



The use of hydrochemical and environmental isotopic tracers to understand the functioning of the aquifer system in the Bou Hafna and Haffouz regions, Central Tunisia



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ABSTRACT

Major ions hydrochemistry and isotopic data (^{18}O , ^2H , ^3H , ^{14}C) have been used to improve the understanding of mineralisation processes, origins, and circulation patterns of groundwaters of the Bou Hafna and Haffouz region in Central Tunisia. Hydrochemical investigation indicates that the salinity in groundwater, which varies greatly from 0.2 to 1.3 g/l, results mainly from the dissolution of evaporates (halite, gypsum and anhydrite), cation exchange and dedolomitization processes. The use of stable isotopes tracers ($\delta^{18}\text{O}$, $\delta^2\text{H}$) has classified groundwaters samples into two groups. The non-evaporated groundwaters are distinguished by relatively depleted isotope contents, highlighting significant recharge at higher altitudes. The evaporated groundwaters are characterized by enriched $\delta^{18}\text{O}$ and $\delta^2\text{H}$ contents, reflecting the contribution of return flow of irrigation waters to the recharge of the studied aquifer system. Tritium contents, varying from 0.03 to 1.23 UT, provide evidence of the presence of two sources of recharge that correspond to pre-nuclear recharge, and to a mixture between pre-nuclear water and the contemporaneous recharge. The ^{14}C activities, ranging between 7.4 and 78.6 pmc, identify two groundwater groups. The first group is dominated by the direct infiltration of present day meteoric water at higher altitude. The second group is formed by a mixture of recent and palaeoclimatic groundwaters.

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1. Introduction

The Haffouz-Bou Hafna aquifer system is one of the most promising groundwater reservoirs in Kairouan region, Central Tunisia. The demand for groundwater from this system has increased continuously for at least two decades, when farmers started drawing water from wells through mechanical pumping for agricultural activities. Furthermore, previous studies conducted in Central Tunisia demonstrated that the major part of recharge for the various aquifers has occurred under colder climatic conditions than at present (Ouda et al., 1998; Dassi et al., 2005; Hamed et al., 2008). Consequently, the long-term withdraw from this resource, which is more than the rate of recharge, has resulted in several major problems including generalized water table decline of up to 10 m and deterioration of groundwater quality. These deleterious consequences, which have serious socioeconomic implication in

the study area, may necessitate integrated water resources development and management.

The present work attempts to investigate the hydrochemical and isotopic data of the Haffouz-Bou Hafna groundwater. The results will help in the identification of the main process and factors controlling the groundwater mineralisation and the origin of different water bodies and their sources of recharge.

2. General features

The Haffouz-Bou Hafna region is located approximately 30 km northwest of the city of Kairouan. It located between latitudes 39.55° and 39.70°N , and longitudes 7.88° and 8.33°E , and incorporates a total area of 1192 km^2 (Fig. 1). Elevations increase from 200 m above mean sea level in the Haffouz plain to 997 m at Trozza Mountain. This region is incised by several drainage systems. The Mourra, Zabbes, and Msilah rivers drain toward the Merguellil river, the most important river of the Kairouan plain (Kingumbi, 2006).

The climate of the study area is semi-arid with mild, wet winters, and warm, dry summers (Kingumbi, 2006). The average

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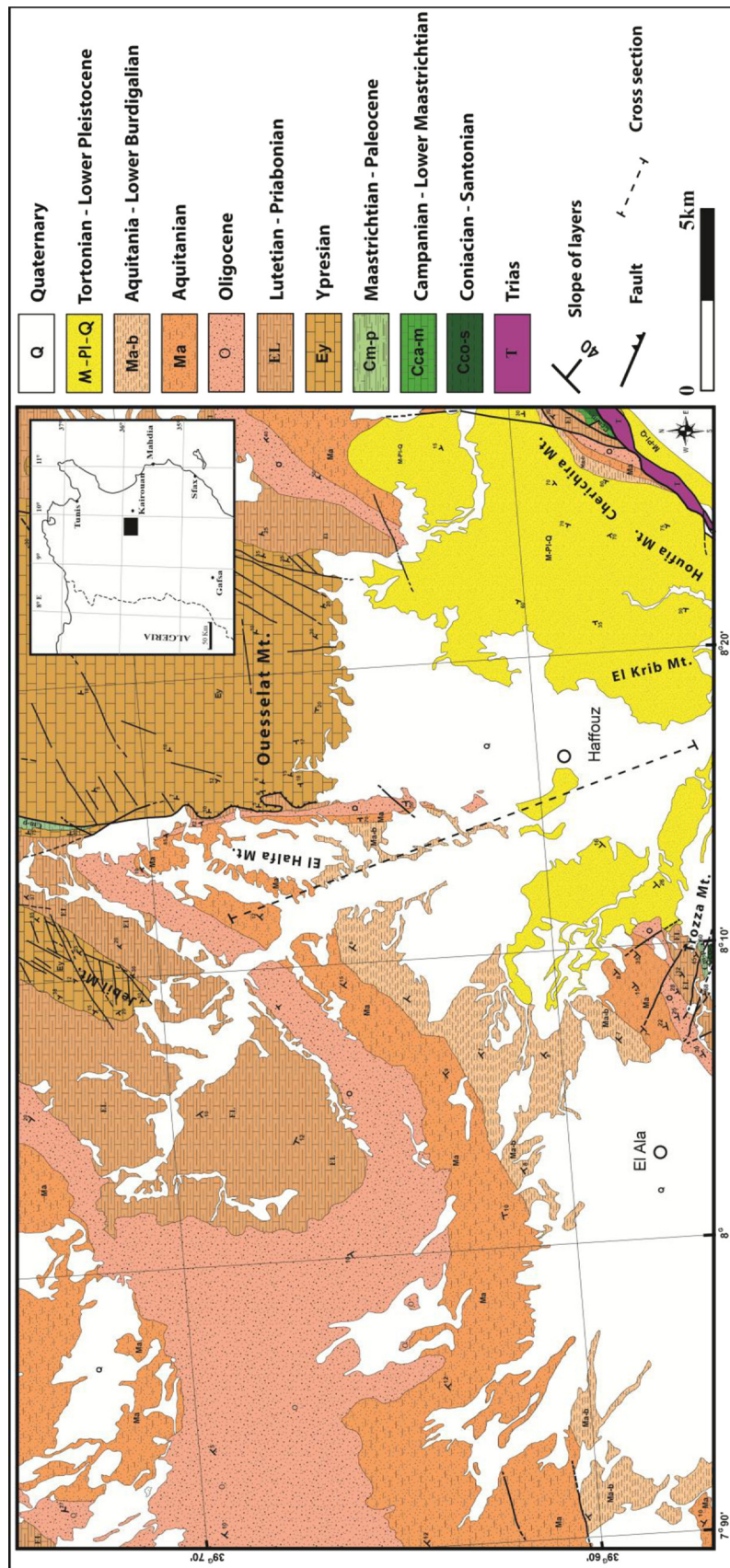


Fig. 1. Location and geological map of the study region.

monthly temperature varies between a minimum of 10.15 °C measured in January and a maximum of 33.07 °C measured in August. It receives a mean annual rainfall of about 350 mm, with maximum value of up to 60 mm in September. The annual total evaporated exceeds 1720 mm Piche (Mejri, 2010).

3. Geological and hydrologic setting

The geologic map and in the lithostratigraphic column show that the age of the geological formations ranges from the Triassic to the Quaternary (Fig. 1) (Castany, 1951; Burollet, 1956; Coiffait, 1974; Abbes, 1979; Ben Jemiaa, 1986; Rigane, 1991; El Ghali, 1993; Yaïch et al., 2000). The Triassic deposits, exposed in Cherichira Mountain, consist mainly of alternating gypsum, clay, and carbonate horizons (Burollet, 1956). The Cretaceous units exposed in the foot of Trozza Mountain constitute Ypsrian limestone of the Alag Abiod and El Metlaoui Formations. These formations are covered by the Lutetian limestone and clay of the Cherhil Formation and Souar Formation, respectively. The Lutetian deposits are overlain by sandy and clayey Oligocene units, with about 350 m thickness. These deposits, which correspond to the Fortuna Formation, are exposed in the central part of the study area. The Miocene deposits are

represented by thick calcareous and clayey layers, which correspond to the Ain Grab and Mahmoud Formations, respectively. These formations are overlain by the sandy clay of the Beglia Formation and the clay Saouaf Formation. The Quaternary sand, clay, and conglomerate deposits occur in the plains of El Ala and Haffouz and in the Merguellil Wadi depression.

From a structural viewpoint, the Bou Hafna basin, which is limited in the east by the major fault of Ouesselat Mountain, corresponds to a syncline and is mainly represented by the sandy sediments of the Fortuna Formation. However, the Haffouz region, which is limited by faults in the east and in the west, is filled by sand, sandstone, sandy clay and clay of Mio-Plio-Quaternary age (Fig. 2).

Hydrologically, the Bou Hafna unconfined aquifer, which has a thickness varying largely from 50 to 300 m, is lodged in the sand and sandstone deposits of the Oligocene. The Lutetian marly deposits of Souar Formation constitute the relatively impermeable bedrock of this aquifer (Fig. 2). The Haffouz unconfined aquifer is hosted in the Mio-Plio-Quaternary detrital deposits with a thickness of about 1000 m.

These aquifers show two groundwater flow directions that are N–S, NW–SE and W–E in the case of Bou Hafna aquifer, and

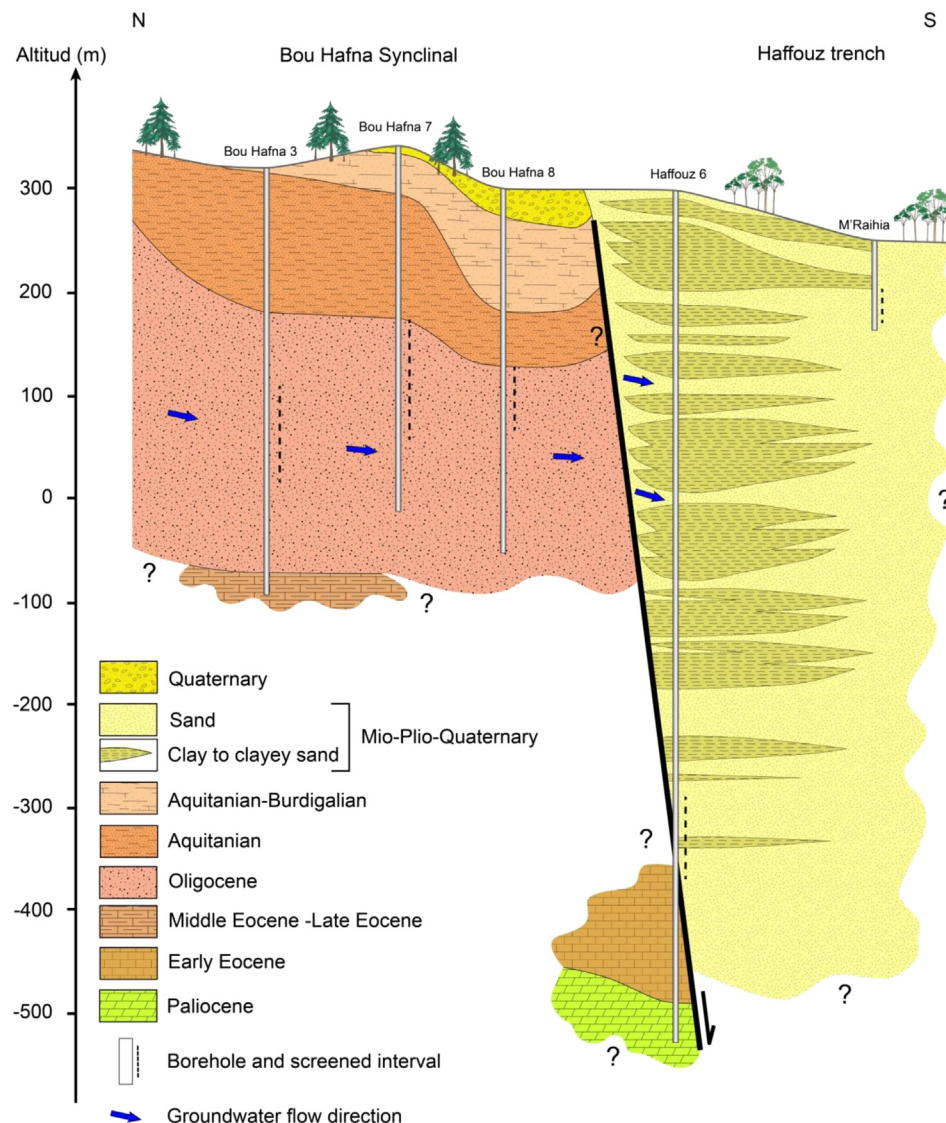


Fig. 2. Hydrogeological cross section of Haffouz and Bou Hafna aquifers.

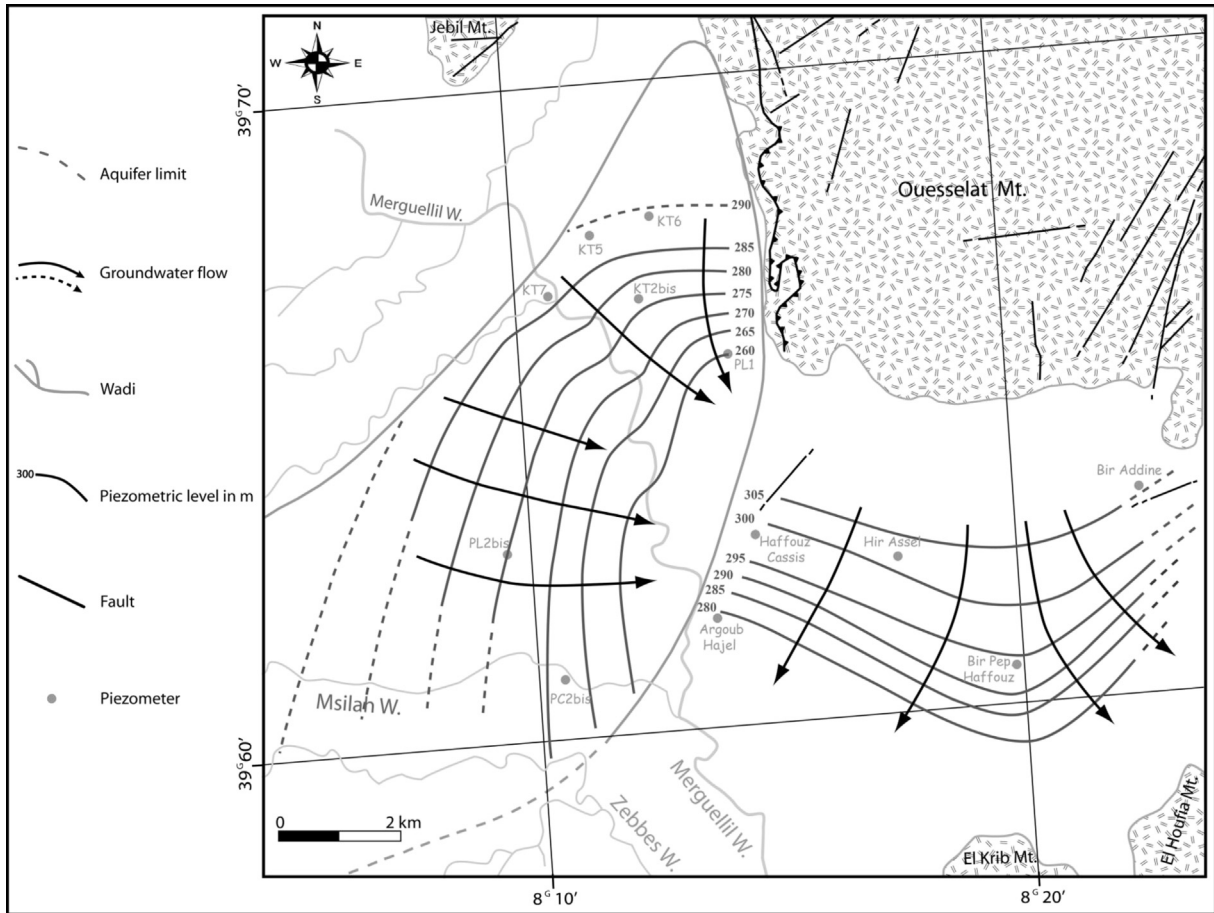


Fig. 3. Piezometric map of Haffouz and Bou Hafna aquifers at 2007.

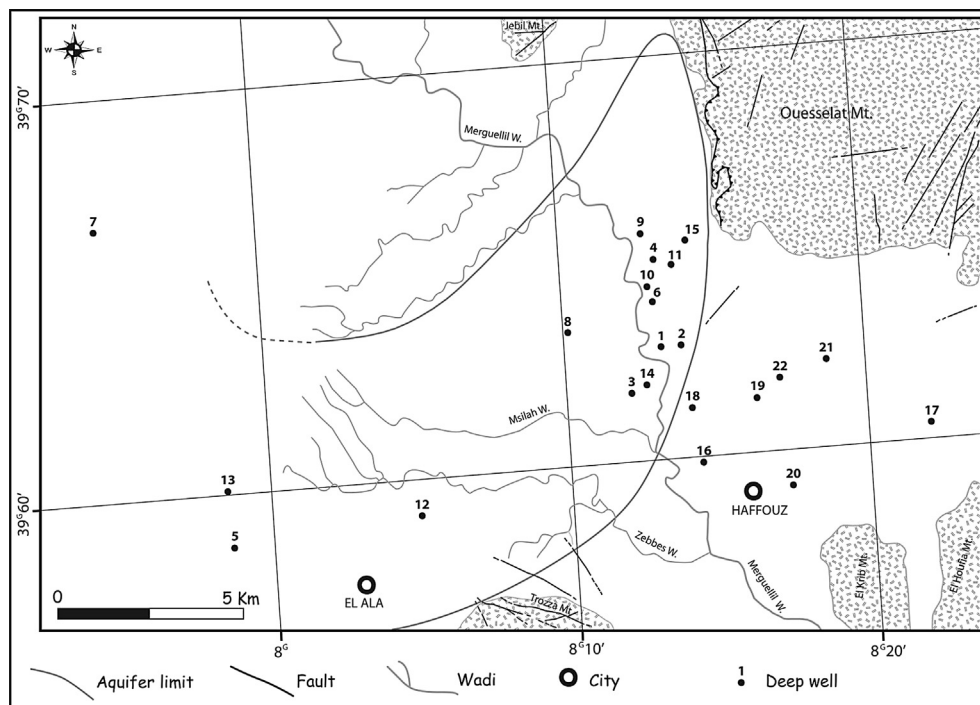


Fig. 4. Sampling map showing the location and numbering of the sampled boreholes.

oriented NW and NE in the case of Haffouz aquifer (Fig. 3). This may indicate that the recharge of Bou Hafna aquifer occurs in the western part of the basin and in the pediment of Ouesselat and Jebil Mountains where the Oligocene sediments are exposed. For the Haffouz region, rainwater infiltrates and recharges the aquifer, locally, in the pediment of Ouesselat Mountain.

4. Sampling and analytical methods

During the sampling campaign, a total of 22 wells were sampled in March 2013, for geochemical and isotopic analyses (Fig. 4). Temperature ($T^{\circ}\text{C}$), pH, and electrical conductivity (EC) were directly measured *in situ* using portable meters allowing temper-

5. Results and discussion

5.1. Hydrochemistry

5.1.1. In situ measurements interpretation

The values of the various physico-chemical parameters of groundwater are given in Table 1. The pH measurements, which range between 7.01 and 7.74, are within the permissible limits of World Health Organization (WHO) standards. The temperature values ranges from 19.9 to 25.3 $^{\circ}\text{C}$. The Electrical Conductivity (EC) is a direct function of its total dissolved solids (TDS). EC and TDS values vary from 422 to 1623 $\mu\text{S}/\text{cm}$ and from 203 to 1188 mg/l , respectively.

Table 1
Geochemical and isotopic data of studied groundwaters.

	N° well	pH	T°	EC (mS. cm3)	TDS (mg/l)	HCO_3^- meq/l	Cl	SO_4	Ca	Mg	Na	K	NO_3	Saturation indexes			$^{18}\text{O}(\text{‰})$	$^2\text{H}(\text{‰})$	^3H (TU)	^{14}C (pmC)
														Gypsum	Anhydrite	Halite				
Bou Hafna aquifer	1	7.5	23.9	939.0	579.0	4.1	1.6	3.2	4.3	2.6	1.7	0.1	0.3	-1.4	-1.7	-7.2	-5.4'	-31.1	1.7	
	2	7.1	24.1	945.0	516.0	3.4	2.0	3.4	3.8	3.0	2.2	0.1	0.2	-1.5	-1.7	-7.0	-5.4	-32.1	0.5	
	3	7.1	22.8	1623.0	1188.0	3.7	2.9	10.7	7.7	4.9	4.2	0.1	0.2	-0.8	-1.1	-6.6	-5.5	-34.3	0.1	
	4	7.3	24.7	1074.0	655.0	4.4	2.1	4.4	5.9	3.4	2.5	0.1	0.1	-1.2	-1.4	-7.0	-5.1	-32.3	0.6	
	5	7.0	22.4	596.0	337.0	3.2	1.6	1.1	2.6	1.6	1.7	0.0	0.1	-2.0	-2.2	-7.2	-5.9	-34.0	0.3	78.6
	6	7.2	24.6	845.0	426.0	3.7	1.6	2.4	3.0	2.8	2.1	0.1	0.2	-1.7	-1.9	-7.1	-5.1	-32.2	0.7	
	7	7.3	22.7	611.0	305.0	3.6	1.0	1.0	1.8	1.8	1.7	0.1	0.3	-2.2	-2.4	-7.4	-5.7	-35.9	0.5	
	8	7.2	22.0	767.0	431.0	4.2	1.4	1.9	3.0	2.1	1.8	0.0	0.3	-1.8	-2.0	-7.3	-5.2	-34.2	0.9	
	9	7.1	24.4	1594.0	1089.0	3.8	2.7	8.0	5.3	4.9	4.8	0.1	0.1	-1.1	-1.3	-6.6	-5.2	-32.4	0.4	
	10	7.2	22.6	733.0	386.0	4.0	1.4	2.0	2.8	2.3	2.0	0.1	0.2	-1.8	-2.0	-7.2	-5.1	-30.8	0.8	65.0
	11	7.3	25.3	1085.0	668.0	4.6	2.3	4.2	4.8	3.5	2.6	0.1	0.1	-1.3	-1.5	-6.9	-6.1	-37.4	0.3	62.0
	12	7.1	23.8	664.0	367.0	3.6	1.5	1.2	2.8	1.9	1.7	0.0	0.2	-1.9	-2.2	-7.3	-5.3	-34.1	0.8	
	13	7.7	23.5	913.0	511.0	3.8	2.0	2.6	3.1	3.1	2.1	0.1	0.4	-1.6	-1.9	-7.1	-5.6	-35.1	1.2	
	14	7.2	23.8	852.0	471.0	3.9	1.7	3.0	3.1	2.5	2.3	0.1	0.1	-1.6	-1.8	-7.1	-5.3	-33.0	0.1	
Haffouz aquifer	15	7.4	22.5	819.0	449.0	4.4	1.9	1.3	3.2	1.5	2.6	0.0	0.5	-1.9	-2.1	-7.0	-5.8	-35.7	0.4	71.5
	16	7.5	19.9	520.1	400.0	3.6	1.4	1.0	3.7	1.1	1.2	0.1	0.0	-1.8	-2.1	-7.4				
	17	7.7	20.0	510.1	464.0	3.6	1.2	1.2	3.5	1.0	1.6	0.1	0.0	-1.8	-2.1	-7.4				
	18	7.5	20.1	834.0	400.0	3.9	1.6	1.3	4.0	1.8	1.7	0.1	0.0	-1.8	-2.0	-7.2				
	19	7.5	21.7	484.0	240.0	3.5	0.7	0.6	1.7	1.9	1.7	0.1	0.1	-2.4	-2.6	-7.6	-5.9	-37.1	0.5	7.4
	20	7.6	22.0	481.0	216.0	3.5	0.7	0.4	1.9	0.8	2.0	0.0	0.1	-2.6	-2.8	-7.5	-5.7	-35.6	0.7	18.1
	21	7.5	21.6	422.0	203.0	3.5	0.6	0.2	2.3	0.8	0.9	0.0	0.1	-2.6	-2.9	-7.9	-5.9	-34.7	0.6	
	22	7.4	24.7	436.0	207.0	4.0	0.5	0.2	2.5	0.8	0.9	0.0	0.0	-2.8	-3.0	-8.0	-5.6	-35.3	1.0	

ature compensation and calibration with appropriate standards. Total Dissolved Solid (TDS) was determined by evaporating the sample and drying it at 105 $^{\circ}\text{C}$. Chemical analysis of the water samples were performed at the Laboratory of Radio-Analyses and Environment of the National Engineering School of Sfax (ENIS: Tunisia). Major cation concentrations were performed on a Waters Ion chromatograph using IC-PakTM CM/D columns. Major anion concentrations were measured using a Metrohm ion chromatograph equipped with CI SUPER-SEP columns. The analysis of bicarbonate was undertaken by titration to the methyl orange endpoint. Based on charge-balance calculations, all hydrochemical data have less than 5 percent error.

Oxygen-18 and deuterium analyses were performed at the Laboratory of Radio-Analyses and Environment of the National Engineering School of Sfax (ENIS: Tunisia) using the Laser Absorption Spectrometer LGR DLT 100 (Penna et al., 2010). Results are reported versus V-SMOW standard (Vienna-Standard Mean Oceanic Water). Tritium (^3H) analyses were performed in the laboratory of the LRAE by electrolytic enrichment and liquid scintillation counting method (Thatcher et al., 1977). Tritium contents were reported in Tritium Unit (TU), in which one TU equals one tritium atom per 1018 hydrogen atoms. Carbon-14 analyses were carried out in the Sfax School of Engineers by using liquid scintillation counting. Radiocarbon data were expressed as percent modern carbon (pmC) with an analytical uncertainty of 0.3 pmC.

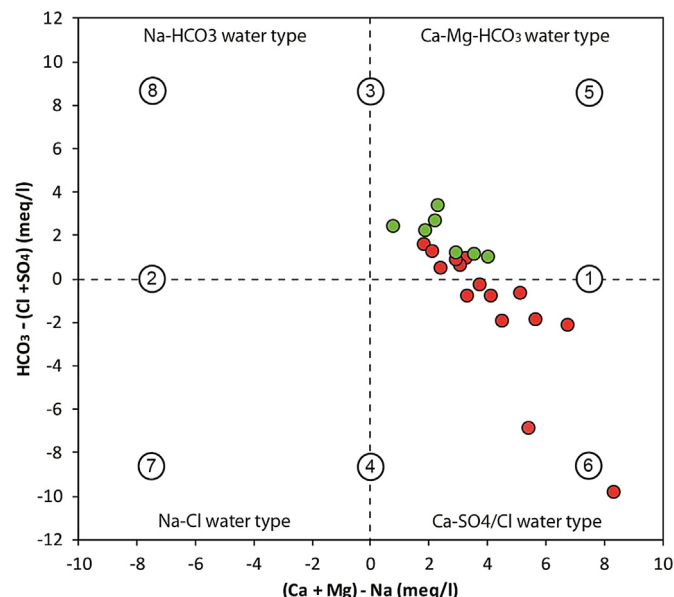


Fig. 5. Chadha diagram of Haffouz and Bou Hafna aquifers.

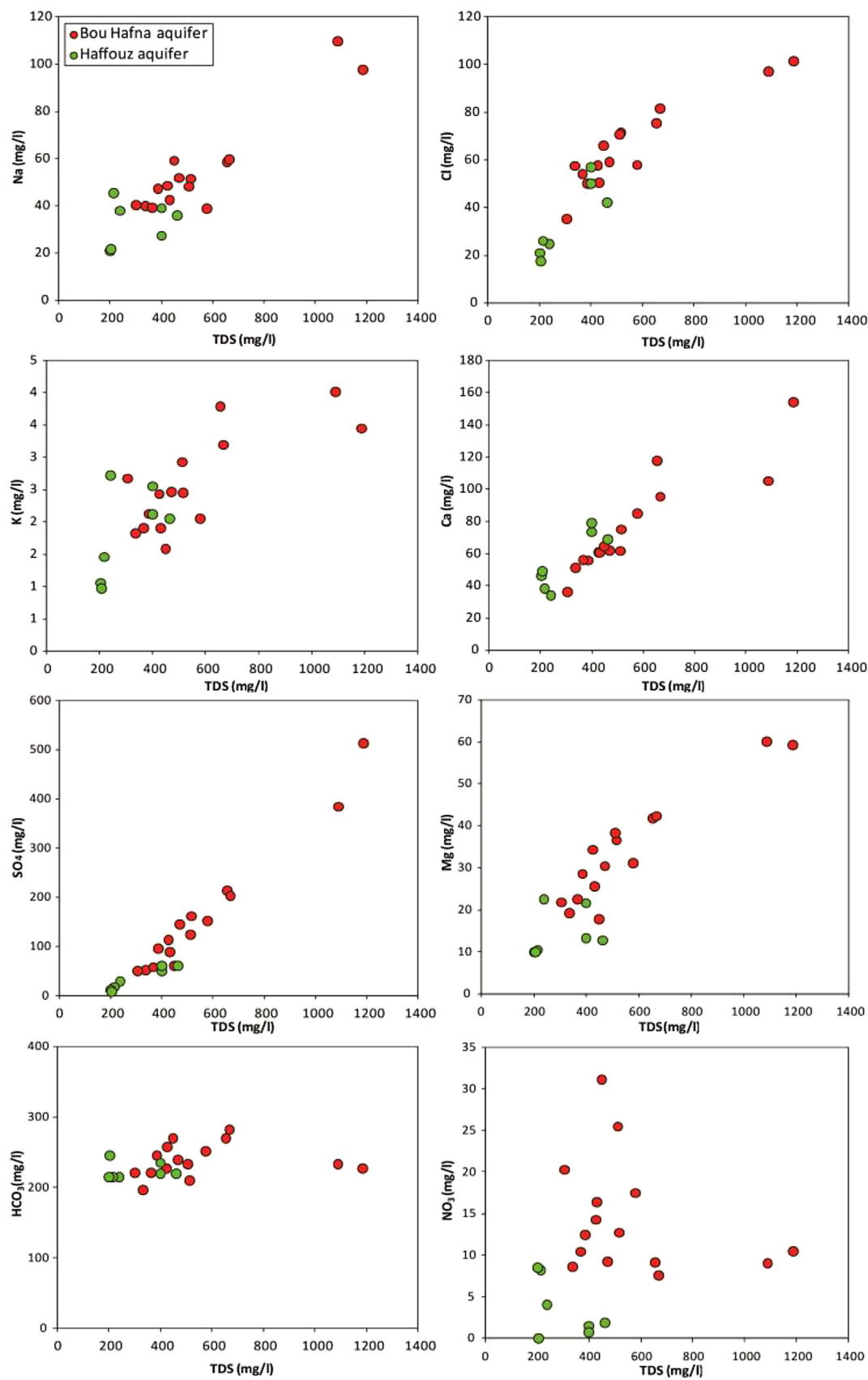


Fig. 6. Major elements and nitrate versus TDS relationships.

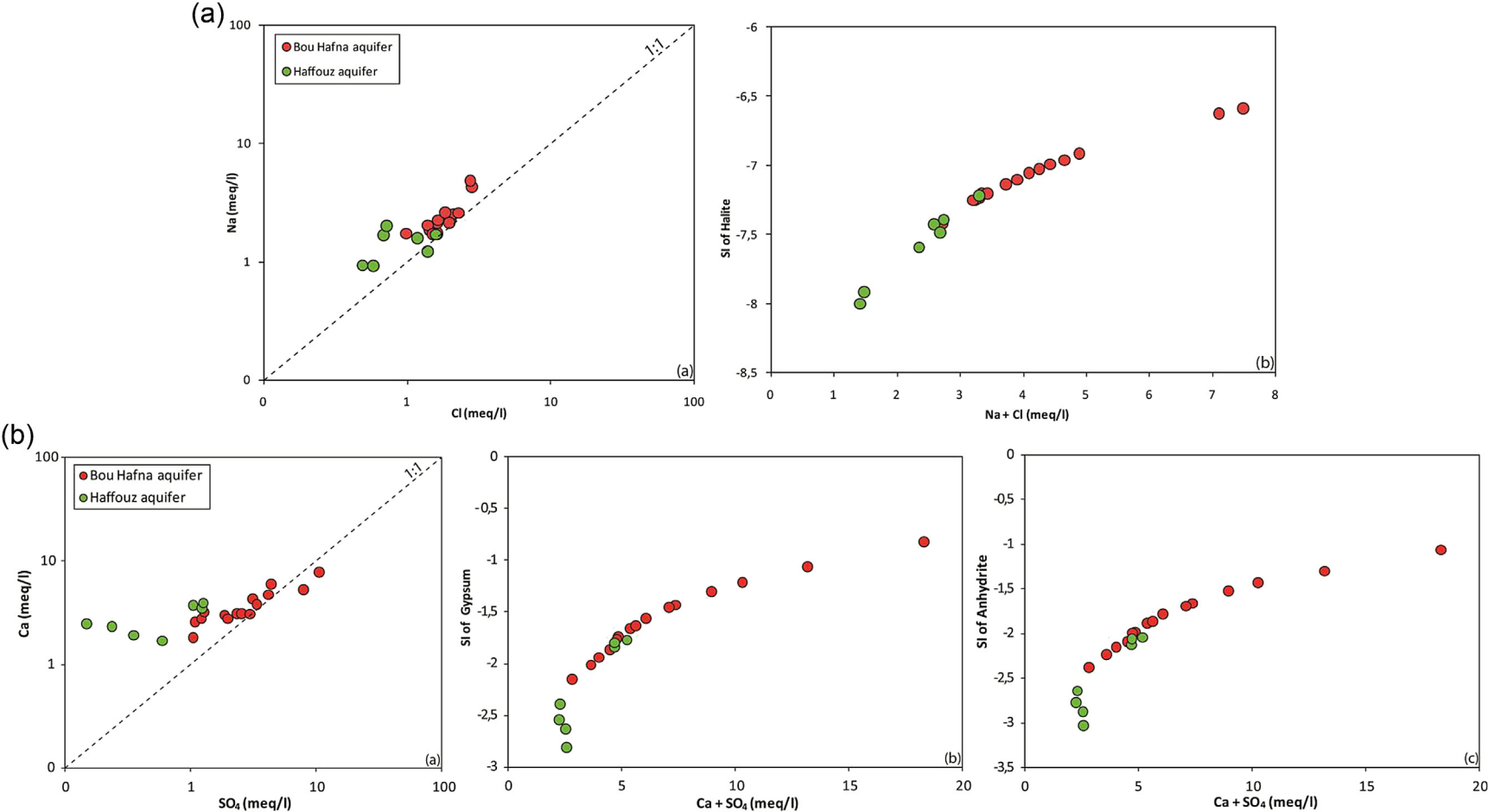


Fig. 7. Plot of Na versus Cl and SI (halite) vs (Na + Cl) (a), Plots of Ca versus SO₄ and SI (gypsum & anhydrite) vs (Ca + SO₄) (b).

5.1.2. Water type

The Chadha plot was prepared for the 22 samples, which provides sufficient information about groundwater facies (Chadha, 1999). Fig. 5 reveals that the major water type in the study area is Ca–Mg–HCO₃. However, some samples collected from Bou Hafna aquifer are of Ca–Mg–SO₄ water-type. From the Chadha plot, the dominant cations in the hydrochemical facies are prominently calcium with magnesium, while the anions vary mainly from sulfate to bicarbonate.

5.1.3. Major ions hydrochemistry

Groundwater samples collected from the Haffouz and Bou Hafna aquifers display positive to strong correlations in the plots of chloride, sulfate, sodium, magnesium, and calcium versus salinity (TDS). The high values of the correlation coefficient ($r > 0.9$) indicate the major role played by the referred ions in the salinisation of the groundwater (Fig. 6).

On the other hand, all groundwater samples have negative saturation indexes (SI) versus evaporate minerals i.e. halite, gypsum and anhydrite (Table 1), indicating an undersaturation state with respect to those mineral phases (Parkhurst et al., 1992). Therefore, the referred minerals are likely to dissolve. The dissolution of halite and sulphate minerals is highlighted firstly through the positive correlation in the plot of Na vs. Cl and Ca vs. SO₄, respectively and secondly by the proportional and parabolic evolution between the negative saturation indexes with respect to halite (SI of halite) and gypsum (SI of gypsum) versus the sum of ions (Na + Cl) and (Ca + SO₄) added to groundwater (Fig. 7a, b).

The increase of the calcium concentrations related to the gypsum dissolution causes a super-saturation state with respect to calcite and engenders its precipitation. As the result of calcite precipitation, the bicarbonate concentration decreases and undersaturates groundwaters with respect to dolomite. Under such condition, dolomite undergoes incongruent dissolution, known as dedolomitization (Appelo and Postma, 1993). The dedolomitization reaction is highlighted through the 1:1 ratio of most samples in the plot of [Ca + Mg] versus [SO₄ + 0.5 HCO₃], (Jacobson and Wasserburg, 2005) (Fig. 8).

All groundwater samples display an excess of sodium in the plot of Na/Cl, which corresponds to a deficient of calcium over sulfate. This may reflect the important contribution of cation exchange process to the groundwater mineralisation. During this process, there is an exchange of calcium and magnesium in water by sodium bound in clay. The ions exchange process is highlighted through the

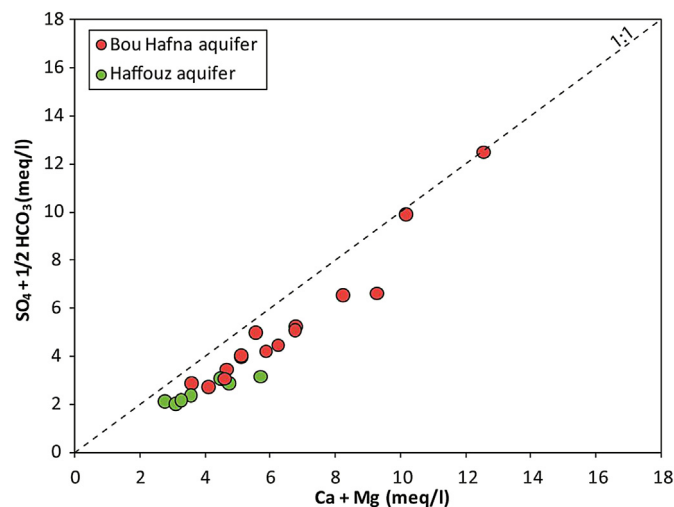


Fig. 8. Plot of (Ca + Mg) versus (SO₄ + 0.5 HCO₃).

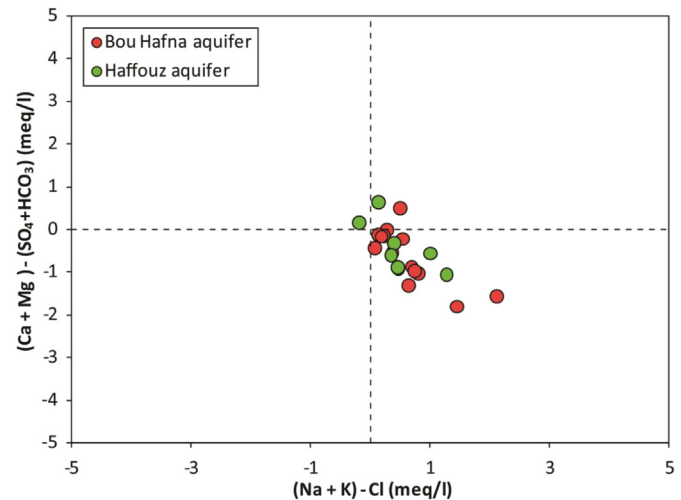


Fig. 9. Plot of (Na + K–Cl) versus [(Ca + Mg)–(SO₄ + HCO₃)].

relationship illustrated in Fig. 9 in which (Na + K – Cl) varies in inverse proportion with respect to [(Ca + Mg) – (SO₄ + HCO₃)] (Mc Lean et al., 2000; Garcia et al., 2001). A conceptual model of groundwater mineralisation processes has been produced for the Haffouz and Bou Hafna aquifers through consideration of hydrodynamic functioning and the results of hydrochemical investigation (Fig. 10).

5.2. Isotopic study

5.2.1. Oxygen-18 and deuterium data

The oxygen-18 and deuterium contents of Bou Hafna and Haffouz groundwater samples are relatively homogeneous and vary from –6.09 to –5.05‰ vs. SMOW and from –30.78 to –37.39‰ vs. SMOW, respectively (Table 1).

Groundwater samples were plotted in the $\delta^{18}\text{O}/\delta^2\text{H}$ conventional diagram together with the Weighted Mean Precipitation in Kairouan City (WMPK: $\delta^{18}\text{O} = -4.5$ and $\delta^2\text{H} = -23.5$) (Jéribi, 2004) and the rainfall input function, represented by the Local Meteoric Water Line (LMWL) of Tunis Carthage (Zouari et al., 1985) (Fig. 11). In this diagram, the Haffouz and Bou Hafna groundwater samples fall on or under the LMWL, indicating that the rainfall contributing to the recharge of these aquifers derives from a Mediterranean origin. The detailed examination of the $\delta^{18}\text{O}/\delta^2\text{H}$ can help to classify the groundwater samples into two distinct groups. The first group includes groundwater samples with relatively depleted isotopic contents and lies on the LMWL. This may indicate that these non-evaporated waters originate from rapid infiltration of rainfall. These samples define a regression line with the equation: $\delta^2\text{H} = 7.8 \delta^{18}\text{O} + 11.2$ ($R^2 = 0.9$). The slope 7.8 of this line is similar to this of LMWL providing insight into the direct and rapid infiltration of rainfall (Gat and Issar, 1974). Nevertheless, the isotopic composition of the first group is depleted than the WMPK by 0.9–1.3 units for oxygen-18 and by 7.5–11.1 units for deuterium, suggesting that these aquifers have been recharged at altitudes higher than the elevation of the WMPK station (EWMPK = 50 m a.s.l.). To verify this hypothesis, the recharge altitude of groundwater (R_A) has been calculated by applying this equation:

$$R_A = E_{\text{WMPK}} + \left(\delta^{18}\text{O}_{\text{WMPK}} - \delta^{18}\text{O}_{\text{Groundwater}} / G \right) \times 100$$

The theoretical $\delta^{18}\text{O}$ gradient is about 0.3‰ per 100 m ($G = 0.3$) (Zuppi et al., 1974; Blavoux, 1978; Maliki et al., 2000;

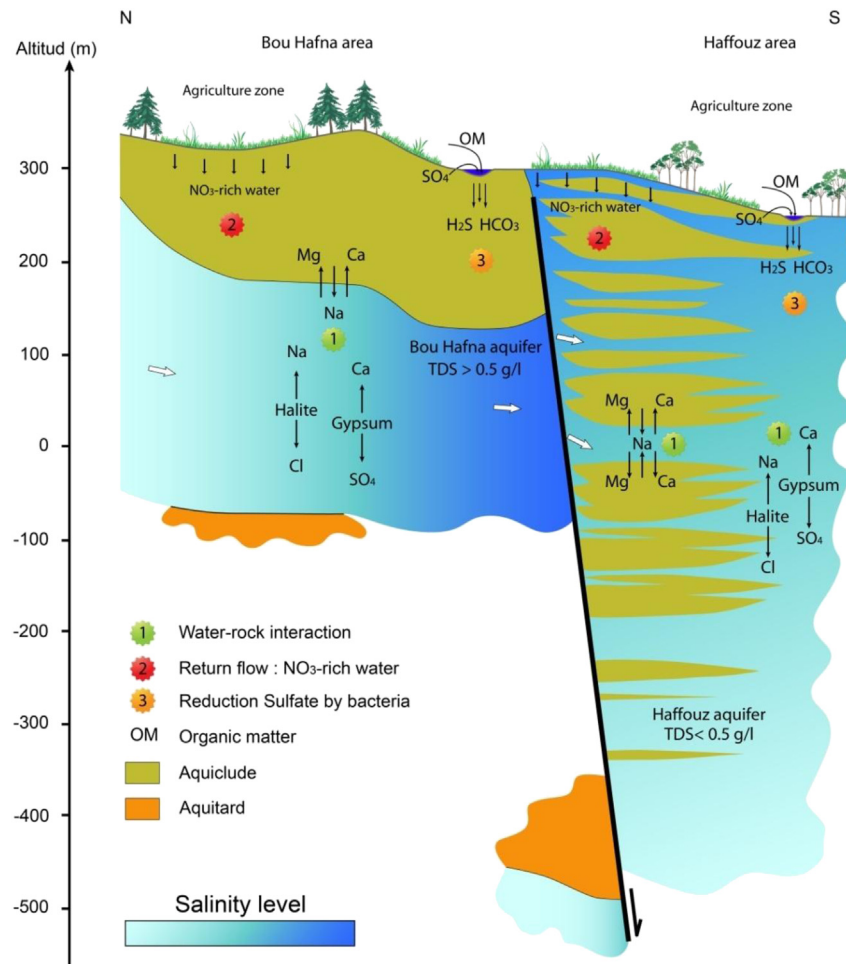


Fig. 10. Conceptual model of groundwater mineralisation processes.

Hamed et al., 2008), the $\delta^{18}\text{O}$ of WMPK is about -4.5‰ vs. SMOW and the $\delta^{18}\text{O}$ of groundwater of this first group is between -6.09 and -5.4‰ vs. SMOW. The calculated recharge altitudes (R_A) are between 350 and 580 m a.s.l., which coincides with the altitude of

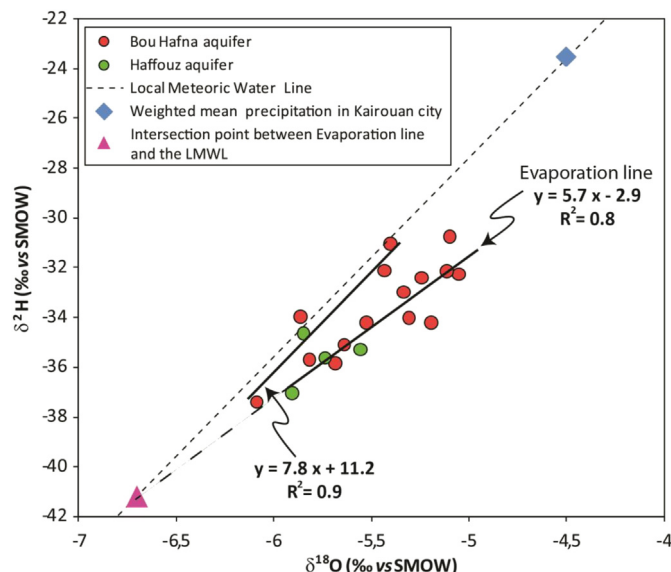


Fig. 11. Conventional diagram of $\delta^{18}\text{O}/\delta^2\text{H}$.

the aquifer outcrops in the study area and thus confirm the proposed hypothesis.

The second group consist of groundwater samples distinguished by relatively enriched isotopic contents and plots under the LMWL, with a regression line: $\delta^2\text{H} = 5.7\delta^{18}\text{O} - 2.9$ ($R^2 = 0.8$). The slope of 5.7 and the intercept (deuterium-excess: d-excess) of -2.9 , indicate that groundwater samples from this group have undergone significant evaporation before infiltration (Tsujiura et al., 2007). The initial stable isotopes composition of water before evaporation, which corresponds to -6.7 for $\delta^{18}\text{O}$ and -41.5 for $\delta^2\text{H}$, is obtained through the intersection between the evaporation line and the LMWL. The oxygen-18 content of the intersection point is depleted from that of the WMPK by about 2.2. This can be explained either by an altitude effect or by a palaeoclimatic effect. However, the calculated groundwater recharge altitude, for this second group, is about 783 m a.s.l. which is substantially higher than the altitude of aquifer outcrops. On the other hand, the palaeoclimatic effect seems to be in contradiction with the evaporated aspect of this water of second group. This may correspond to a mixture of palaeoclimatic old groundwater and evaporated recent groundwater related to the return flow of irrigation water.

5.2.2. Interpretation of tritium and carbon isotope data

Tritium (^3H) is a useful groundwater age tracer for estimating the timing of modern recharge into aquifer systems, less than 50 years ago (Mann et al., 1982; Lucas and Unterwieser, 2000; Solomon and Cook, 2000). The tritium contents of the Haffouz and Bou Hafna

groundwaters vary from 0.03 to 1.23 UT. These relatively low values seem to be the result of pre-nuclear recharge and/or a mixture between pre-nuclear and contemporaneous recharge (Table 1).

^{14}C is largely used to characterize old hydrological systems and specify the different rates of mixing between young and old groundwater bodies (Clark and Fritz, 1997). The Haffouz and Bou Hafna groundwaters samples display ^{14}C activities ranging between 7.4 and 78.6 pmc, which identify two water groups. The first group includes groundwater samples distinguished by relatively high ^{14}C activities, suggesting their recent origin related to the recharge by present day rainfall in the foot of the bordering highland. The second group is composed of groundwater samples characterized by relatively depleted ^{14}C activities, indicating their palaeoclimatic origin in relation with recharge during the humid period of the Holocene and the Late Pleistocene (Fontes et al., 1983; Mamou, 1990; Ouda, 2000; Edmunds et al., 2003; Zouari et al., 2003; Jéribi, 2004; Dassi et al., 2005; Kamel et al., 2005; Kamel, 2007; Hamed et al., 2008).

6. Conclusion

Groundwater hydrodynamic and mechanisms of mineralisation of Haffouz and Bou Hafna aquifers have been investigated using conventional hydrogeological field investigations, major ions, and isotope hydrology data. The hydrologic investigation has demonstrated that the studied aquifers, which are unconfined, flow from the higher altitudes in the northern and the western parts of the study region to the discharge areas in the south and east. The interpretation of chemical data suggests that the mineralisation of Ca-Mg-HCO_3 and Ca-Mg-SO_4 groundwaters is mainly controlled by water–rock interactions represented by the dissolution of evaporate, dedolomitisation, and cation-exchange.

The stable isotope signatures (^{18}O , ^2H) reveal the existence of two groundwater groups. The first group, which corresponds to the non-evaporated groundwaters, is related to direct infiltration of present-day meteoric water. The second group, which consists of evaporated groundwater, shows an initial stable isotope composition highlighting a paleoclimatic origin and/or a mixture of recent and paleoclimatic sources. The tritium contents suggest that the studied groundwaters correspond to a mixture of pre-nuclear and contemporaneous water. Based on ^{14}C activities, two components of recharge have been identified: recent recharge related to the infiltration of present day rainfall in the foot of the bordering highland; and palaeoclimatic recharge occurring during the humid period of the Holocene and the Late Pleistocene.

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