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Hydrochemical Investigation and Quality Assessment of Groundwater in the BouHafna-Haffouz Unconfined Aquifers, Central Tunisia

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Abstract

Multivariate statistical techniques were applied to improve the understanding of the aquifers hydrodynamic and to identify the natural and anthropogenic processes that control the BouHafna and Haffouz groundwater quality. Some other parameters, such as sodium adsorption ratio (SAR), percent sodium (%Na), residual sodium carbonate (RSC), and permeability index (PI), were used to examine the suitability of groundwater for irrigation applications. Groundwater samples are classified into Ca-Mg-HCO_3 and Ca-Mg-SO_4 water-type. The statistical investigation permits to identify three different groups. The first group reflects the influence of water-rock interaction in relation with the dissolution of evaporatic minerals, the cation exchange process with phyllosilicates and the dedolomitization. The second and third groups, including the weakly mineralized groundwater samples, suggest, firstly, that the return flow of irrigation waters has a small, but not negligible contribution to the groundwater contamination, and secondly, the reduction of nitrate (NO_3) to nitrogen gas (N_2). Furthermore, it has been demonstrated that the majority of the groundwater samples are suitable for irrigation uses.

Keywords: Central Tunisia, statistical techniques, water-rock interaction, dissolution, cation exchange, suitable, irrigation uses

1. Introduction

In most parts of Central Tunisia, and particularly in Haffouz and BouHafna regions, groundwater has played a fundamental role in shaping the social and economic development.

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Due to rapid demographic growth and agricultural progress, exploitation of groundwater has increased dramatically to provide drinking water to rural community, support irrigation, and maintain ecosystems. During the past 30 years, the exponential increase in water abstraction from Haffouz and BouHafna aquifers has caused ground water depletion, a term often defined as long-term water-level declines, and an increase in salinity of groundwater pumped from wells situated mainly downstream. On the other hand, recent changes in agricultural land use and irrigation may result in groundwater contamination throughout agricultural fertilizers and pesticides applied to fields. Therefore, information about irrigation groundwater quality is critical to the understanding of necessary management changes for long-term productivity [1]. Proper assessment of groundwater sustainability requires understanding and quantification of human effects on water resources using analysis, application of management practices, and revision.

Within this framework, a combined hydrogeological and hydro-chemical data were examined, using statistical methods, to determine (i) natural and anthropogenic processes that control the groundwater mineralization; (ii) the origin of different water bodies and their sources of recharge; and (iii) to assess the suitability of groundwater for agricultural purposes.

2. General features

The Haffouz study areas, which make up part of the Kairouan plain in Central Tunisia, cover about 1192 Km^2 and lie between longitudes 39G 55′ and 39G 70′ north and latitudes 7G 88′ and 8G 33′ east (**Figure 1**). This region is bounded by Ouesselat and Jebil Mountains in the north, the Trozza Mountain in the south, and the plain of El Ala in the west. The altitude of the study area ranges from 200 m a.m.s.l. at Haffouz plain to 997 m at Trozza Mountain. The study area has a semi-arid climate with mild, wet winters and warm, dry summers [2]. The average 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 an annual rainfall ranging between 300 and 500 mm/year. The annual total evaporated exceeds 1720 mm Piche [3].

The drainage network consists of several nonperennial Wadis such as Mourra, 55 Zabbes, and MsilahWadis that drain toward the Merguellil Wadi, the most important Wadi of the Kairouan plain [2] (**Figure 5**).

2.1. Geological setting

Several geologic studies [4–11] have focused on the stratigraphy, structure, and surficial and subsurface deposits characteristics in the study district. As shown in the geologic map and in the lithostratigraphic column, the geological formations, which outcrop in the study area, are represented by sedimentary series ranging from the Trias to the Quaternary (**Figures 1** and **2**). The Trias deposits, which outcrop in Cherichira Mountain, consist mainly of an alternation of gypsum, clay, and carbonate levels [6]. The Cretaceous units that outcrop in the foot of Trozza

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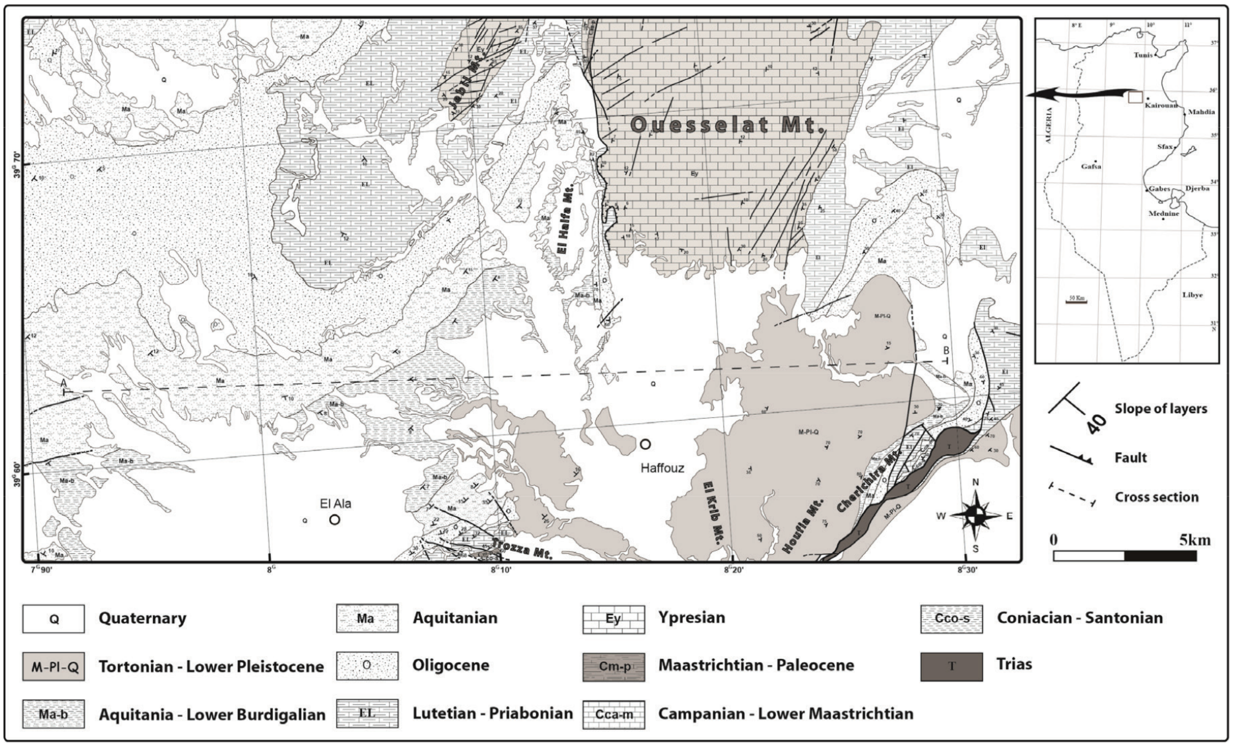

Figure 1. Location and geological map of the study areas.

Mountain are constituted of the Yprisian limestone of AlagAbiod and El Metlaoui formations. These formations are covered by the Lutetian limestone and clay of Cherahil and Souar formations, respectively. On the Lutetian deposits, the sandy and sandstone units of the Oligocene repose with an average thickness of about 350 m. These deposits belong to the Fortuna formation out crop in the central part of the study area. The Miocene deposits are represented by thick calcareous and clayey layers, which correspond to A in Grab and Mahmoud formations, respectively. These formations are overlaid by the sandy clay of the Beglia Formation and the clay Saouaf Formation. The Quaternary sediments that are represented by sand, clay, and conglomerate deposits occur in the plains of El Ala and Haffouz and in the Merguellil Wadi depression.

Structurally, the BouHafna basin is bordered to the east by the major fault of Ouesselat Mountain and corresponds to a syncline structure, which consists of the sandy deposits of Fortuna Formation. However, the Haffouz region, which is limited by the faults F1 in the east and F2 in the west, corresponds to a Graben structure filled by the sand, sandstone, sandy clay, and clay of Mio-plio-quaternary (**Figure 3**).

2.2. Hydrogeological setting

The BouHafna aquifer is lodged in the sand and sandstone deposits of the Oligocene. This aquifer, which is unconfined overall the basin, has a thickness varying largely from 50 to

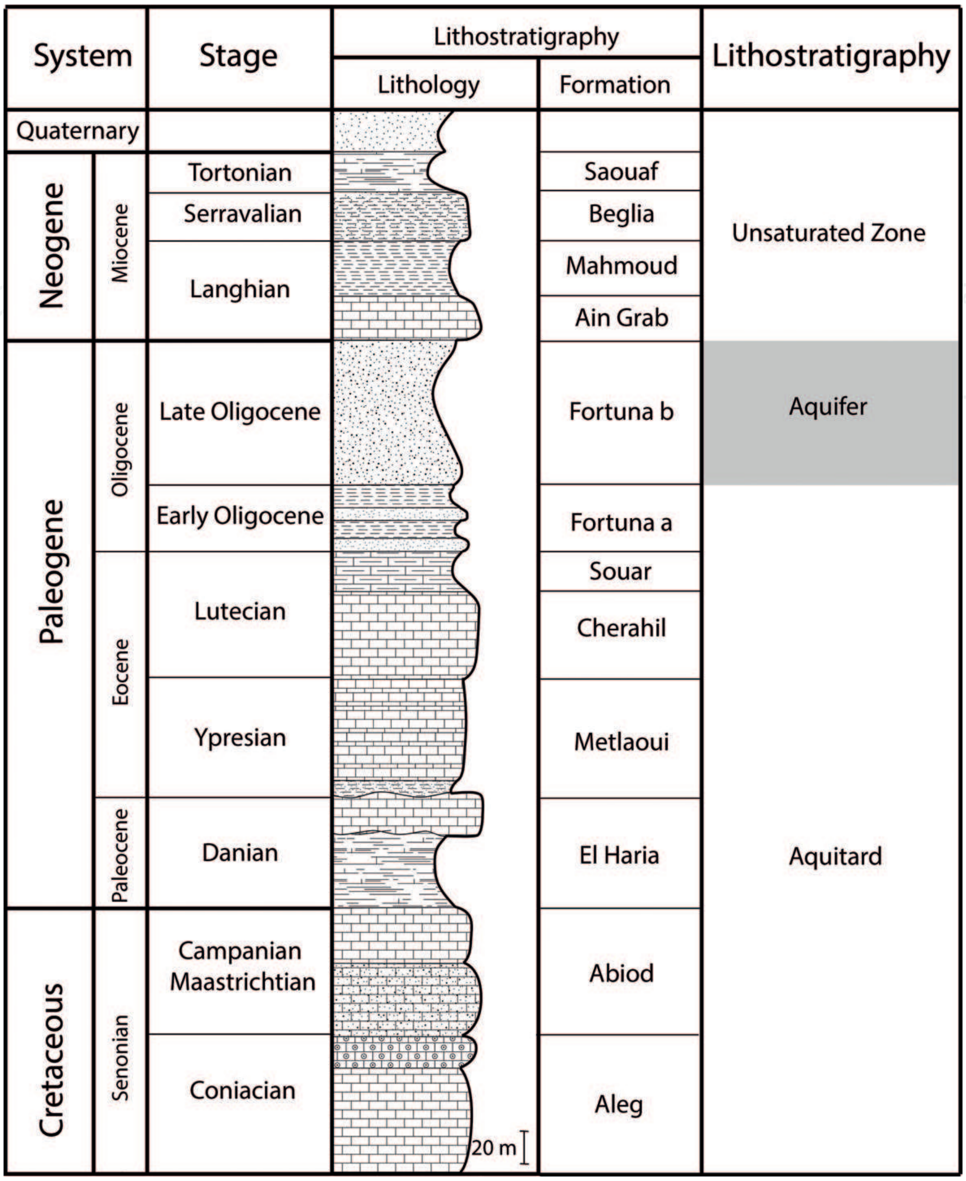

Figure 2. Simplified lithostratigraphic column of the study areas.

300 m. The bedrock of this aquifer is constituted of the Lutetian marly deposits of Souar Formation (**Figure 3**). Nevertheless, the Haffouz unconfined aquifer is constituted of the Mio-Plio-82 Quaternary detrital deposits with a thickness of about 1000 m.

The piezometric map (**Figure 4**) shows that the general directions of groundwater flow are N-S, NW-SE, and W-E in the case of BouHafna aquifer, and they are oriented NW and NE in the case of Haffouz aquifer. This may indicate that the recharge of BouHafna aquifer occurs in the Western part of the basin and in the pediment of Ouesselat and Jebil Mountains, where the Oligocene sediments outcrop largely. For the Haffouz region, rainwater infiltrates and recharges the aquifer, locally, in the pediment of Ouesselat Mountain. The hydraulic gradient of BouHafna and Haffouz aquifers varies from 0.009 to 0.003, highlighting the importance of localized recharge in the pediment of mountains, in the northern part, and the linear recharge by the Merguellil Wadi, in the southern part of the region. This variation of hydraulic gradient can also be explained by the lateral variation of lithology caused by abundance of clayey layer, especially in the south of this aquifer.

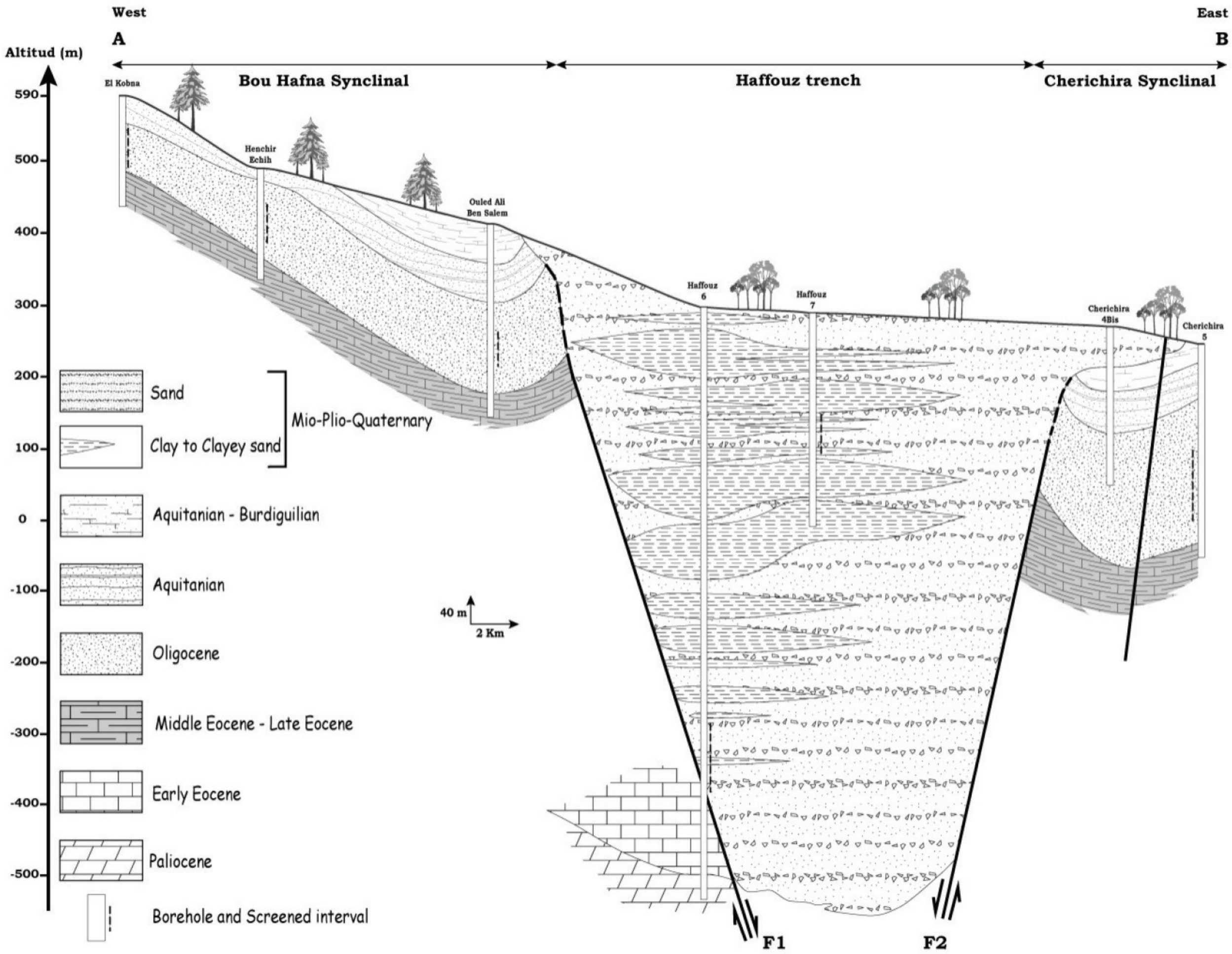

Figure 3. Hydrogeological cross section of Haffouz and BouHafna aquifers.

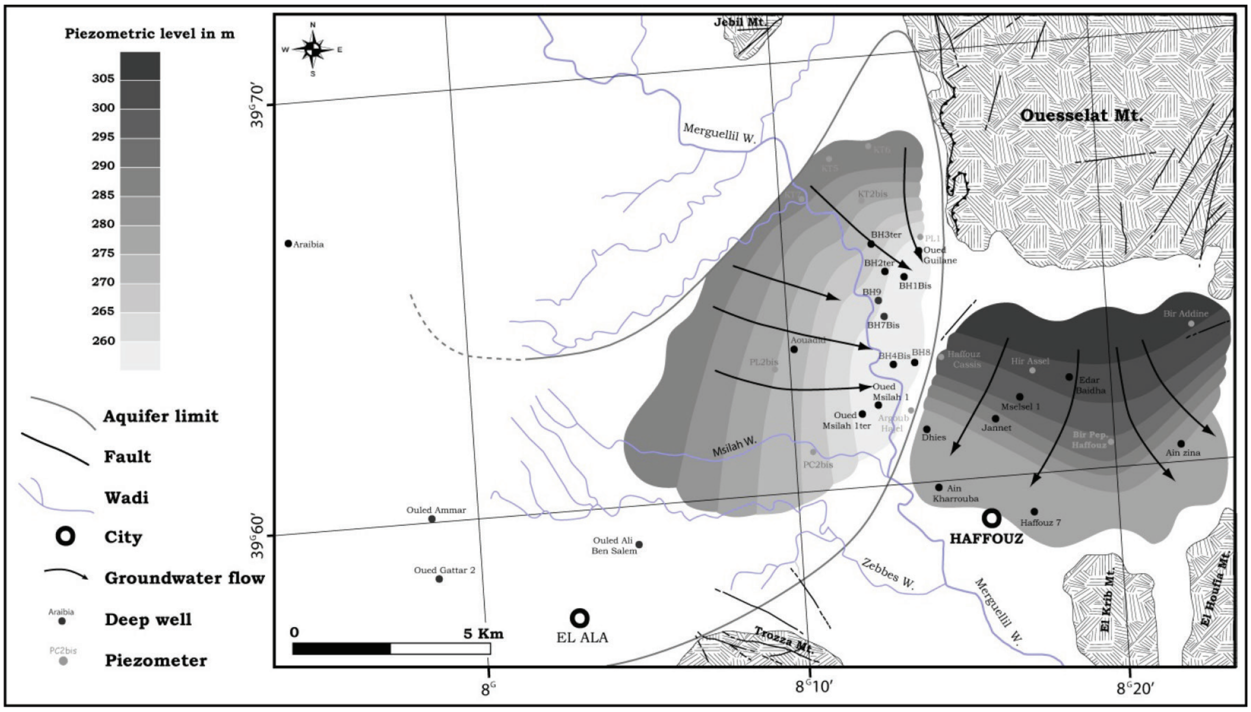

Figure 4. Piezometric and sampling map of Haffouz and BouHafna aquifers [12, 13].

3. Sampling and analytical methods

A total of 22 boreholes were sampled for chemical analysis, 15 samples collected from the BouHafna aquifer and 7 samples from the Haffouz aquifer. The physicochemical parameters such as Temperature (T°C), pH, and electrical conductivity (EC) were measured directly in situ using portable meters. Groundwater samples were analyzed for major ions in the laboratory of Radio-Analyses and Environment of the school of engineers of Sfax, Tunisia. Major cation concentrations were determined by 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.

4. Results and discussion

4.1. In situ measurements interpretation

The physicochemical parameters and overall hydrochemical data of Haffouz and BouHafna groundwater samples are presented in **Table 1**. Groundwater temperature values are relatively homogenous and vary from 19.9 to 25.3°C. The pH measurements range between 7.39 and 7.73 for Haffouz aquifer and between 7.01 and 7.74 for BouHafna aquifer. This may indicate a neutral to slightly alkaline pH but suitable for drinking and agricultural purposes. Electrical conductivity (EC) values, which vary in a wide range between 422 and 1623 μS/cm, are probably related to the signification variation of the TDS values that range from 203 to 1188 mg/l, respectively.

Aquifer	Well	Cl	NO3	SO4	HCO3	Na	K	Mg	Ca	pH	TDS (mg/l)	EC (μs/cm)	T°C
		(mg/l)											
Haffouz	AK	50,00	1,50	50,00	219,00	27,40	2,12	13,20	73,50	7,53	400,00	520,10	19,90
	AZ	42,00	1,90	60,00	219,00	35,70	2,05	12,60	69,05	7,73	464,00	510,10	20,00
	DH	57,00	0,70	60,20	235,00	39,10	2,55	21,50	79,30	7,53	400,00	834,00	20,10
	JA	24,62	4,06	28,86	213,50	37,98	2,72	22,52	34,00	7,49	240,00	484,00	21,70
	H 7	25,88	8,15	17,04	213,50	45,21	1,46	10,34	38,50	7,61	216,00	481,00	22,00
	DEB	20,81	8,49	11,31	213,50	20,75	1,06	9,86	46,10	7,46	203,00	422,00	21,60
	M 1	17,23	0,00	7,26	244,00	21,53	0,97	9,79	49,00	7,39	207,00	436,00	24,70
Bou Hafna aquifer	BH 4bis	57,75	17,46	151,92	250,10	38,50	2,05	31,07	85,00	7,47	579,00	939,00	23,90
	BH 8	71,21	12,67	161,51	208,60	51,50	2,45	36,51	75,00	7,11	516,00	945,00	24,10
	OM 1 ter	101,36	10,47	512,37	225,70	97,42	3,44	59,17	154,00	7,14	1188,00	1623,00	22,80
	BH 2 ter	75,35	9,07	213,18	268,40	58,38	3,78	41,74	117,44	7,31	655,00	1074,00	24,70
	OEG 2	57,40	8,56	51,79	195,60	39,57	1,82	19,23	51,10	7,01	337,00	596,00	22,40
	BH 7 bis	57,49	14,23	113,97	225,70	48,58	2,43	34,26	60,85	7,19	426,00	845,00	24,60
	EA	35,05	20,23	50,17	219,60	39,96	2,67	21,75	36,10	7,34	305,00	611,00	22,70
	AO	50,22	16,37	89,17	256,20	42,12	1,90	25,57	60,50	7,21	431,00	767,00	22,00
	BH 3 ter	96,89	9,01	383,54	231,80	109,42	4,01	60,07	105,00	7,14	1089,00	1594,00	24,40
	BH 9	49,86	12,41	95,70	244,00	46,94	2,12	28,54	55,65	7,22	386,00	733,00	22,60
	BH 1 bis	81,53	7,52	202,66	280,60	59,37	3,19	42,30	95,35	7,26	668,00	1085,00	25,30
	OABS	53,94	10,38	58,39	219,60	38,95	1,90	22,51	55,90	7,09	367,00	664,00	23,80
	OA	70,48	25,42	124,14	231,80	48,21	2,92	38,26	61,53	7,74	511,00	913,00	23,50
	OM 1	58,88	9,21	144,81	237,90	51,87	2,46	30,35	61,78	7,23	471,00	852,00	23,80
	OEG	65,95	31,10	61,23	268,40	59,23	1,58	17,72	64,50	7,41	449,00	819,00	22,50

Table 1. In situ measurement and geochemical data of groundwater samples.

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4.2. Water type

The data plotted in the Piper diagram [14] show that Haffouz and BouHafna groundwater samples have the same Ca-Mg-HCO_3water-type, except for some samples collected from BouHafna aquifer, which are distinguished by Ca-Mg-SO_4 water-type (**Figure 5**).

4.3. Correlation matrix

The correlation matrix of 12 parameters (Cl, NO_3, SO_4, HCO_3, Na, K, Mg, Ca, TDS, EC, pH, and T°C) was computed in order to calculate the contribution degree of each hydrochemical parameters to the groundwater mineralization [15, 16] (**Table 2**).

Overall groundwater samples display positive and strong correlations between Cl, SO_4, Na, Mg, and Ca versus TDS (>0.9), providing insight into the large contribution of these ions to BouHafna and Haffouz groundwater salinization. There is well positive correlation between Na and Cl ($r = 0.84$), indicating the same origin of these elements likely related to the halite dissolution. The strong and positive relationship between Ca and SO_4 ($r = 0.98$) suggests that these ions derive from the same origin probably in relation with the dissolution of gypsum and/or anhydrite. The moderate correlation between NO_3 and the majority of ions can be explained by an anthropogenic effect related to the pollution through return flow of irrigation water.

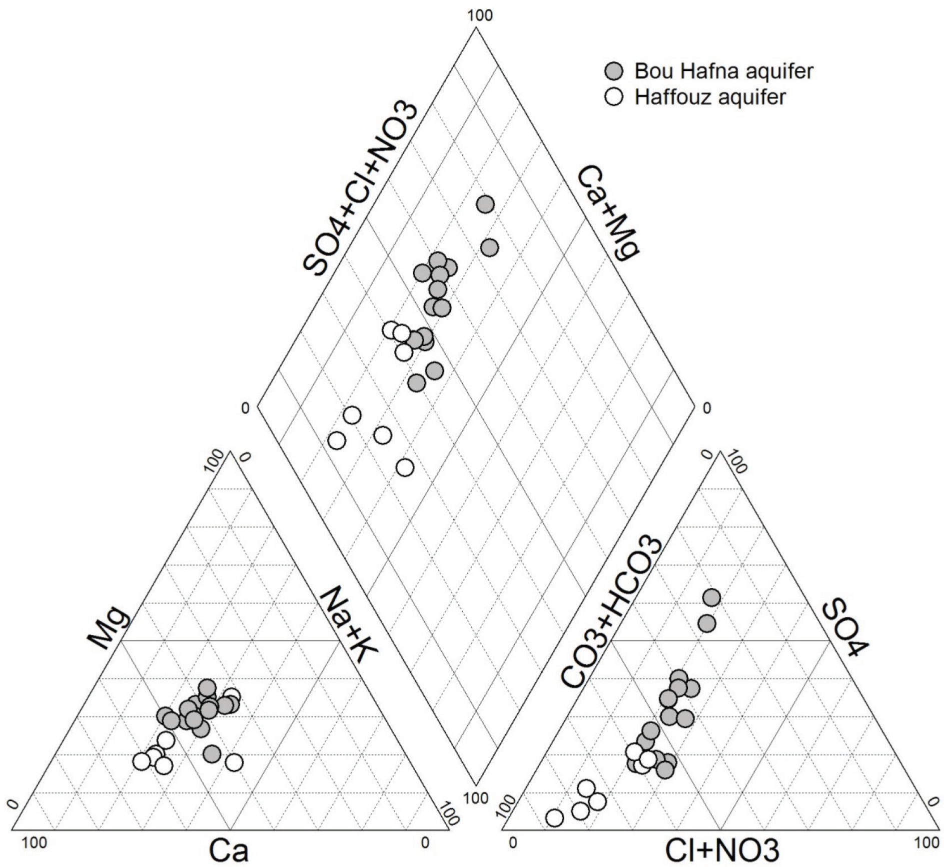

Figure 5. Piper diagram of Haffouz and BouHafna aquifers.

	Cl	NO_3	SO_4	HCO_3	Na	K	Mg	Ca	pH	TDS	EC	T°C
Cl	**1,000**											
NO_3	0,263	**1,000**										
SO_4	**0,858**	0,076	**1,000**									
HCO_3	0,322	0,276	0,203	**1,000**								
Na	**0,839**	0,209	**0,902**	0,207	**1,000**							
K	**0,759**	0,035	0,757	0,226	0,750	**1,000**						
Mg	**0,882**	0,199	**0,924**	0,271	**0,874**	**0,865**	**1,000**					
Ca	**0,835**	-0,055	**0,891**	0,363	**0,720**	**0,676**	**0,772**	**1,000**				
pH	-0,419	-0,050	-0,402	0,009	-0,402	-0,212	-0,443	-0,250	**1,000**			
TDS	**0,900**	0,098	**0,976**	0,260	**0,906**	**0,766**	**0,901**	**0,908**	-0,329	**1,000**		
CE	**0,927**	0,210	**0,956**	0,334	**0,923**	**0,791**	**0,954**	**0,861**	-0,407	**0,961**	**1,000**	
T°C	0,385	0,270	0,384	0,403	0,370	0,323	0,550	0,246	-0,502	0,320	0,454	**1,000**

Table 2. Correlation matrix of the 22 physicochemical parameters.

4.4. Principal component analysis

The principal component analysis (PCA), which is widely used in environmental studies, exhibits complex associations among several variables and individuals [17, 18]. Factors analysis was applied to the hydrochemical data set (Na, K, Mg, Ca, Cl, SO_4, HCO_3, NO_3, EC, and TDS) of BouHafna and Haffouz aquifers in order to precisely specify the main processes controlling the groundwater mineralization (**Figure 6a**). The PCA approach has preserved only the first two factors, which represent 74.63% of total samples variance (62.77% for F1 and 11.86% for F2). In the variables space, the F1 factor displays strong positive loadings for Na, K, Mg, Ca, Cl, SO_4, NO_3, and TDS. The strong correlations for the referred major ions suggest that the groundwater mineralization is acquired through water-rock interaction processes. The positive loading for NO_3 may reflect the influence of the return flow of irrigation water as a potential source of contamination related to the application of fertilizers. The F2 factor takes positive loadings for pH and negative loading for NO_3 and HCO_3. The inverse relationship between pH and NO_3 with respect to F2 factor lends support to the implication of the denitrification process in the groundwater salinization.

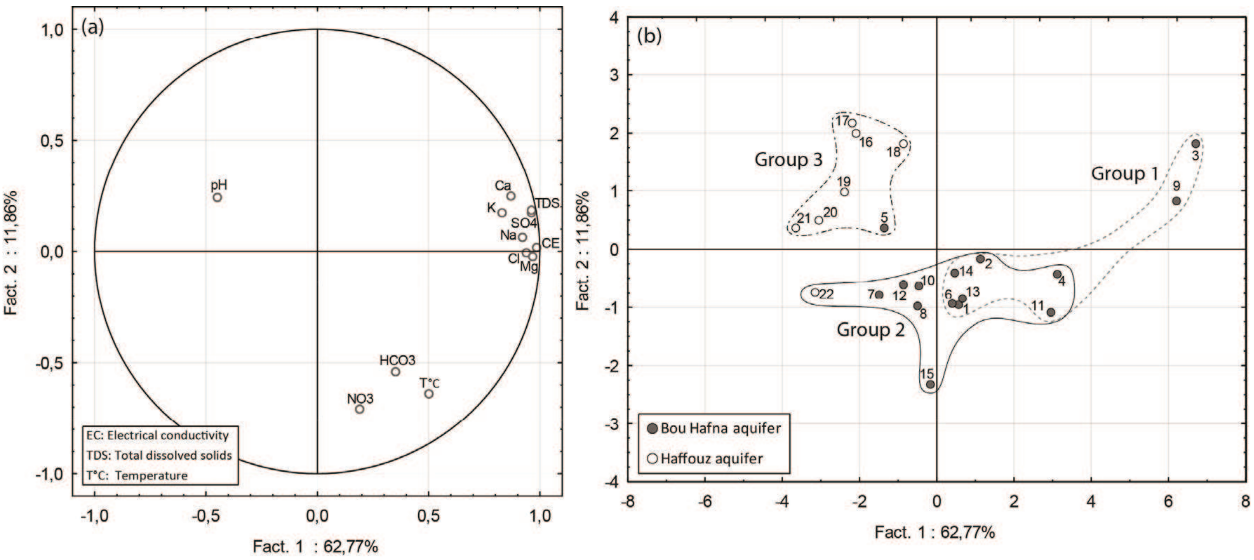

Figure 6. Variable space deduced from the geochemical PCA (a); cluster analysis main sample groups according to their scores for F1 and F2 (b).

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The projection of the 22 samples on the same first factorial plan (F1, F2) permits to classify groundwater samples into three groups (**Figure 6b**). The first group, which lies in the positive side of the first factor (F1), is mainly represented by the BouHafna groundwater samples. This group is mainly influenced by natural processes of mineralization in relation with the dissolution of evaporatic minerals, dedolomitization, and cation exchange. These processes are summarized in the schematic model, which indicates that all groundwater samples display an undersaturation state with respect to gypsum and anhydrite, suggesting that dissolution of these minerals takes place there (**Figure 7**). Supplementary concentration of Ca^{2+}deriving from gypsum dissolution can cause calcite precipitation [19]. On the other hand, the decrease of bicarbonate concentration related to the precipitation of calcite causes the groundwater to be undersaturated with respect to dolomite and promotes the incongruent dissolution of this mineral known as dedolomitization [20–22].

The second group is mainly composed of BouHafna groundwater samples, which are strictly associated with intensive agricultural activities. This group, which plots in the negative side of the second factor (F2), is strongly associated with nitrate and highlights the considerable contribution of the return flow of irrigation waters to the contamination of groundwater. The third group comprises mainly the groundwater samples collected from the Haffouz aquifer. This group, which falls in the negative side of F1 and the positive side of F2, is extremely related to pH and negatively correlated with nitrate element. This position lends support to the predominance of denitrification processes, which corresponds to the biological reduction of nitrate (NO_3) to nitrogen gas (N_2).

4.5. Gibbs plot

Gibbs plot is used in the present investigation to confirm the significant role played by the natural hydrochemical processes already cited and their effect on groundwater quality [23]. Plot of (Na + K)/(Na + K + Ca) *versus* TDS shows that all the groundwater samples of the BouHafna and Haffouz aquifers fall in the field of water-rock interaction suggesting that the weathering of rocks is the major process that controls the groundwater mineralization in this region (**Figure 8**). Moreover, the plot of Cl/(Cl + HCO_3) *versus* TDS displays that groundwater

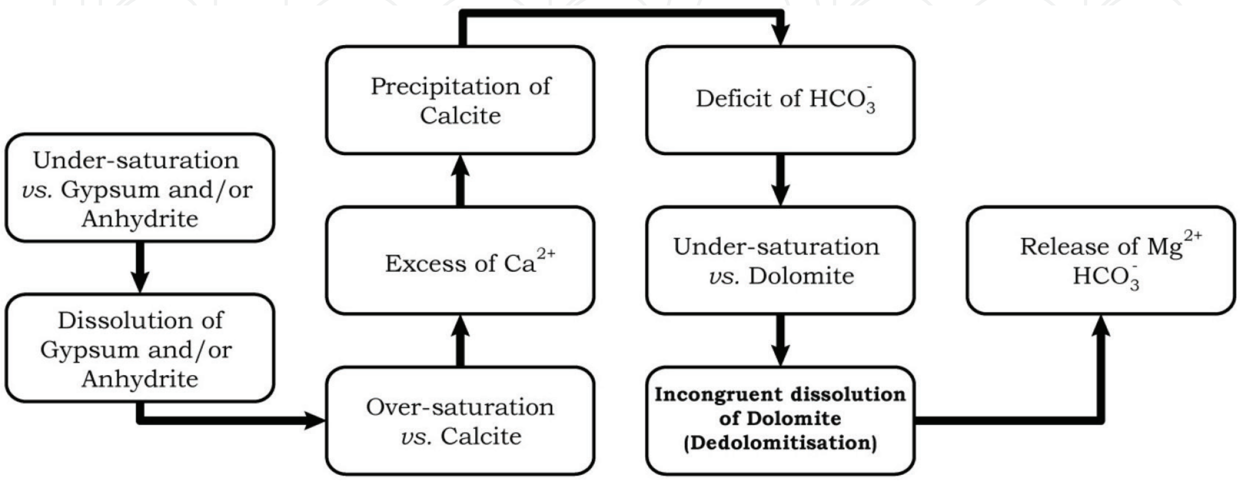

Figure 7. Schematic model showing the dedolomitization process.

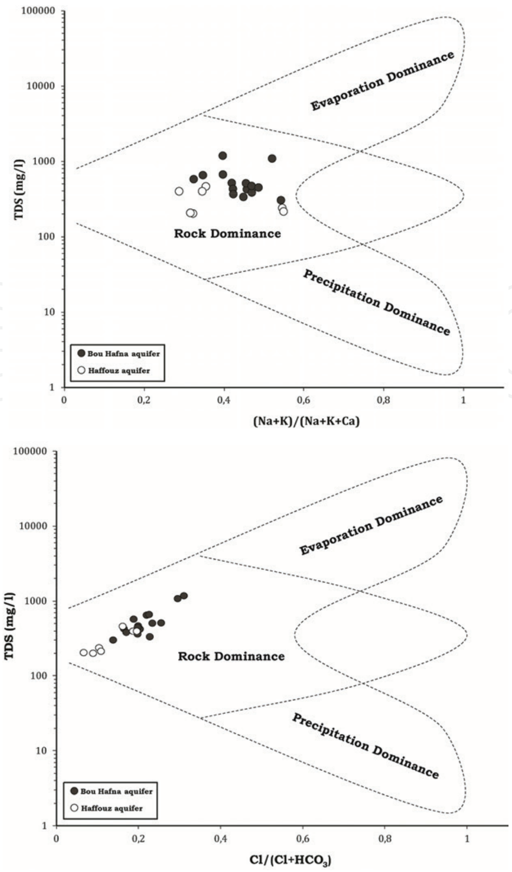

Figure 8. Gibbs plots explain groundwater geochemical process in the Haffouz and BouHafna regions.

samples fall on a linear trend on the field of rock dominance with a slight tendency toward the evaporation domain, highlighting the contribution of the evaporation process to the chemical composition of groundwater in the study area. In fact, for the Bouhafna groundwater samples, evaporation greatly increases the concentration of major ions resulted from chemical weathering, leading to higher salinity [24].

4.6. Suitability of groundwater for irrigation

Several parameters can be used to determine the suitability of groundwater for irrigation, that is, the electrical conductivity (EC), sodium adsorption ratio (SAR), and percent sodium.

The plot of analytical data on the Wilcox (1955) diagram shows that 83% of groundwater samples collected from the Haffouz aquifer belong to excellent category. All groundwater samples collected from the BouHafna aquifer, and only one sample of the Haffouz aquifer falls in the field of good to permissible (**Figure 9**). These very low to low SAR and low to medium salinity suggest that the studied groundwaters are suitable to moderately suitable for irrigation purposes without any threat of imposition of any hazard. Therefore, the application of these groundwaters in irrigation will be very advantageous as it will increase the agricultural yield.

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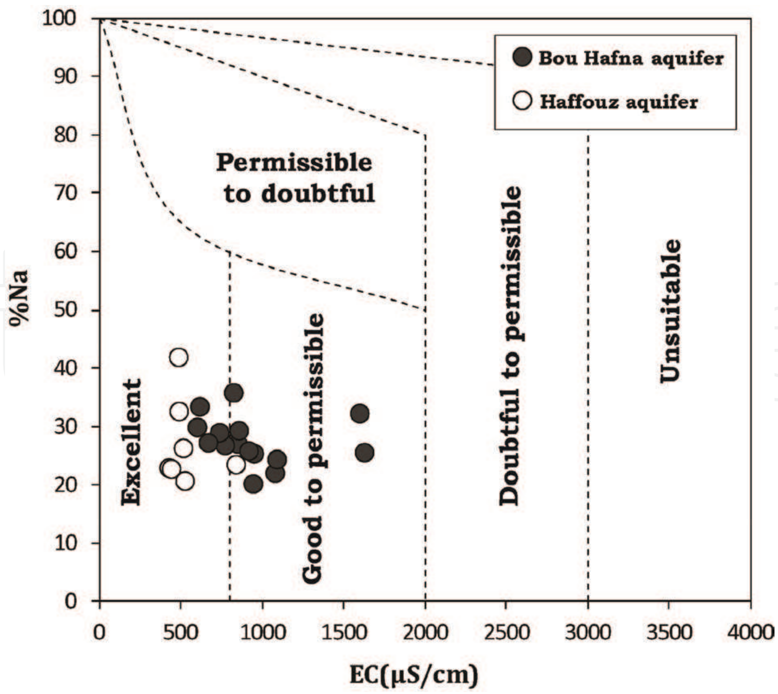

Figure 9. The quality of groundwater in relation to salinity and sodium hazard.

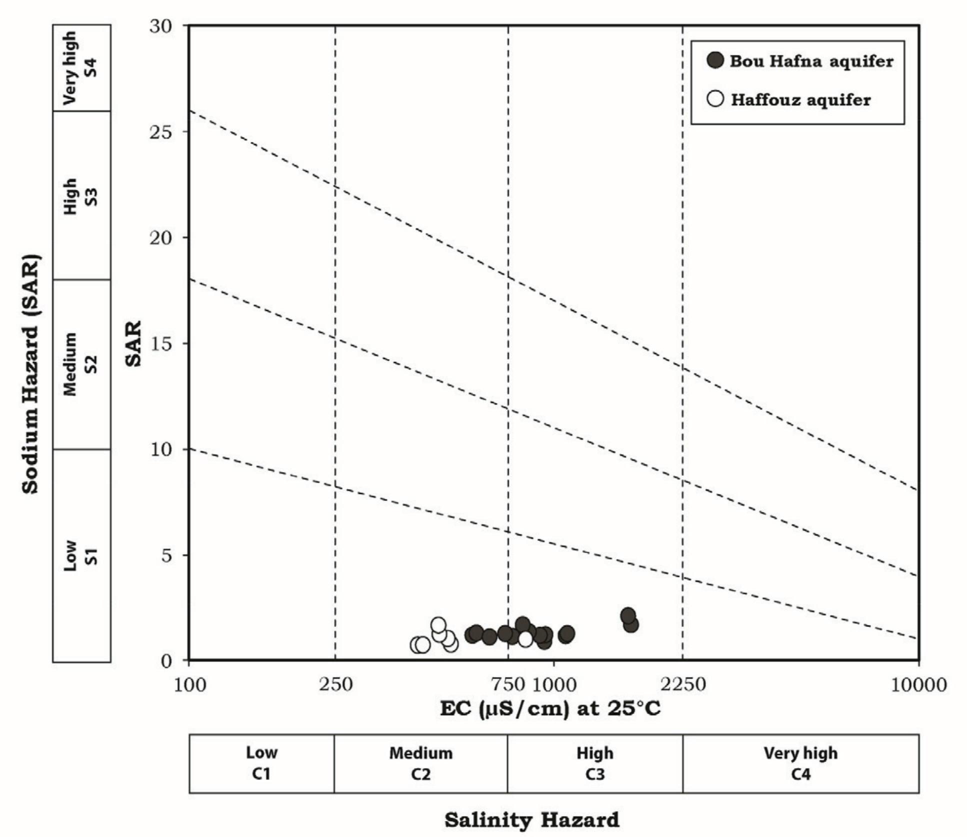

Figure 10. The quality of groundwater in relation to electrical conductivity and percent sodium (Wilcox diagram).

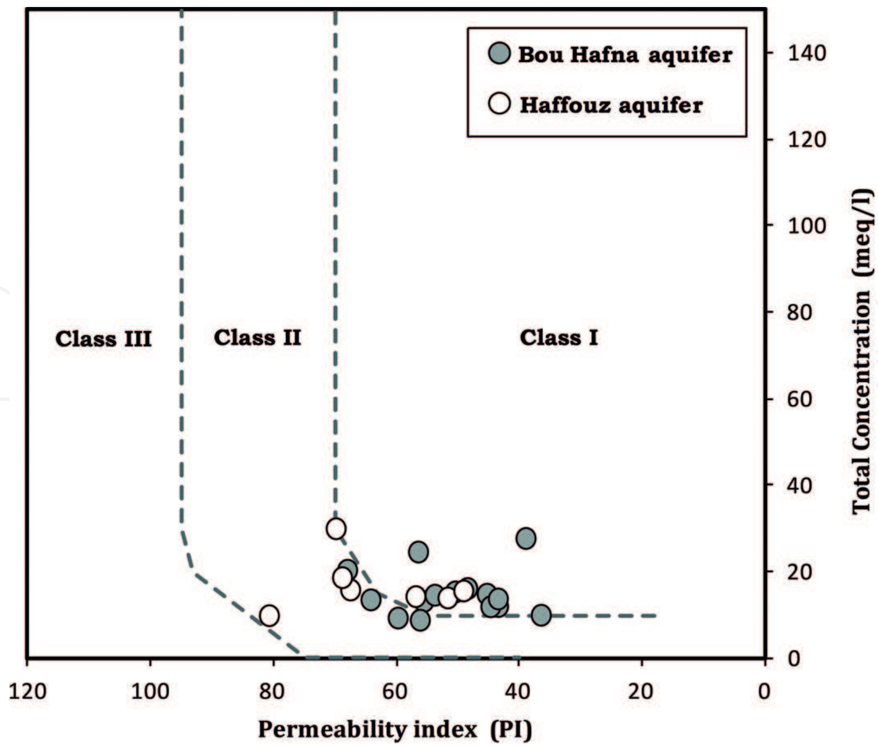

Figure 11. Doneen plot for Haffouz and BouHafna groundwater samples.

The correlation of sodium adsorption ratio (SAR) *versus* electrical conductivity shows that 55% of groundwater samples fall in the field of C3–S1, highlighting high salinity and low sodium in groundwater, which is suitable for the irrigation of all types of soil with little danger of exchangeable sodium. However, 45% of the samples fall in the field of C2–S1, reflecting low alkalinity hazard and medium salinity of groundwater. This may indicate that irrigation water can come from the referred groundwaters without danger of exchangeable sodium on all types of soils (**Figure 10**).

4.7. Permeability index (PI)

The permeability index (PI) parameter was used to assess the suitability of groundwater for irrigation. Indeed, the long-term irrigation with relatively enriched Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- groundwater can affect soil permeability [25]. Groundwater in the study area displays PI value ranging from 43 to 70% with an average value of 55% (PI greater than 25%) indicating that are good and suitable for irrigation purposes. Moreover, Doneen plot shows that groundwater samples in the study area fall in the fields of Class I and II, highlighting excellent to good permeability (**Figure 11**).

5. Conclusion

The hydrochemistry of BouHafna and Haffouz aquifer was investigated employing multivariate statistical approach in order to identify different processes that control groundwater mineralization. This investigation reveals the predominance of Ca-Mg-HCO_3 and Ca-Mg-SO_4 water-types. These water facies are derived mainly from water-rock interaction processes, i.e., the dissolution of halite, gypsum, the dedolomitization, and the cation exchange. On the other hand, return flow of irrigation water has resulted in elevated nitrate concentrations in groundwater especially in the agricultural zones, which are characterized by an excessive use of fertilizer. Thus, it is important to protect the aquifers against overexploitation and groundwater quality deterioration related to the evaporate dissolution and agricultural contamination. For these reasons, in the BouHafna and Haffouz regions where groundwater resources are under the great development stress and environmental pressure, some preventive measures should be taken. These are (1) control the exploitation groundwater; (2) the definition of special groundwater resources protection zones; (3) control the potential processes and sources of salinization; and (4) improvement of diffuse source groundwater pollution.

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