



Evaluation of the quality of groundwater for its appropriateness for irrigation purposes using Water Quality Index (WQI), Mchira-Teleghma aquifer case study, northeastern Algeria

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Abstract

The Mio-Plio-Quaternary groundwater of Mchira-Teleghma suffers from an increasing rate of salinity especially in the northwestern part. To identify the reason for the water's salinity and its aptitude for irrigation, physico-chemical analyses of 20 water samples, which were based on the different physical and chemical parameters (electric conductivity EC, pH, Ca²⁺, Mg²⁺, Na⁺, K⁺, HCO₃⁻, Cl⁻, SO₄²⁻, NO₃⁻ and Sr²⁺), were carried out during the period of October 2015. This study showed disquieting anomalies of electric conductivity that reached the value of 4376.14 μS cm⁻¹. The statistical analyses, the multivariate statistics: the principal component analysis, Q-mode cluster analyses, Sr²⁺/Ca²⁺ ratio and water type showed that the hydrochemistry of Mchira-Teleghma groundwater is controlled by the dissolution of carbonate rocks and the leaching of evaporite processes, which proved that these anomalies of the MPQ groundwater's salinity of Mchira-Teleghma are mainly determined by the leaching of Triassic gypsum formations process. This hydrogeochemical process generates an unsuitable quality of water based on Wilcox's and Water Quality Index's methods, whereas Richard's method classifies all water samples to C3S1 and C4S1 classes as they are recommended to be used with salt-tolerant species in well-drained and leached soils.

Keywords Water Quality Index · Hydrogeochemical process · Salinity · Triassic gypsum · Mchira-Teleghma aquifer and irrigation

Introduction

Climate change has a significant impact on water resources, particularly in the Middle East and North Africa (MENA) region. These latter are generally characterized by the irregularity of the rainfall and the high prevailing temperatures that cause a strong evapotranspiration. In addition to the presence of evaporitic rocks, particularly the gypsum, in the North Africa region (Aubert 1975) that are leached by groundwater, water's salinity is consequently increased and this can explain the deterioration of groundwater quality. In this context, several researches have been conducted on groundwater to assess the hydro-chemical processes, groundwater quality and water suitability for the irrigation of this region. They have shown that groundwater hydrochemistry depends on two important resources: natural and anthropogenic processes (Barkat et al. 2021; Bouteraa et al. 2019; Khedidja and Boudoukha 2015; Mihoubi 2009). They proved that the hydrochemistry of the studied groundwaters is mainly controlled by two primordial processes: the leaching of the evaporitic rocks and the dissolution of the carbonate massif.

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Taking into account the impact of the evaporation which synchronizes the two previous processes and contributes to the increase in the rate of mineralization, the aim of the present paper is to determine the Mchira-Teleghma groundwater mineralization origin, with thorough comprehension of the major processes that controlled this mineralization, and to evaluate the water quality for its appropriateness for irrigation purposes.

Geological and hydrogeological settings

The plain of Mchira-Teleghma is an agricultural region located in the territory of Mila’s province, about 320 km from the capital Algiers. It is a part of the exoreic basin of Kebir Rhumel (Mebarki 2005) in north-eastern of Algeria. The plain of Mchira-Teleghma is a flat plain surrounded by different mountains with different altitudes, such as: DJ. Faham (1165 m), DJ. Teioualt (1285 m), DJ. Tadjerout (1011 m), DJ. Timetlas (1019 m), DJ. Feltene (1113 m), DJ. Grouz (1187 m) and DJ. Chettabbah (1263 m). The semi-arid climate prevails in this area with a precipitation

of about 300–400 mm/year (Mebarki 1994). The plain is drained by several wadis with a less dense hydrographic network. The most important wadi is O. Rummel, which extends from the southwest to the northeast along the plain. The hydrogeological system of Mchira-Teleghma consists of mio-plio-quaternary MPQ aquifer and Jurassic–Cretaceous aquifer. The superficial unit of the mio-plio-quaternary is constituted from unconsolidated materials (gravel, silt, pebbles, rolled stones, rolled blocks and conglomerates), which form an alluvial tablecloth. The Jurassic–Cretaceous units are generally constituted of marls and carbonate massifs (limestone and/or dolomite rocks (Vila 1977b) forming karstic underground water. It is noted of the presence of Triassic evaporitic outcrops (clay and gypsum), which stand above the northern part and western borders of the study area (Vila 1977a) (Fig. 1). In order for establishing the piezometric map of MPQ groundwater (Fig. 2), the piezometric campaign was carried out in October 2015, where the water table depth ranges from 0.7 to 26.7 m (Table 1). The piezometric study shows that the flow of water generally occurs in the south-west to the northeast.

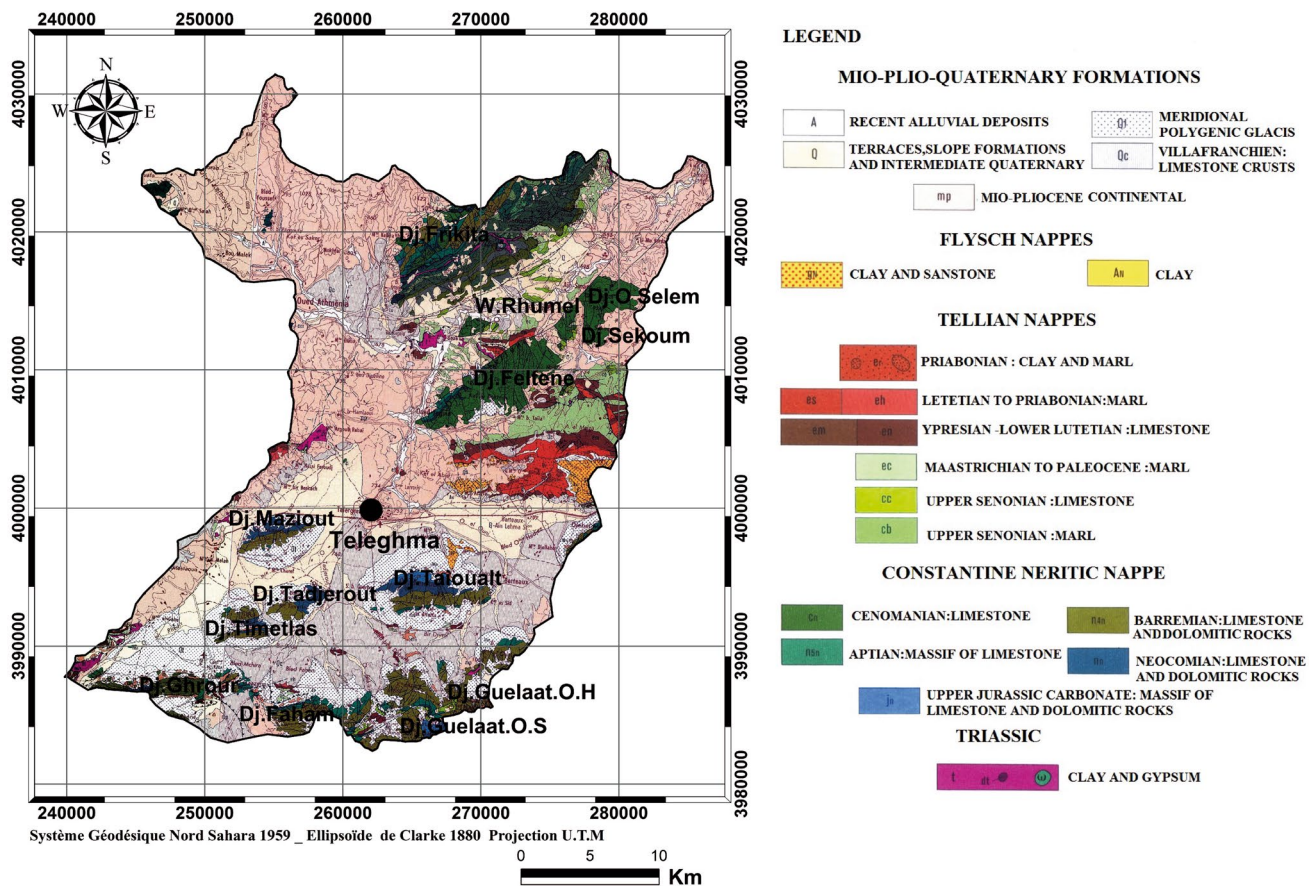
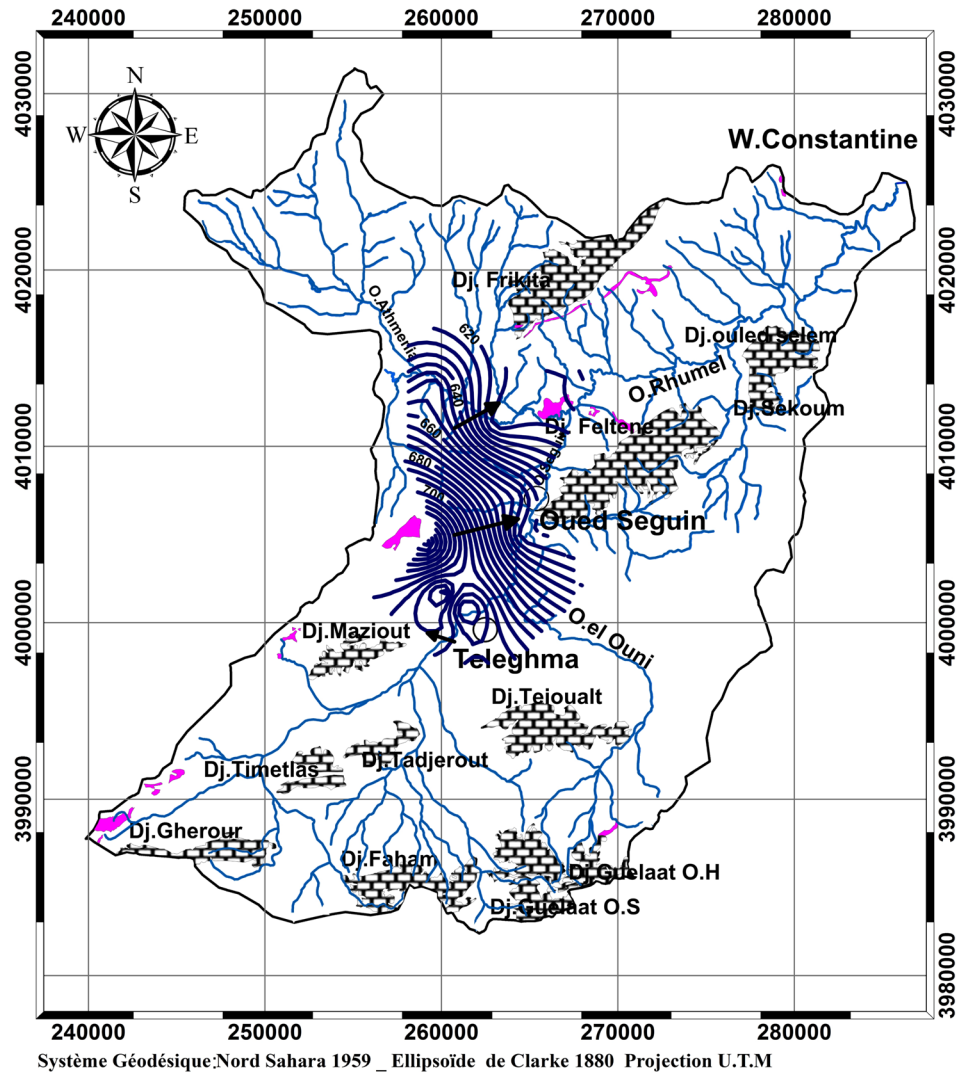








Fig. 1 Geological map of Mchira-Teleghma area (Villa 1977)

Fig. 2 Hydrogeological map of Mchira-Teleghma aquifer in October 2015



LEGEND:

-  : Carbonate Massif.
-  : Clay and gypsum.
-  : Hydrographic network.
-  : piezometric contour.
-  : Flow direction.
-  : City.

Materials and methods

Sampling analysis

The collection of water samples is a delicate process in which the greatest care must be taken as the analytical

results and interpretation that will be given rely on it. The sample should be homogeneous, representative and obtained without modifying the physical and chemical characteristics of water (dissolved gases, suspended matters, etc.) (Rodier 2009). The field investigation led us to choose twenty wells that are spread all over the area to cover the whole plain.

Table 1 Physico-chemical analysis values and well depth

Well	EC ($\mu\text{S cm}^{-1}$) Corrected to 20 °C	EC ($\mu\text{S cm}^{-1}$) Corrected to 25 °C	pH	Cations (mg L^{-1})				Anions (mg L^{-1})				Sr^{2+}	Depth (m)
				Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}		
P1	1482.91	1654.51	6.6	132.27	36	118.11	8.355	244	248.5	180	1.2	/	13.25
P2	2436.95	2718.95	6.8	212.43	46.44	87.86	3.155	213.5	330.15	265	0.1	/	15
P3	1503.65	1677.65	6.9	100.2	15.6	95.44	3.273	372.1	195.25	175	0.2	/	9.75
P4	1503.65	1677.65	6.9	164.33	45.6	85.99	2.177	274.5	159.75	175	0.2	1.675	4.3
P5	995.52	1110.72	7.2	56.12	49.08	79.12	2.035	201.3	95.85	160	0.2	/	0.7
P6	3142.11	3505.71	6.7	204.41	158.16	151.28	12.715	311.1	337.25	400	72	11.4	3.25
P7	1690.31	1885.91	7.1	116.24	71.76	120.06	9.313	286.7	248.5	255	0.1	/	4.1
P8	1275.51	1423.11	7.2	76.16	59.88	111.55	8.311	329.4	159.75	180	48	1.025	17.4
P9	1119.96	1249.56	6.9	96.2	40.68	59.9	0.668	231.8	149.1	120	35	/	17.7
P10	1348.10	1504.1	6.8	128.26	23.76	92.46	2.995	347.7	134.9	140	68	/	13
P11	850.34	948.74	7.1	88.18	35.88	38.64	0.084	170.8	106.5	90	68	/	15.5
P12	3225.07	3598.27	7.2	152.31	66.96	151.34	11.998	207.4	337.25	330	84	3.977	26.7
P13	1596.98	1781.78	6.9	140.28	42.96	102.04	6.866	237.9	301.75	175	56	1.693	8.25
P14	3670.98	4095.78	6.7	360.72	121.92	168.16	13.012	390.4	425.6	480	87	4.815	2.15
P15	2955.45	3297.45	7.1	364.73	88.32	172.14	13.288	353.8	405.75	730	0.5	15.22	3.7
P16	3100.63	3459.43	7.3	573.15	88.08	145.55	9.772	152.5	220.1	760	24	23.80	0.7
P17	2177.70	2429.7	6.9	192.39	74.16	85.1	1.365	225.7	485.25	350	64	3.425	8.15
P18	4376.14	4882.54	6.7	625.25	150.36	195.9	16.265	481.9	337.25	1140	2.1	9.685	3
P19	3422.10	3818.10	7.1	497	124.2	175.2	14.017	195.2	425.65	760	33	21.6	4.65
P20	1078.48	1203.28	7.1	140.28	16.8	86.98	2.813	323.3	88.75	104	18	1.015	2.3

These wells are primarily used for an agricultural purpose. This study is based on the physical and chemical analyses (EC, pH, Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} , HCO_3^{-} , Cl^{-} , SO_4^{2-} , NO_3^{-} and Sr^{2+}) of twenty samples that were taken during the dry period (October 2015) (Table 1). The conductivity was measured by conductivity meter BEVAC. The pH was measured by pH meter BEVAC. Sulfates and Nitrates were dosed by the spectrophotometer type DR2000 (HACH). Sodium, potassium, magnesium and strontium were dosed by flame spectrophotometry atomic absorption (PYE UNICAM PHILIPS). Calcium, Chloride and Bicarbonate were dosed by titrimetric methods. These chemical processes were performed in the Hydrogeology Laboratory of Constantine 1 University, Algeria.

Statistical analysis

To classify groundwater analyses and identify the major mechanisms influencing groundwater chemistry, on the basis of their physical and chemical characteristics, we used the linear correlation and multivariate statistical analysis (principal component analysis PCA and Q-mode cluster analysis Q-CA). In groundwater research, multivariate statistical analysis is a quantitative approach to groundwater classification allowing the grouping of groundwater samples and making correlations between samples and their chemical parameters (Kouadra et al. 2019). Many

researchers have successfully used the multivariate statistical analysis tool to classify water samples (Ayadi et al. 2018; Belkhiri et al. 2011; Bouaicha et al. 2019; Foued et al. 2017; Khelif and Boudoukha 2018; Kouadra et al. 2019), because of its efficiency to determine the different hydro-chemical processes occurring in the studied groundwaters.

Base exchange (CAI-I and CAI-II)

The chloro-alkali Indices (CAI-I and CAI-II) are used to evaluate the influence of ion exchange process in water mineralization between Ca^{2+} , Mg^{2+} , Na^{+} and K^{+} . Positive index suggests the exchange of Na^{+} and K^{+} in water with Ca^{2+} and Mg^{2+} in aquifer materials, whereas negative index CAI indicates the exchange of Na^{+} and K^{+} in aquifer materials with Ca^{2+} and Mg^{2+} in water. In our case, the aquifer materials responsible for the base exchange are: the clay minerals and organic substances (Humus). The chloro-alkali indices are calculated using the following equations: (1) and (2) (Schoeller 1959):

$$\text{CAI I} = (\text{Cl} - (\text{Na} + \text{K}))/\text{Cl}, \quad (1)$$

$$\text{CAI II} = (\text{Cl} - (\text{Na} + \text{K}))/((\text{HCO}_3 + \text{CO}_3 + \text{SO}_4 + \text{NO}_3)). \quad (2)$$

All the ions are expressed in meq/L.

Saturation Index (SI)

To determine the water–mineral state of studied groundwater, we use the Saturation Index. SI of a given mineral is calculated by the following Eq. (3):

$$SI = \log_{10}(IAP/K_{sp}), \quad (3)$$

IAP is the ion activity product and K_{sp} is the equilibrium constant.

There are three water–mineral states: undersaturated, in equilibrium and supersaturated. If SI is below 0, the water is undersaturated with respect to the mineral in question. An SI of 0 means water is in equilibrium with the mineral, whereas an SI is greater than 0 means a supersaturated state with respect to the mineral in question. PHREEQ-C was used to calculate the SI in our research.

Irrigation water quality criteria

In classifying irrigation water, it is assumed that the water will be used under average conditions with respect to soil texture, infiltration rate, drainage, quantity of water used, climate, and the crop's salt of the crop (Wilcox 1955). The salts affect directly plant's development and reduce the growth of crops and their production. The salts also affect the vegetation indirectly, particularly the sodium, by degrading the soil's structure where it becomes compact (Aubert 1975). The sodium adsorption ratio (SAR), sodium percentage (Na%) and Water Quality Index (WQI) are used in this work to evaluate the Mchira-Telegma groundwater suitability for irrigation purposes (Agoubi et al. 2016; Haritash et al. 2017; Ravikumar et al. 2011). The SAR of a soil solution is simply related to the adsorption of the sodium by the soil, this ratio is defined by the following Eq. (4) (Richards 1954). The percentage of sodium (Na%) is calculated by the following Eq. (5) (Todd and Mays 2005) where the evaluation of the sodium's hazard and the SAR's hazard also depends on the water's electrical conductivity (Wilcox's and Richard's diagrams). The WQI is a powerful tool for the assessment of water quality with respect to drinking water or irrigation. WQI is based on the comparison of water quality parameters with the respective international standards. This index translates many of the data into simple terms (excellent, good, poor, etc.) (Horton 1965; Brown et al. 1970). The WQI is calculated by the following Eq. (6).

$$SAR = Na / \sqrt{((Ca + Mg)/2)}, \quad (4)$$

$$Na\% = [(Na + K)/(Ca + Mg + Na + K)] \times 100(\%). \quad (5)$$

All the ions are expressed in meq L^{-1} .

$$WQI = \sum_{i=1}^n Q_i W_i / \sum_{i=1}^n W_i. \quad (6)$$

where Q_i is the quality rating for the i th parameter, W is the unit weight of each parameter and n is the number of parameters.

Calculation of Q_i value

$Q_i = [(V_i - V_0)/(S_i - v_0)]$ V_i is the observed value of the i th parameter, V_0 is the ideal value of the i th parameter in pure water, V_0 is zero for all parameters except for pH 7.0, S_i is the standard permissible value of the i th parameter. The calculation of the unit weight, W_i is inversely proportional to the standard permissible value S_i for water quality parameters $W_i = K/S_i$ where K is the proportionality constant of the weights $K = 1/\sum_{i=1}^n 1/S_i$. According to Wilcox's and Richard's methods, the assessment of sodium's and SAR's risk, respectively, requires the availability of the second parameter, which is the conductivity, as illustrated in Fig. 7. The classification of samples through the calculation of WQI is based on Table 2.

Results and discussion

Statistical analysis

The linear correlations EC vs. major elements

The linear correlation results of physical and chemical parameters with the EC (Table 3, Fig. 2) indicate that the pairs of (EC vs Ca^{2+}), (EC vs. Mg^{2+}), (EC vs Na^+), (EC vs K^+), (EC vs Cl^-) and (EC vs SO_4^{2-}) have a strong correlation, where the coefficient of correlation (R) oscillates between 0.76 and 0.89. This latter indicates that these elements largely contribute to water mineralization, which came from the leaching of evaporates. (Brisin et al. 2014).

Table 2 Classification of groundwater on the basis of WQI

Parameter	Range	Water class
WQI	< 50	Excellent
	50–100	Good
	100.1–200	Poor
	200.1–300	Very poor
	> 300	Unsuitable for irrigation purpose

Table 3 Pearson's correlation matrix

	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	EC	pH
Ca ²⁺	1									
Mg ²⁺	0.71	1								
Na ⁺	0.77	0.80	1							
K ⁺	0.69	0.80	0.97	1						
HCO ₃ ⁻	0.21	0.28	0.42	0.38	1					
Cl ⁻	0.52	0.66	0.65	0.60	0.12	1				
SO ₄ ²⁻	0.95	0.79	0.84	0.78	0.31	0.59	1			
NO ₃ ⁻	-0.10	0.2	0.02	0.08	-0.10	0.23	-0.13	1		
EC conductivity	0.84	0.86	0.89	0.84	0.30	0.76	0.88	0.15	1	
pH	-0.03	-0.18	-0.10	-0.08	-0.46	-0.28	-0.02	-0.05	-0.18	1

Bold values indicate the most significant correlation coefficients

However, the linear correlation results of (EC vs HCO₃⁻) and (EC vs NO₃⁻) show a weak positive correlation with salinity ($R=0.30$, and 0.15) which indicates that the carbonate rocks and nitrates have no importance in the increasing rate of salinity.

The linear correlations with major elements

The linear correlation results between the different chemical parameters (Ca²⁺, Mg²⁺, HCO₃⁻, SO₄²⁻, Na⁺, Cl⁻ and Sr²⁺) (Table 3 and Fig. 3) show that the pairs of (Ca²⁺, HCO₃⁻), (Mg²⁺, HCO₃⁻) have a low correlation rate ($R=0.21$, 0.28) because the dissolution of carbonate rocks does not have a significant importance. The pair of (Ca²⁺, Mg²⁺) has a strong correlation ($R=0.71$) that can be explained by the reverse bases exchanges phenomena in which the sodium is fixed on the surface of clay minerals and the calcium and magnesium are released (Ben Alaya et al. 2014). (Na⁺, Cl⁻) and (K⁺, Cl⁻) pairs have a medium correlation ($R=0.65$, 0.60) due to the leaching of the halite and sylvite, which have a medium importance. Finally, the pair of (Ca²⁺, SO₄²⁻) has a strong correlation ($R=0.95$) which is explained by the high importance of the leaching of gypsum CaSO₄·2H₂O. The linear correlation results of physical and chemical parameters with the strontium (Sr²⁺) (Table 3), in which it is used as tracer element for indicating of water with evaporitic origin, indicate that the pairs of (Sr²⁺, Ca²⁺) and (Sr²⁺, SO₄²⁻) have a strong correlation ($R=0.82$, 0.73). These results suggest a leaching of evaporitic rocks process which is mainly controlled by the leaching of gypsum CaSO₄·2H₂O that comes from the Triassic gypsum formations.

Principal component analysis (PCA)

Twenty water samples were collected and 10 physico-chemical parameters were determined. These water quality data were analyzed using principal component analysis (PCA). This statistical tool showed three significant

factors. The first factor 1 explains 58.20% of the total variance (Fig. 4a), and has strong positive loadings on evaporitic elements: Ca²⁺, Mg²⁺, Na⁺, K⁺, Cl⁻, SO₄²⁻, and EC which were 0.863, 0.895, 0.951, 0.910, 0.747, 0.922 and 0.966, respectively (Table 4). High positive loadings indicated strong linear correlation between the factor and parameters. Thus, factor 1 can be termed as salinization factor. This axis reflects the role of the participation of some evaporite minerals: Halite and Triassic gypsum in the acquisition of saline load of groundwater in the region. Factor 2 explains 13.60% of the total variance of the dataset and has strong positive loading on pH and strong negative loading on HCO₃⁻ which were 0.873 and -0.707, respectively. This axis reflects the role of dissolution of some carbonate minerals of Constantine Neritic Nappe in the aquifer. Factor 3 explains 12.40% of the total variance of the dataset and has strong positive loading on NO₃⁻ which is 0.921. This axis explains the effect of anthropogenic pollution, which is usually identified in the urban and agriculture-intensive areas due to the domestic wastewater discharge and agricultural activities (Khelif and Boudoukha 2018).

Q-mode cluster analysis (Q-CA)

In our case study, Q-mode cluster analysis is used to categorize the waters samples into different groups based on their physico-chemical parameters. This analysis resulted in the grouping of water samples into two clusters relying on their physical and chemical characteristics (Fig. 4b):

- Cluster 1: Formed by nine wells (P2, P3, P4, P5, P9, P10, P11, P17 and P20) with a mean value of EC conductivity equals to 1446.03 $\mu\text{S cm}^{-1}$, indicating low salinity (min = 850.34 $\mu\text{S cm}^{-1}$, max = 2436.95 $\mu\text{S cm}^{-1}$, mean = 1446.03 $\mu\text{S cm}^{-1}$). This group is dominated by calcium (min = 56.12 meq L⁻¹,

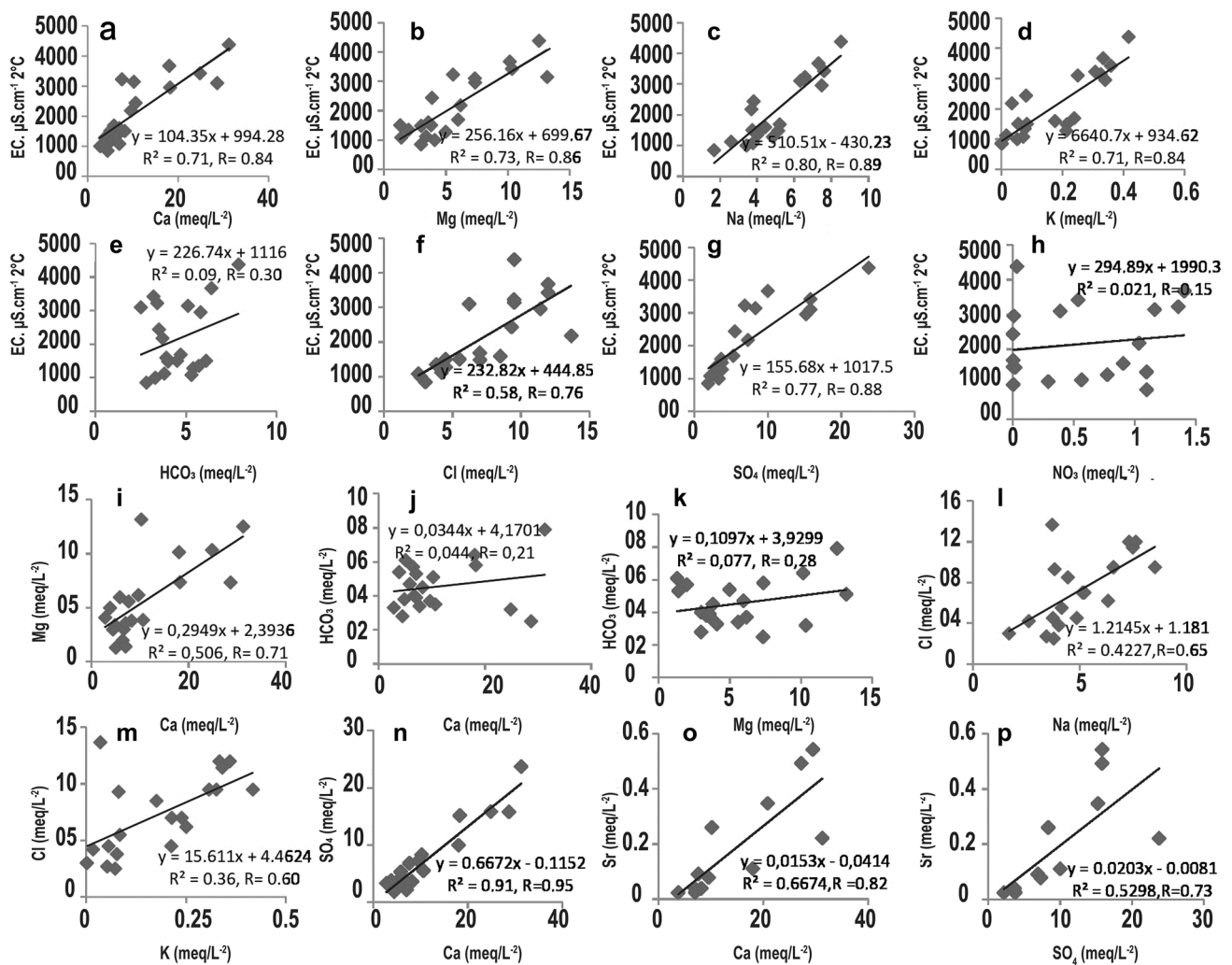


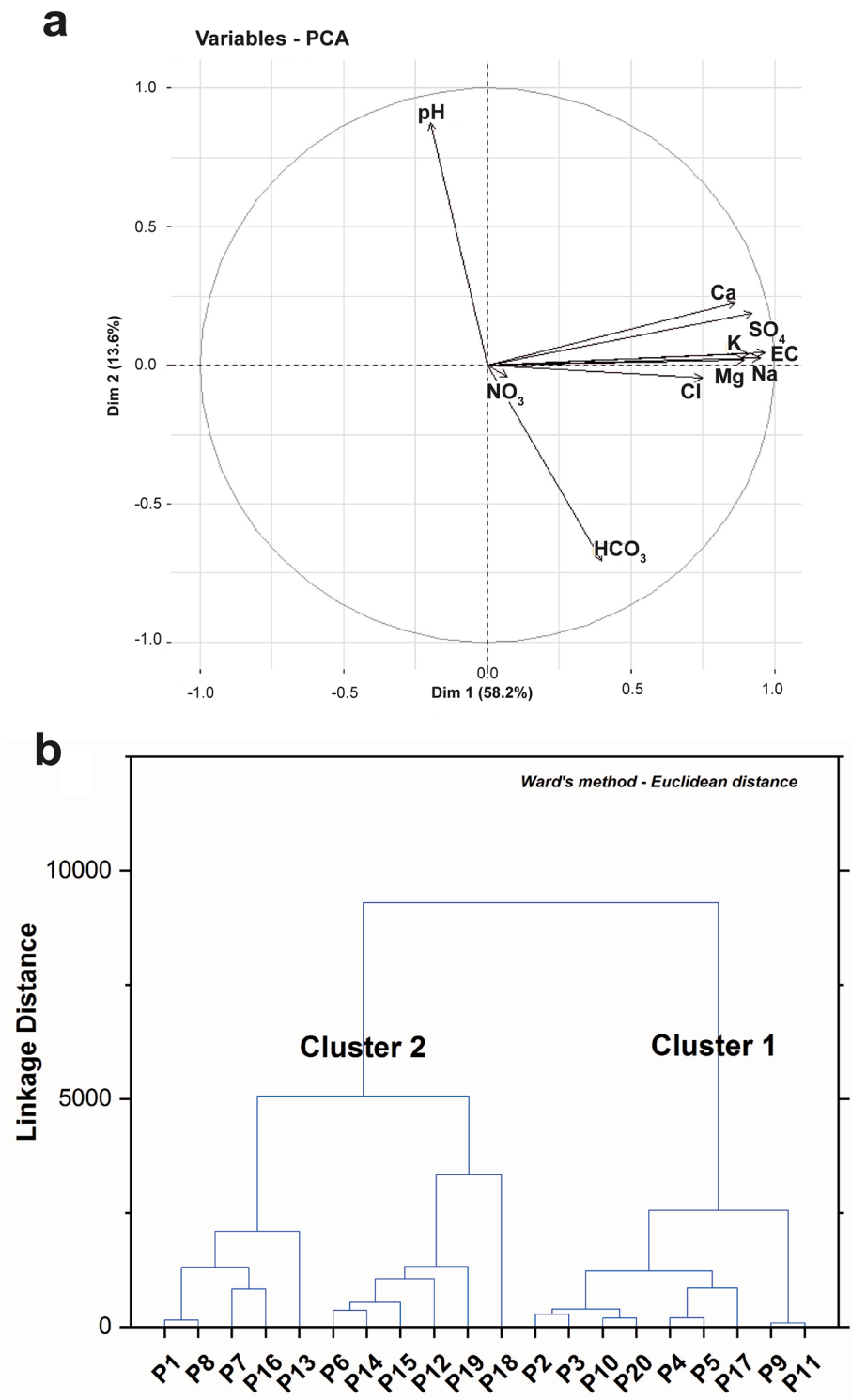
Fig. 3 a–h Correlation of chemical elements with salinity, i–k correlation of carbonate elements, l–n correlation of evaporitic elements, o, p correlation of Strontium vs. Ca and Strontium vs. SO₄

max = 212.43 meq L⁻¹, mean = 130.93 meq L⁻¹ and bicarbonate (min = 170.8 meq L⁻¹, max = 372.1 meq L⁻¹, mean = 262.3 meq L⁻¹) (Table 5). The majority of the wells are localized between the carbonate massifs of Constantine neritic nappe.

- Cluster 2: Formed by eleven wells (P1, P6, P7, P8, P12, P13, P14, P15, P16, P18 and P19) with a mean value of EC Conductivity equals to 2721.65 µS cm⁻¹, indicating a very high salinity (min = 1275.51 µS cm⁻¹, max = 4376.14 µS cm⁻¹, mean = 2721.65 µS cm⁻¹). This group is dominated by calcium (min = 76.16 meq L⁻¹, max = 625.25 meq L⁻¹, mean = 294.77 meq L⁻¹ and sulfate (min = 175 meq L⁻¹, max = 1140 meq L⁻¹, mean = 490 meq L⁻¹) (Table 5). The majority of wells are localized near the outcrops of the evaporitic triassic formations. Based on the results obtained from the previous Cluster analysis, we can say that the study area is influenced by two primordial processes:

- *The dissolution of the carbonate rocks process:* corresponds to the Cluster 1, suggesting that the mineralization is mainly controlled by the dissolution of the carbonate massif of Jurassic and cretaceous carbonate of the Constantine neritic nappe. It generates a high quantity of calcium and bicarbonate where the rate of salinity is not important (mean EC = 1446.03 µS cm⁻¹).
- *The leaching of the evaporitic rocks process:* corresponds to the Cluster 2, suggesting that the mineralization is mainly controlled by the dissolution of the evaporitic rocks of Triassic gypsum, and generates a high quantity of calcium and sulfate. This group has an important impact on the increasing rate of salinity (mean EC conductivity = 2721.65 µS cm⁻¹) that reaches 4376.14 µS cm⁻¹. It should be noted that the existence of the chloride and sodium with an important quantity in both Clusters suggests a secondary process of leaching the halite NaCl that synchronizes these processes.

Fig. 4 **a** Factorial plan F1–F2, **b** dendrogram of Q-mode cluster analysis



Evaluation of Hydrogeochemical process and origin of salinity

Piper diagram and strontium-calcium ratio

The analyses results carried on the Piper’s diagram (Piper 1944) (Fig. 5) show that 19 wells (P1–P19) are positioned

on the chloride and sulfate calcium and magnesium pole, while one sample (P20) is positioned on the bicarbonate calcium and magnesium pole. The positioning of the majority of samples (95%) in a chloride and sulfate calcium and magnesium pole confirms the common origin of the samples, which is influenced by the dissolution of evaporites (Brinis 2011), because of the enhanced leaching of Triassic

Table 4 Rotated factor loading matrix, Eigenvalue, % Variance and Cumulative variance values

Parameter	PC1	PC2	PC3
Ca (mg L ⁻¹)	0.863	0.227	- 0.212
Mg (mg L ⁻¹)	0.895	0.019	0.165
Na (mg L ⁻¹)	0.951	0.026	- 0.073
K (mg L ⁻¹)	0.910	0.042	- 0.008
HCO ₃ (mg L ⁻¹)	0.399	- 0.707	- 0.325
Cl (mg L ⁻¹)	0.747	- 0.046	0.367
SO ₄ (mg L ⁻¹)	0.922	0.186	- 0.231
NO ₃ (mg L ⁻¹)	0.070	- 0.042	0.921
pH	- 0.197	0.873	- 0.102
EC (conductivity) (μS cm ⁻¹)	0.966	0.046	0.099
Eigenvalue	5.821	1.356	1.240
%Variance	58.2	13.6	12.4
Cumulative %	58.2	71.8	84.2

Bold values indicate the most significant Factor-variable correlation

formations (Ayadi et al. 2018). This process has generated several chemical elements, especially sulphates, chlorides, magnesium and calcium (Khedidja 2016; Khedidja and Boudoukha 2015). The water samples that represented the triangle relevant to the cations begin in the middle (mixed part) and tend toward the pole of calcium, whereas the water samples that represented the triangle of anions begin in the middle (mixed part) and tend toward the sulfated or chloride pole. To further confirm the results, we used the strontium because it is a very strong indicator to determine the origins of groundwater mineralization that is used in the hydro-chemistry domain (Chabour et al. 2021; Lebid et al. 2016; Shout et al. 2020). Strontium (Sr²⁺) is a good tracer for the existence of evaporites. It makes it possible to distinguish between sulfates resulting from the oxidation of sulfide (low content) and those resulting from the dissolution of evaporites (high content) (Abdesselam et al. 2000). The ionic ratio

(in molar concentration) Sr²⁺/Ca²⁺ is a very useful tool to indicate the groundwater origin. If it is equal or greater than 1 ‰, the groundwater has an evaporitic origin (Bakalowicz 1988). In this context, we have selected the water samples with high to very high mineralization that are considered as anomalies so as to make the dosage of strontium (Table 6). The obtained results show that the Sr²⁺/Ca²⁺ ratio is bigger than 1 ‰ in all cases. It actually exceeds 6 ‰ in all cases. These results confirm the primordially evaporitic origin of mio-plio-quaternary groundwater's mineralization of Mchira-Teleghma that mainly depends on the dissolution of the evaporitic formations of triassic gypsum.

Chemical facies (water type) and hydrochemical process

The conductivity values in Table 7 illustrated from Fig. 6 show that the water samples have a Calcium Sulfate facies SO₄-Cl-Ca-Na and SO₄-Cl-Ca-Mg (typical facies of gypsum CaSO₄·2H₂O) and calcium chloride secondarily sulfate facies Cl-SO₄-Ca-Mg and Cl-SO₄-Ca-Na are characterized by a high to a very high mineralization with conductivity oscillates between 2177.7 μS cm⁻¹ and 4376.14 μS cm⁻¹ (P2, P12, P14, P15, P16, P17, P18, P19), settle on the northwest of the study area, around or near to the outcrops of Triassic clay-gypsum formations. The water samples have a calcium bicarbonate facies Ca-Mg-HCO₃-Cl and Ca-Na-HCO₃-Cl (typical facies of limestone CaCO₃), magnesium bicarbonate facies Mg-Na-HCO₃-Cl and Mg-Na-HCO₃-SO₄ (typical facies of the dolomite rocks CaMg(CO₃)₂) and Calcium Chloride secondarily bicarbonate facies Ca-Mg-Cl-HCO₃ are characterized by a low to a medium mineralization with conductivity varying between 850.34 μS cm⁻¹ and 1503.65 μS cm⁻¹ (P3, P4, P5, P8, P9, P10, P11, P20), settle in the southeast part of the plain, between the carbonate massifs of Constantine neritic Nappe. The water samples have a Calcium Chloride facies, secondarily sodium Ca-Na-Cl-HCO₃

Table 5 Parameter values of the two principal water groups

Parameters	Cluster 1				Cluster 2			
	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation
Ca (mg L ⁻¹)	56.12	212.43	130.93	51.48	76.16	625.25	294.77	198.81
Mg (mg L ⁻¹)	15.6	74.16	38.67	18.44	36	158.16	91.7	41.65
Na (mg L ⁻¹)	38.64	95.44	79.05	18.28	102.04	195.9	146.48	30.23
K (mg L ⁻¹)	0.084	3.273	2.06	1.14	6.866	16.265	11.26	2.91
HCO ₃ (mg L ⁻¹)	170.8	372.1	262.3	70.68	152.5	481.9	290.02	96.19
Cl (mg L ⁻¹)	88.75	485.25	193.94	131.54	159.75	425.65	313.39	87.35
SO ₄ (mg L ⁻¹)	90	350	175.44	83.26	175	1140	490	317.23
EC (conductivity) (μS cm ⁻¹)	850.34	2436.95	1446.03	539.99	1275.51	4376.14	2721.65	1034.99

Bold values indicate excessive values for cations, anions and conductivity

Fig. 5 Piper's diagram

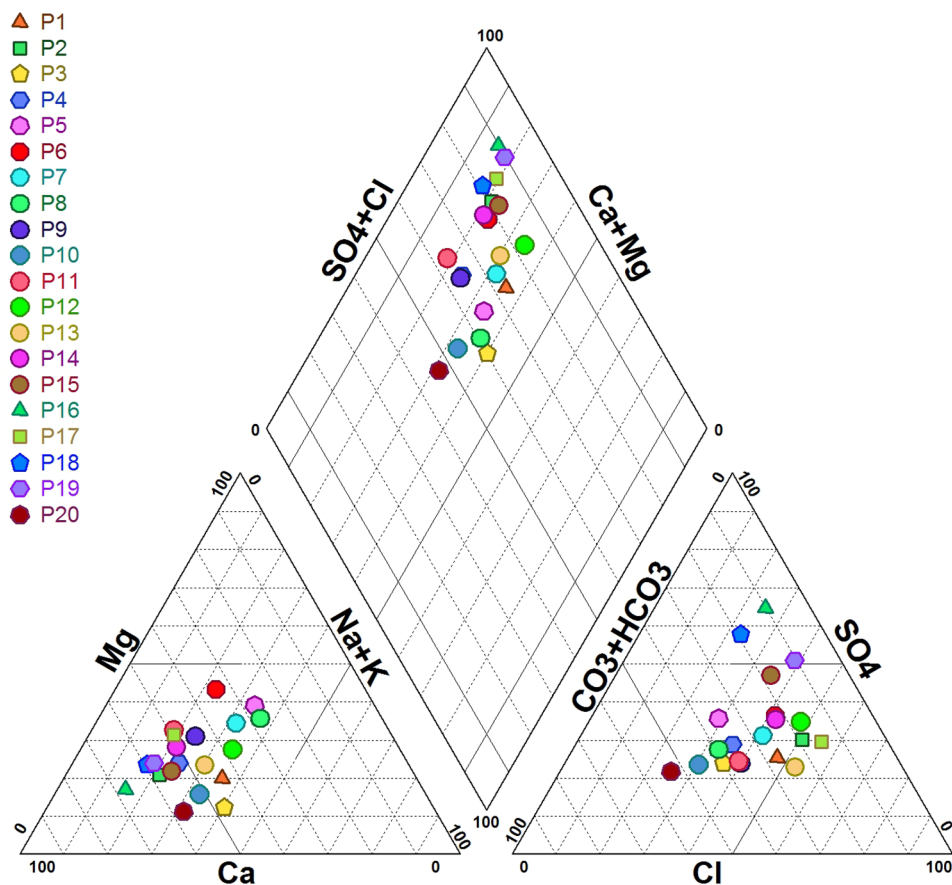


Table 6 Strontium manipulation

Well	EC Corrected to 20 °C ($\mu\text{S cm}^{-1}$)	EC Corrected to 25 °C ($\mu\text{S cm}^{-1}$)	Sr^{+2} (mg L^{-1})	Ca^{2+} (mg L^{-1})	$\text{Sr}^{+2}/\text{Ca}^{2+}$ (‰) (meq L^{-1})
P6	3142.11	3505.71	11.4	204.41	25.5
P12	3225.07	3598.27	3.977	152.31	11.94
P14	3671	4095.78	4.815	360.72	6.1
P15	2955.45	3297.45	15.22	364.73	16.70
P16	3100.63	3459.43	23.80	573.15	18.46
P17	2178	2429.7	3.425	192.39	8.14
P18	4376.14	4882.54	9.685	625.25	7.08
P19	3422.1	3818.1	21.6	497	18.12

are characterized by a medium mineralization with conductivity of $1482.91 \mu\text{S cm}^{-1}$ and $1596.98 \mu\text{S cm}^{-1}$ in P1 and P13 water samples, respectively, suggesting a secondary halite leaching process. The existence of calcium chloride facies is often an indicator of pollution, where the chloride (Cl) in the water is considered as tracer for groundwater Contamination. It comes from weathering of minerals, such as halite and other anthropogenic sources, such as domestic effluents, septic tanks, leachates from landfills, in addition to being the main

chemical element in the composition of detergents and fertilizers (Marghade et al. 2011; Mihoubi 2009). P6 and P7 water samples that have a magnesium chloride facies Mg–Ca–Cl–SO₄ with conductivity of $3142.11 \mu\text{S cm}^{-1}$ and $1690.31 \mu\text{S cm}^{-1}$, respectively, located in the center of the study area, suggest a mixture water state. The presence of sulphated facies in all samples that are characterized by high to very high mineralization validates that the evaporitic formations, especially of Triassic gypsum is the main factor for increasing the rate of salinity in

Table 7 EC, WQI, SAR, CAI. I, CAI. II, Na% and Saturation indices values

Well	Group	EC ($\mu\text{S cm}^{-1}$) Corrected to 20 °C	EC ($\mu\text{S cm}^{-1}$) Corrected to 25 °C	WQI (irrigation)	SAR	CAI. I	CAI. II	Na%	Saturation index				
									Gypsum	Anhydrite	Halite	Calcite	Dolomite
P2	Cluster 1	2436.95	2718.95	97.687	1.419128	0.58	0.60	21.21	-0.95	-1.32	-6.15	-0.18	-0.76
P3		1503.65	1677.65	101.297	2.336162	0.23	0.13	40.15	-1.33	-1.7	-6.32	-0.11	-0.78
P4		1503.65	1677.65	68.450	1.525268	0.157	0.09	24	-1.18	-1.56	-6.46	-0.05	-0.39
P5		995.52	1110.72	66.965	1.852571	-0.293	-0.12	33.62	-1.59	-1.96	-6.7	-0.3	-0.41
P9		1119.96	1249.56	64.579	1.286196	0.376	0.23	24.22	-1.51	-1.88	-6.64	-0.32	-0.75
P10		1348.10	1504.1	175.868	1.962377	-0.08	-0.03	32.80	-1.35	-1.72	-6.5	-0.14	-0.76
P11		850.34	948.74	89.070	0.873449	0.44	0.23	18.52	-1.64	-2.01	-6.97	-0.27	-0.66
P17		2177.70	2429.7	123.307	1.316422	0.73	0.83	19.12	-0.92	-1.3	-6.01	-0.13	-0.42
P20		1078.48	1203.28	111.057	1.843764	-0.54	-0.17	31.41	-1.41	-1.78	-6.7	0.19	-0.28
P1		Cluster 2	1482.91	1654.51	257.454	2.342249	0.23	0.21	35.75	-1.24	-1.62	-6.13	-0.49
P6	3142.11		3505.71	485.147	1.922897	0.27	0.18	22.78	-0.92	-1.3	-5.93	-0.2	-0.26
P7	1690.31		1885.91	291.810	2.149769	0.22	0.15	31.64	-1.2	-1.57	-6.13	0	0.04
P8	1275.51		1423.11	320.589	2.31241	-0.12	-0.06	36.53	-1.48	-1.86	-6.35	0	0.15
P12	3225.07		3598.27	479.453	2.561698	0.27	0.22	34.29	-1.02	-1.4	-5.91	0.04	-0.02
P13	1596.98		1781.78	282.349	1.927648	0.46	0.46	30.33	-1.23	-1.61	-6.11	-0.18	-0.85
P14	3670.98		4095.78	511.815	1.947225	0.36	0.24	21.33	-0.65	-1.02	-5.79	0.11	0.01
P15	2955.45		3297.45	416.103	2.092082	0.31	0.17	23.41	-0.46	-0.83	-5.8	0.45	0.55
P16	3100.63		3459.43	338.459	1.491637	-0.06	-0.02	15.45	-0.29	-0.67	-6.14	0.47	0.39
P18	4376.14	4882.54	508.698	1.820211	0.06	0.018	16.94	-0.17	-0.54	-5.85	0.35	0.33	
P19	3422.10	3818.10	480.136	1.815724	0.33	0.20	18.47	-0.37	-0.74	-5.78	0.31	0.28	

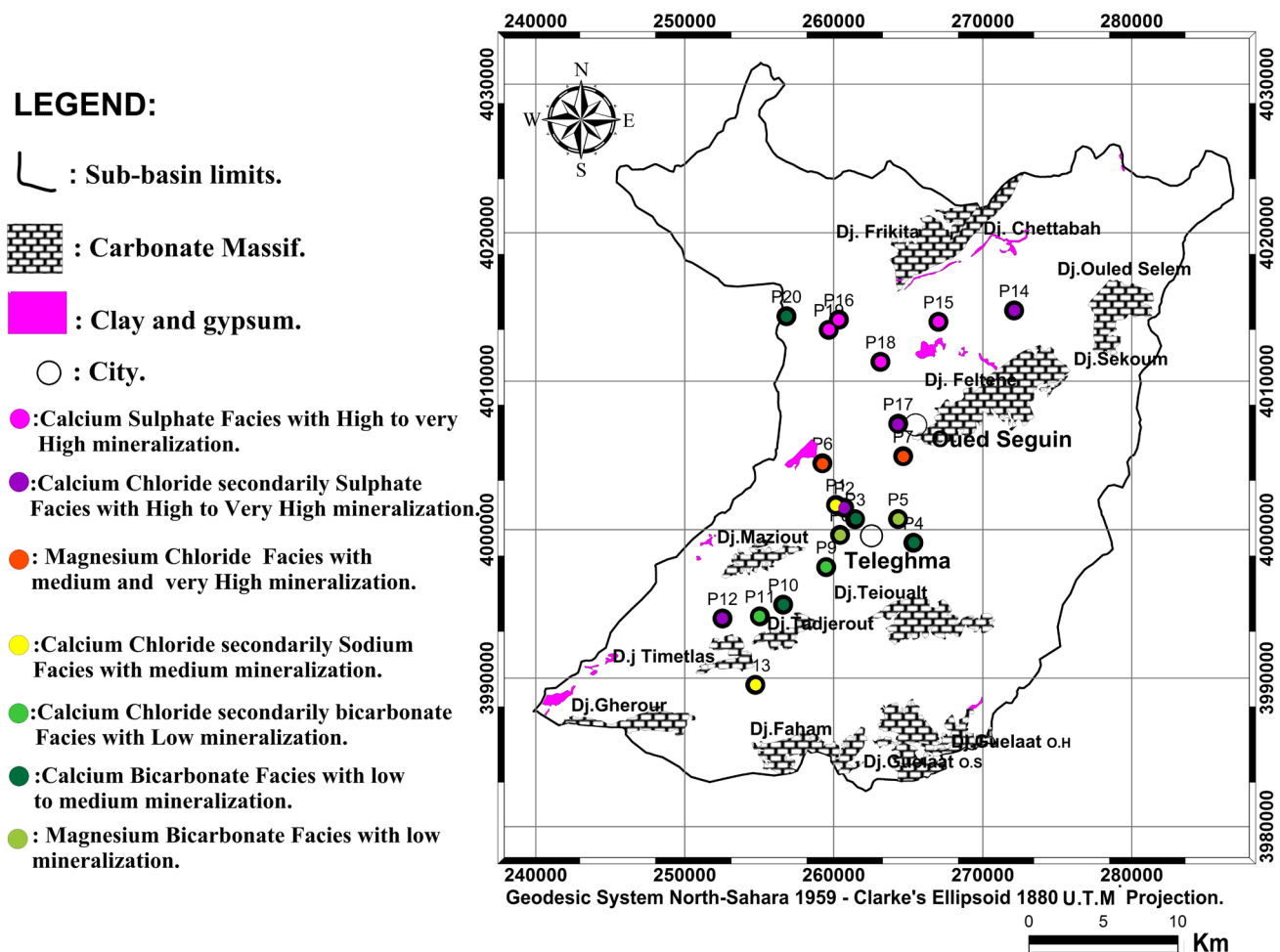


Fig. 6 Chemical facies distribution around Mchira-Teleghma basin

the northwest, where the majority of these samples are included in Cluster 2.

Base exchange of Mchira-Teleghma groundwater

The CAI-I value of water samples varies from -0.54 to 0.73 and the CAI-II values vary from -0.17 to 0.83 (Table 7). These results show that 75% of the water samples have a positive chloro-alkaline which indicates the exchange between Na^+ and K^+ in groundwater with Ca^{2+} and Mg^{2+} in aquifer materials. The other 25% of the water samples show a negative chloro-alkaline which indicates the exchange of Na^+ and K^+ in aquifer materials with Ca^{2+} and Mg^{2+} in groundwater.

Saturation state of Mchira-Teleghma groundwater

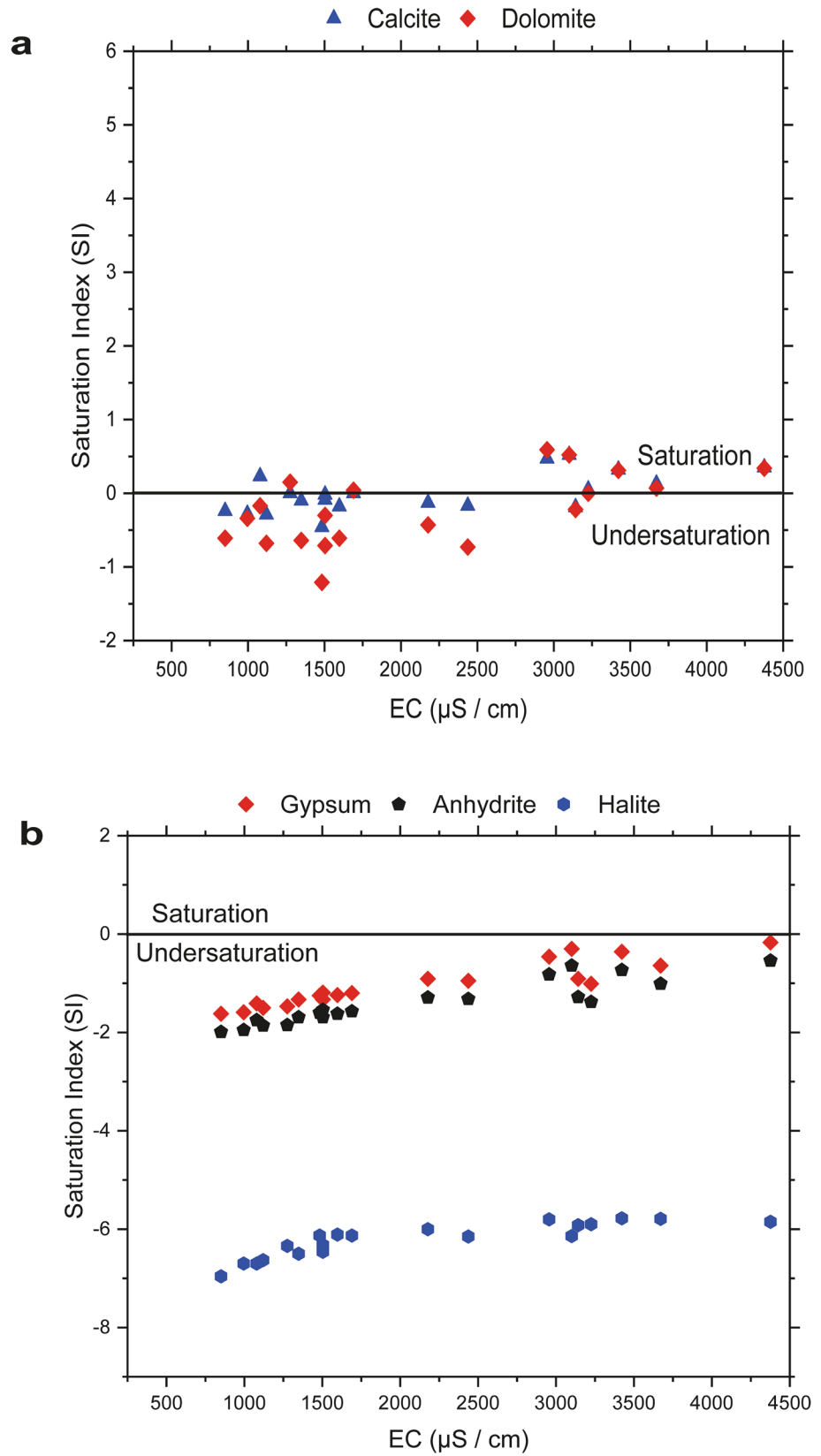
According to Table 7 and Fig. 7a, b, the results showed that 55% and 65% of the water samples have an $\text{SI} < 0$, these samples are undersaturated, respectively, by calcite and

dolomite (is the dominant), which suggests a dissolution process. 10% of water samples have an $\text{SI} = 0$, which suggests that these water samples are in equilibrium by calcite. 35% of water samples have an $\text{SI} > 0$, these water samples are supersaturated by the calcite and dolomite, which indicates the precipitation process. The totally of water samples are undersaturated ($\text{SI} < 0$) with gypsum, Anhydrite and halite suggesting that their soluble component Na^+ , Cl^- , Ca^{2+} and SO_4^{2-} concentrations are not limited by mineral equilibrium, which indicates the dissolution process (Belkhiri and Mouni 2013; Bouteraa et al. 2019).

Assessment of water quality for irrigation purposes

The following diagrams (Fig. 8) classify the water samples in relation to irrigation purposes. These latter indicate an excess of mineralization (conductivity corrected to 25°C). According to Wilcox's method (Wilcox 1948),

Fig. 7 **a** Calcite and dolomite saturation index, **b** gypsum, anhydrite and halite saturation index



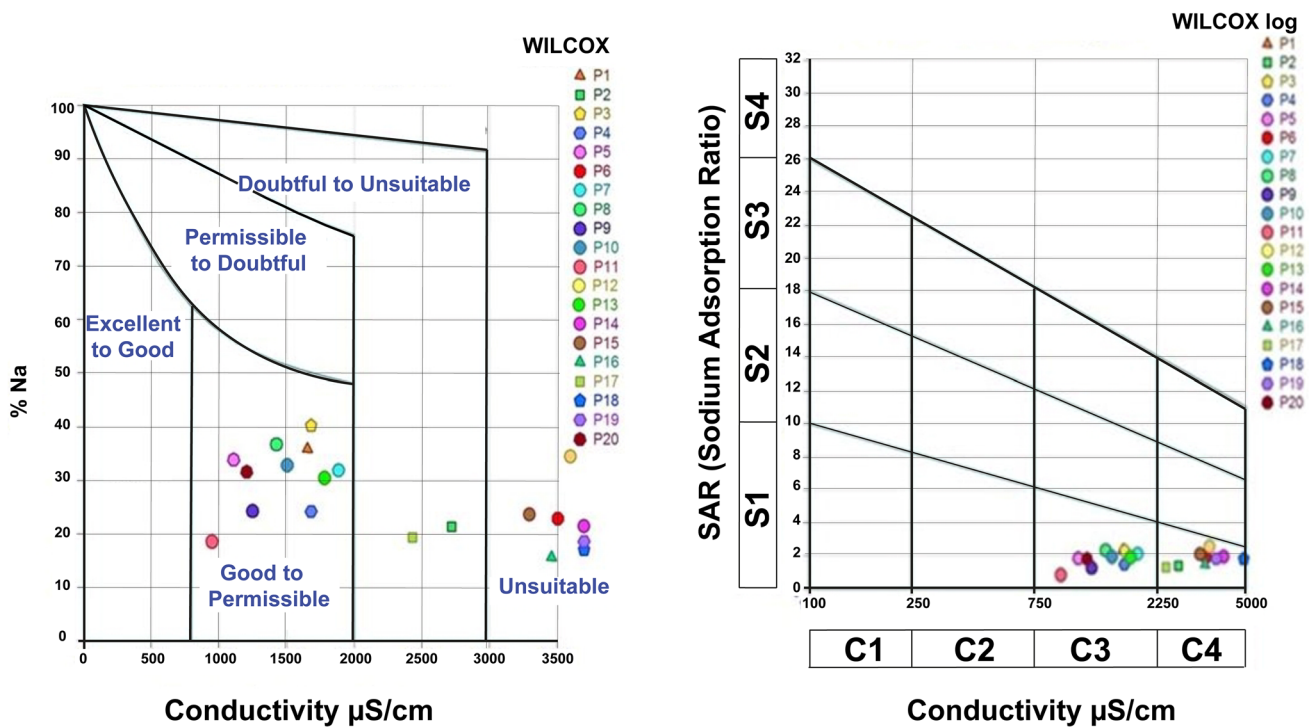


Fig. 8 Waters classification, according to: a Wilcox's and b Richard's methods

the percentage of sodium oscillates between 15.45 and 40.15%, where the water samples are classified into three categories: good to permissible quality category is the dominant group by 55% (P1, P3, P4, P5, P7, P8, P9, P10, P11, P13 and P20). This category indicates a low salinity hazard and risk of sodium where the majority of these samples are included in Cluster 1 in which its salinity is controlled by the dissolution of carbonate massif of neritic Constantine nappe, doubtful to unsuitable category dominates by 10% (P2 and P17) and unsuitable quality category dominates by 35% (P6, P12, P14, P15, P16, P18 and P19). This category indicates an important salinity hazard and low risk of sodium where these samples are totally included in cluster 2 in which its salinity is mainly controlled by the leaching of the evaporitic rocks process of Triassic gypsum. According to Richard's method (Richards 1954), the SAR values oscillate between 0.87 and 2.56, where the water samples are classified into two classes: C3S1 class (admissible quality) by 55% (P1, P3, P4, P5, P7, P8, P9, P10, P11, P13 and P20). It characterized by a low alkali hazard SAR and low risk of mineralization; the majority of these samples are included in Cluster 1. C4S1 class (mediocre quality) dominates by 45% (P2, P6, P12, P14, P15, P16, P17, P18 and P19). It characterized by a low alkali hazard SAR and high risk of mineralization where the majority of these samples are included in Cluster2. These water classes are generally suitable for irrigation

of certain crop species that tolerate salts in well-drained and leached soils (Gouaidia et al. 2012; Khedidja 2016). According to WQI's method, the WQI values (Table 7) oscillate between 46.58 and 508.70 where 25% of wells (P2, P4, P5, P9 and P11) have a good water quality, these samples are totally included in Cluster 1. 20% of wells (P3, P10, P17 and P20) have a poor water quality, 15% of wells (P1, P7 and P13) have a very poor water quality and 40% of wells (P6, P8, P12, P14, P15, P16, P18 and P19) are unsuitable at all for irrigation. The wells that have a very poor water quality to unsuitable for irrigation purposes are totally included in the Cluster 2, in which its salinity is controlled mainly by the leaching of the evaporitic rocks process of Triassic gypsum.

Conclusion

Mchira-Teleghma MPQ groundwater suffers from a growth of salinity in the northwestern part (it can reach 4376.14 $\mu\text{S cm}^{-1}$). The $\text{Sr}^{2+}/\text{Ca}^{2+}$ ratio and piper diagram suggest evaporite dominance in the hydrochemistry processes occurring in the studied aquifer, where the evaporitic elements are mainly responsible for anomalies of salinity because its strong correlation with EC conductivity. The assessment of these results by the statistical tool: principal component analysis (PCA) and Q-mode cluster analysis (Q-CA) confirms that the hydrochemistry of Mchira-Teleghma is controlled by two

main processes: the dissolution of carbonate massifs process of neritic Constantine nappe and the leaching of evaporite rocks process, synchronizes by secondary process of leaching the halite NaCl. The assessment of water quality by water type showed that the anomalies of salinity are mainly due to the leaching of Triassic gypsum process that outcrops in the northern part and western borders of the study area, this process gives sulfated facies that is characterized by high to very high mineralization. The studied groundwater suffers from anthropogenic pollution confirmed by a strong positive loading on NO_3^- which is 0.921, due mainly to the domestic wastewater discharge and agricultural activities. The assessment of base exchange process in water using the Chloro-Alkali Indices (CAI-I and CAI-II) showed that 75% of the water samples have a positive chloro-alkaline (are the dominant) which indicates the exchange between Na^+ and K^+ in groundwater with Ca^{2+} and Mg^{2+} in aquifer materials, consequently an enrichment of the water table by calcium and magnesium. Saturation indices (SI) indicate that the water is undersaturated (55% calcite, 65% dolomite) with respect to most of the carbonate minerals, and supersaturated with a reduced percentage (35%), while evaporitic minerals are totally undersaturated with respect to evaporite minerals confirming water–rock interactions by dissolution and precipitation processes of carbonate minerals and the dissolution process only of evaporitic minerals. To assess the water quality of the studied groundwater for irrigation purposes, we used three methods: Wilcox, Richard and WQI methods. Wilcox's method classified the water samples into three categories: good to permissible quality category: is the dominant group by 55%, doubtful to unsuitable category: dominates by 10% and unsuitable quality category dominates by 35%. Richard's method classified the water samples into two classes: C3S1 class (admissible quality) by 55% and C4S1 class (mediocre quality) dominates by 45%. To perform the irrigation with these water classes, they have to be used with salt-tolerant species in well-drained and leached soils. The WQI values oscillate between 46.58 and 508.70. The WQI method classified the water samples into four categories: 25% of water samples have a good water quality, 20% of samples have a poor water quality, 15% of samples have a very poor water quality and 40% of water samples are unsuitable at all for irrigation. The water samples that have a good water quality characterized by low salinity. These water samples are totally included in Cluster 1 in which its salinity is controlled mainly by the dissolution of the carbonate formations rocks, while the water samples that have a very poor water quality to unsuitable for irrigation purposes characterized by a high salinity. These water samples are totally included in the Cluster 2, in which its salinity is controlled mainly by the leaching of the evaporitic rocks process of Triassic gypsum.

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