl ion, therefore, evidence of a mixture of the initially charged waters and the less loaded waters from the southwest region.

Most of the elements show an evolution with interruptions, observed in the part of the Saharan foothills, indicating a local heterogeneity, which can only be explained by punctual contributions. This reflects the complexity of the flow system and the difficulty in interpreting changes in the chemical composition of water along the flow axes. The absence of significant evaporate formations in the West and North-West zones means that the resulting water supplying the Zibans is less mineralized. The mixed zone is located in the Tolga region; the water flows to the main outlets, which are the areas of the Chotts. On the other hand, the anomalies occurring in the same zone can only be explained by strong drainage (vertical currents) through defects. The Ca and SO4 ions evolve in the same direction. Their grades are relatively low in the Aurès region and then increase in the El Outaya plain. This increase continues in the Saharan platform, notably in the areas of Tolga (near the foothills) and Doucen. There is, however, at the same time a decrease in grades in some contents in some samples located in the central corridor between Tolga and Doucen. The increase in Ca and SO_4 concentrations indicates a continuity in the dissolution of gypsum. Their decrease reflects a mixture of water of different origins. The HCO_3 show a decrease in concentrations from the Aurès to the Saharan Platform, the decrease is very significant for some points.
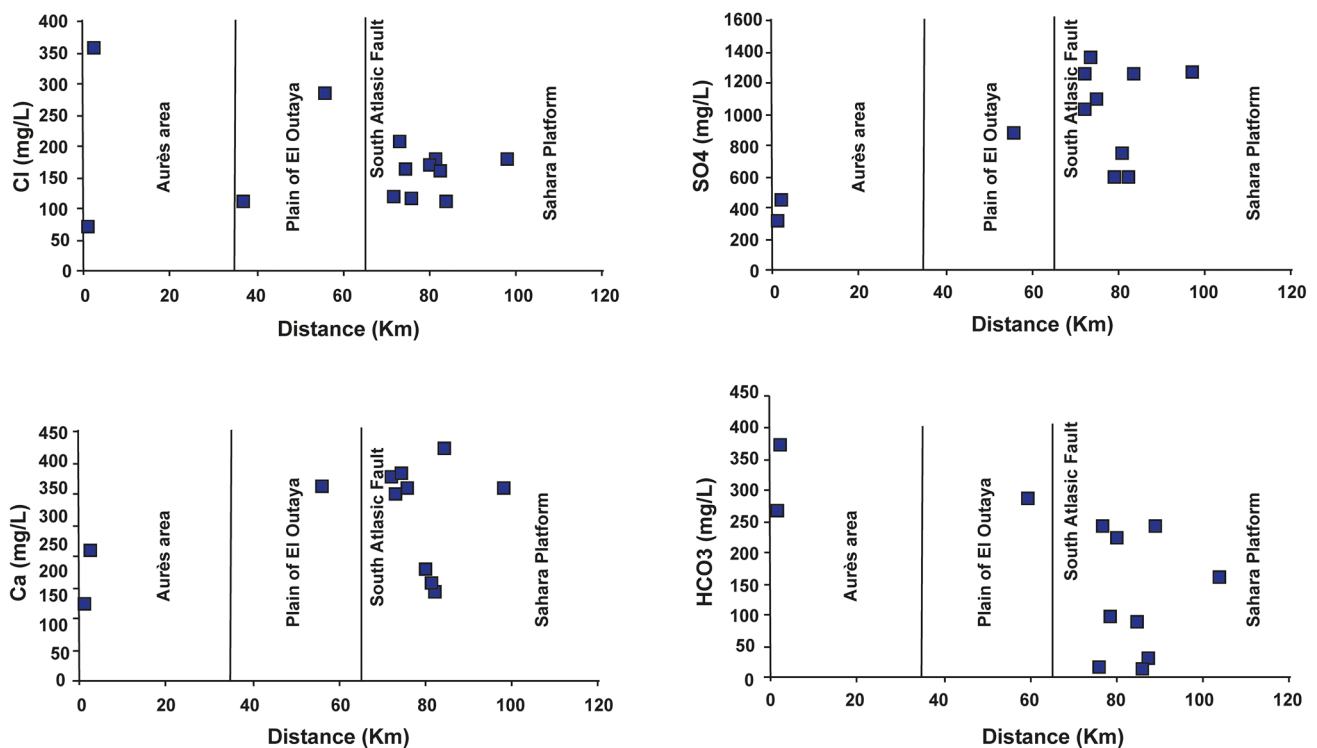

Fig. 8 Evolution of the contents of Cl, SO4, Ca and HCO3 from the Aurès to the level of the Oued Djedi (Saharan platform)

Isotopic geochemistry

The waters of the CI (formerly inherited during recharges occurring in colder conditions), such as very recent ones, will impose their fingerprints. The results of the isotopic studies present, several interpretations and distorted by the effects of climate changes. Generally, the isotopic signatures depleted of deep groundwater (CI) in these arid and semi-arid areas with high evaporation correspond to episodes of aquifer recharge occurring under colder and wetter climatic conditions than those prevailing currently (Conrad and Fontes 1970). These waters of the CI show a spatial homogenization of the isotopic composition of the waters (Guendouz et al. 2003). It is, therefore, necessary to distinguish these old waters from those infiltrated in altitudes (altitude of the Aurès mountains above 2000 m.), in a highly fractured karstic system (even depleted). The aquifers of the Zibans will, therefore, inherit from three large groups: the Aurès, the Eastern Saharan Atlas (lateral contribution) and the CI (leakage process). Knowledge of the isotopic geochemical characteristics of these provinces contributes effectively to understanding the chemical evolution of the waters of the Zibans. In the Eastern Erg zone, the CI aquifer is characterized by ^{18}O contents ranging from -7.43 to -8.84 ‰ (Guendouz 1985), with spatial quasi-homogenization, indicating an old recharge and a prolonged residence time (Gonfiantini et al. 1974). All waters of the CI basin at the eastern basin scale were found to be virtually devoid of tritium (Moula and Guendouz 2003). These waters would be linked to the major wet phase recharge of the lower Pleistocene. In the Biskra region, the waters are relatively old, the corrected ages determined from Carbon 14 for Oriental Erg vary between 20,000 and 40,000 years (OSS 2003). This lack of differentiation in the stable isotope contents in the CI waters makes it difficult to calibrate with the supposed recharging zones and the direction of aquifer's flow. The artesian character of the waters of the CI is the basis of large mixtures with shallower waters. The value -7.43 ‰ of ^{18}O content is found at Ouled Djellal which is located in the most northern sector of the Lower Sahara and is part of the most southern Ziban zone; it shows the relatively more enriched nature of the waters. The deuterium content varies between -52.9 and -64.1‰ (Guendouz 1985), and the extreme value of -52.9‰ concerns, once again, the Ouled Djellal region. The stable isotopic contents of the Terminal Complex (Atlas Saharian and Aurès region), including the Ziban aquifer, show great dispersal (Guendouz 1985; Ould Baba Sy 2005). They vary between -3 ‰ and -8.9 ‰ for oxygen 18 and between -34 ‰ and -64 ‰ for deuterium.

The isotopic composition of the Ziban limestone aquifer shows fairly dispersed heavy isotope contents with average of -7 ‰ + or -0.47 ‰ ^{18}O and -49 ‰ + or -3.57 ‰ in deuterium, which means an excess in average deuterium of $+10$. Their excess in deuterium indicates that the waters have practically not undergone evaporation, which assumes a rather rapid infiltration of precipitations in the limestone outcrop in the Saharan Atlas.

The mio-pliocene waters of the Northern Chotts zone have average contents of ^{18}O and deuterium levels of -5.3 and -49 ‰, respectively (Guendouz et al. 2003). The waters are located below the current meteoric water line, evaporating before reaching the water table (Guendouz 1985).

The studies of Bellion (1973), on the waters of the springs located in the western part of the Belezma, are focused on oxygen 18 and tritium. Due to the carbonate nature of the formations (karstic system), the precipitation is rapidly infiltrated and therefore does not evaporate. Thus, the average isotopic composition of spring water can be assimilated to that of precipitation infiltrated at different altitudes. The results (Bellion 1973) allowed the establishment of an altimetric gradient for ^{18}O. The general average of -9 ‰ of the ^{18}O contents, varying between -8 ‰ and -10 ‰ represent the average isotopic composition of precipitation falling between 1400 and 1800 m (Bellion 1973). Springs alimentation comes from the eastern part of the Aurès massif, which is also the recharge area of the springs located in the south and southwest of the Aurès, so it is this water that feeds the Ziban's aquifers.

The results obtained in the South of Barika by Gonfiantini and Dinçer (1975) gave for deep aquifers contents of ^{18}O varying between -7.68 and -9.15 ‰ and deuterium contents varying between -51.5 and -60.1 ‰. These waters are similar to those of the CT, thus denoting the same origin. The radiocarbon age of the TC in the Biskra region is 20,000 years more or less 1000 (Guendouz 1985).

The difficulty that can be encountered in differentiating the different families of groundwater aquifers is that water for irrigation and water discharged into the groundwater after use, comes from different horizons: the waters of the CI, the CT and shallow aquifer. After irrigation and discharge, these waters are all found in the superficial aquifer which in some regions has led to the rise of water and asphyxia of all agricultural systems (Messekher and Chabour 2012). The conjunctive use of nitrate element and isotopic tracers is a good indicator of recharge areas. The origin of nitrates in this sector related to irrigation and sometimes to domestic discharges. Areas with agricultural vocation are located in the plains as well as in the bottom of the canyons. Indeed, the waters located in the Aurès massifs have very low levels of nitrate (no more than 1.8 mg/l of nitrate) (Hamel 2009). In the Ghassira valley, the average nitrate content is 5.25 mg/l (Brinis et al 2015).

The points shown in diagram ^{18}O—deuterium (Fig. 9) appear to align on the right with the global meteoric water line (GMWL), except for two points indicating high
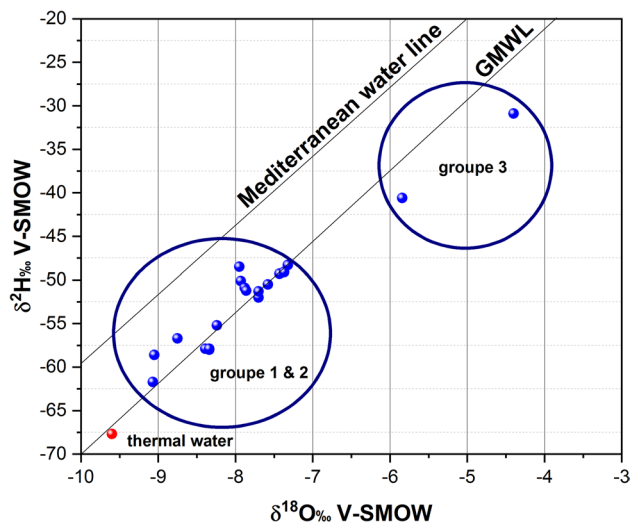
Fig. 9 Relationship of ^{18}O and ^2H related to the global meteoric water line and Mediterranean water line

evaporation. Waters whose tritium levels are less than 0.6 UT correspond to old waters. In-group 1, we find the water point located at Tihmamine whose altitude is 1240 m., this is in accordance with the altimetric gradient of ^{18}O established by Bellion (1973) in the Bellezma Mountains. This water is depleted and relatively recent (− 8.75 ‰ for O18 and − 56.7 ‰ for deuterium); this is the consequence of the rapid infiltration across the fissural network of the karstic formations of the Aurès. The other point showing a meteoric water and not having undergone strong evaporation, concerns the Chicha region, which, however, is found in the mio-pliocene–quaternary formations and at an altitude of 218 m. For the region of Sériana (115 m altitude.), the waters are relatively recent but are much enriched (− 4.4 ‰ for O18 and 30.9 ‰ for deuterium). The other highly enriched water is in the region of Serge M'Lili, unlike Seriana waters, these are relatively old (tritium less than 0.6 TU). The rest of the water points at different altitudes and belonging to the Turonian and Senono-Eocene formations present relatively old waters (tritium content less than 0.6 TU) and depleted in ^{18}O and deuterium. These are waters mixed with water of deep origin infiltrated during the old periods in cold climate; here, we see the signal of the waters of the CI. Sometimes, CI water flows through the faults without mixing or evaporation and rising as thermal springs (temperature are consistent with that of the CI in this region). The spring of Hammame Salhine with grades of − 9.6 ‰ for O18 and − 67.7 ‰ for deuterium (located at an altitude of 137 m.) is an example.

Schematic flowpath and recharge

Estimates of water balance (recharge, drainage, renewal rate) are essential for water management and understanding of

water transfers between aquifer systems. However, in heterogeneous environment, compartmentalized (aquifers with distinct hydrodynamic characteristics) with complex structures. Recharge of aquifers is generally achieved by direct penetration of precipitation (water seepage) into outcrop areas, from surface water, lateral and vertical exchanges between aquifers. Water seepage is the part of precipitation that escapes evaporation and runoff (Margat 1972). For arid zones (which is the case of a large part of the southern of the study area), the effective infiltration is useless because of the importance of evaporation, which can retake all the water precipitated (monthly potential evapotranspiration being higher than total precipitation). However, the irregularity of precipitation, during large floods (rare high rainfall events) that the largest recharges are made, starting from precipitation and runoff. The Hodna and Aurès mountains ensuring the junction with the Saharan platform (Fig. 5), and play the role of water towers, they feed the Neogene aquifers, which often form their foothills. However, before reaching by relay the aquifers of the South, a part of the recharge waters made at altitude, re-emerges through springs in the mountainsides.

The estimation of the water balance requires in addition to the quantification of the recharge and the outlet. The main drainage areas are the evaporation zones (the Chott Melghir forms the main final outlet), springs and pumping wells.

All this allow us to adopt the regional flows theory preconized by Toth (1999) taking into account the recharge, transit and discharge subsystem as a whole. Due to the rapid changes in climatic conditions, geomorphology and lithology of soil between different basins, it is necessary to properly evaluate the results, to treat the study in its regional context (Flint 2007).

However, it is in the western part between Biskra and Tolga that the carbonate aquifer formations of the Senono-Eocene are the most important, which makes this region the intermediate main outlet of the groundwater. According to Guiraud (1990), natural and artificial outlets in the Ziban region (especially the Tolga region) have to drain water from the eastern end of the Saharan Atlas, Hodna and El Outaya. As a result, the springs appearing in the Saharan plain at the last mountain foothill, in favor of deep faults (sources of M'lili, Oumache and the thermal springs) represent points of drainage of regional flows, whose origin must be distant and deep. Faults are known to influence the direction of groundwater flow and to contribute to the appearance of cold or hot springs (Rojstaczer et al. 1995; Curewitz and Karson 1997; Melchiorre and Criss 1999), several sulphated hot springs are related to deep tectonics. The anticlinical structures reveal very old formations and thus break the isolation of these deep reservoirs giving rise to thermal springs. In the Saharan Atlas and at the edge of the Saharan Platform, springs giving highly mineralized and very warm waters up to 90° C are concentrated along the

fractures and probably originate from very deep sediments in relation to the anticlinal structures (the Djebel Azreg). The thermal springs in the Biskra region as well as the most important springs, including those of M'lili and Oumache (230 and 160 l/s, respectively, measured in 1975), are generally located on the fault line. The waters rising parallel to the alignment of these southern faults manage to regain the surface when they encounter hydrogeological barriers. These sources supply the groundwater of the neogene formations and are at the origin of the Debdeb formations on the surface (calcaro-gypsum crust). A certain amount of moisture is maintained at the level of diffuse springs that cannot emerge on the surface.

The study carried out by the BCEOM-BG-SOGREAH Group (1983) on behalf with ANRH (Study on the Update and Finalization of the National Water Plan for the Central and Eastern Hydrographic Regions) gave values for the rate of renewal for different hydrogeological units by evaluating the seepage coefficient by type of outcrop. An annual renewal volume was summarized to each hydrogeological unit for the total area with an average value (dry and wet year value) (Table 3). The southern part (the foot of the hill where the Tolga aquifer is located) was not taken into consideration due to its location under Neogene's cover with an average thickness of 200 m. This study shows that the Aurès massif receives more than 138 mm^3/year for the wet years for an area of 2762.67 km^2. While the El Outaya plain, which is part of the Ziban aquifer playing the role of transition zone towards the limestone aquifer of Tolga, receives only 4.55 mm^3/year for an area of 1302.86 km^2 (the calculation of the volume provided by the floodwaters of the wadis not taken on).

A previous study by Haouchine et al. (2010), describing the recharge rate, allowed the classification of the El Outaya plain in five levels, revealing a zoning of values ranging from 0.02 to 16.25% of precipitation, allowing an overall recharge of 30 mm/year. Numerical models have been adopted to assess the flux of groundwater recharge of the Tolga aquifer from the north and northwest (Chabour 2006; Larbes 2005). This aquifer is supposed to be captive and does not receive any recharge from meteoric waters. It emerges that the flow system is dominated at the inlet

Table 3 Renewal rate of different hydrogeological units

Site name	Area (Km^2)	Renewable resources (mm^3/year)		
		Value for the average year	Value for the wet year	Value for dry year
El Outaya plain	1302.86	2.83	4.55	1.41
Aurès massif	2762.67	70.65	138.27	12.93
Chott Hodna	7126.80	137.06	165.54	33.83

by the lateral recharge and at the outlet by the extraction by drill holes. The water balance (Chabour 2006) shows a total lateral recharge of 4.91 m^3/s (3.1 m^3/s is from the West and South-West zone, 1.22 m^3/s from the North). The outlets are represented by wells exploitation volume with 2.32 m^3/s, a downstream flow and a seepage loss estimated at 2 m^3/s.

Conclusion

The regional hydrogeology of the Zibans is very complex and summarily documented. In addition, there are no precise data on the rate of extraction of groundwater for domestic / or irrigation purposes. Data show that the geology, topography and climate that manage the recharge areas distribution, flow directions, and drainage areas in the south. The study at the regional level of recharge and flow has highlighted the extent of the travel distance and the mixing of groundwater between the different areas. First, it shows that the distribution of recharge and groundwater flow on a regional scale is strongly influenced by topography. An important aquifer recharge occurs further north in altitude (Aurès) and are subsequently transferred in relay to other systems located further south (Zibans). However, due to the importance of tectonics (compartmentalization of hydrosystems), lithostratigraphic variations and discharge from deep groundwater aquifers), knowledge of recharge areas and regional evolution of water quality remains very limited. The conceptual flow model of groundwater, as defined, was validated by the hydrochemical study, the latter shows that regional flows (long time transit and the mixing with the waters of deep aquifer of Continental Intercalaire) are in part, and the cause of the high mineralization. However, it is also the predominance of evaporite formations (including intermediate layers) traversed by lateral flows (much greater than the vertical flux of the recharge) which is responsible for the widespread of the sulfated facies at the expense of the initial inherited bicarbonate facies in the Aurès massif. The Ziban region has high values, particularly with Na and Cl, with maximum values of 687 and 408 mg/l, respectively. The high values of Ca and SO$_4$ (618 and 2830 mg/l, respectively) also reflect the influence of evaporites. Isotopic chemistry, although presenting multiple interpretations (climate change, drainage and mixtures of water from the CI), distinguishes the contemporary waters infiltrated in the karstic massifs in altitudes of those evaporated and enriched of the neogeneous formations of the piedmont. In the study area, recharge, springs flow rate (including exploitation) and groundwater, despite its importance, remain poorly understood. The results of this study will allow a better elaboration of the hydrodynamic and hydrochemical models.

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