GEOCHEMICAL AND ISOTOPIC CHARACTERIZATION OF HIGH-MG GROUNDWATERS IN AN ENDORHEIC BASIN, AIN OUSSERA, ALGERIA

Naïma Mebrouk[1]	[1]University of Oran es Sénia, FSTGAT, Earth Science Department, Water and Environment Laboratory, Oran, Algeria
Bernard Blavoux[2]	[2]Université d'Avignon et des Pays du Vaucluse,
Abderrahmane Issaadi[3]	Laboratoire d'Hydrogéologie, Avignon, France
Vincent Marc[2]	[3]Université des Sciences et Technologies Houari Boumediene, Dpt. Sciences de la Terre, Alger, Algeria

In the Ain Oussera plain of Algeria, most boreholes and wells discharge undifferentiated groundwaters from the complex Quaternary-Albian aquifers. Existing piezometric and hydrochemical maps do not show a clear difference between aquifer sources. This study uses temperatures and redox potential measurements to identify water from the different aquifers The analysis of temperatures allows the identification of thermal anomalies existing between various source levels within the aquifers. Redox potential measurements confirm the presence of two zones defined as shallow, cold, and oxidizing waters and deep, warmer, and reducing waters. Between these two extremes there are zones of mixing between the systems. Salinity, expressed as electrical conductivity, varies from 590 to 4260 µs/cm, and waters are dominated by magnesium ion. The hydrochemical zonation in the aquifers has been verified by isotopic measurements of tritium and oxygen l8. Adjusted carbon 14 ages were also calculated using different models.

INTRODUCTION

A clear understanding of a hydrogeological system usually requires more than the study of its lithological characteristics and hydrodynamic parameters. Additional information supplied by physico-chemical parameters and isotopic data is useful to deal with questions regarding any complex situation. In this paper a hydrogeological investigation was carried out using joint measurements of temperature, redox potential, and the environmental isotopes tritium, oxygen 18 and carbon 14.

STUDY SITE CHARACTERIZATION

Setting

The plain of Ain Oussera is part of the Central Algeria High Plains (Figure 1). It is located between 2°11' and 3°45' longitude, and 35°00' and 35°40' latitude. The altitudes increase southwards, ranging between 700 and 800 m. It is a closed, or endorheic basin with internal drainage

There is a more dense network of streams in the west than in the east where rare perennial streams are observed. Ain Oussera is part of the Chelif watershed, one of the most important hydrologic systems in Algeria. The climate is semiarid to arid with a mean annual rainfall of 201 mm.

Geology

The main geological formations (Caratini, 1970) are known from outcrops or borehole investigations (Figure 2). They comprise:

The Triassic, which consists of two series: a detrital layer, formed by fine-grained sandstones, limestones and conglomerates, and a clay stone layer, formed by a mixture of anhydrite, black argillites, dolomites and limestones. The Jurassic consists of calcareous and marly-calcareous formations of the Liassic; limestones with filaments of the Dogger, gritty detrital formations of the Callovo-Oxfordian; and marly-clayey formations of the Oxfordian-Valanginian.

The Cretaceous is mainly composed of fine clayey sandstones, sandy limestones and coarse sandstone, sandy limestones, oolitic limestones and gritty formations, gritty sediments; limestone intercalations with dolomitic and marly limestones, and marls and gypsiferous clays.

The Plio-Quaternary covers the major part of the plain, and is represented by holocene deposits, recent alluviums of the oueds and calcareous crust.

From a structural point of view, the region of Ain Oussera is a vast anticline with a cretaceous axial part mainly oriented ENE-WSW (Figure 2).

MATERIAL AND METHODS

Groundwater samples were collected from more than 60 wells and boreholes. Complete information (depth, static level, pumping rate, aquifer thickness) is available for boreholes dug by ANRH (National Agency for Water Resources, Algiers) but little information exists for shallower wells dug by private individuals and farmers.

Water samples were collected in clean 1 liter polyethylene plastic bottles and stored in a cooler. From each well or borehole, three water samples were collected, one was acidified with nitric acid for anion analysis. The two others samples were used for cations, oxygen 18 and tritium.
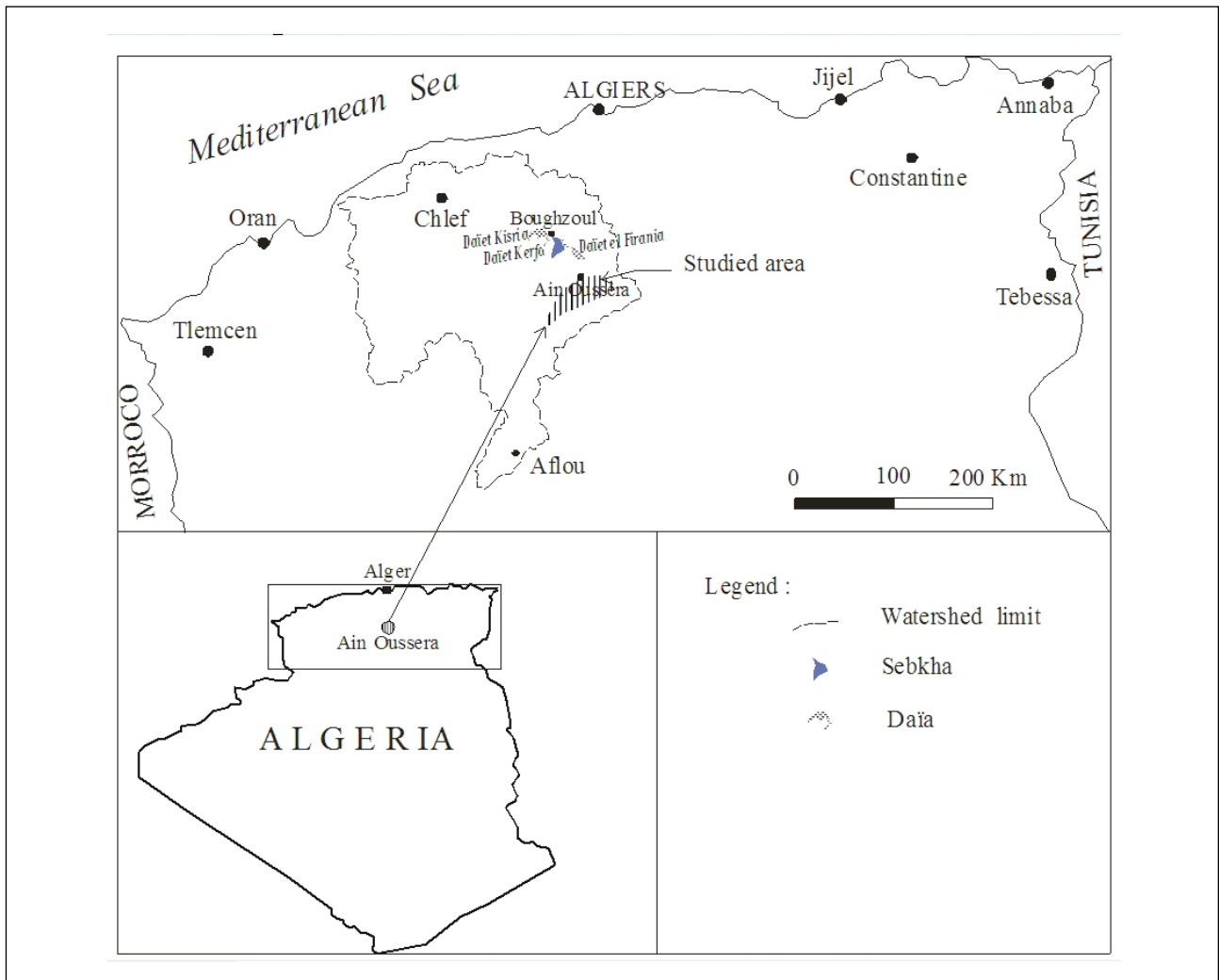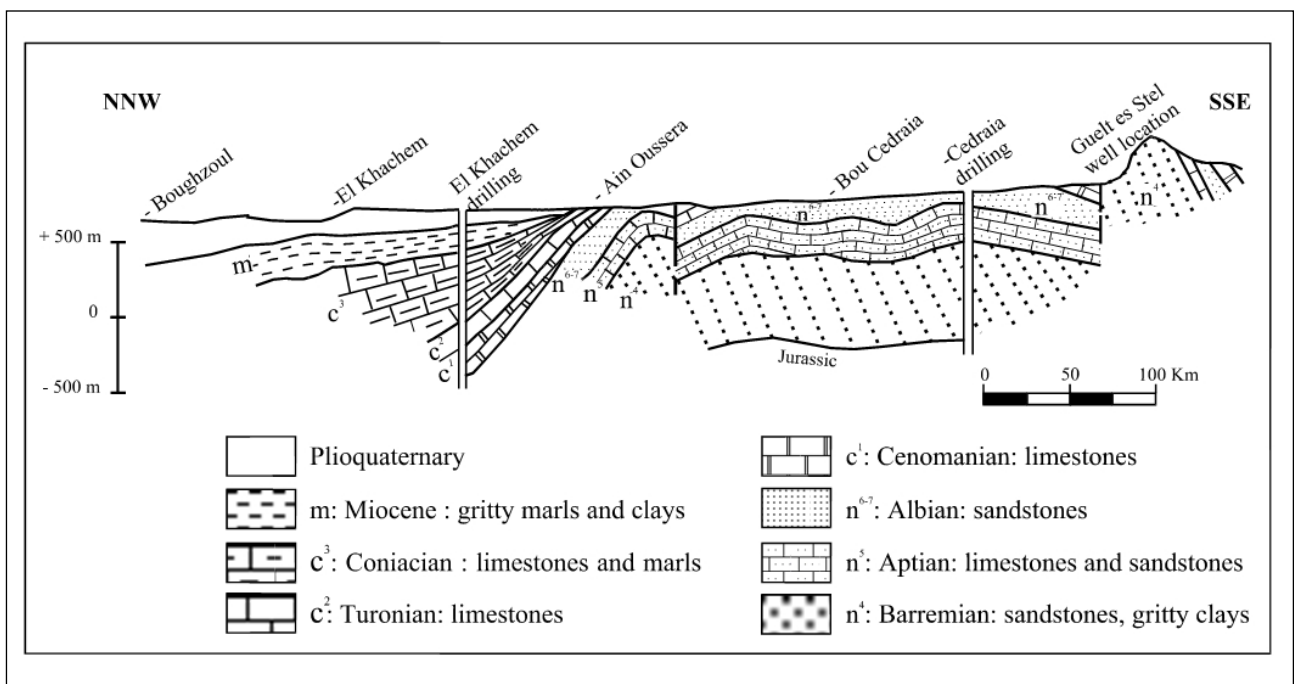
Figure 1. Map location.

Figure 2. Synthetic geological cross section of the Ain Oussera region (Bechtel, 1977, modified)

Temperature, pH, electrical conductance, Eh and alkalinity were measured in the field in December 1991.

In the laboratory, analysis of the cations Ca, Mg, Na, K was carried out using a Perkin Elmer UV Atomic Adsorption Spectrophotometer (Lambda 10). Standard titration methods were used for the estimation of Cl, SO_4, HCO_3, CO_3, and NO_3.

A hydrochemical study of the aquifer enabled us to map the major ion spatial distribution in order to get the chemical evolution of waters.

Table 1 represents major element chemistry, expressed in mg/l and field measurements of physical parameters. Using the electro-neutrality principle, samples with ionic balance more than ±6% were not taken into account in our study.

In November 1990, 12 samples were first collected by CDTN (Development Center of Nuclear Techniques, Algiers) from deep boreholes for isotopic analysis. In December 1991, a more complete field sampling campaign was carried out.

Samples for stable isotope analysis were analyzed by mass spectrometry. For radiocarbon analysis, dissolved inorganic carbon was precipitated in the field, from at least 60 L of water by the addition of $BaCl_2$ for 11 samples. Radiocarbon contents were measured by conventional counting techniques. Tritium was determined by liquid scintillation counting after electrolytic enrichment at the CDTN laboratory.

Hydrogeology

From previous geological and geophysical studies, the region has been categorized into 4 hydrogeologic entities (Ayad, 1983). These are:

a) A shallow aquifer in the Plio-Quaternary deposits, mainly formed by conglomerates and pudding stones which are very common in the plain. A large number of wells take water from these formations. The water has a relatively low salt content with a dry residue averaging 1.5 g/l. The quaternary aquifer rests on the Albian, particularly where the plain extends in the central part of the anticline.

b) Turonian deposits are known in the regions of Ain Oussera, Taguine, and the north spurs of the Saharan Atlas, and also form the synclinal structure of the Algerian Chotts. The wedging rocks are frequently cavernous fissured limestones, with an obvious thickness of 60-70m. This aquifer is rarely used because of its depth, its low productivity and the salinity exceeding 3g/l. The Turonian is confined under the Miocene marls and the Coniacian calcareous and marly formations, particularly to the north of the plain. It constitutes the northern side of the great anticline forming the area structure.

c) The Albian sandstones comprise the greatest aquifer in the region. It outcrops in several areas, mainly in the center of the plain where the water table is unconfined. Elsewhere, the aquifer may be confined or semi-confined. The solute content is generally low with a dry residue lower than 1 g/l. The Albian substratum consists of limestones and sandstones, with marly levels of the Aptian.

d) The Barremian formation consists in sandstones and gritty clays. It is considered a major reservoir owing to its large thickness and good permeability. Nevertheless, the water quality is poor with its total dissolved solids of 4 g/l.

A piezometric field campaign was carried out in December, 1991 (Mebrouk, 1994) using all the available wells indicated in Figure 3. However, many boreholes take water indistinctly from the

Table 1. Major elements chemistry, in mg/l and physical parameters (December, 1991).

Sample code	Ca	Mg	Na	K	Cl	SO$_4$	HCO$_3$	CO$_3$	NO$_3$	T°C	pH	Eh (mv)	EC µs/cm	E.N. %
P12	16	83	89	4.8	166	196	174	0	54	19.6	8.07	-61.5	1240	-4%
60-221	20	43	45	2.4	54	82	180	0	8	17.5	8.06	-60.6	708	2%
59-221	20	58	38	2.4	136	69	134	0	10	18.9	8.04	-60.1	909	1%
P10	32	79	56	4.8	225	115	128	0	2	19.5	7.94	-52.3	1272	-1%
52-221	16	84	51	2	127	121	183	6	17	18.8	7.95	-54.6	1033	2%
34-221	28	95	57	2.9	228	78	201	6	17	17.3	8.00	-57.2	1116	0%
35-221	28	122	71	4.3	339	103	146	0	8	17.6	7.95	-54.5	1390	1%
58-221	48	123	104	3.8	340	207	137	0	9.4	18.5	7.90	-52.0	1955	3%
22-221	140	98	132	3.4	455	170	122	0	20	17.5	7.93	-53.3	1990	6%
18-221	32	59	46	1.5	95	108	148	0	43	16.9	8.80	-60.5	873	3%
10-221	196	97	67	3.4	208	506	107	0	51	14.7	8.01	-53.3	1940	4%
16-221	392	152	238	20.8	786	711	296	0	85	16.4	8.27	-71.5	4260	0%
127-221	176	87	118	3.4	270	350	192	0	67	17.5	7.96	-54.5	1926	5%
123-221	40	85	36	2.4	154	68	168	0	109	18.6	8.00	-56.5	1103	2%
124-221	164	72	54	2	280	93	146	0	316	17.8	7.71	-42.0	1698	-2%
25-221	24	94	91	7.6	198	268	140	0	6	16.5	7.98	-56.5	1429	-2%
P4	8	49	71	7.6	125	60	156	0	34	18.9	9.23	-122.9	732	-1%
104-192	12	82	30	2	141	91	128	0	21	18.1	8.13	-64.8	936	2%
106-192	12	58	45	0.1	130	60	153	0	16	18.3	8.18	-67.1	819	-2%
P6	20	70	72	3.8	143	141	186	0	20	17.4	8.26	-70.1	925	-2%
36--221	16	72	41	1.5	97	89	186	0	30	18.8	7.88	-51.2	875	3%
116-192	16	51	58	1.5	104	82	171	0	3	18.7	7.99	-56.7	797	0%
P15	92	126	235	10.4	634	394	98	0	7	19.1	7.85	-49.0	2710	-4%
B1	20	36	51	2.9	50	63	168	3	1	19.7	8.30	-73.1	640	6%
B3	32	24	45	0	44	67	140	0	3	18.2	8.06	-60.6	590	5%
86-192	268	160	414	18	871	825	284	0	47	17.3	7.83	-48.4	3960	-2%
21-220	84	211	321	18	567	843	174	0	15	18.7	7.82	-47.5	3300	1%
18-220	220	125	345	14.4	801	824	116	0	13	18.4	7.78	-45.8	4090	-7%
84-221	104	158	142	3.9	348	291	180	0	176	16.2	8.10	-62.1	2280	6%
F HCR	40	32	69	1	98	107	165	0	14	/	/	/	850	-2%
02-220	36	137	156	1.6	317	293	125	2	129	18.0	7.83	-47.6	1895	2%
08-220	20	107	147	0.6	272	306	156	6	23	18.1	7.88	-51.2	1566	-3%
102-221	20	79	54	0.6	155	128	128	3	14	17.8	8.10	-62.6	950	2%
129-221	16	72	56	0.6	99	107	125	3	82	18.4	7.88	-50.7	992	4%
105-221	28	120	118	3.4	330	235	137	3	83	16.0	8.06	-60.3	1665	-4%
27-220	16	86	152	0.6	177	315	177	9	43	19.1	8.05	-60.2	1480	-3%
28-220	176	175	311	3.9	710	674	198	15	34	18.3	8.11	-63.3	3820	-2%
15-251	16	83	139	0	409	1	174	6	31	16.2	8.39	-77.6	1559	-5%
16-251	20	92	49	1.1	216	72	116	0	89	15.9	8.41	-77.9	1020	1%
17-251	24	56	20	0.6	46	47	134	3	99	16	8.18	-65.5	614	4%
22-251	16	70	51	1.6	98	104	165	15	46	16.3	7.93	-53.5	952	0%
09-251	12	49	57	0.6	103	102	134	3	32	17.6	8.42	-78.8	714	-5%
31-220	48	84	97	0.6	131	161	149	6	194	16.7	7.87	-54.4	1234	3%
02-251	20	78	99	0.6	173	217	140	0	74	17.6	8.39	-74.6	1155	-5%
21-281	16	83	65	0.6	162	148	171	6	18	18.5	7.92	-53.9	1008	-2%
128-250	4	39	32	0.6	30	49	128	3	54	16.4	7.88	-49.1	656	-1%
101-250	12	59	49	5.8	67	0	299	15	36	/	/	/	720	1%
13-281	136	100	95	3	169	665	107	0	19	16.5	7.63	-38.1	1692	-4%
37-281	72	168	284	4.4	536	702	174	12	41	15.8	7.71	-41.9	2650	-6%
36-281	24	98	109	3.4	272	213	162	0	28	17.1	7.55	-33.0	1501	-4%
87-250	12	94	181	0.6	221	254	201	12	24	15.9	7.94	-54.0	1425	2%
35-220	4	61	55	0	90	86	137	3	24	18.4	8.28	-71.6	716	4%
23-220	12	86	110	0.2	174	222	137	6	66	16.9	8.13	-63.4	1287	-2%
06-220	8	125	141	0.2	235	238	134	3	112	17.6	7.92	-53.3	1522	3%
130-219	12	61	34	0	124	51	113	3	15	18.4	8.08	-61.9	693	2%
F4-220	16	103	153	0.6	284	319	119	3	9	18.2	7.85	-46.5	1545	-3%
08-251	8	47	56	0.6	73	71	122	3	70	18.4	9.19	-67.5	723	0%

Albian and the overlying plio-quaternary waters. A closer look to the piezometric map (Figure 4) shows a radial water table with convergent flows in the eastern part of the plain and divergent flows in the western part.

To the east of the axis Ain Oussera-Guelt es Stel, the relief is flat. The small oueds stemming from the Sebaa Rous Mountains disappear in the plain, without reaching the north. The main flow axes are convergent northward, especially towards Koudiat Ben Nahr where all the water table measurements have nearly the same altitude. To the west of the axis Ain Oussera-Guelt es Stel, the aquifer is drained by Oueds Makhloufi, Guernini, El Mouilah or Nefida which either flow out into the Oued Touil, or run off northward. The hydraulic gradients are lower in the west than in the east. The uplands rising in the south and east boundaries of the plain (Sebaa Rous Mounts) feed the aquifer. A slight convexity of the potentiometric level 750 m points out the drainage of the Oued Guernini. To the north, wells 27-220 and 28-220 (see Figure 3 for well locations) seem to be the cause of the thrust of the 700 meters isopiestic line at this level. Clayey windows of the Aptian in this area interrupt the Albian continuity. In the east (south of Bouira-Sahary), the highest hydraulic gradient (0.016) is observed. Hydraulic gradient rarely exceeds 0.005 in the west.

The Albian formation varies in thickness and depth (respectively from 1.4 m in P12 to 53.2 m in B2, and from 100 m in P9 to 700 m in P3). The aquifer may be unconfined or confined depending on the areas. Variations in permeability and transmissivity are observed due to clayey levels which prevent the continuity of the aquifer in some areas.
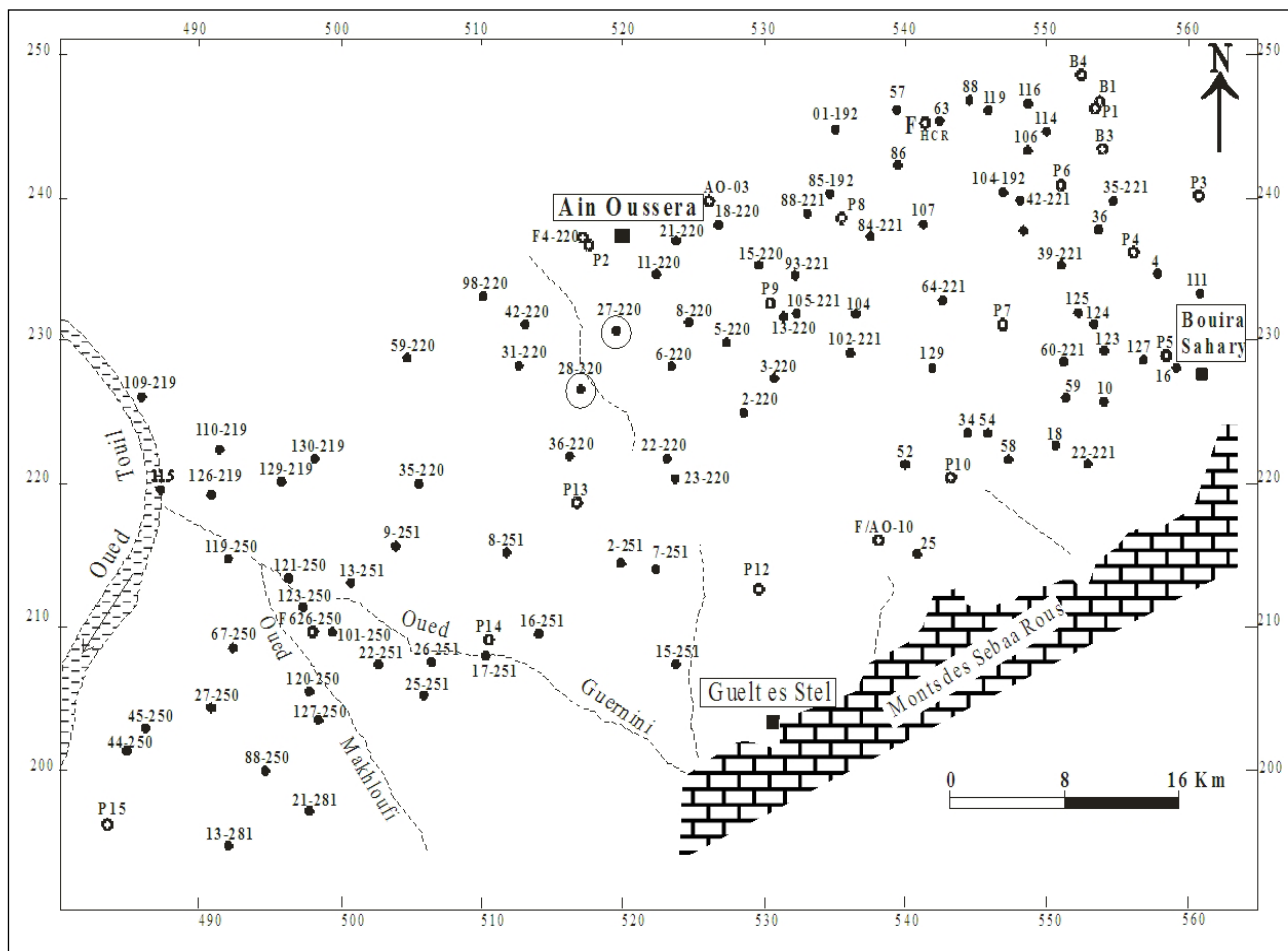

Figure 3. Sampling site location in the Ain Oussera plain. Empty points correspond to deep boreholes (100 meters and more).
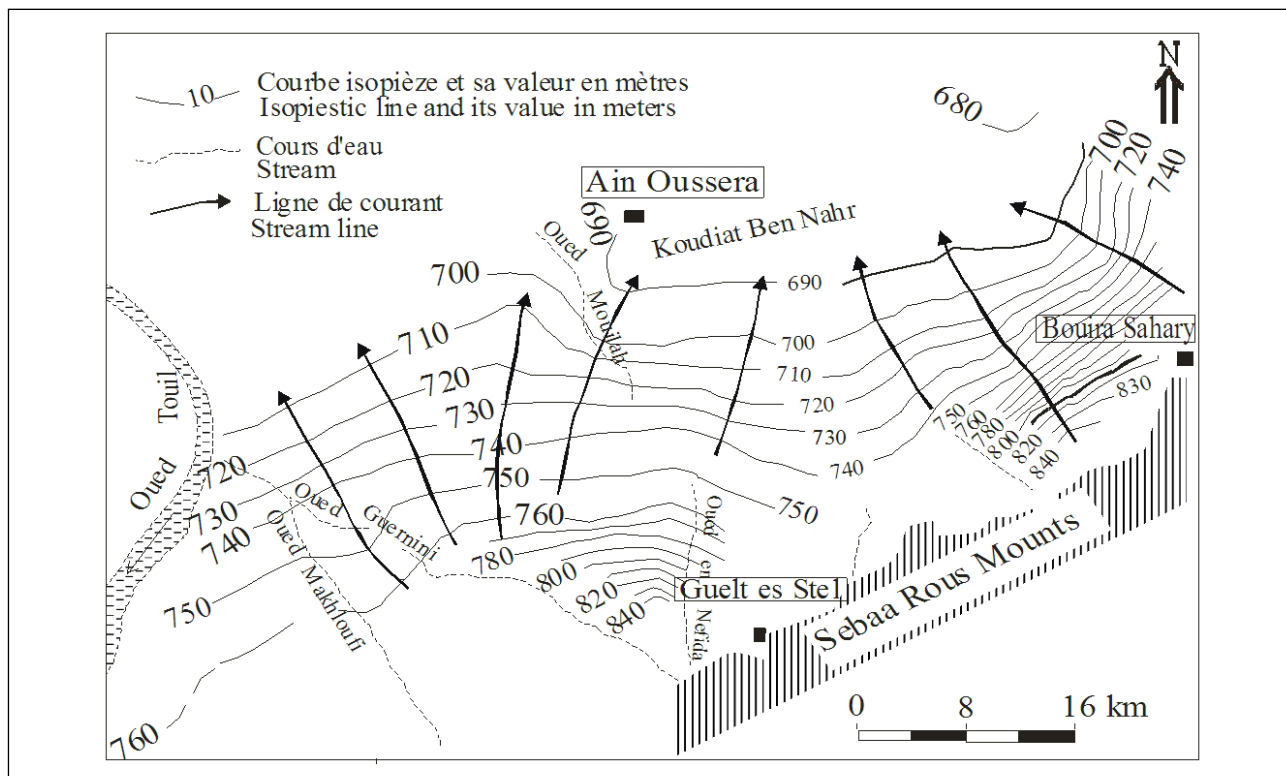
Figure 4. Piezometric map of the Ain Oussera plain (December, 1991).

Generally, transmissivities measured by aquifer tests on the Ain Oussera plain are on the order of 10^{-3} m^2/s. In the gritty-clayey and marly levels of the Aptian, the transmissivity is as low as 10^{-5} m^2/s. By contrast, transmissivities up to 10^{-2} m^2/s can be measured in the Barremian and Cenomanian formations.

Water temperatures and redox potential

Generally, the temperature of shallow waters is influenced by the air temperature. The mean annual value of air temperature is 17.1°C.

The groundwater temperature map shows a great variability mirroring measurement depth and location (Figure 5). The lowest temperature is 12.2°C whereas the highest is 21.6°C. The former was measured in a shallow aquifer already noted by its high content in salts (well 01-192) whereas the latter was observed at a depth of 312 m (Drilling code: F5-221), (See sampling maps, Figures 3 and 17)

For boreholes and piezometers exceeding 100 m depth, the temperature varies between 18 and 20°C. For other wells, the temperature increases according to the depth.

We can distinguish at least three groups of aquifers based on their groundwater temperature. These are:

- Groundwaters with temperature varying between 12 and l5°C corresponding to the shallow aquifer,

- Groundwaters with temperature varying between 15 and 18°C corresponding to the intermediate aquifer.

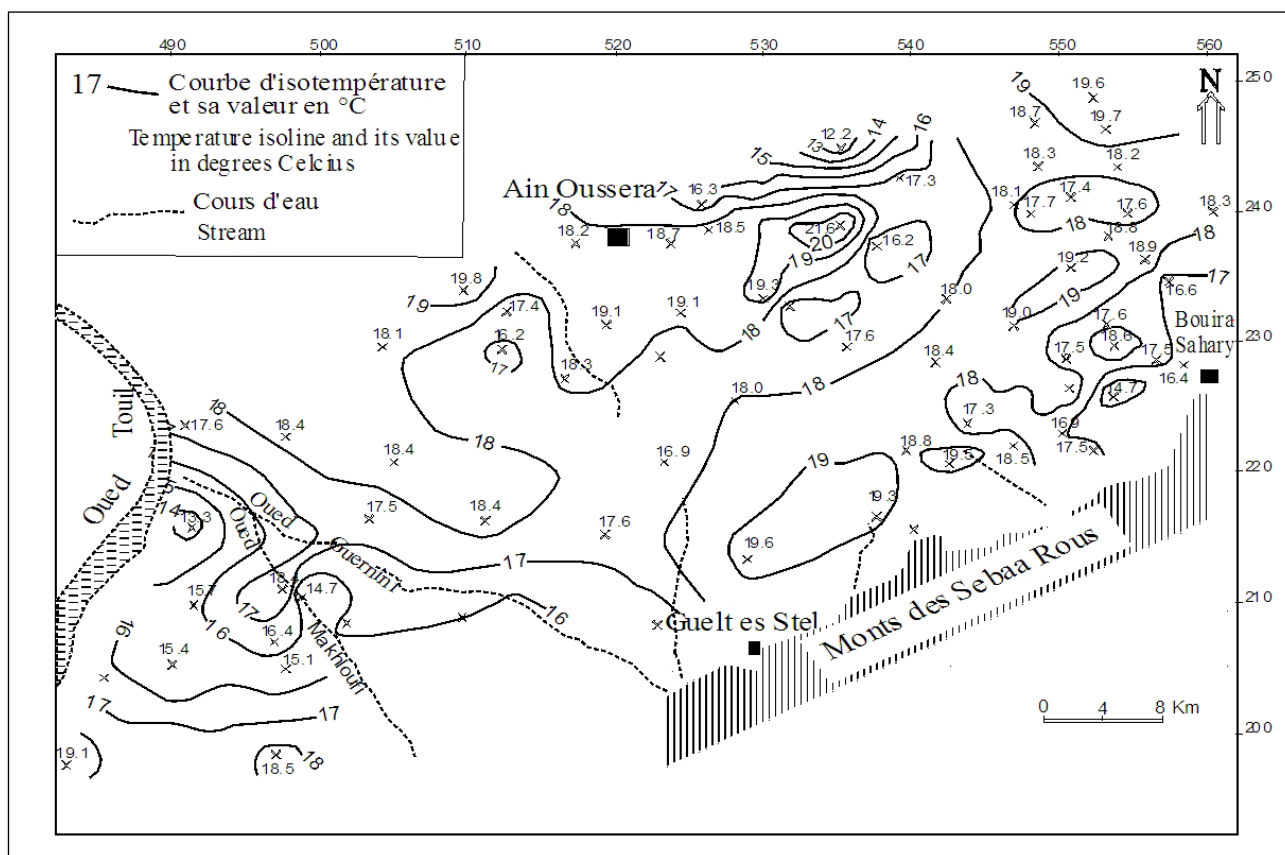- Groundwaters with temperature varying between 18 and 22°c corresponding to the deep aquifer.

Figure 5. Water temperature isolines in the Ain Oussera plain.

Redox potential (Eh) values of waters were also measured in situ during the field survey. Eh is the measure of the hydrogen equilibrium of the environment. It characterizes the ability of the environment to be reduced or oxidized. In practical terms, the reducing potential of a water sample represents the redox potential of the environment under study. Oxidation phenomena are very important in areas crossed by waters of shallow origin (Rodier, 1978). At great depth, most of the oxygen is consumed, and waters are in a reduced state.

In the study region, highest values are observed in the north of the plain (Figure 6). They characterize waters of the shallow aquifer. The lowest values correspond to groundwaters sampled from depths exceeding 100 m.

Redox potential distribution in the groundwaters mirror the temperature distribution of the groundwaters. Shallow aquifers show a redox potential varying between -15 and -50 mv. The deep aquifers show a redox potential exceeding –100 mv. Groundwaters of intermediate depth show a redox potential varying between -50 and -100 mv.

ORIGIN OF CHEMICAL COMPOSITION OF THE GROUNDWATERS

The total dissolved salt increases from south to north following the groundwater flow direction (Figure 7). Areas with low mineral content are located along the section that spreads from the west to the northeast of the plain. This corresponds to groundwaters from the Albian. The highest values of electrical conductivity are located in the north of the plain, to the east of Ain Oussera city.

A noticeable feature of the geochemical characteristics of the groundwaters in the region is that they are dominated by magnesium ion as indicated in the Piper diagram (Figure 8). Magnesium dominated water represents 86% of the total analyzed samples. Around 68% of magnesium
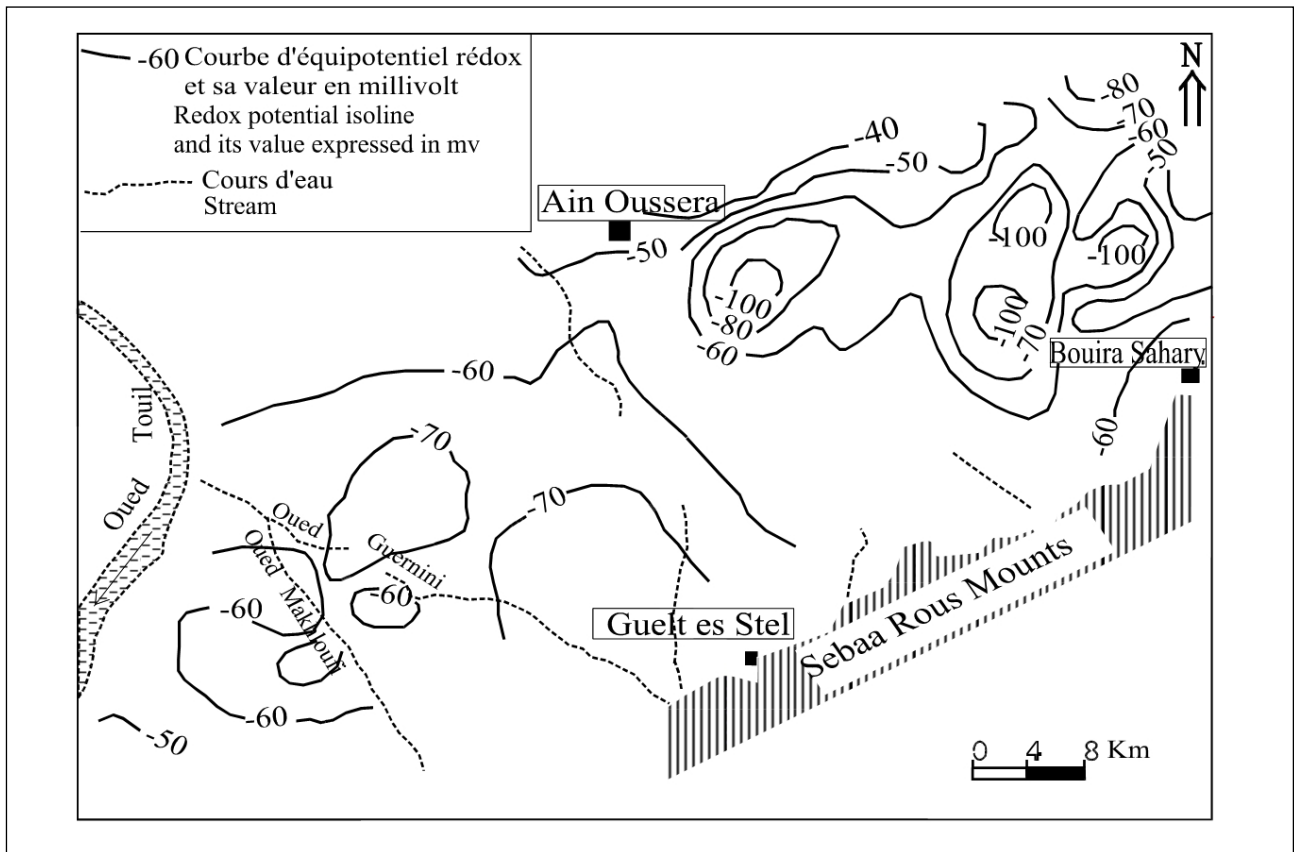
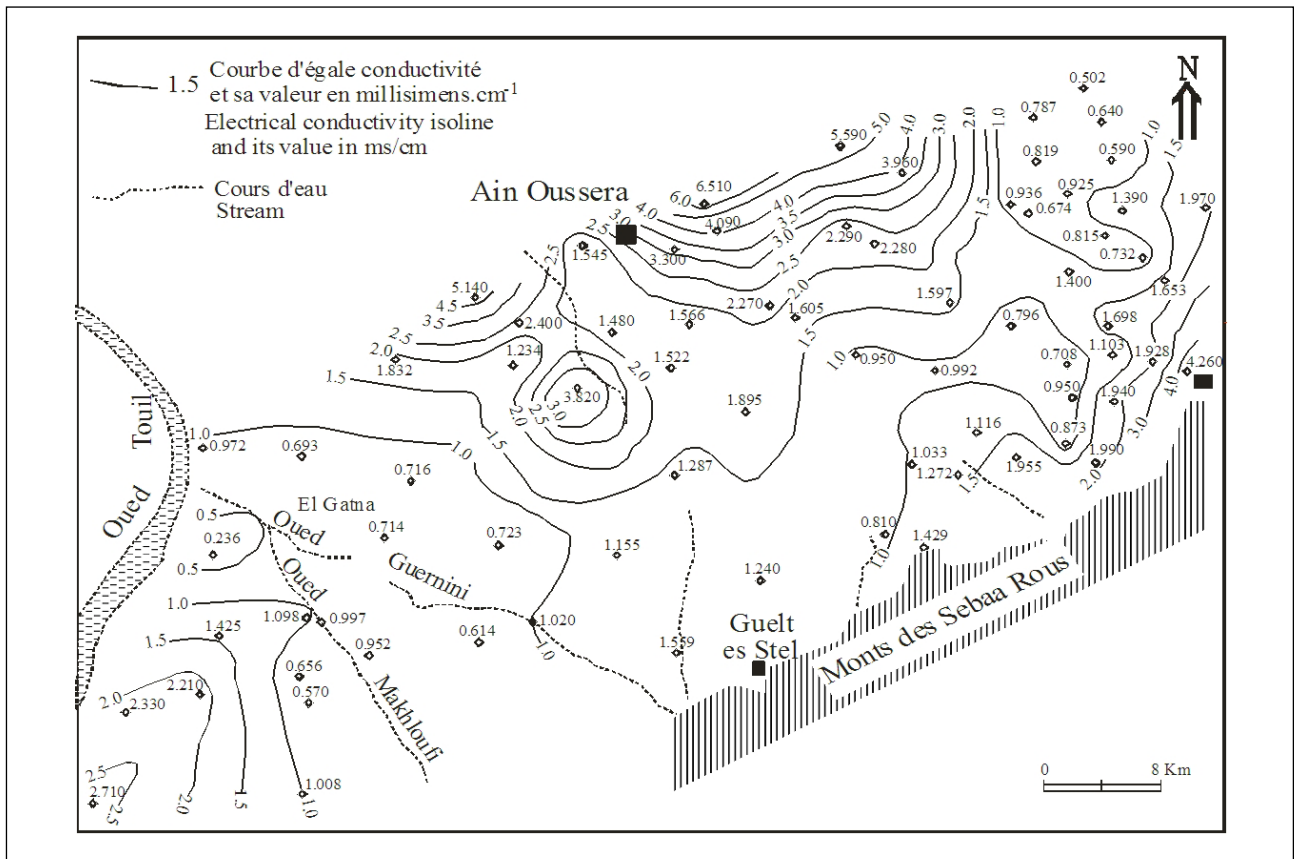Figure 6. Redox potential map of waters in the Ain Oussera plain.

Figure 7. Electrical conductivities of waters in the Ain Oussera plain (December, 1991).

dominated waters are also dominated by chloride, 12% are dominated by bicarbonate and the remaining 6% are dominated by sulfate ions.

The magnesium is very well represented in the studied waters. However, in arid regions, waters containing 200 mg/l of Mg are usually consumed. In fact, only well 21-220, north of the plain, exceeds this value, with a content of 211 mg/l.

There is a good correlation between Mg and Cl, Mg and Na, and to some extent Mg and SO$_4$, especially for water slightly and fairly mineralized (Figures 9 and 10). We can deduce that magnesium results primarily from the leaching of salts contained in the calcareous crust (Durand, 1953), taken back by evaporation and probably from a progressive salts dissolution (chloride and sulfate salts) that settled in old sebkhas.

However, in Figure 10, for weakly mineralized waters, magnesium increases very quickly for a little variation of sulfate content. Thus, Mg sulfates and Mg chlorides would have different origins. The latter would mainly derive from the quaternary limestone crust, which is widespread over the whole surface of the plain, whereas sulfates would result from evaporites which are encountered only to the north of the plain. Small daïas (Daïet el Firania, Daïet el Kerfa, Daïet el Kisria) and sebkhas (Sebkha of Boughzoul) in the north of the plain are the source of evaporitic deposits.

ISOTOPIC CHARACTERIZATION OF THE RAINFALL AND GROUNDWATERS

Isotopes in Rainfall

Figure 11 shows a plot of δ^2H versus δ^{18}O from rain data collected and monitored by the CDTN of Algiers (Edmunds et al., 1997). The best fit line that defines the local meteoric water line
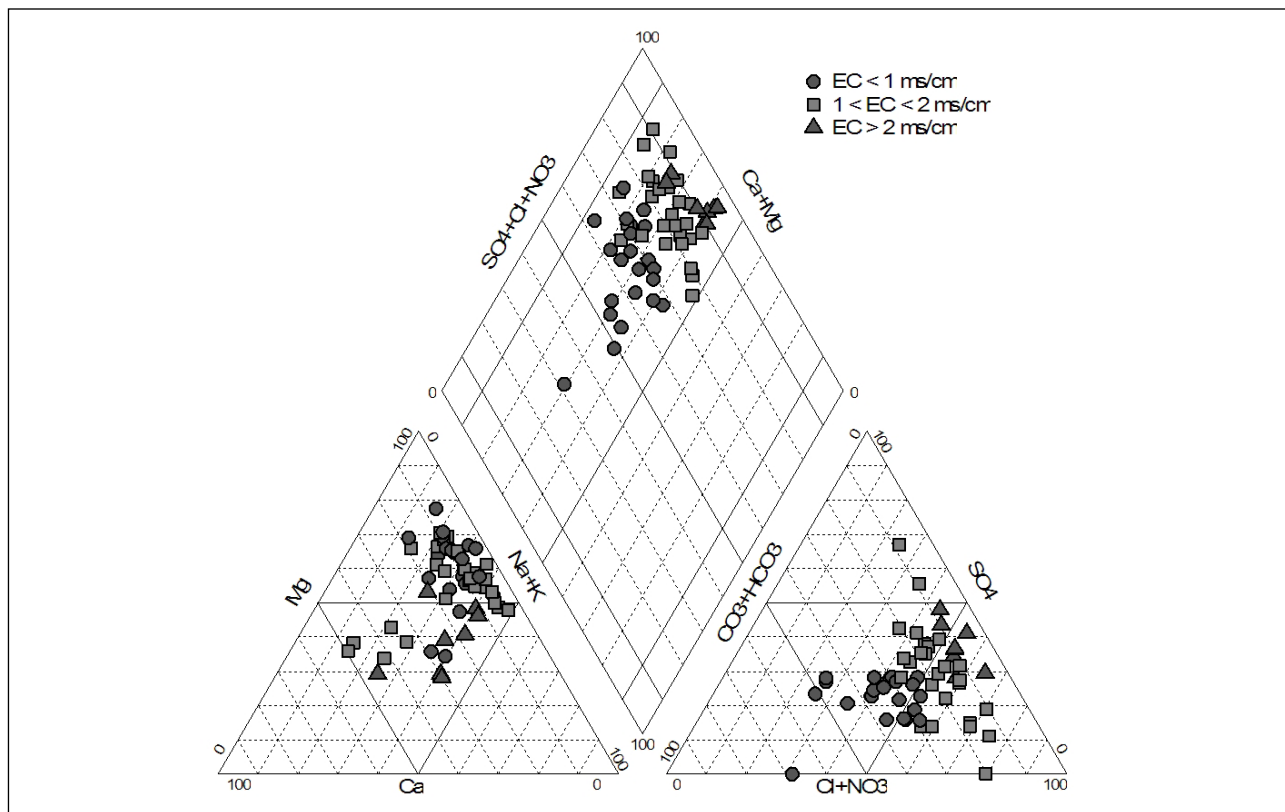

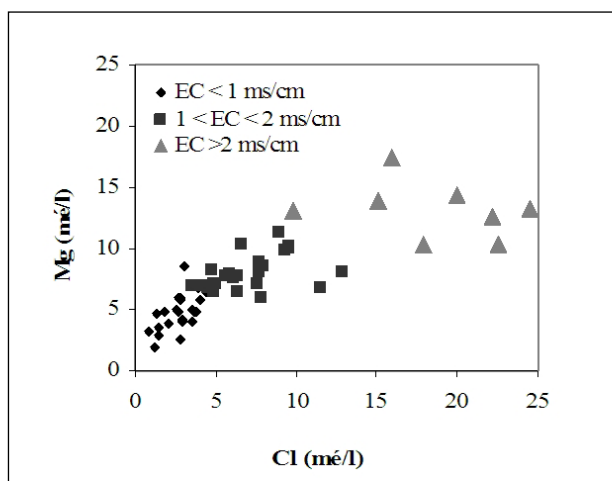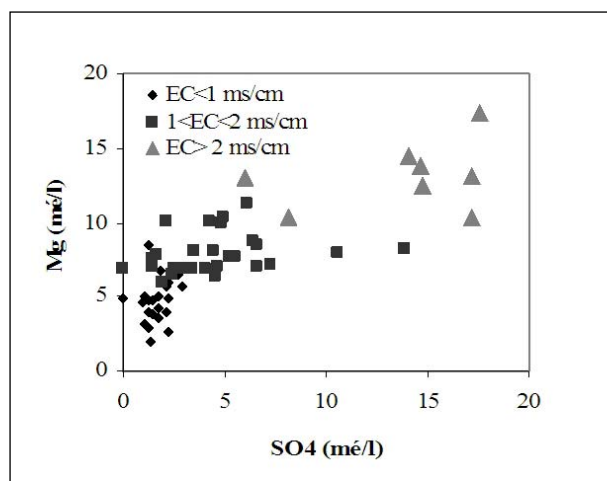Figure 8. Piper diagram showing different water types and their salinization.

Figure 9. Mg vs Cl.

Figure 10. Mg vs SO$_4$.

(LMWL) at Ain Oussera has the relation $\delta^2H = 4.4\ \delta^{18}O$ -8.4. The weighted average composition of precipitation is -4.6‰ for $\delta^{18}O$ and -31‰ for δ^2H. The low slope observed for the Ain Oussera LMWL indicates that rainfall has undergone some evaporative enrichment during its descent. Such an isotope enrichment of rainfall is common in arid and semiarid regions (Fontes, 1967).

Seasonal variation in the $\delta^{18}O$ and tritium in rainfalls collected between 1990 and 1991 are presented in Figure 12. Contents in $\delta^{18}O$ vary between -9‰ and +9‰ with a weighted average of -1.50‰. We can notice that the lowest value was measured in February whereas the highest value appears in August. The heaviest precipitation shows the most depleted $\delta^{18}O$ compositions. The $\delta^{18}O$ enrichment characterizing the dry season is due to evaporation of raindrops.

The same phenomenon was observed by G. Conrad and J.C. Fontes on the data collected in the Béni-Abbès region, in the Algerian Occidental Sahara, between 1964 and 1974 where they suggested evaporation of rain waters during their fall to explain the enrichment in heavy isotopes.

Tritium contents in rain varies between 4 and 16 TU, with an average content of 9.2 TU (Figure 12). The tritium content increases in spring and in summer. This increase may be attributed to the seasonal cycle, as it was observed on longer observation series in Thonon, in France (Blavoux, 1978).

On the same graph (Figure 12), we also deferred $\delta^{18}O$ and ^3H contents of rainwater in Thonon (France) for the same period. The tritium content curve in Thonon, which is at N45° latitude, is above that of Ain Oussera, which is located more to the south, at N35° latitude, approximately by a factor of 2.

Isotopes in Groundwater

Oxygen 18

The $\delta^{18}O$ values (Figure 13 and 14), vary slightly according to the aquifer scale. They are mainly included between -5 and -7‰. However, two particularly high values: -1.6‰ and -2.3‰ suggest an actual local recharge of the aquifer by evaporated and recent waters brought by temporary drainages of oueds that flow nearby.

The statistical representation of $\delta^{18}O$ contents does not allow a good distribution of the groups (Figure 14). This is illustrated by a mixture line between a pole of recent meteoric water and a pole of paleowater. However, a weak inflection of the line at two levels (-5.4‰ and -6.5‰ approximately) leads to a differentiation of 3 groups:
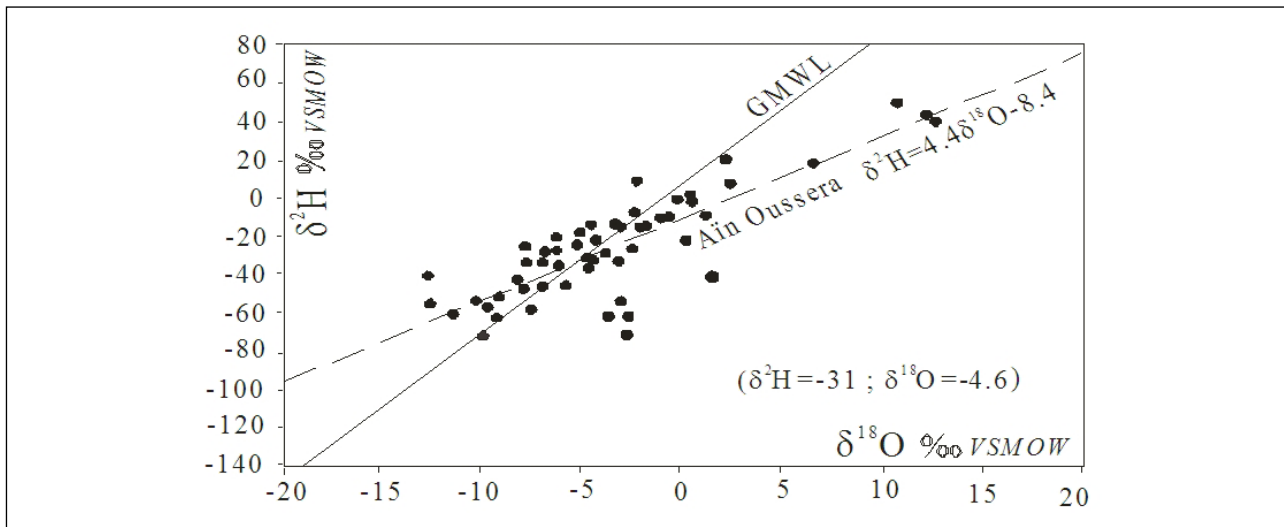
Figure 11. δ^2H-δ^{18}O plot of rainfall at Ain Oussera. Solid line represents Global Meteoric Water Line and dashed line is regression through the data (Edmunds et al., 1997).
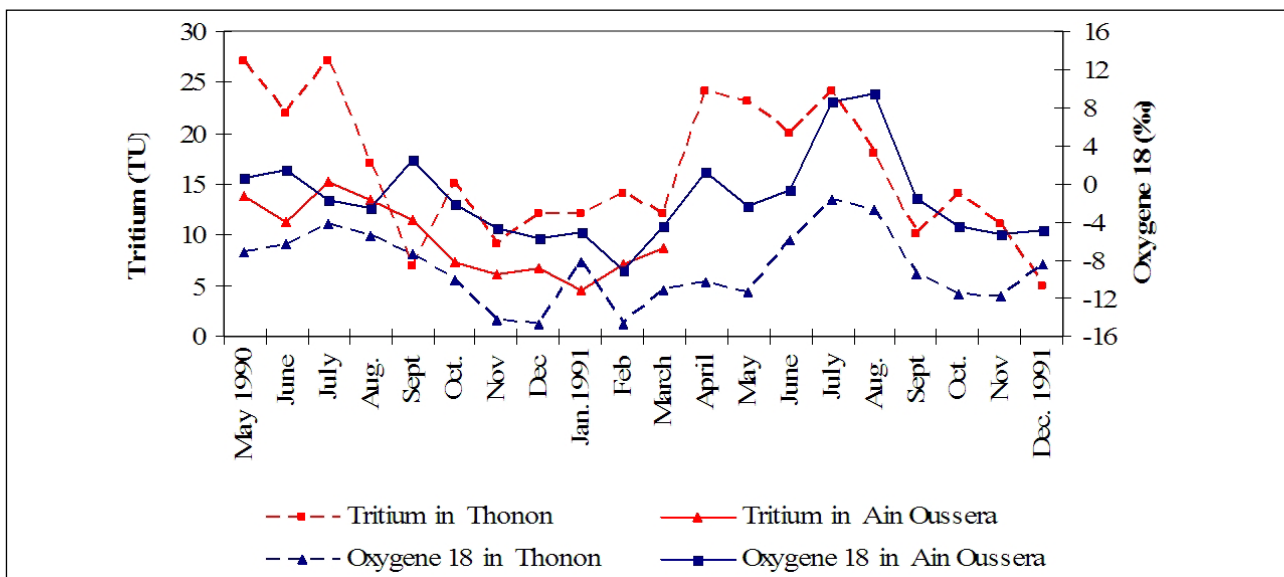

Figure 12. Tritium and δ^{18}O of rain in Ain Oussera and Thonon.

- Recent meteoric waters in a first pole (as group 1)

- Paleowaters in a second pole (as group 3)

- All numerous intermediate waters that form mixtures between these two extremes (as group 2)

Tritium

Tritium in groundwater is not significantly affected by chemical processes. Its more important use is in distinguishing between water that entered an aquifer prior to 1952 (prebomb water) and water that was in contact with the atmosphere after 1952 (Drever, 1997).

In our case, as we do not have long series of tritium measurements, regular in time, we adapt an interpretation model according to the available data.

We have two series of data on tritium contents of water in the plain of Ain Oussera, one carried out on only 10 boreholes in November 1990 (Table 2), and another more complete, including 82
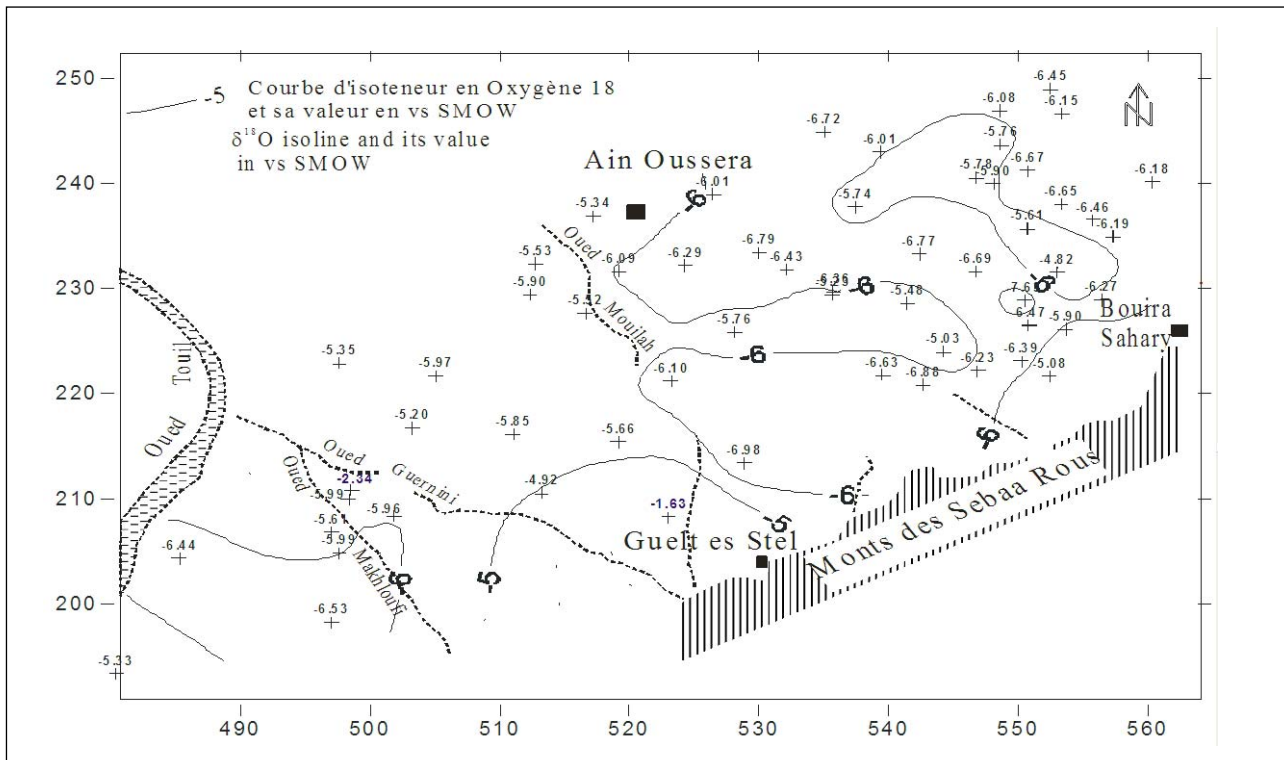
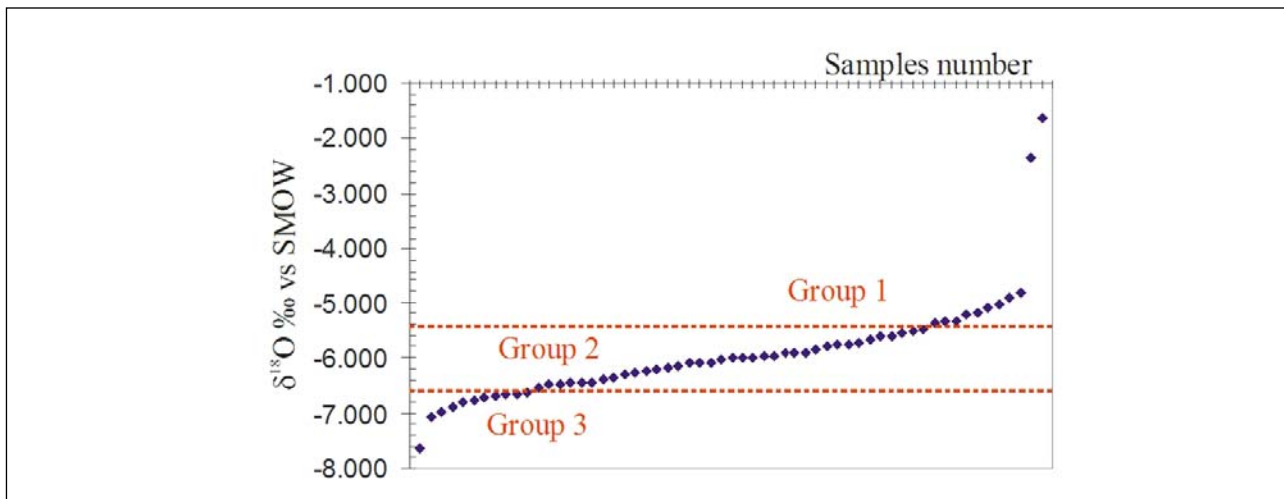Figure 13. ^{18}O contents of waters in the Ain Oussera plain (December, 1991).

Figure 14. δ^{18}O (vs Smow) variations in the Ain Oussera plain.

wells and boreholes, well spread through the entire plain in December 1991.

According to the Clark and Fritz (1977) classification, a qualitative interpretation for continental regions could be made and allow us to distinguish the different groups:

* <0.8 TU: Submodern water, recharged prior to 1952

* 0.8 to 4 TU: Mixture between submodern and recent recharge

* 5 to 15 TU: Modern (<5 to 10 years)

* 15 to 30 TU: Some "bomb" ^{3}H present

* >30 TU: Considerable component of recharge from 1960s or 1970s

* >50 TU: Dominantly the 1960s recharge

Table 2. Isotopic and pH values of boreholes for November 1990.

Drilling code	δ^{13}C PDB Nov. 1990	A^{14}C PMC Nov. 1990	pH Nov. 1990	Tritium (UT) Nov. 1990
F4-220	-9.00	26.1	8.0	3.4
F7-220	-8.70	4.8	7.9	0.7
F3-220	-7.24	18	8.0	0.9
B4	-7.70	ND	8.5	1.1
B3	-8.80	25.7	8.3	0.1
FAO-10	-9.30	31.6	6.2	1.0
F611	-9.10	22	8.3	ND
F.HCR	-7.48	13	8.3	2.9
F4-221	-8.81	3.1	8.3	ND
F6-221	-6.80	40.4	7.9	8.7
F7-221	-9.13	50.1	8.3	0.5
F5-221	-9.30	28.1	8.3	1.8

According to the Blavoux and Letolle classification (1995) for average latitudes, we can distinguish:

- tritium contents lower than 2 TU correspond to old waters (prior to 1952)

- tritium contents between 2 and 10 correspond to a contribution of post-nuclear water mixed in older water.

- tritium contents between 10 and 20 correspond to waters recharged during the last decade. It could be also a post-nuclear water, mixing partially with an older water.

- tritium contents above 20 TU correspond to water with a mean age of some ten years because it is marked by the strong contents of the rains of the peak of 1963.

The two classifications are close if we consider that the second one (of Blavoux et al., 1995) relates to N45° latitude zones and that contents must be undervalued of a factor 2 for the N35° latitude.

By combining the qualitative classification of Fritz (1997) and that proposed by Blavoux and Letolle (1995) for the average latitudes of the northern hemisphere, and by taking into account a decrease of a factor of 2 in rain contents for Ain Oussera's latitude, we propose to distinguish 4 groups of waters according to their tritium content in 1991 (Figure 15):

* < 1 TU: waters recharged prior to 1952 (as group 3)

* $1 \leq T \leq 5$ TU : mixture (as group 2)

* $5 \leq T \leq 10$ TU: modern waters (as group 1) (*)

* $T \leq 10$ TU: some bomb ^{3}H present, with a dominant component from 1960-1970 when T = 25 TU (as group 1)

In Figure 15, we can consider that the group of modern waters is included between 5 and 8 TU concerning the 3rd class of our previous subdivision (*).

Modern waters, with more than 5 TU and 8 TU of tritium content, are grouped in a single group (group 1). Beyond 8 TU, the 1963 peak influence is bigger as tritium content also increases.
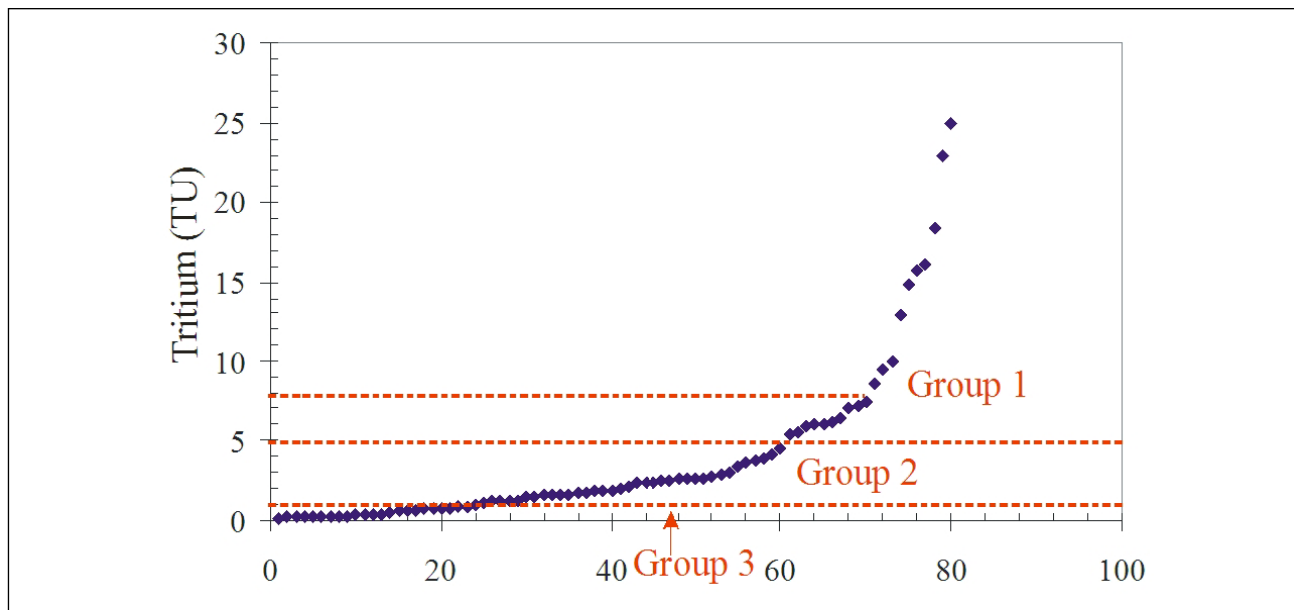
Figure 15. Tritium contents in December 1991 and their frequency.

Overall, in our case, contents of tritium indicate a very weak recharge of the aquifer in some areas. Figure 15 shows that a great number of samples are from mixing waters (group 2).

Figure 16 shows the relationship between nitrates and tritium measurements in December 1991. It confirms the mixing phenomena between groundwater and shallow water which corresponds either to the plioquaternary aquifer water, generally more concentrated in nitrates than that of the Albian, or to a recharge from surface oueds, as was already demonstrated with oxygen 18 contents. However, some wells taking old or mixed waters according to their tritium contents, show relatively high nitrate contents. These wells are located in the areas where the Albian aquifer is outcropping or suboutcropping.

Carbon 14 Paleoclimatic Record

In general, groundwaters are mixtures of waters from separate infiltration episodes and often along different flow paths. The term "groundwater age" though convenient can be misleading and its true meaning is the average of residence time distributions (Fontes, 1983).

The ^{14}C analysis used 11 samples (Figure 17 and Table 2). Contents vary between 3.1 and 50.1 PMC (Percent of Modern Carbon). In the literature, several models have been proposed for estimating A_0, the initial carbon activity. They are listed on Table 3. Some of these models are based either on the chemical (Tamers and Olive models) or isotopic dilution (Pearson model) of the TDMC (total dissolved mineral carbon) between two sources (CO_2 (g) of the ground and the carbonates of the aquifer matrix). Others are based on the isotopic exchange phenomenon with or without isotopic divisions between the TDMC, the gaseous phase and the carbonated matrix (models AIEA, Mook, F&G, Evans and Eichinger). The details of these models can be consulted in Fontes (1985, 1992), Clark and Fritz (1997), Olive (1998), Kalin (1999), Geyh (2000) and Mook (2000).

For each way of defining A_0, predefined default values of parameters are associated with the model. Computing age results from different models are given on Table 4. Apparent ages given by Olive, Fontes and Garnier, and Pearson are very close. Those given by Evans, Eichinger and Tamers stay in the same order, whereas those of Mook and the IAEA seem to be overestimated.
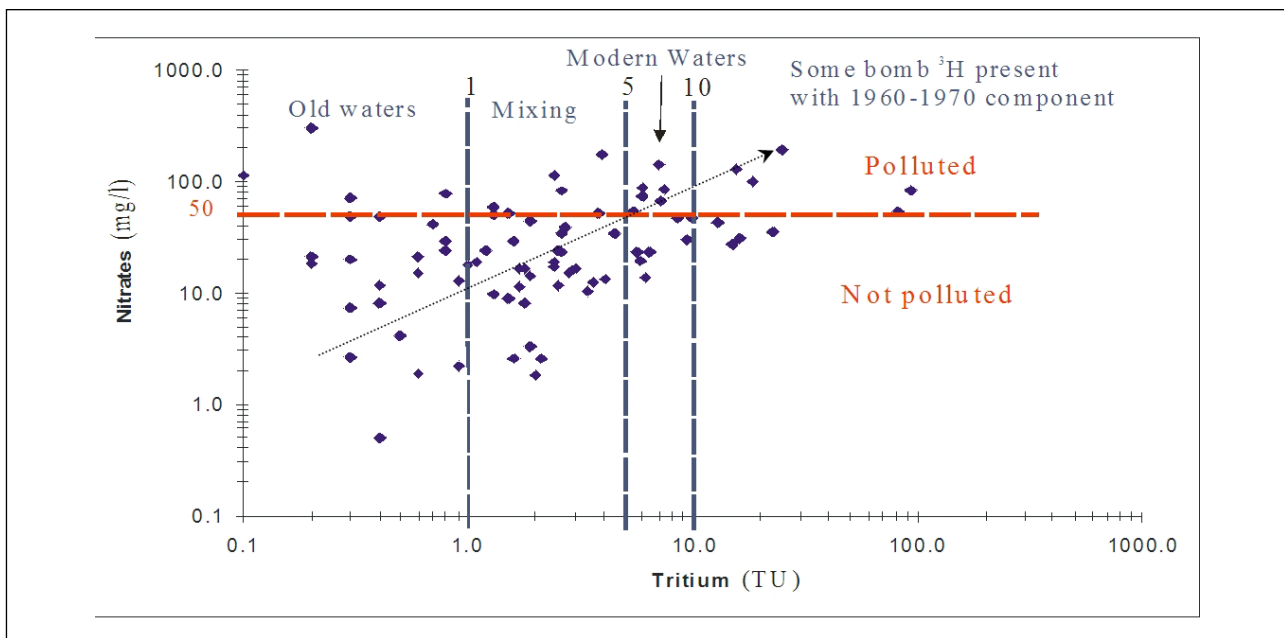
Figure 16. Nitrates versus tritium in groundwaters of Ain Oussera.

The highest values measured in PMC are those closer to the recharge area (F6-221, F7-221).

The well F7-221 corresponds to the most recent water. It is likely that the model activity is close to 50 %. The oldest water comes from well F7-220 which shows a ^{14}C activity of 4.8 and a tritium content below detection. The ^{14}C age corresponds to an age of at least 17000 years. Among the other wells, some show an intermediate age (case of F3-220) whereas others are mixtures between old waters and recent waters, with detectable contents in tritium (case of the borehole F.HCR for example). Therefore, the advanced ages of Table 4 have no meaning for waters resulting from mixtures.

A link can be made between the oldest waters detected by their activity in Modern Carbon and waters with depleted contents in oxygen 18 studied previously as group 3, with contents lower than -6.5 ‰ vsmow. The weighted average content of precipitation is about -4.6‰, the depletion between recent water and old water would be of 2δ approximately (between -4.6‰ and -6.5‰) and could be thus attributed to a paleoclimatic effect.

These waters entered the aquifer during an old geologic period, under climatic and morphological

Table 3. Initial Carbon Activity in PMC.

|	Ao	Ao	Ao	Ao	Ao	Ao	Ao	Ao
	Tamers	Pearson	Mook	F & G	AIEA	Evans	Eichinger	Olive
F4-220	51.21	42.86	75.82	42.62	72.93	41.25	39.94	43.92
F7-220	51.50	41.43	73.33	41.14	70.30	39.74	38.37	43.65
F3-220	51.20	34.48	63.78	33.99	58.51	32.58	31.33	43.92
B3	50.60	41.91	74.63	41.63	70.35	40.05	39.06	44.46
FAO-10	80.40	44.29	43.60	43.24	75.15	42.68	20.01	17.64
F611	50.61	43.33	77.09	43.12	73.54	41.70	40.56	44.45
F.HCR	50.61	35.62	66.10	35.19	60.44	33.76	32.73	44.45
F4-221	50.61	41.95	75.12	41.70	71.19	40.28	39.16	44.45
F6-221	51.50	32.38	60.45	31.83	54.95	30.43	29.05	43.65
F7-221	50.61	43.48	77.29	43.27	73.78	41.84	40.71	44.45
F5-221	50.61	44.29	78.44	44.10	75.15	42.68	41.53	44.45
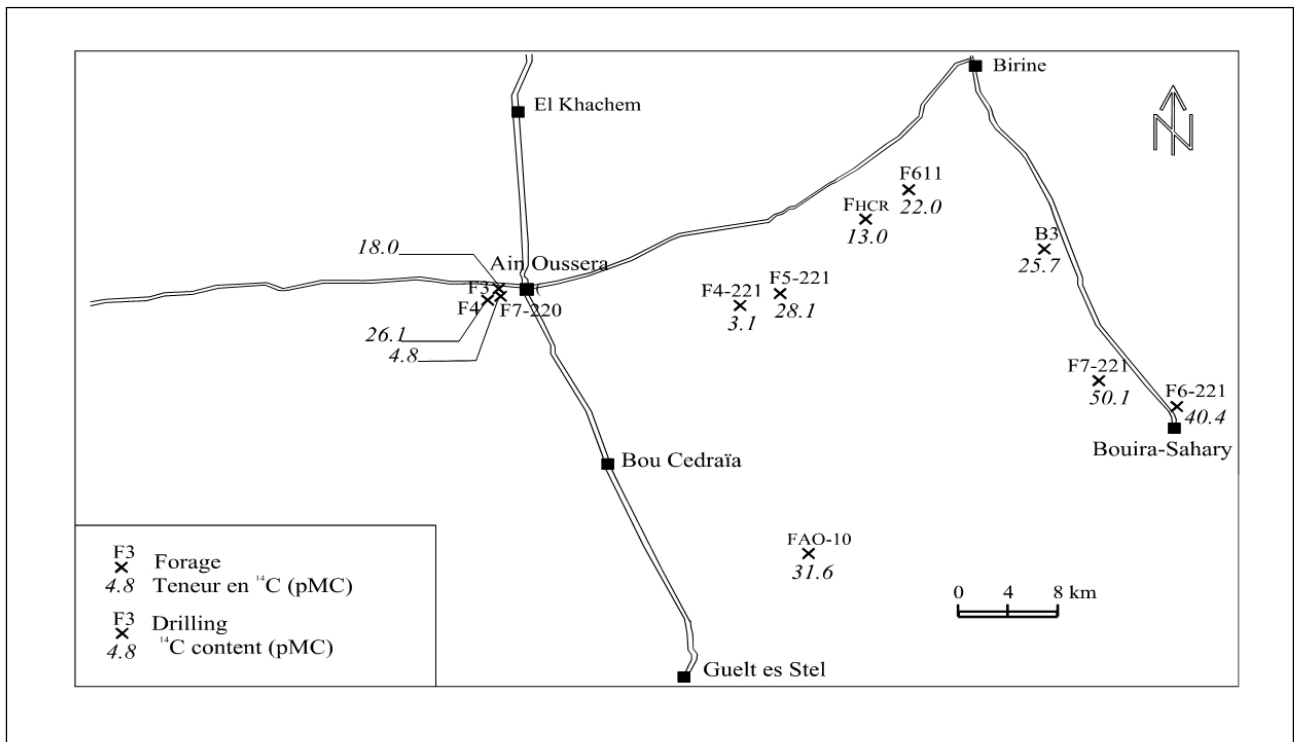
Figure 17. ^{14}C contents of waters in the Ain Oussera plain.

conditions different from current conditions, are preserved (Castany and Margat, 1977). Ages for waters containing measurable ^{14}C and corrected using various models (Guendouz et al., 1997) for the Continental Intercalaire aquifer in the Algerian Sahara, with the measured δ^{13}C give Late Pleistocene ages for the recharge, up to 25 Ka BP (Edmunds et al., 2003).

A correlation between our results and those established for the Continental Intercalaire aquifer and the radiometric ages given for north Occidental Sahara (Conrad, 1969), allowed us to attribute the studied waters to Late Pleistocene, which age limit varies between 8 and 60 Ka BP (Conrad, 1969). Our waters would thus have infiltrated during the 3rd Pluvial (according to Alimen, Chavailllon and Conrad subdivision, 1959, in Chavaillon, 1964) that occurred in Late Pleistocene.

Table 4. Adjusted ^{14}C ages from different models.

Drilling Code	Tamers	Pearson	Mook	Fontes & Garnier	IAEA	Evans	Eichinger	Olive
F4-220	5571	4100	8816	4054	8494	3784	3516	4301
F7-220	19618	17818	22539	17760	22190	17474	17184	18250
F3-220	8642	5373	10459	5256	9745	4906	4582	7374
B3	5600	4042	8813	3987	8325	3668	3461	4532
FAO-10	7721	2790	2660	2593	7162	2484	actuel	actuel
F611	6887	5604	10366	5564	9976	5286	5057	5815
F.HCR	11236	8333	13444	8231	12705	7889	7634	10164
F4-221	23087	21537	26352	21487	25909	21200	20967	22015
F6-221	2007	actuel	3331	actuel	2543	actuel	actuel	639
F7-221	84	actuel	3584	actuel	3200	actuel	actuel	actuel
F5-221	4864	3761	8487	3726	8133	3455	3229	3792

CONCLUSION

We summarize in Table 5 various groups representing each of the previous parameters.

On the basis of the previous grouping, waters could be classified according to their belonging in each of three groups. For 20 samples common to the field campaign measurements of December 1991, results are presented in Table 6.

As seen in this table, there is no water belonging strictly to a single group. All the samples show that waters of Ain Oussera's plain correspond, in reality, to mixtures between shallow and deep water, with variable proportions.

If we consider the spatial distribution of these three groups through the aquifer, waters of group II seem to be more located to the southeast, lining the Mountains of Sebaa Rous, and towards the center of the plain, whereas waters where group I dominates are encountered near the Oueds en Nefida, Guernini and Makhloufi. Waters of group III seem to be located at the north east of the plain.

Table 5. Characteristic values of different groups.

	T°C	Eh (mv)	δ^{18}O ‰	^{3}H (UT)
Group I	12 à 15	> -50	> - 5.4	=5
Group II	15 à 18	-50 à -100	- 5.4 à - 6.5	1=T=5
Group III	18 à 22	< -100	< - 6.5	< 1

Table 6. Water group classification according to their physico-chemical and isotopic parameters.

Sample code	T°C		Eh (mv)		δ^{18}O‰		Tritium (U.T)	
	Value	Group	Value	Group	Value	Group	Value	Group
21-281	18.5	III	-53.9	II	-6.532	III	0.2	III
P6	17.4	II	-70.1	II	-6.666	III	0.3	III
22-251	16.3	II	-53.5	II	-5.959	II	0.3	III
36-221	18.8	III	-51.2	II	-6.649	III	0.4	III
22-221	17.5	II	-53.3	II	-5.084	II	0.4	III
58-221	18.5	III	-52	II	-6.225	II	1.2	II
10-221	14.7	I	-53.3	II	-5.898	II	1.5	II
P4	18.9	III	-122.9	III	-6.463	II	2.6	II
8-220	18.1	III	-51.2	II	-6.293	II	2.6	II
P12	19.6	III	-61.5	II	-6.978	III	5.4	I
16-251	15.9	II	-77.9	II	-4.918	I	6	I
2-251	17.6	II	-74.6	II	-5.655	II	6	I
102-221	17.8	II	-62.6	II	-6.357	II	6.2	I
23-220	16.9	II	-63.4	II	-6.099	II	7.2	I
18-221	16.9	II	-60.5	II	-6.013	II	12.9	I
36-281	17.1	II	-33	I	-5.331	I	14.9	I
2-220	18	II	-47.6	I	-5.762	II	15.7	I
15-251	16.2	II	-77.6	II	-1.625	I	16.1	I
128-250	16.4	II	-49.1	I	-5.61	II	81.7	I
129-221	18.4	III	-50.7	II	-5.477	II	93.7	I

In conclusion, in the region of Ain Oussera, distinguishing different aquifers based on a physical approach has been difficult because of the close hydrodynamic relationships. Lithostratigraphical and piezometric studies did not help to understand the groundwater flow systems. For this purpose, hydrochemical and isotopic measurements have been used simultaneously to better understand aquifer dynamics. The salinity increases from south to north according to the groundwater flow direction. Changes in chemical and isotopic composition are generally functions of evaporating phenomena and lithological variations. Waters are particularly of magnesium type because of leaching of salts contained in the calcareous crust and from a progressive dissolution of magnesium salts deposited in old sebkhas.

Using temperature and redox potential data, we can separate three groups, corresponding respectively to shallow, deep and mixed waters, belonging to intermediate systems. The isotopic study based on the contents $\delta^{18}O$, tritium and ^{14}C confirm these results suggesting the presence of three distinct groundwater systems with significant mixing in many areas.

ACKNOWLEDGMENTS

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ADDRESS FOR CORRESPONDENCE
Naïma Mebrouk
University of Oran es Sénia, FSTGAT
Earth Science Department
B.P. 1524 Oran el M'naouer
Oran 31000
Algeria

Email: nmebrouk@hotmail.com