



# A GIS mapping assessment of the suitability of the Oued Rmel aquifer for irrigation in the Zaghouan district (north-eastern Tunisia)

Meriem Ameur<sup>1</sup> · Fadoua Hamzaoui-Azaza<sup>1</sup> · Lilia Ben Cheikha<sup>1,2</sup> · Toqeer Ahmed<sup>3</sup> · Moncef Gueddari<sup>1</sup>

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## Abstract

A total of twenty-three water samples were collected in winter 2013 to assess groundwater quality in the Oued Rmel aquifer in the Zaghouan governate in Tunisia. These samples were subject to in-field measurements of some physico-chemical parameters (temperature, pH, and salinity), and laboratory analysis of major elements. Several parameters were used to assess the quality of water destined for irrigation, including electrical conductivity (EC) and sodium adsorption ratio (SAR). As part of this work, GIS was used to study spatial distributions of SAR, EC, residual sodium carbonate, sodium percentage (%Na), Doneen's permeability index, Kelly's ratio, and magnesium hazard and, therefore, evaluated the water quality of Oued Rmel (good, fair, or poor) regarding irrigation. The major ions most abundantly found in the waters of Oued Rmel were in the following order:  $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$  and  $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ . 56% of water samples from the Oued Rmel aquifer showed a low alkalization risk, where SAR was lower than 10, 39% have a medium soil destabilization risks ( $10 < \text{SAR} < 18$ ), and just 5% indicated high alkalinity hazards ( $\text{SAR} > 26$ ). Samples of water intended for irrigation showed a medium to high sodicity and alkalization risk. It is expected that output may help in assessing the impacts of water quality of the Oued Rmel aquifer used for irrigation.

**Keywords** GIS · Water resources · Water quality for irrigation · Oued Rmel aquifer · Tunisia

## Introduction

Irrigation is most important in arid or semi-arid countries where rainfall is scarce to sustain agricultural yields to feed the population, particularly in regions where there is rapid population growth. At the global level, about 70% of groundwater is used for agriculture, 20% for the industrial sector, and 10% for domestic consumption. Most developing countries use 90% of their fresh water to irrigate their land, while industrialized countries use only 40% (Pimentel et al. 2004). Asia alone contains more than 2/3 of the irrigated

land, as the cultivation of rice has intensified to cope with the increase in population (Cariou 2015).

In addition, developing countries such as Tunisia are often experiencing strong population growth, leading to an increase in crops and thus in the demand for water used to irrigate these crops. In 3/4 of its territory, Tunisia remains an arid to semi-arid country. It is characterized by the scarcity of its water resources and by an accentuated variability of the climate in space and time. Accordingly, water is the essential element for the development and prosperity of agriculture (Rockström et al. 2017).

The groundwater of Oued Rmel, the subject of this study, belongs to the governorate of Zaghouan and enjoys a privileged and median position between the governorates of the north, north-west, and centre of Tunisia (Ameur et al. 2015b).

The governorate of Zaghouan covers an area of 2820 km<sup>2</sup>—1.8% of the national territory. The region benefits from a large agricultural area (282,000 ha, of which 185,000 is arable land and 87,000 is covered by grazing and forests).

✉ Meriem Ameur  
meriem\_ameur@yahoo.fr

<sup>1</sup> Research Unit of Geochemistry and Environmental Geology, Faculty of Sciences of Tunis, University of Tunis El Manar, Tunis, Tunisia

<sup>2</sup> National Center for Nuclear Sciences and Technologies, 2020 Sidi Thabet, Tunisia

<sup>3</sup> Centre for Climate Research and Development (CCRD), Comsats Institute of Information Technology (CIIT), Park Road, Chak Shahzad, Islamabad 44000, Pakistan

In the last few decades, farmers have been using excessive amounts of chemical fertilizers and pesticides (herbicides, insecticides, and fungicides) in order to intensify crop yields and fertilize their farmland. This excess of nutrients leads to the deterioration of the chemical quality of the groundwater and can produce extensive groundwater pollution. The water resource of the Oued Rmel aquifer is currently excessively exploited and has been affected by intense agricultural activity. This has led to the degradation of water quality and can damage soils through the effects of alkalization, sodicity, and salinization. The main objective of the study was to assess the suitability of groundwater in the Oued Rmel aquifer for irrigation purposes and to determine whether the ongoing use of groundwater for this purpose could or not damage soils in agricultural areas.

### Study area characteristics and description

The study area, the Oued Rmel aquifer, is located in north-eastern Tunisia in the Zaghouan governorate. A coastal watershed of the Oued Rmel is equipped with a dam on the main stream in the region. The Rmel wadi, with its eight tributaries, drains a very large area of about 74,000 ha. The downstream part is arranged in an irrigated perimeter for the most part (3100 ha). It measures about 46 km and has a remarkably steady slope of 3%, throughout its path. The climate of the region is influenced by maritime effects from the Mediterranean Sea and continental effects from arid regions to the south. The average temperature is about 18.5 °C. The region has a hot Mediterranean type climate (Csa in the Köppen climate classification system) with an average annual rainfall that varies between 350 and 600 mm (Attia et al. 2005). The Oued Rmel aquifer is constrained topographically by the Sidi Zid mountain to the north-east and to the south-west by the mountain of the Zaghouan (Fig. 1).

Agricultural activity in the Zaghouan region has an important place in the economy of the governorate. The crop productions of this governorate are, on average, 0,14 million tonnes of cereals; 50,000 tons of fruit, covering an area of 50,000 ha; and 130,000 tons of vegetables, which cover an area of 4600 ha. The olive groves cover 3500 ha, followed by aromatic and medicinal plants (1000 ha), cereals (300 ha), almond trees (150 ha), and legumes (10 ha). Forests in the region cover an area of 20,000 ha (DDR 2012). Livestock grazing constitutes one of the main agricultural resources of the Zaghouan region, after arboriculture (olive trees, in particular) and field crops (Fig. 1).

### Geological and hydrogeological setting

The Zaghouan region is located in eastern Tunisia and is part of the Tunisian dorsal. The massif of Zaghouan is the most important orographic unit of the area. The Djebel Zaghouan

dominates the region to the east by a cliff (The consequence of the great fault of Zaghouan). The formations encountered in the study area range in age from Triassic to Quaternary (Arnould 1946; Rekaya 1981; Turki 1985; Soussi 2000) (Fig. 2a).

The Triassic outcrops in the form of small islets at anticlinal axes are in Zaghouan, in Djebel Mcella, and in Hammam Djedidi. Triassic outcrops most often mark abnormal contact (Turki 1985; Briki 2013).

The Triassic sediments consist of black fine-grained dolomitic mineralized breccias of Pb, Zn, Ba, Sr, and F, cemented by clay, and can reach a total length, and a maximum width is, respectively, about 550 and 80 m at Hammam Djedidi. From a lithological point of view, Djebel Sidi Salem is formed by sandy schist, dolomitic limestone, sandstone, dolomite and breccias of gypsum.

The Jurassic occupies anticlinal axes and outcrops to the dome of Hammam Zriba. The complete series is exposed in Zaghouan, where the NARA formation exceeds 1000 m of thickness. It is essentially formed by limestones in massive beds, becoming fissured towards the summit and marly limestone (Rekaya 1981; Briki 2013).

The Cretaceous is well developed especially to the south-east of Hammam Djedidi, where the series are complete, and the thickness is important. The Cretaceous formations divided in seven important lithologies complex of clays, marls and limestones (the southern part of the study zone), interbedded clays and marls (well developed in the north-western part of the Djebel Zaghouan), interbedded limestones and marls (West of the Djebel el Messella and the Djebel Sidi Salem and Hammam Djedidi area), marls with limestone intercalations (North-West of the Djebel el Mcella, the Djebel Sidi Salem and Djebel Rebaia), marls (North-East of the Bir M'Cherga village and near the Djebel Zaghouan), marly limestones (North-West of the Djebel Zaghouan), limestones (Hammam Djedidi zone and Hammam Zriba village where it reaches 26 m).

The transition from sediments of Cretaceous age to the Tertiary is characterized by a marly sequence, generally known as "Marls of transition", in the East of Djebel Sidi Salem, its thickness exceeds 170 m. Sediments of Tertiary age are also found in the Hammam Zriba region, characterized by olive green to black marl and with a thickness of 30 m.

In the study area, the Quaternary formations are very developed and widespread on the mountain foot slopes and on the plane. The tectonics of the Zaghouan region is marked by brittle and duplicative structures and by collapse features. The Zaghouan fault, which trends in a NE–SW direction, is a major structural feature in the region. This fault extends for about 80 km and borders on the east the Jurassic massifs of the Tunisian dorsal. It is considered as one of the most important structural features of Tunisia (Turki 1985;

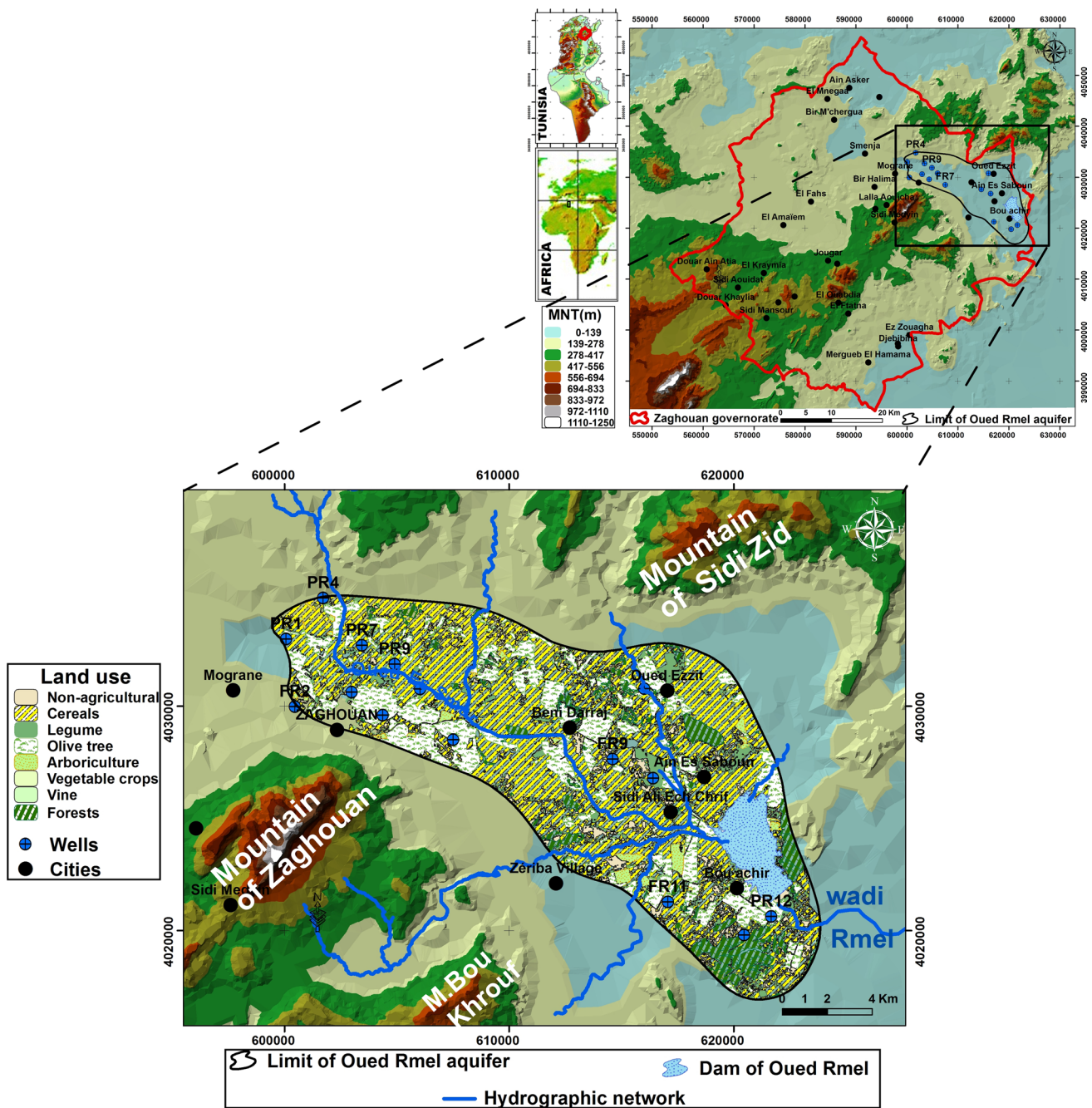


Fig. 1 Land use map of the study area with the locations of sampled wells

Briki 2013). From NE to SW, there are two grabens of Bir M’cherga-Sminja and Mograne-Bhuret Zaghouna, which have deep truncations N140 to N160 and are arranged transversely compared to the main Atlantic anticlinal direction N30 to N60 (Fig. 2e).

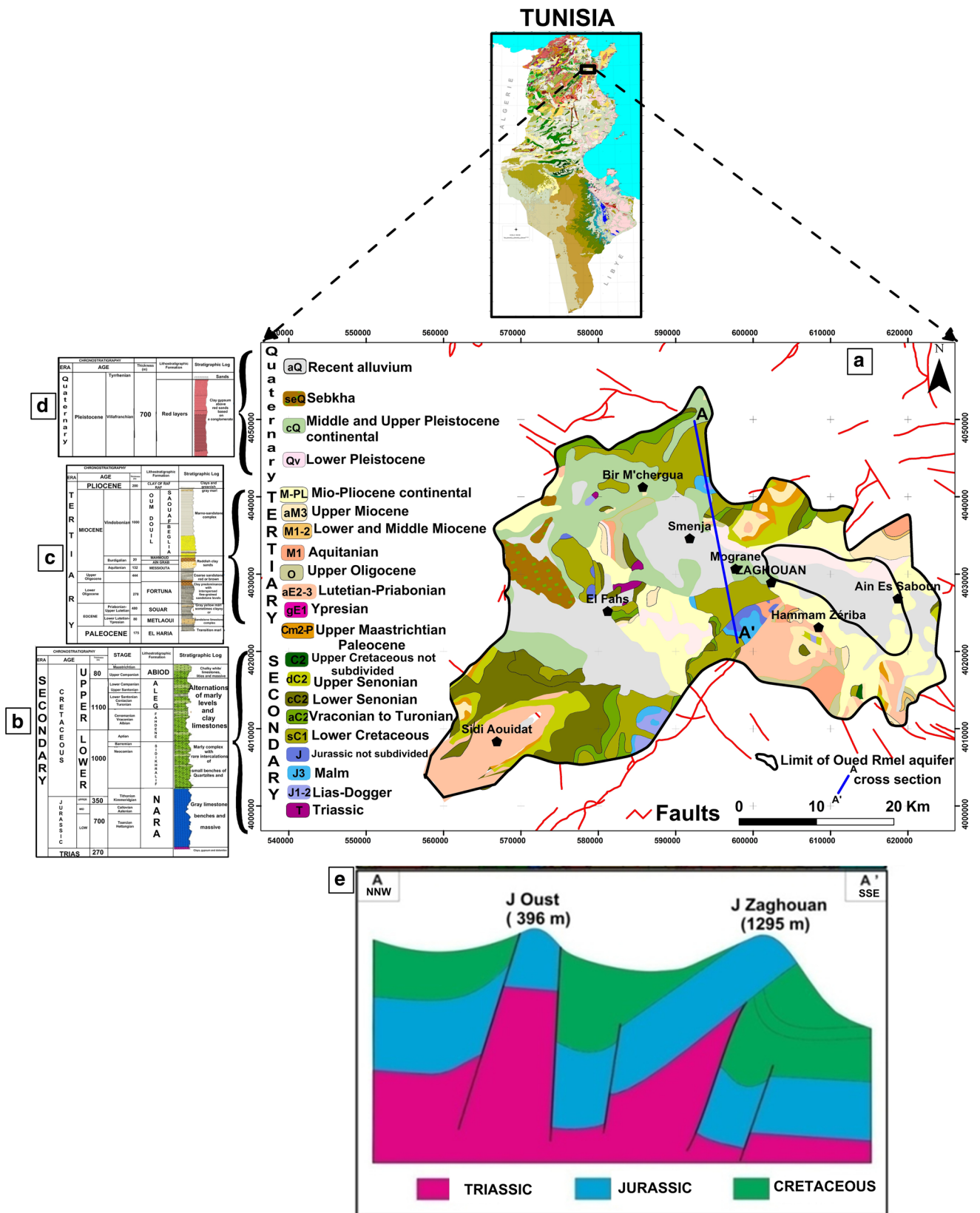
The governorate of Zaghouna has five shallow aquifers located in the plains of Nadhour, El Fahs, Sminja, Oued Rmel and Boucha, and seven deep aquifers in the Jurassic limestone formations of Djebel Zaghouna, Bent Sâadane,

and Zrass, and in Oligocene and Miocene sandstones of the Nadhour-Saouaf syncline (Khanfir 1984).

There is a dense and well-developed surface drainage network in the region that has developed around the Oued Rmel stream (Fig. 3). The main tributaries draining the Rmel watershed are Oued Hammam Zriba, Oued Meleh, Oued Zit, Oued Hadjar, Oued Sbayhia, and Oued Smar.

Based on geology, two lithostratigraphic sections have been constructed in the study area based on drilling and





**Fig. 2** a Geological map (assembly of the 1/50,000 geological maps of Zaghoun and Bouficha), b–d lithostratigraphic log of the study area, e Djebel Oust–Djebel Zaghoun structural diagram (Jallouli 2000)



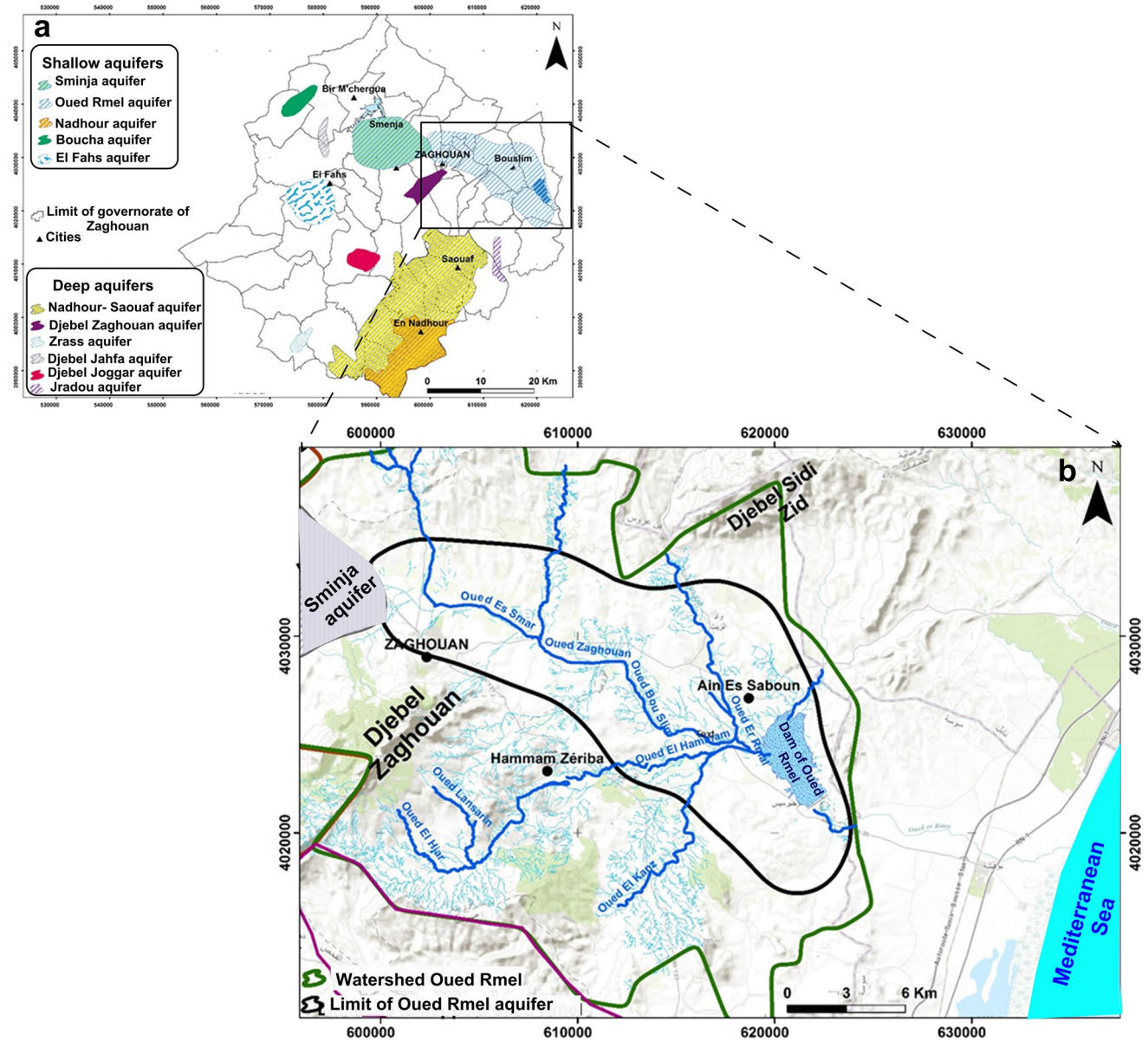


Fig. 3 a The big aquifers in Zaghouna region, b location of the Oued Rmel aquifer

geophysical data (Rekaya 1981; Briki 2013) (Fig. 4). These cross sections were chosen so that each one passes at least through a at least one reconnaissance borehole to show the spatial morphology of the Oued Rmel aquifer (9462/2 = 177 m), (10,370/2 = 170 m), and (16,831/4 = 200 m).

Cross section BB': It, which passes through the 177 m deep borehole 9462/2, has intersected a series very similar to that found at 10,370/2, with notable clay enrichment towards the base.

Cross section CC': It passes at the level of the outlet of the Oued Rmel basin and joins towards the south of borehole 16831/4. It intersected a shallow sequence of cobbles,

gravels, and sands up to 50 m in thickness, which is underlain by a sequence of clays up to 120 m in thickness. These clays in turn are underlain by a sequence of gravels and sandy clays that are up to 200 m thick.

### Piezometry and exploitation of the aquifer

The Oued Rmel aquifer is the most important phreatic aquifer in the governorate of Zaghouna.

The groundwater flow direction in the Oued Rmel aquifer is essentially from west to east, i.e. towards the Mediterranean Sea. The sea is the natural outlet of this aquifer (Rekaya 1981). The discharge is by evaporation, via the

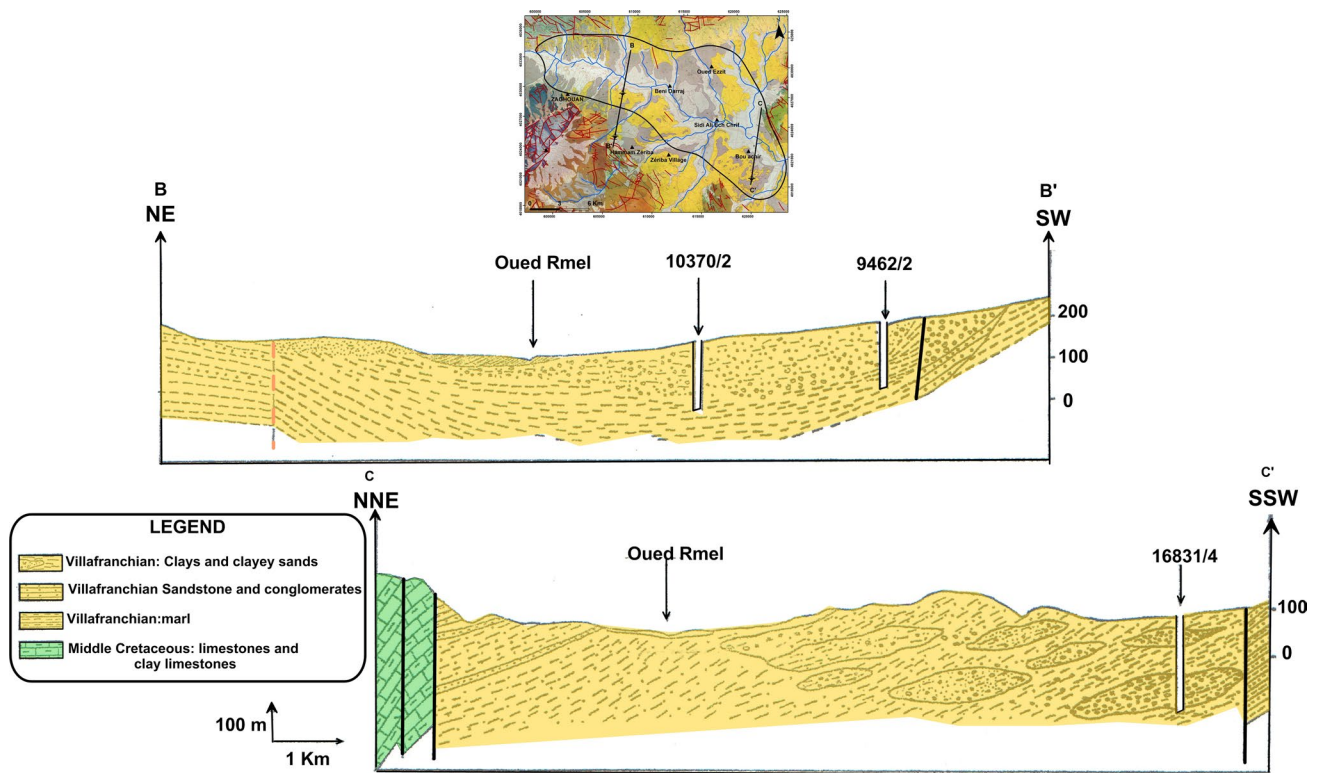


Fig. 4 Schematic hydrogeological cross section of Oued Rmel aquifer along the sections BB' and CC'

Oued Rmel, and by underground flow to the Bouficha plain (Khanfir 1984).

The fluctuation of the piezometric level of the Oued Rmel aquifer between the low- and high-water periods of 2010 is 0.18 and 4.36 m, respectively (Fig. 5). This decrease is due to the rainfall deficit observed during this year, with the drying of several hill dams. From 1985 to 2015, there was a tendency to increase exploitation, which

manifested as a decrease in the piezometric level of the Oued Rmel aquifer.

The exploitation of this groundwater began sporadically in the 1970s, intensified, and reached an annual abstraction rate 0.42 Mm<sup>3</sup> in 1985 and 0.81 Mm<sup>3</sup> in 2015 (Fig. 6). The overall volume of water stored in the aquifer is estimated to be 8.30 Mm<sup>3</sup>, while the number of surface wells is 1005, of which 636 are equipped with motor pumps (DGRE 1985).

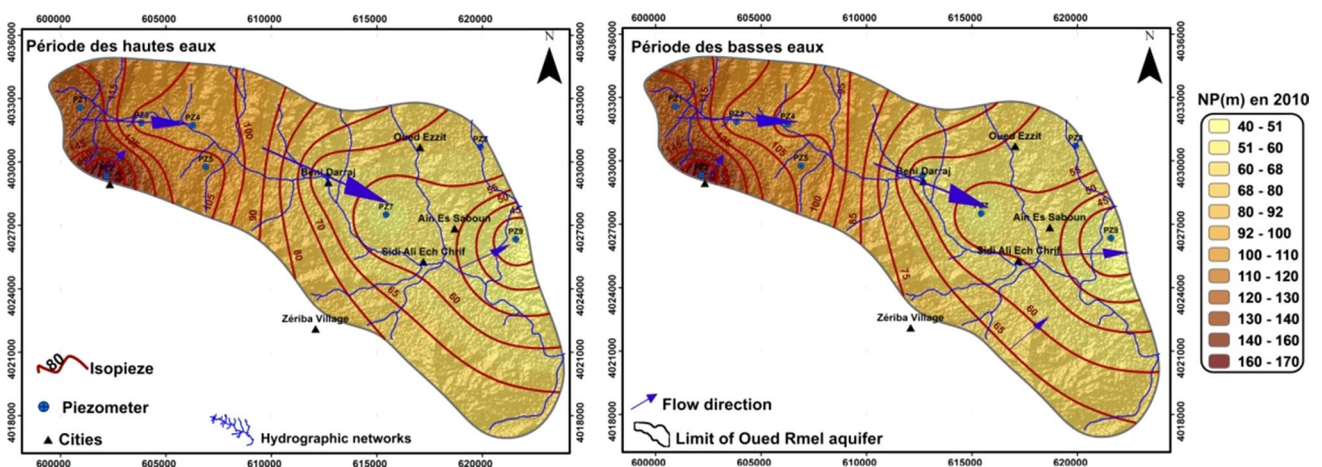


Fig. 5 Piezometric level map of the Oued Rmel aquifer and the sample locations of piezometers

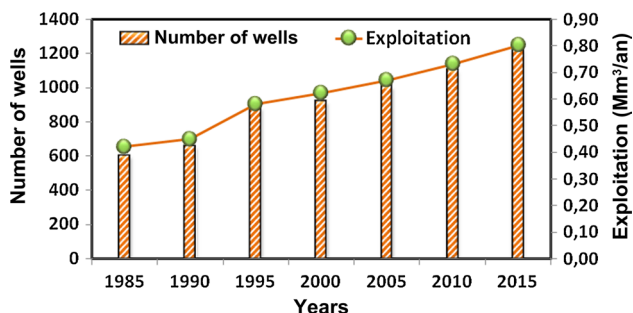


Fig. 6 Evolution of the exploitation of the Oued Rmel aquifer between 1985 and 2015

## Materials and methods

### Sampling and Physico-chemical analysis

A total of 46 water samples were collected from the Oued Rmel aquifer in January and August 2013. During sampling, measurements of pH, dissolved oxygen (DO), and electrical conductivity (EC) were carried out in the field. Chemical analyses of samples were undertaken in the laboratory of the Research Unit of Geochemistry and Geology of the Environment at the Faculty of Sciences, University of Tunis. The choice of wells and boreholes to be sampled was made to cover the maximum amount of the study area. Wells equipped with motor pumps were preferentially selected to simplify the sampling procedure and to enable the stagnant water column in each well to be easily purged before sampling (Ameur et al. 2016).

All water samples were tested in situ with a multifunctional field instrument for temperature, pH, dissolved oxygen (DO), and electrical conductivity (EC) to obtain representative values of the real aquifer conditions (Hamzaoui-Azaza et al. 2012; Ameur et al. 2015a). Water samples were stored in a controlled temperature of less than of 4 °C in order to be transported to the laboratory. The samples were collected in polyethylene bottles which were clean, demineralized, and properly labelled as per standard practice. In the laboratory, groundwater samples were filtered using 0.45-µm filters.

Table 1 summarizes the standard methods adopted in the laboratory for the analysis of major elements and nutrient elements in water samples from the Oued Rmel aquifer.

### GIS mapping method adopted for irrigation water quality of study area

GIS software such as ArcGIS 10.2 used to provide information in real time about the quality of groundwater resources in aquifers such as the Oued Rmel aquifer and to enable the superposition of thematic maps, such as geological maps, piezometric maps, and distribution maps of some parameters such as (SAR), (EC), (RSC), (% Na), (PI). In this study, the location of the groundwater sampling points was performed in the field by GPS in the UTM cylindrical projection system, which is the most used projection type in Tunisia. A flow chart of the GIS-based approach used in this study to assess the suitability of groundwater for irrigation in the study area is shown in Fig. 7.

## Results and discussion

### Geochemistry of the Oued Rmel aquifer

Results of chemical analyses and field measurements of water samples of the Oued Rmel aquifer showed a variation in the different parameters. Average pH was 7.22, while TDS were 2747.09 mg/L. Similarly, detail of other parameters is given in Table 2.

The order of abundance of cations in the Oued Rmel aquifer is  $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ . The sodium ion is the dominant cation, with concentrations ranging between 169 and 850 mg/l, with a mean value of 415 mg/l. The order of abundance of the major anions of Oued Rmel is  $Cl^- > SO_4^{2-} > HCO_3^-$  (Fig. 8). The waters of the Oued Rmel aquifer are characterized by positive saturation indices ( $SI > 0$ ) with respect to calcite and dolomite, indicating that these waters are saturated or supersaturated with respect to these minerals (Fig. 9). These waters are, however, subsaturated with respect to gypsum.

Table 1 Methods used for major chemical analysis of water samples

Parameters	Methods (Rodier 2009)
Chloride ( $Cl^-$ )	Mohr method (standard $AgNO_3$ titration)
Bicarbonates ( $HCO_3^-$ )	potentiometric method (titration with $H_2SO_4$ )
Sulphate ( $SO_4^{2-}$ )	Gravimeter method using $BaCl_2$
Sodium ( $Na^+$ ) Potassium ( $K^+$ )	Atomic emission spectrophotometry (flame photometry)
Calcium ( $Ca^{2+}$ ) Magnesium ( $Mg^{2+}$ )	Titrimetrically using standard ethylenediaminetetraacetic acid (EDTA)



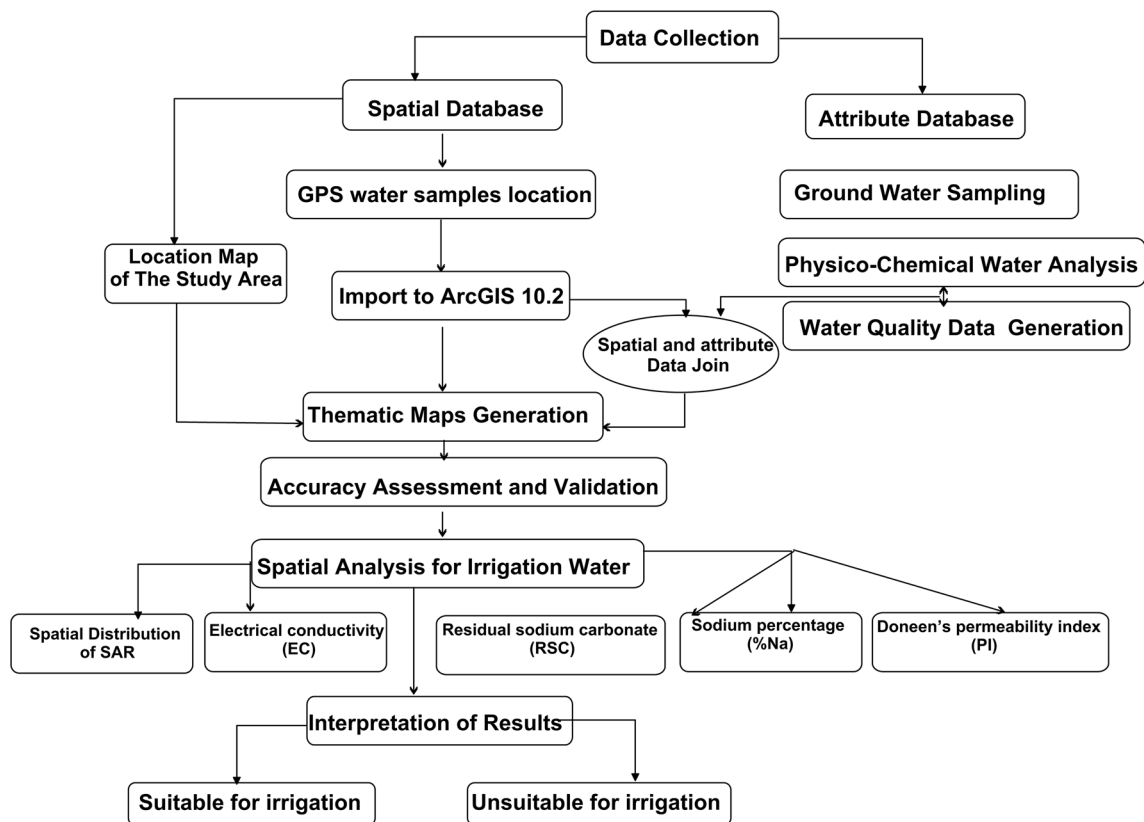


Fig. 7 Flow chart of the methodology adopted

**Table 2** Analytical results of physico-chemical analyses of Oued Rmel aquifer

Parameters	Min	Max	Mean
TDS (mg/L)	1227.96	6109.48	2747.09
T (°C)	10.40	25.00	19.57
pH	6.90	7.65	7.22
Na <sup>+</sup> (mg/L)	168.00	850.00	415.29
Ca <sup>2+</sup> (mg/L)	62.01	415.72	189.97
Mg <sup>2+</sup> (mg/L)	35.00	156.34	79.83
K <sup>+</sup> (mg/L)	1.10	10.26	5.61
EC (ms/cm)	1.62	8.06	3.62

**Hydrogeochemical water types**

To identify the chemical facies of the waters of the Oued Rmel aquifer, the major ions were plotted on a Piper diagram (Fig. 10a). The Piper diagram enables us to determine the ionic composition of the water samples and their classifications. The waters of the Oued Rmel aquifer show three types of facies (Fig. 10b): 70% of the water samples have Na–Ca–Cl–HCO<sub>3</sub> facies, in the upstream part of Oued Rmel aquifer, 13% of the water samples show a type facies Na–Ca–Cl–SO<sub>4</sub>, in the central part of the aquifer, and 17% of the water samples present Na–Cl facies, in the downstream part of the aquifer. It is noted

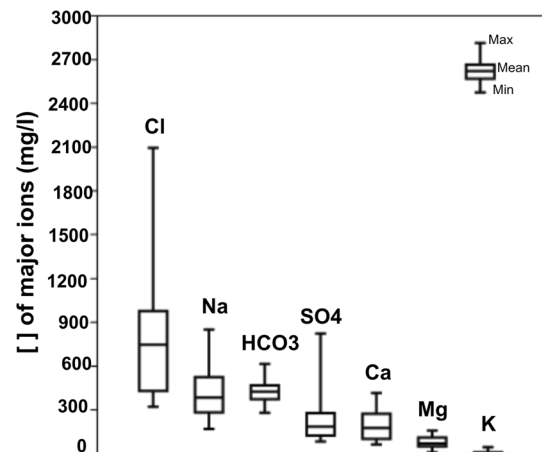
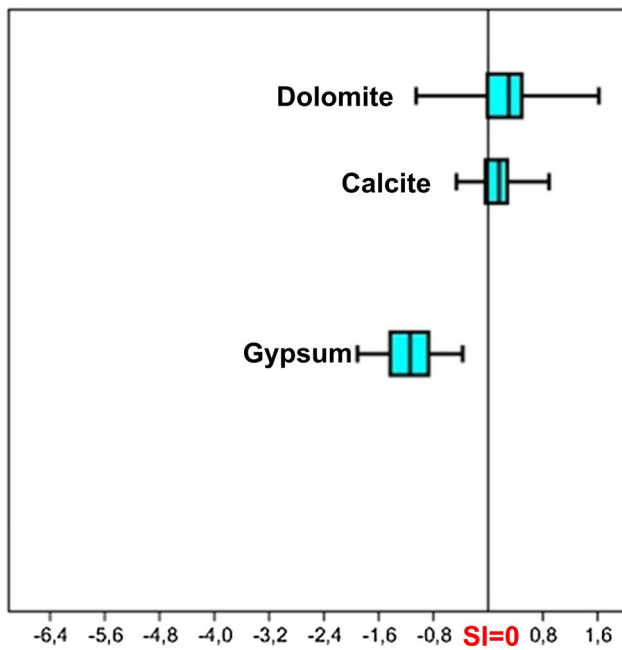


Fig. 8 Box plots of major ions (mg/l) of the Oued Rmel aquifer

that the spatial distribution of these chemical facies varies in the direction of groundwater flow depending on the geological nature of the aquifer.

**Irrigation water quality assessment**

Zaghouan is among the important agricultural regions of Tunisia; the assessment and management of the chemical



**Fig. 9** Boxplots indicating the saturation indices (SI) of the waters of Oued Rmel aquifer with respect to calcite, dolomite, and gypsum

quality of its water resources is paramount. Most of the shallow wells that intercept the Oued Rmel aquifer are exploited for irrigation. However, these waters have a high salinity ranging between 1620 and 8060 mg/l, a level of salinity that can cause adverse effects on soil structure.

There are many parameters to be checked to ensure the quality of irrigation water from the Oued Rmel aquifer, including sodium adsorption ratio (SAR), electrical conductivity (EC), residual sodium carbonate (RSC), sodium percentage (%Na), Doneen’s permeability index (PI),

Kelly’s ratio (KR), and magnesium hazard (MH) (Ayers and Westcot 1994).

**Sodium adsorption ratio and USSL diagram**

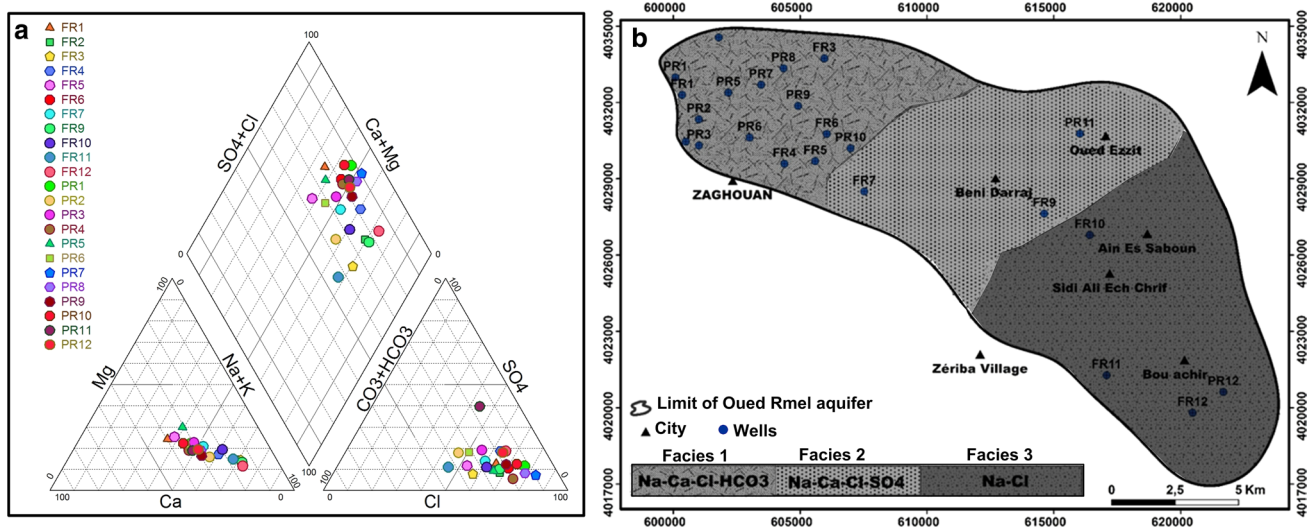
The SAR (sodium adsorption ratio) assesses the suitability of water for irrigation, and the potential risk of sodicity and salinization associated with its use. It determines the degree of danger to crops by measuring sodium hazard and alkalinity (Todd 1980). It involves the concentrations of sodium, calcium, and magnesium (Subba Rao 2006) and is calculated using the following formula (1):

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+}+Mg^{2+})}{2}}} \text{ (meq/l).} \tag{1}$$

The values of SAR varied from 4 to 18. Figure 11a shows that 56, 39, and 5% of groundwater samples from the Oued Rmel aquifer present, respectively, low, medium, and high alkalinity hazard to crops. The USSL diagram (Fig. 11b) combines two parameters, SAR and EC, and places most of the water samples from the Oued Rmel aquifer in the C4a-S2 and C4b-S3 categories, which present medium to high risks of sodicity and alkalization for irrigation.

**Electrical conductivity**

Electrical conductivity measures the ability of water to transmit electrical current. The desirable EC limit in drinking water is set by the World Health Organisation as 1500 μS/cm (WHO 2011).



**Fig. 10** a Piper diagram and b spatial distribution of the chemical facies of the Oued Rmel aquifer

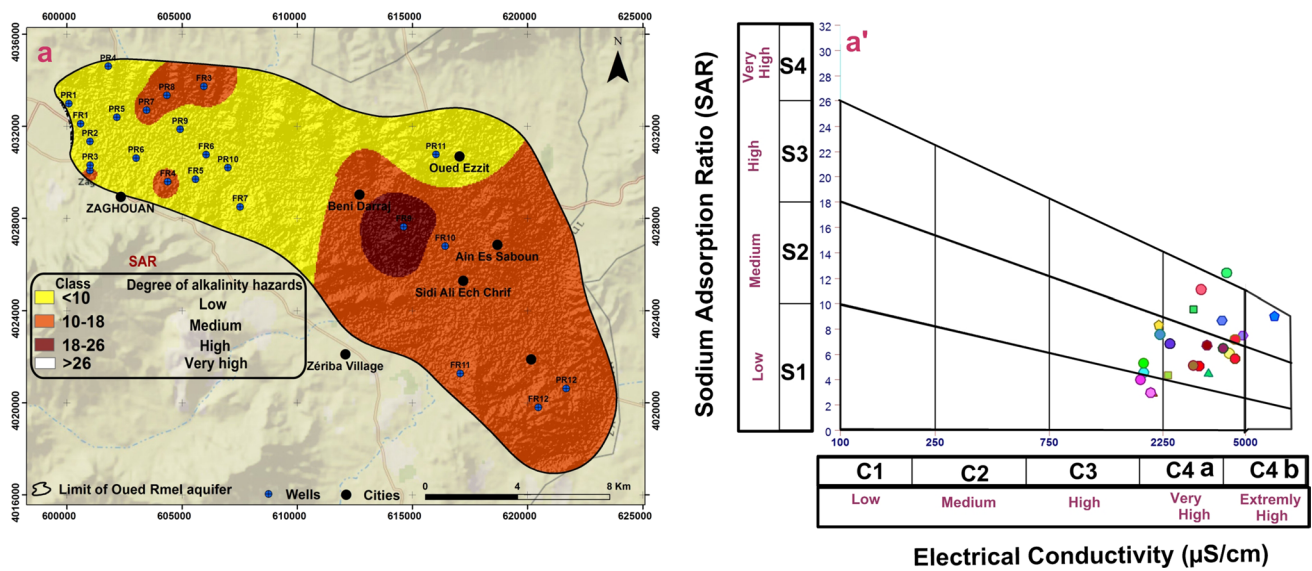
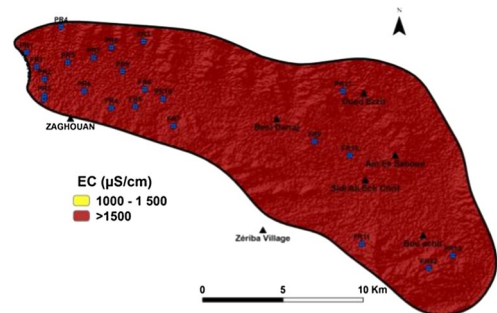


Fig. 11 a Spatial distribution of SAR and a' USSL diagram of the Oued Rmel aquifer

Table 3 Suitability of the groundwater for irrigation, based on electrical conductivity (EC)

Parameters	Range	Class	No. of samples	Percentage of samples	Spatial distribution
EC (μS/cm)	< 500	Excellent	0	0	
	500–750	Good	0	0	
	750–1000	Moderate	0	0	
	1000–1500	Doubtful	0	0	
	> 1500	Unsuitable	23	100	



The values of electrical conductivity (EC) vary from 1620 to 8060 μS/cm, with an average of 3623 μS/cm. According to EC values, 100% of samples of Oued Rmel aquifer are unsuitable for irrigation purposes based on this parameter (Table 3).

**Sodium percentage (%Na)**

The percentage of sodium in the water (%Na) is another important parameter, of the same importance as SAR and EC, and is widely used to assess the suitability of groundwater for irrigation (Wilcox 1948).

High levels of sodium in irrigation water will be absorbed by clay particles and, consequently, the ions Ca<sup>2+</sup> and Mg<sup>2+</sup> will be displaced. Therefore, elevated concentrations of

sodium may have damaging effects on soils and plants by reducing soil permeability and limiting plant growth (Vasanthavigar et al. 2010; Ameer et al. 2015a). According to Wilcox (1955), sodium percentage (%Na) is expressed as follows:

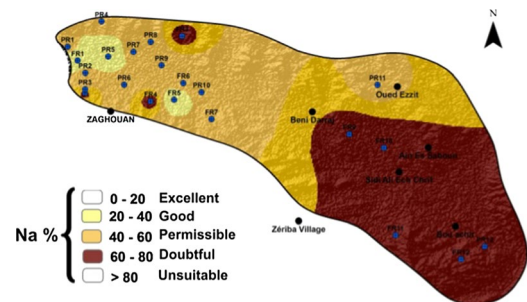
$$\%Na = \frac{(Na^+ + K^+) \times 100}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \tag{2}$$

In the study area, it was observed that the sodium percentage (% Na) was between 20 and 60% in 81% of samples. This means that the water is acceptable for irrigation on the basis of this parameter, except for seven water samples located in the downstream part of the Oued Rmel aquifer, which are in the category of Na between 60 and 80%, which is not suitable for agricultural purposes (Table 4).



**Table 4** Suitability of the groundwater for irrigation based on sodium percentage (%Na)

Parameters	Range	Class	No. of samples	Percentage of samples	Spatial distribution
%Na	0–20	Excellent	0	0	
	20–40	Good	3	21.74	
	40–60	Permissible	13	60.78	
	60–80	Doubtful	7	13.04	
	> 80	Unsuitable	0	0	



**Residual sodium carbonate (RSC)**

In addition to the sodium percentage, the bicarbonate hazard, expressed using residual sodium carbonate (RSC), is another indicator of water quality for irrigation. RSC is an index that indicates the excess of bicarbonate and carbonate in irrigation water.

In water, if the sum of the concentrations of bicarbonates and carbonates is greater than the calcium and magnesium levels, there is a strong possibility of the appearance of a precipitate of  $Ca^{2+}$  and  $Mg^{2+}$  (Eaton 1950; Ragunath 1987).

Residual sodium bicarbonate was calculated according to Gupta and Gupta (1987) using the following equation:

$$RSC = [(CO_3^{2-} + HCO_3^-)] - (Ca^{2+} + Mg^{2+}). \quad (3)$$

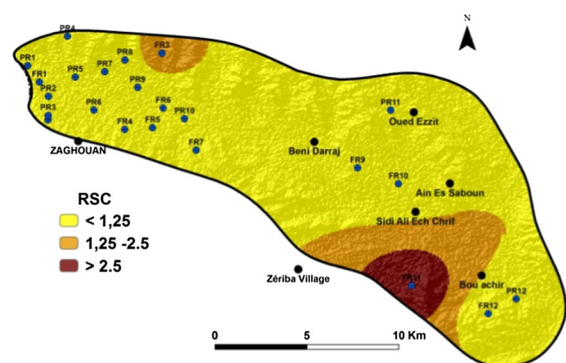
By referring to RSC values, 92% of water from the Oued Rmel aquifer was found to have a safe level of residual sodium carbonate (i.e. RSC is less than 1.25 meq/L). Only one sample has RSC values between 1.25 and 2.5 meq/L indicating a marginal quality of water and another sample has an RSC value greater than 2.5 meq/L, which is certainly not suitable for irrigation (Table 5).

**Doneen’s permeability index (PI)**

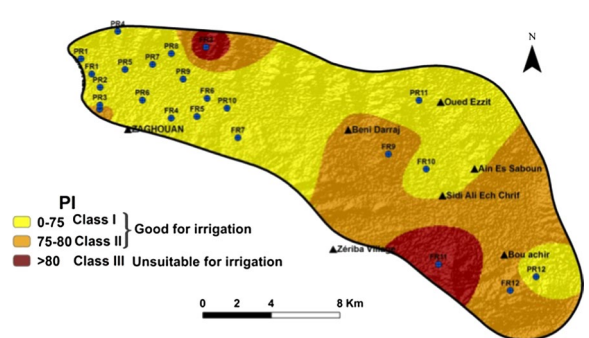
Doneen’s index is used to assess the risk that high cation concentrations (sodium, calcium, and magnesium) and bicarbonates present in water would affect soil permeability if used for irrigation on a long-term basis. Poor irrigation practices are the main cause of the decrease of soil

**Table 5** Suitability of the groundwater for irrigation based on residual sodium carbonate (RSC)

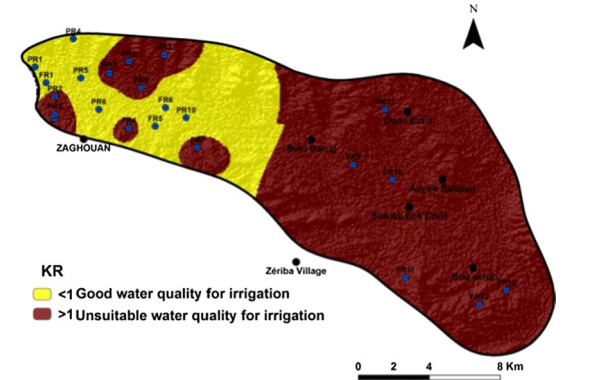
Parameters	Range	Class	No. of samples	Percentage of samples	Spatial distribution
RSC	< 1.25	Good	21	92	
	1.25–2.5	Doubtful	1	4	
	> 2.5	Unsuitable	1	4	



**Table 6** Suitability of the groundwater for irrigation based on Doneen’s permeability index (PI)

Parameters	Range	Class	No. of samples	Percentage of samples	Spatial distribution
PI	0–75	Class I Good for irrigation	18	78	
	75–80	Class II Good for irrigation	3	13	
	> 80	Class III Unsuitable for irrigation	2	9	

**Table 7** Suitability of groundwater for irrigation based on Kelly’s ratio (KR)

Parameters	Range	Class	N° of samples	Percentage of samples	Spatial distribution
KR	<1	Good	8	35	
	>1	Unsuitable	15	65	

permeability, which is expressed by the ratio of sodium and bicarbonate concentrations to those of calcium, magnesium, and sodium in water (Doneen 1964). The PI had been expressed using the following equation:

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100. \tag{4}$$

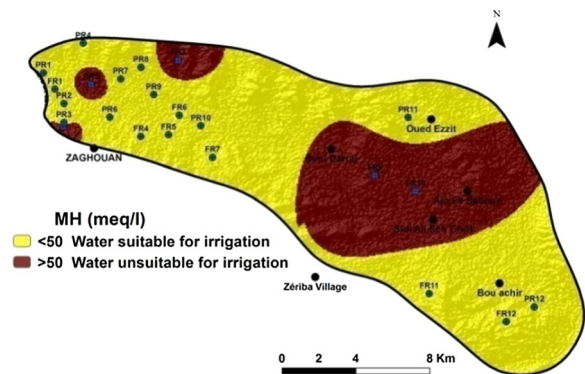
The water samples from the Oued Rmel aquifer with a PI of less than 80% represented 91% of the total samples and indicated good quality for irrigation on the basis of this index. Just 9% were unsuitable for irrigation activities (Table 6).

**Kelly’s ratio (KR)**

Kelly’s equation is another formula for classifying water for irrigation, calculated by considering the ratio of the content of sodium ions against the content of calcium and magnesium ions. If the Kelly’s index is greater than 1, there is a high concentration of sodium in the water and, consequently, it is not suitable for irrigation. In the study area, 65% of samples would be considered to unfit for irrigation on the basis of this ratio, and the remainder were of good quality (Table 7). KR was given by Kelly (1963) and based on the following equation:

**Table 8** Suitability of the groundwater for irrigation based on magnesium hazard (MH)

Parameters	Range	Class	No. of samples	Percentage of samples	Spatial distribution
MH	< 50	Suitable for irrigation	18	78	
	> 50	Unsuitable for irrigation	5	22	



**Table 9** Suitability of samples of Sminja and Oued Rmel aquifer for agriculture purposes

Suitability classification of wells for irrigations uses in				
Parameters	Sminja aquifer (Ameur et al. 2015a)		Oued Rmel aquifer	
	Suitable	Unsuitable	Suitable	Unsuitable
SAR		*		*
EC		*		*
Na%		*		*
RSC	*			*
PI		*		*
KR		*		*
MH		*		*

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (5)$$

**Magnesium hazard (MH)**

The magnesium adsorption ratio represents the excess magnesium concentration compared to the sum of the amount of calcium and magnesium in the water (Paliwal 1972). In the present study, MH values vary between 35 and 52 meq/L, and more than 78% of the water samples from the Oued Rmel aquifer have MH < 50, showing the suitability of these waters on the basis of this parameter. Just 22% were unsuitable for irrigation (Table 8). MH was defined by the equation:

$$MR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100. \quad (6)$$

Due to the absence of historical water quality data for the Oued Rmel aquifer, the results obtained in this study were compared with data from the Sminja aquifer which is in hydraulic connection with the Oued Rmel aquifer (Table 9).

Most waters of Sminja and Oued Rmel aquifers were found unsuitable for irrigation purposes. These results were expected because of the large amounts of chemical fertilizers and pesticides used by farmers to increase crop yields, and this had led to a widespread groundwater pollution.

The interpretation of the water analysis results of the Oued Rmel has shown without a doubt that they were not suitable for irrigation, hence the necessity that policy makers should take preventive and radical solutions to these damages. Among the envisaged solutions is the sensitization of the farmers to decrease the use of the fertilizers according to the needs of the plants to reduce the amounts of salts that leach to groundwater (lixiviation and to use more salt-tolerant crops.

**Conclusions**

Climate change, drought, and water scarcity are the main constraints that hinder the development of irrigation on a global scale, and especially in African countries and MENA regions. In irrigation, water is essential to meet the growing needs of plants and soil, not only from a quantity perspective but also from the quality perspective that is the subject of this study. Water must meet the irrigation criteria so as not to harm plant development or soil fertility. Poor water quality can cause many problems, including salinity hazards, alkalinization, and sodicity. Very salty irrigation water can damage the structure of soils and crops (Ayars 1993). Twenty-three



samples from Oued Rmel aquifer were analysed to evaluate the suitability of their waters for irrigation uses. The analysis of the composition of major ions and their distributions in the Piper diagram made it possible to distinguish three main chemical facies of the waters of the Oued Rmel aquifer: Na–Ca–Cl–HCO<sub>3</sub>, Na–Ca–Cl–SO<sub>4</sub>, Na–Cl, from upstream to downstream, respectively. The abundance of cations and anions in the water of Oued Rmel was in the following order: Na<sup>+</sup>>Ca<sup>2+</sup>>Mg<sup>2+</sup>>K<sup>+</sup> and Cl<sup>-</sup>>SO<sub>4</sub><sup>2-</sup>>HCO<sub>3</sub><sup>-</sup>, respectively.

In the study area, water was found saturated with calcite and dolomite, with a saturation index greater than 1, whereas it was under-saturated with gypsum (SI < 1, which indicated the possibility of the acquisition of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> by dissolving these minerals present in the aquifer. The technique of inverse distance weighting interpolation (IDW) from ArcGIS was used to visualize the spatial distribution maps of water quality parameters of the aquifer (SAR, EC, RSC, % Na, PI, KR, and MH) for irrigation purposes and will subsequently be supported tools for decision-makers in the region.

According to the values (%) of Na, RSC, PI, KR, and MH, it is possible to conclude that more than half the water was found permissible for irrigation, and the second half of the samples were plotted in doubtful to unsuitable classes for irrigation. The results of chemical analyses plotted in the USSL diagram showed that most of water samples were found in the C4a-S2 and C4b-S3 categories, indicating a medium to high danger of sodicity and alkalization hazards. The spatial distribution maps of these parameters showed, predominantly, the degradation of the water quality was in the eastern part of the aquifer where the samples were doubtful to be unsuitable for irrigation purposes. This part of the Oued Rmel aquifer was a zone with a large farming area and misuse of chemical fertilizers. From the research that has been undertaken, unfortunately, the damage to soil and water resources by agriculture is often irremediable and the processes are irreversible, such as loss of fertile soil layers, salinization of aquifers, and pollution by nitrates, fluorides, and heavy metals.

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