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# Spatial analysis and mapping of the groundwater quality index for drinking and irrigation purpose in the alluvial aquifers of upper and middle Cheliff basin (north-west Algeria)

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## ABSTRACT

The proposed study aims to assess groundwater quality and suitability of the Upper and Middle Cheliff plains (northwest of Algeria) for irrigation and drinking. Here the groundwater is the main source for domestic, agricultural and industrial activities similarly to any other region of the world. The suitability for drinking and for irrigation was evaluated on the basis of water quality index, salinity risk, hardness risk, sodium risk, magnesium risk, permeability index, water infiltration rate, Kelly index and Wilcox and Richards diagrams. The aquifer system is mainly composed of alluvium (gravel, sand, silt, clay, …) from the Mio-Plio-Quaternary. The results of this study highlighted that the majority of the chemical elements analyzed exceed the WHO's drinking water standards and FAO's irrigation water standards. Based on the GroundWater Quality Index (GWQI) results, the Upper and Middle Cheliff groundwater plains shows Doubtful class in most of the plains. In addition, the GroundWater Quality Index for Irrigation (GWQII) shows the predominance of the Good/Permissible groundwater quality class in most of the plains. According to these results, drinking water can cause health problems (a danger) for the human consumption making necessary a proper treatment be able to use it. As for irrigation water, it does not present a danger for irrigating for the vast fields of the region, with the exception of sensitive crops such as: garlic, onion, beans and strawberry. The proposed approach demonstrated to be appropriate in assessing the groundwater quality for irrigation and drinking water supply since it can be easy applicable and suitable in humid, arid or semi-arid regions around the world.

**Key words:** GIS, groundwater, GWQI, GWQII, semi-arid region

## HIGHLIGHTS

- The study aims to assess groundwater quality of the Upper and Middle Cheliff plains (northwest of Algeria) for irrigation and drinking water supply.
- Groundwater Quality Index for drinking shows a predominance of the Doubtful class in the plains.
- Groundwater Quality Index for Irrigation shows a predominance of the Good/Permissible class in the plains.

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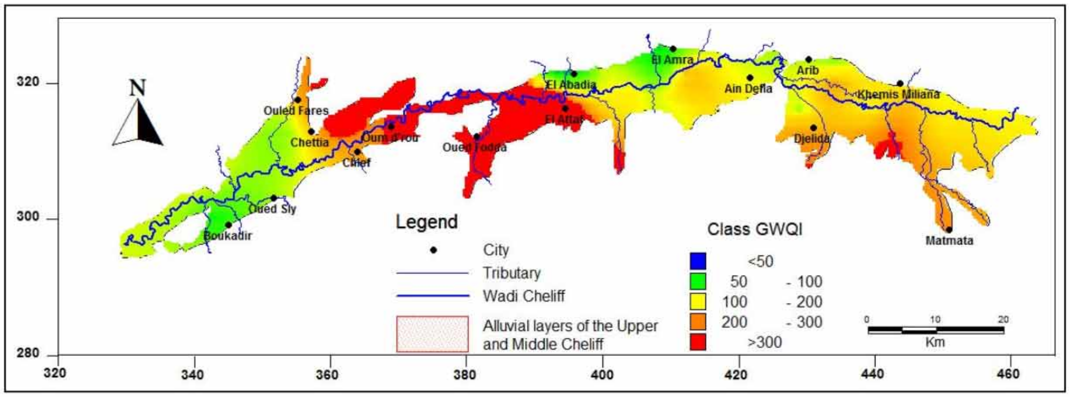
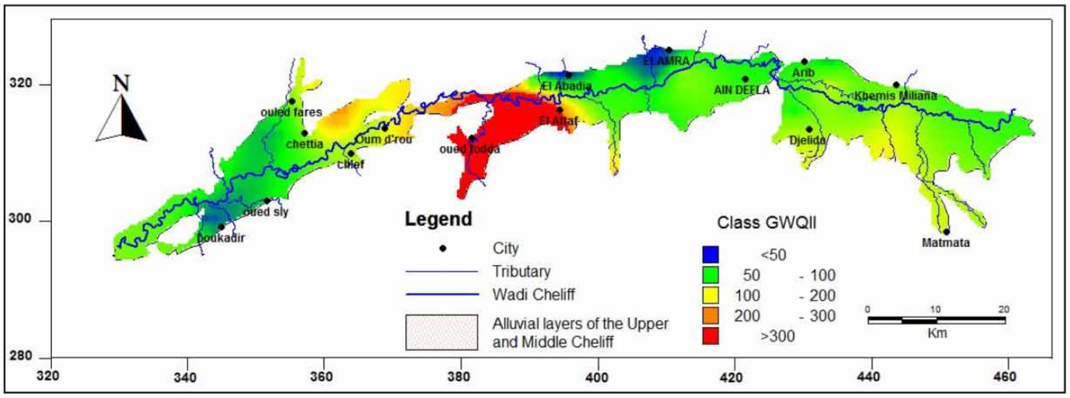
## GRAPHICAL ABSTRACT




**Index map (GWQI) of the groundwater quality in the Upper and Middle Cheliff alluvial aquifers for Dry period 2017**




**Index map (GWQII) of the irrigation groundwater quality in the Upper and Middle Cheliff alluvial aquifers for Dry period 2017**

## INTRODUCTION

Groundwater represents the main resource of potable water all over the world (Margat & Van Der Gun 2013), with an estimated exploitation rate of 982 $km^3$/year. About 70% of the latter is commonly used for irrigation (Siebert *et al.* 2010) providing nearly half of the world's drinking water needs (Smith *et al.* 2016). The Mediterranean region, which is considered as one of the water-poorest regions in the world (Leduc *et al.* 2017), could even reach higher than average percentage of water exploitation. This is particularly true in the state of Algeria where the exploitation index of renewable water (surface water and groundwater) is reaching its maximum of sustainability (El Jihad & Taabni 2019) with a rate approximately of 67%.

In Algeria, water is a precious and rare resource since it can be scarce and very poor in many places. Groundwater is the main source of potable water in the country (irrigation and municipal use) due to its relatively easy utilization, but the growing overexploitation has driven to an increasing reduction and pollution of this precious resource. According to this scenario, the necessity of a specific and reliable groundwater quality study become imperative (FAO 2016).

The Upper and Middle Cheliff alluvial aquifers, located in northwestern Algeria, are a perfect example of arid places with a semi-arid climate characterized by a high evapotranspiration rate. In recent years, the area saw important population growth as well as an industrial and agricultural development. The application of the National Program for the Development of Agriculture (NPDA) developed in 2000 along with the National Fund for the Regulation of Agricultural Development (NFRAD) in 2001 triggered a huge increase of water demand for irrigation, leading to an intensive overexploitation of the local alluvial aquifers. This overexploitation also generated a worrying situation of groundwater quality deterioration and pollution susceptibility making mandatory to determine the spatial discretization of groundwater quality.

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Several tools have been proposed and tested around the world using both physicochemical and biological parameters for describing water quality and among the others, the water quality indices (WQIs) are the most used one (Machiwal *et al.* 2018). The WQI approaches are useful tools used to convert complex databases into easily interpretable results and have been widely used in recent years to characterize the groundwater quality (Papazotos *et al.* 2019).

Mehdaoui *et al.* (2019) studied physicochemical and bacteriological characterizations for groundwater quality assessment in the Middle Ziz Valley, south-east of Morocco. Abboud (2018) evaluated the geochemistry and groundwater quality of the Yarmouk Basin aquifer in northern Jordan. An & Lu (2018) investigated the main hydrogeochemical processes and causes of groundwater pollution in the northern Ordos Basin in China. Chitsazan *et al.* (2019) examined the hydrochemical processes, quality change and pollution of groundwater, in Iran. Khodabakhshi *et al.* (2015) coupled WQI with DRASTC methodology in Iran while Rufino *et al.* (2019) and Rufino *et al.* (2021) proposed specifics WQI for potable, drinking and irrigation purpose, along with a drinking hazard risk for South Italy.

In Algeria, Gouaidia *et al.* (2013), Touhari *et al.* (2015), Bouderbala (2017), Gorine *et al.* (2020), Rezig *et al.* (2021) already investigated groundwater quality and surface water status for drinking and irrigation purposes. They identified the main anthropogenic hydrogeochemical processes responsible for groundwater pollution (domestic waste, untreated wastewater and intensive use of chemical fertilizers in agriculture) and for groundwater quality degradation. Accordingly, groundwater quality assessment has become a necessary and mandatory task to achieve for the current and future qualitative management groundwater, also in view of expected climate changes, which will further decrease the groundwater availability in Mediterranean regions (Busico *et al.* 2021).

In this scenario, the main goal of this study is to evaluate the spatio-temporal groundwater suitability for human consumption and irrigation in the Upper and Middle Cheliff plains. This study tried to updated the preexistent scientific basis in the groundwater quality deterioration and its sources in this region and to provide valuable insight for future research.

A combination and implementation of hydrogeological and hydrogeochemical approaches such as piezometry variation (wet and dry periods) and physicochemical quality will be applied and evaluated simultaneously to obtain a more accurate and reliable evaluation of groundwater availability and quality. Moreover, the results of four measurement and sampling campaigns carried out in different years (2012 and 2017) will allow the analysis of groundwater quality changes through time. All date have been digitalized and spatialized using geographic information system (GIS) to allow a reliable spatial distribution of the results (Ramachandran *et al.* 2020). Four indices were calculated: Groundwater Quality Index (GWQI) for human consumption, sodium adsorption index (SAR), percent sodium (%Na) and percent exchangeable sodium (ESP) for agricultural use.

## Study area

The basin of the Upper and Middle Cheliff is an intra-mountainous basin, located in the northwest of Algeria and it is part of the Cheliff hydrographic basin (ABH 2004). Geographically, the study area (Figure 1) is located between longitudes 1° 00′ and 3° 20′ East and latitudes 35° 40′ and 36° 30′ North. The study area corresponds to the center of what geographers call the 'Maghreb'. It can be divided into eleven sub-basins areas according to the geomorphological delimitations. They are drained by the Chlef wadi which crosses them over a length of about 349 km (ABH 2004). It covers an area of 10,916 $km^2$. The valley of the Upper and Middle Cheliff crossed by the Chlef wadi is located in the northern part of the watershed, which occupies 10% of the total area of the basin. It is composed of three plains: the plain of the Upper Cheliff (plain of El-Khemis), the plain of the Middle Eastern Cheliff (plain of El Abadia-El Amra) and the plain of the Middle Western Cheliff (plain of Chlef). These plains are made up of coarse alluvial deposits, occupying an area of 1,070 $km^2$ (Upper Cheliff: 370 $km^2$, Middle Eastern Cheliff: 360 $km^2$, Middle Western Cheliff: 340 $km^2$).

The study area is characterized by Mediterranean climate (semi-arid). The rainfall distribution is very spatially marked. North of the study area, interannual precipitation (1972–2014) is very important on the southern slopes of the Dahra and Zaccar mountains, with a yearly average of more than 600 mm. Precipitation decreases in the plains of Upper and Middle Cheliff where it varies between 300 and 400 mm for year. The average annual temperature is about 18.5 °C.

Geologically, the upper and middle Cheliff basin corresponds to a large synclinorium of the Neogene and Quaternary age where more than 3,000 meters of sediments have been accumulated through time (Glangeaud 1955; Perrodon 1957; Mattauer 1958; Kireche 1977; Meghraoui 1982). However, this system is mainly made of formations of Mio-Plio-Quaternary age (Figure 2) (Meghraoui *et al.* 1986; Kireche 1993; Achour *et al.* 1998). The quaternary formations are represented by alluvium while the Miocene and the Pliocene sediment are represented by sandstone. The carbonate formations that border the plain

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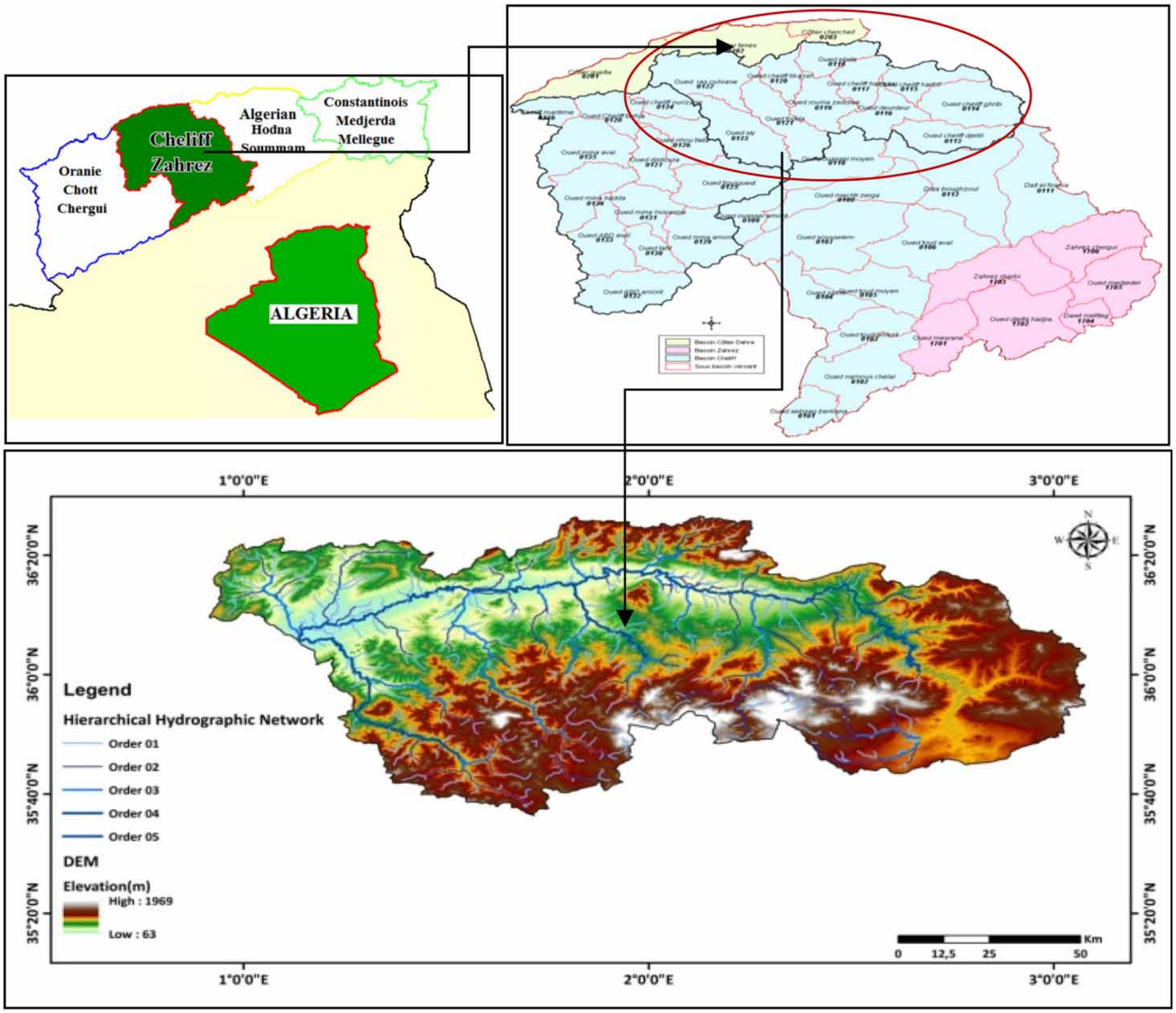


**Figure 1** | Location of the Upper and Middle Cheliff watershed.

are of secondary age (Zaccar, Doui, Témoulgat and Dahra massifs) (Perrodon 1957; Mattauer 1958; Lepvrier 1971; Lepvrier 1978; Kireche 1977; Meghraoui 1982; Djeda 1987; Achour 1997).

From a hydrogeological point of view and based on the lithostratigraphic and structural characteristics of the study area, five main aquifers have been identified (Figure 3):

(i) fissured limestones with lithothamnium, (ii) the Astian marine sandstones and the dune sands with helix, (iii) sandstones, conglomerates and sands of Villafranchian (red layer), (iv) the coarse alluvium of the Cheliff and its tributaries; and finally (v) the ancient quaternary complex.

## Piezometry

The piezometric monitoring allowed to define the general flow direction and to identify the main hydraulic gradient. The piezometric maps reveal no significative changes in the piezometric curve morphology during the wet and the dry periods in the two years 2012 and 2017 reflecting the same overall flow regime. All the piezometric maps indicate that the water table flows from the edges towards the central axis of the valley before taking an east-west direction parallel to the main watercourse of the Chlef wadi (Figures 4 and 5). Anomalous disturbance of the piezometric levels is observed in some places, along the Chlef wadi, due to wells overexploitation to ensure supplies.

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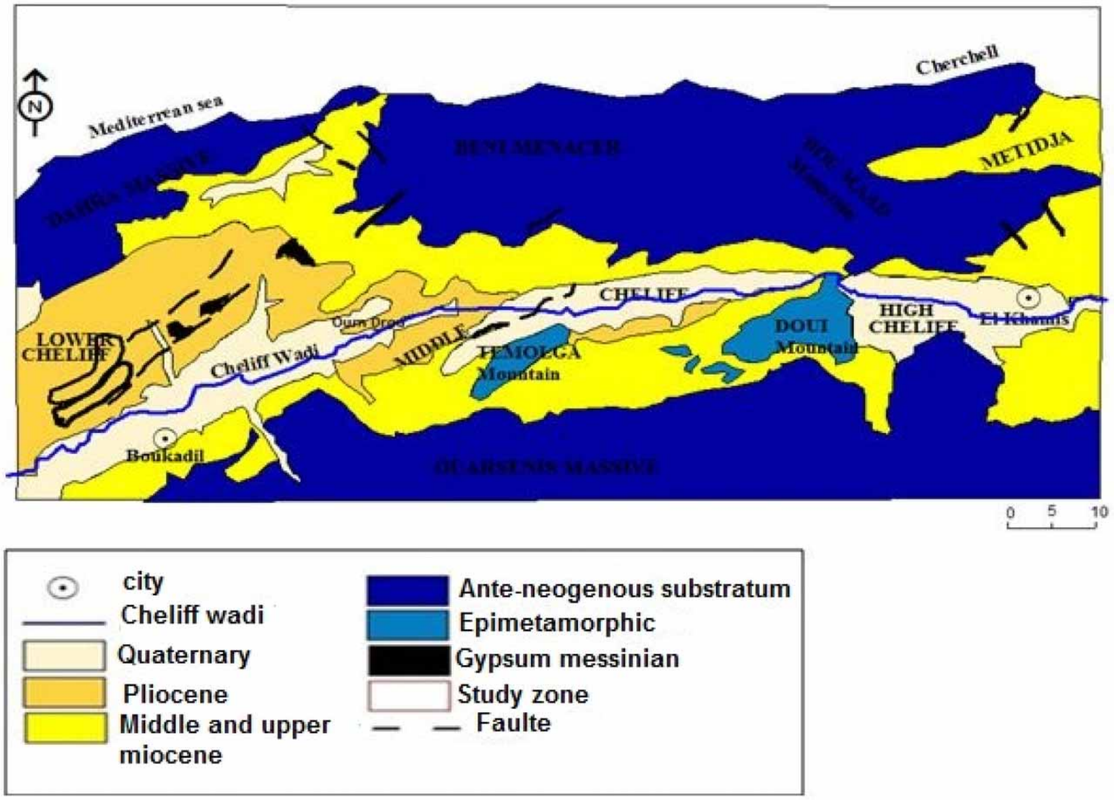


**Figure 2** | Simplified geological map of the study area (Perrodon 1957; Mattauer 1958).

## MATERIALS AND METHODS

### Data collection and analysis

Water samples belonging to the Upper and Middle Cheliff alluvial aquifers were collected from wells and piezometers during the months of May, June, October and November following the wet and dry periods of 2012 and 2017. The database includes two sampling campaigns: in 2012 with 63 water samples (43 wells and 20 piezometers) in the wet period and 71 water samples (47 wells and 24 piezometers) in the dry period. However, another series of two sampling campaigns, organized respectively in the months of May and October of the year 2017, allowed the collection of 38 water samples (26 wells and 12 piezometers) in the wet period and 48 water samples (33 wells and 15 piezometers) in the dry period. The physicochemical parameters include pH, electrical conductivity (EC) and temperature (T), which were measured *in situ*. In addition, $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Cl^{-}$, $SO_4^{2-}$, $HCO_3^{-}$ and $NO_3^{-}$ were determined using a Dionex 120 ion chromatography in the CRNA laboratory and using a UV Spectrophometer, turbidimeter and colorimeter in the ANRH laboratory.

The ionic balance-error is within the acceptable limit of $\pm 5\%$. The results obtained in this study were analyzed, interpreted and presented in the form of tables and thematic maps to give an idea about the quality of the water quality and their spatial and seasonal evolution by using GIS (the software ArcGis) and the statistical software (the software SPSS).

### Groundwater quality index (GWQI)

The GWQI has been calculated to determine the suitability of water for drinking and irrigation purpose. The WQI, allow to obtain a number that expresses the water quality based on several quality parameters (Kumar & Dua 2009). The methodology of calculating the GWQI is described in details by many authors (Pradhan *et al.* 2001; Asadi *et al.* 2007; Dwivedi & Patha 2007; Yidana *et al.* 2008; Varol & Davraz 2015; Aher *et al.* 2016; Bouderbala 2017; Bekkoussa *et al.* 2018; Bodrud-Doza *et al.* 2020; Ramachandran *et al.* 2020; Talhaoui *et al.* 2020; Mehreen *et al.* 2021).

The calculation procedure consists of three steps. In the first step (1), a weight (wi) based on their perceived effects on human health (Table 1) was assigned to each parameters. The maximum weight of 5 was assigned to EC, $Cl^{-}$, $SO_4^{2-}$ and

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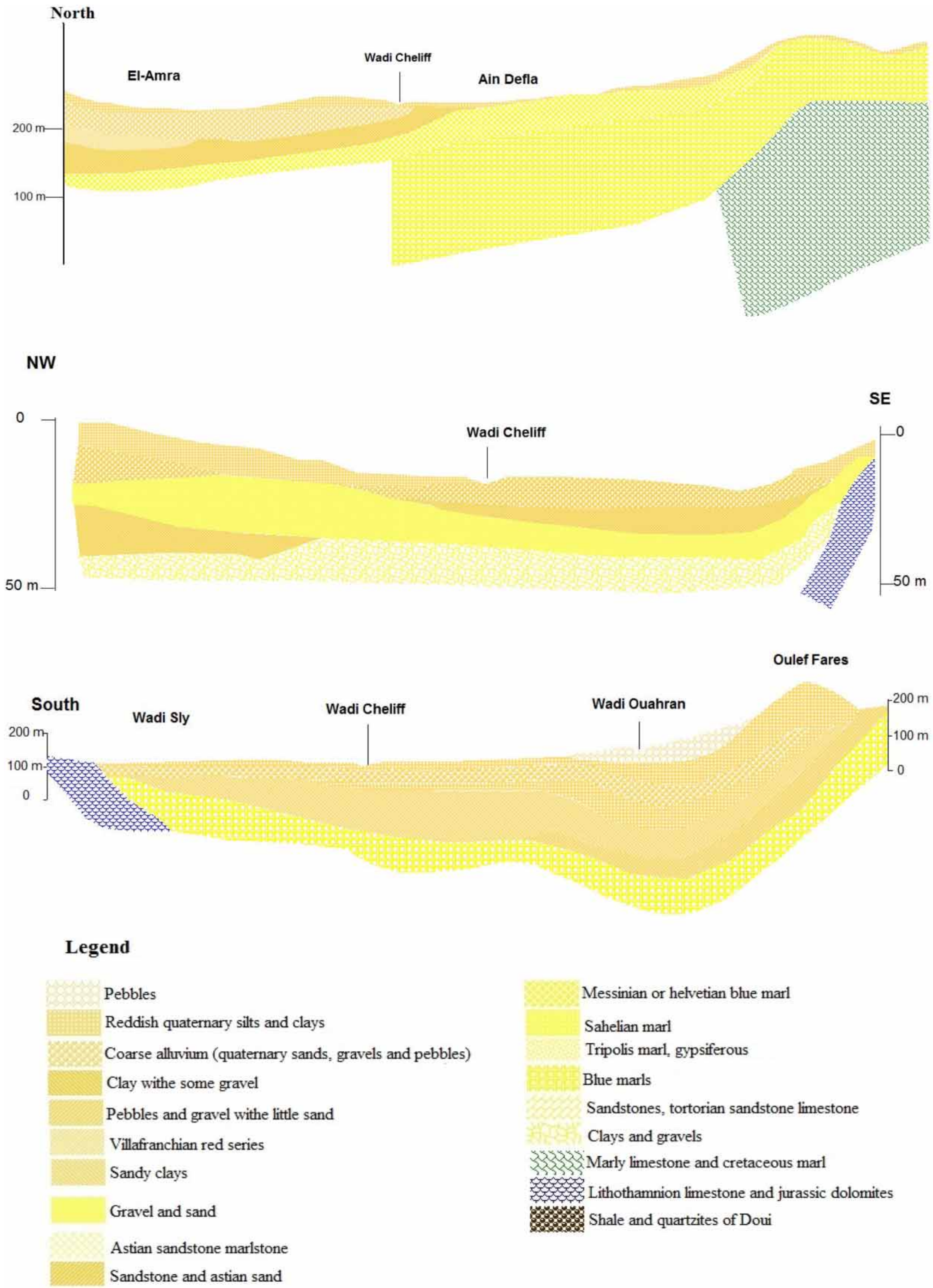


**Figure 3** | Interpretative hydrogeologic sections in the study area.

$NO_3^-$ due to their importance in assessing water quality (Srinivasamoorthy *et al.* 2011). The minimum weight of 1 was instead assigned to $HCO_3^-$ and $K^+$, as they do not play a significant role in the water quality evaluation. Finally, $Ca^{2+}$, $Mg^{2+}$ and $Na^+$ were assigned a weight between 2 and 5 according to their importance in the overall quality of drinking water. Generally, the

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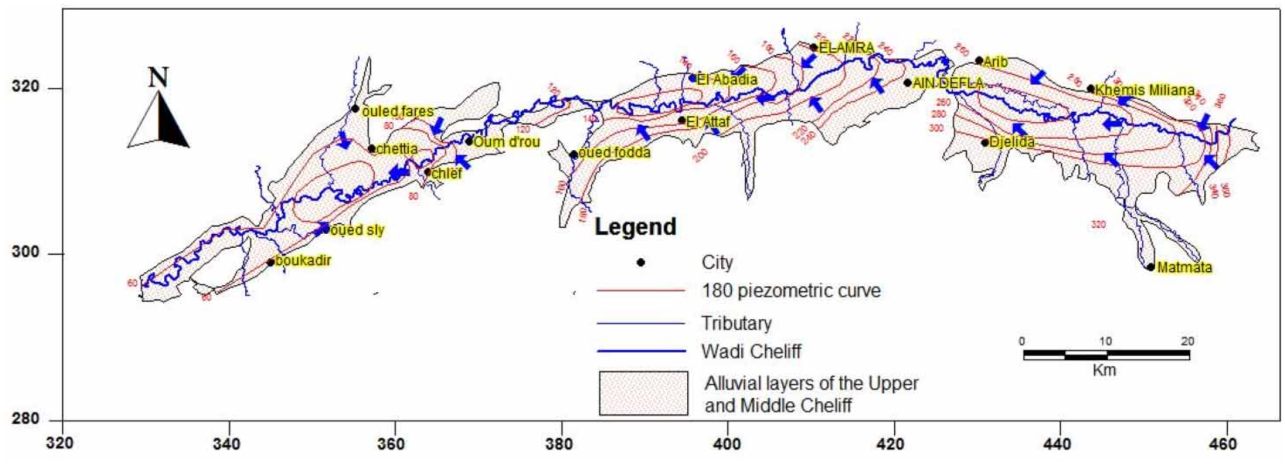


**Figure 4** | Piezometric map of May 2012 (Dry period).

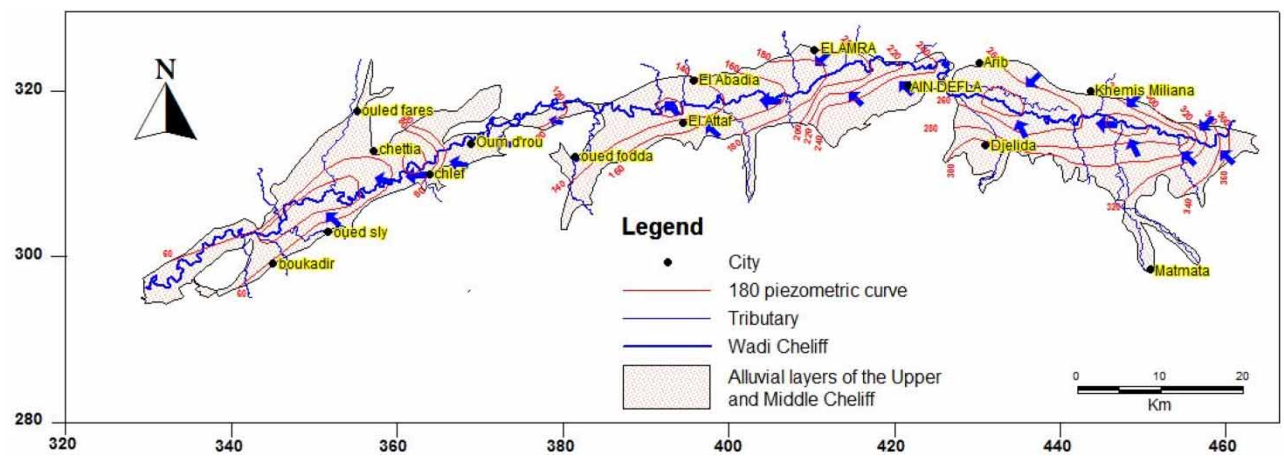


**Figure 5** | Piezometric map of June 2017 (Wet period).

**Table 1** | Water quality parameters, standard values, ideal values and water weight factors (Bouderbala 2017)

| | Drinking water | | | Irrigation water | | |
|---|---|---|---|---|---|---|
| **Parameters** | **($S_i$)** | **Weight (wi)** | **Relative Weight ($W_i$)** | **Ayers & Westcot (1988)** | **Weight (wi)** | **Relative Weight ($W_i$)** |
| pH | 9 | 3 | 0.081 | 9 | 3 | 0.075 |
| Electrical conductivity ($\mu$S/cm) | 1,500 | 5 | 0.135 | 2,250 | 5 | 0.125 |
| Chloride (mg/L) | 250 | 5 | 0.135 | 350 | 5 | 0.125 |
| Sulphates (mg/L) | 250 | 5 | 0.135 | 250 | 5 | 0.125 |
| Calcium (mg/L) | 100 | 2 | 0.054 | 200 | 5 | 0.125 |
| Sodium (mg/L) | 150 | 5 | 0.135 | 200 | 5 | 0.125 |
| Potassium (mg/L) | 12 | 1 | 0.027 | 10 | 3 | 0.075 |
| Magnesium (mg/L) | 50 | 5 | 0.135 | 100 | 5 | 0.125 |
| Bicarbonates (mg/L) | 250 | 1 | 0.027 | 400 | 2 | 0.05 |
| Nitrates (mg/L) | 50 | 5 | 0.135 | 50 | 2 | 0.05 |
| Total | 37 | 01 | | 40 | 01 | |

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weights (wi) were assigned to the measured parameters based on their relative importance in the overall water quality for irrigation purposes and potential effects on soils and plants (Bouderbala 2017).

In the second step (2), the relative weight ($W_i$) of each parameter is calculated using the following formula:

$$W_i = \frac{wi}{\sum_{i=1}^{n} wi}$$

where $W_i$ is the relative weight, wi is the weight of each parameter, n is the number of parameters.

The weight (wi), relative weight ($W_i$) and WHO standards for each parameter are given in Table 1.

In the third step (3), a quality rating scale ($q_i$) for each parameter is assigned by dividing its concentration in each water sample by its respective standard according to the WHO guidelines established in 2008 and FAO (Ayers & Westcot 1988), using the following equation:

$$q_i = (C_i/S_i) \times 100$$

where $C_i$ is the concentration of each parameter, $S_i$ is the threshold limit according to the standard expressed in mg/l. Finally, the water quality index is calculated by the following formula (Krishan *et al.* 2016):

$$GWQI = \sum W_i q_i$$

The final groundwater classification for drinking and irrigation will be made according to the Table 2.

## Salinity and irrigation indices

Along with GWQI, several other indices were considered to determine the water suitability for irrigation purpose (Table 3): salinity (EC), sodium absorption ratio (SAR), %Na, soluble sodium percentage (PSS), residual sodium carbonate (RSC), exchangeable sodium percentage (ESP), permeability index (IP), magnesium adsorption ratio (MAR), Kelly's Ratio and graphical methods (Wilcox and Richards diagram). Specifically:

EC is a useful parameter to estimate mineralization (Hceflcd 2006). The electrical conductivity of water is an indirect measure of the ions content ($Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $HCO_3^-$, $SO_4^{2-}$, $Cl^-$, $NO_3^-$, ...). A water with an EC of more than 3,000 μS/cm is generally considered unsuitable for irrigation.

The SAR is an indicator of the water sodization risk that can generate the irrigation water for a well-defined situation and is an important parameter in determininig the groundwater suitability for irrigation (USSL 1954). This index is calculated by the formula developed by Gapon (1933) and Richards (1954). It is a measure of alkali/sodium hazard to crops. A very low SAR (less than 2) indicates no sodium hazard; a low SAR (2 to 12) indicates a low sodium hazard. Medium hazard is indicated between 12 and 22 and high hazard is presented between 22 and 32. A very high hazard over than 32.

The combination of EC and SAR has also been used to determine the water suitability for irrigation (Richards 1954).

Chloride occurs naturally in groundwater due to leaching of salt deposits including halite, dissolution of salt deposits and anthropogenic pollution. The $Cl^-$ concentration in water depends on the water origin, the terrain through which it flows, the

**Table 2** | Water classification according to the GWQI (Sahu & Sikdar 2008)

| Class and color | Quality Index | Definition of the quality class |
|---|---|---|
| 01 | < 50 | Excellent Water |
| 02 | 50-100 | Good Water |
| 03 | 100-200 | Permissible water |
| 04 | 200-300 | Doubtful |
| 05 | > 300 | Water unsuitable for drinking or irrigation |

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**Table 3** | Water quality parameters used for the calculation (All ionic concentrations in the formulas are expressed in meq/L; and %Na and IP in %)

| Water quality parameters | Formulas | References |
|---|---|---|
| Sodium absorption ratio (SAR) | $SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$ | Richards (1954) |
| Sodium percentage (% Na) | $\%Na = \frac{Na + K}{Ca + Mg + Na + K} \text{ x } 100$ | Wilcox (1955) |
| Soluble sodium percentage (SSP) | $SSP = \frac{Na \text{ x } 100}{Ca + Mg + Na + K}$ | Eaton (1950) |
| Residual sodium carbonate (RSC) | $RSC = (CO_3 + HCO_3) - (Ca + Mg)$ | Richards (1954) |
| Exchangeable sodium percentage (ESP) | $ESP = \frac{100 \text{ x } (-0.0126 + 0.0147 \text{ SAR})}{1 + (-0.0126 + 0.0147 \text{ SAR})}$ | Abdul Hameed *et al.* (2010) |
| Permeability index (IP) | $IP = \frac{Na + \sqrt{HCO_3}}{Ca + Mg + Na} \times 100$ | Doneen (1964) |
| Magnesium adsorption ratio (MAR) | $RAM = \frac{Mg}{Mg + Ca} \times 100$ | Szabolcs & Darab (1964) |
| Kelly's ratio | $RK = \frac{Na}{Ca + Mg}$ | Kelly (1963) |

chemical composition of the soils, the pollution of septic tanks and rocks that are in contact with the water sources. Generally it is not absorbed or retained by soils but absorbed by crops. Toxicity limits of $Cl^-$ for some fruit crops are given by Ayers & Westcot (1988) with a concentration above 12 meq/l.

Excessive $Na^+$ in relation to $Ca^{2+}$ and $Mg^{2+}$ concentrations could causes damage to the soil structure. It reduces the permeability of the soil to water and air, resulting in less water availability for the plant and negative effects on soil aeration (Arveti *et al.* 2011). Several classifications are used to assess the water quality for irrigation. The most used are the Wilcox classification based on EC and $Na^+$ content in water expressed as a percentage (Gouaidia 2008), the %Na and SSP. According to the World Health Organization (WHO), %Na of 60 is the maximum recommended limit for the irrigation water.

It has been found that in cases where the chemical facies of agricultural water is chlorinated, SAR frequently minimizes the sodalization and alkalization risks. For this reason, the determination of RSC was chosen to assess the quality watery of irrigation. RSC is a rapid test to determine if the irrigation water can release free $Ca^{2+}$ and $Mg^{2+}$ into the soil. All water with a RSC value less than 1.25 meq/L is considered suitable irrigation. SSP and RSC are used to assess the sodium risk (Meena & Bisht 2021).

ESP is the main factor considered in determining the water suitability for irrigation. The %Na/ESP versus EC parameters using the Wilcox diagram was commonly used to classify the irrigation water (Richards 1954; Wilcox 1955).

PI is a key factor in determining the water quality of irrigation in relation to the soil for agricultural improvement (Doneen 1964).

The Magnesium Adsorption Ratio (MAR) is indicator that can be used to specify the danger of $Mg^{2+}$. It is proposed, defined and developed for irrigation water by Szabolcs & Darab (1964) and Raghunath (1987). In ordinary cases, excess $Mg^{2+}$ in groundwater can reduce soil structure which influences crop yield (Arveti *et al.* 2011; Nagaraju *et al.* 2014). MAR values exceeding 50 are considered unsuitable for irrigation (Raghunath 1987).

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Kelly's Index (Kelly 1963) is calculated to assess the water suitability for irrigation. A Kelly's ratio greater than 1 indicates excess sodium in the water.

### Spatial representation map

The spatial distribution maps of GWQI values were created using the inverse distance weighting (IDW) interpolation technique. IDW is a deterministic method for multivariate interpolation where the relative influence of an observation point decreases with the distance (Benjamin 2007). The IDW method proved to produce satisfactory results in several similar studies. It was successfully used by several authors to estimate the spatial distribution of groundwater quality (Venkatramanan *et al.* 2016; Hamouche *et al.* 2021; Koussa & Berhail 2021).

The produced maps allowed the representation of the geo-spatial distribution of groundwater quality and specifically give the possibility to:

(i) classify the water points according to their quality indices, (ii) to plan water management (drinking water, industry or other uses), (iii) to identify suitable areas for exploitation and (iv) point out the pollution sources on the territory.

## RESULTS AND DISCUSSIONS

### Descriptive statistics

The descriptive analysis for the two years is shown in Table 4. The descriptive statistical indices were the minimum and maximum values, the mean, the standard deviation and the coefficient of variation.

Table 4 shows that the standard deviation values in most cases are lower than the mean indicating low dispersion. They highlight an hydrochemical homogeneity of the water sampled in the aquifer.

The coefficients of variation calculated in 2012 and 2017 are high for $Ca^{2+}$, $Mg^{2+}$, $SO_4^{2-}$ and $NO_3^-$ ions and very high for $Na^+$, $K^+$ and $Cl^-$ ions which indicates a significative spatial variability (spatial heterogeneity) of these elements. The results show that the pH varies between 7 to 9.4 in 2012 and 5.1 to 9.4 in 2017. The pH does not show a large difference between the four sampling periods.

The mineralization is relatively high with a dry residual value ranging from 470 to 12,727 mg/l in 2012 and 392 to 9,423 mg/l in 2017. Chloride ion can be a very good indicator of surface pollution in areas far from the sea. The $Cl^-$ concentrations range from 81 mg/l to 7,660 mg/l in 2012 and 87 mg/l to 5,700 mg/l in 2017.

**Table 4** | Statistical results of groundwater physicochemical variables in 2012 and 2017

| | | | Wet period | | | | | Dry period | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Parameters** | | **Max** | **Min** | **Mean** | **SD** | **CV** | **Max** | **Min** | **Mean** | **SD** | **CV** |
| 2012 | $Ca^{2+}$ | mg/l | 979 | 38 | 219 | 150.23 | 0.68 | 1,143 | 35 | 246 | 165.39 | 0.67 |
| | $Mg^{2+}$ | | 940 | 25 | 145 | 121.18 | 0.83 | 1,266 | 20 | 186 | 164.01 | 0.88 |
| | $Na^+$ | | 1,650 | 43 | 329 | 299.13 | 0.91 | 1,990 | 13 | 322 | 342.53 | 1.06 |
| | $K^+$ | | 30 | 1 | 6 | 7.06 | 1.23 | 50 | 01 | 7 | 7.87 | 1.14 |
| | $Cl^-$ | | 4,980 | 124 | 804 | 792.03 | 0.98 | 7,660 | 81 | 932 | 1,072.03 | 1.14 |
| | $SO_4^{2-}$ | | 2,610 | 31 | 461 | 426.07 | 0.92 | 2,590 | 9 | 456 | 434.00 | 0.95 |
| | $HCO_3^-$ | | 641 | 76 | 318 | 110.67 | 0.34 | 763 | 31 | 342 | 142.07 | 0.41 |
| | $NO_3^-$ | | 100 | 0 | 50 | 38.42 | 0.77 | 195 | 0 | 53 | 44.26 | 0.82 |
| | TDS | | 12,727 | 700 | 2,442 | 1,841.92 | 0.75 | 15,764 | 470 | 2,884 | 2,304.80 | 0.79 |
| | pH | | 9.4 | 7.00 | 7.90 | 0.33 | 0.04 | 8.7 | 6.8 | 7.8 | 0.34 | 0.04 |
| 2017 | $Ca^{2+}$ | mg/l | 990 | 14 | 275 | 173.52 | 0.63 | 701 | 4.1 | 214 | 132.15 | 0.62 |
| | $Mg^{2+}$ | | 240 | 5 | 68 | 55 | 0.80 | 140 | 3.8 | 70 | 35.08 | 0.50 |
| | $Na^+$ | | 2,100 | 55 | 320 | 379.56 | 1.18 | 2,900 | 11 | 393 | 490.55 | 1.25 |
| | $K^+$ | | 20 | 02 | 05 | 3.56 | 0.65 | 38 | 0 | 8 | 7.51 | 0.98 |
| | $Cl^-$ | | 4,720 | 110 | 786 | 863.22 | 1.09 | 5,700 | 87 | 752 | 911.30 | 1.21 |
| | $SO_4^{2-}$ | | 1,035 | 01 | 310 | 253.00 | 0.81 | 1,100 | 4.2 | 284 | 223.26 | 0.78 |
| | $HCO_3^-$ | | 534 | 46 | 280 | 106.71 | 0.38 | 488 | 27.45 | 278 | 108.46 | 0.39 |
| | $NO_3^-$ | | 111 | 0 | 40 | 34.01 | 0.85 | 225.5 | 0 | 61 | 60.20 | 0.98 |
| | TDS | | 7,659 | 392 | 2,125 | 1,529.57 | 0.72 | 9,423 | 497 | 1,975 | 1,584.04 | 0.80 |
| | pH | | 8.3 | 7.1 | 7.9 | 0.28 | 0.03 | 9.4 | 5.1 | 7.6 | 0.62 | 0.08 |

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More than 90% of the analyzed water points show a $Cl^-$ increasing trend. These contents exceed the OMS fixed standard, which is 250 mg/l. The excessed $Cl^-$, in this aquifer, may be related to dissolution of evaporate formations (the dissolution of halite) and wastewater infiltration. The increase in $Cl^-$ concentrations that accompanied the low $Na^+$ concentration is due to the base-exchange phenomenon as the bedrock clays can release $Ca^{2+}$ ions after binding $Na^+$.

For the $HCO_3$, the evolution of concentrations shows that only 40% of the points analyzed have values above the WHO drinking water standard (50 mg/l). This is due to the excessive use of nitrogen fertilizers and pesticides in agricultural activities, and from the carbonate rock. Livestock and wastewater may be another origin of $HCO_3$ in this area. Nitrates can be used as indicators of water chemical pollution. As reported by different authors (Girard & Hillaire-Marcel 1997; Njitchoua *et al.* 1997; Stadler *et al.* 2008; Bernard-Jannin *et al.* 2017; Busico *et al.* 2018; Leulmi *et al.* 2021), the presence of high $NO_3$ concentrations in aquifers under arid climate would be due to anthropogenic pollution.

The results of physicochemical analyses were also compared to the standards recommended by the World Health Organization. Water intended for human consumption must be free of all pollutants and impurities. The physicochemical analysis percentage values of the samples are represented in Table 5.

The physicochemical analysis for the two observation periods shows that more than 60% of the water points exceed the recommended standard for the drinking water. The pH measurements show that all the water points are within the range of drinking water standards during the wet and dry periods in the both years. This indicates that the pH values are close to the natural values. The main sources of $Ca^{2+}$ and $Mg^{2+}$ in groundwater is related mainly to two natural origins: the dissolution of carbonate formations such as dolomite ($CaMgCO_3$), the dissolution of gypsum formations such as gypsum ($CaSO_4$) and other minerals such as apathite ($Ca_5(PO_4)_3$) or fluorite (CaF) (Bakalowicz 1979).

The water potability can be evaluated by the total water hardness presented by the sum of the $Ca^{2+}$ and $Mg^{2+}$ concentrations. It is expressed in French degrees and calculated by the following formula:

$$\text{Total hardness} = (rCa^{2+} + rMg^{2+}) \times 5(^\circ F)$$

The results of the calculation of this parameter are shown in Table 6.

The total hardness calculated for the groundwater of the Upper and Middle Cheliff alluvial aquifers shows hard to very hard water. These results show that the groundwater has a Permissible to Doubtful for drinking.

## Classification of waters according to the Piper diagram

The interpretation of the hydrochemical analyses results allowed having an idea about the groundwater chemical facies of the Upper and Middle Cheliff aquifers, their evolution over time and the natural or anthropogenic conditions. According to the Piper diagram representation (Figure 6), the water chemical facies of the Upper and Middle Cheliff alluvial aquifers is dominated by the $Ca^{2+}$, $Na^+$ and $Cl^-$ (cations/anions), which explains the dominance of the chloride-sodium and chloride-calcium facies for the two observation years (2012 and 2017). It is can be due to the alluvial formations dissolution of the Mio-Plio-Quaternary and the evaporate formations (gypsum formations) presented in the study area.

## Groundwater quality index (GWQI)

Ten parameters analyzed from 134 water points in 2012 and 86 water points in 2017 were used to calculate GWQI. The parameters used are: pH, EC, $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $Cl^-$, $HCO_3^-$, $NO_3^-$ and $SO_4^{2-}$.

**Table 5** | Physicochemical analysis percentage values of the samples

| Year | Element | $Ca^{2+}$ mg/l | $Mg^{2+}$ | $Na^+$ | $K^+$ | $Cl^-$ | $SO_4^{2-}$ | $HCO_3^-$ | $NO_3^-$ | TDS | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | WHO standards | 100 | 50 | 150 | 12 | 250 | 250 | 250 | 50 | 1,500 | 6,5< pH <9,5 |
| 2012 | Wet period | 22% | 13% | 33% | 87% | 19% | 48% | 21% | 51% | 32% | 100% |
| | Dry period | 15% | 11% | 46% | 87% | 14% | 45% | 22% | 49% | 28% | 100% |
| 2017 | Wet period | 25% | 50% | 85% | 92% | 12% | 52% | 42% | 72% | 40% | 100% |
| | Wet period | 18% | 31% | 23% | 85% | 21% | 54% | 39% | 58% | 52% | 98% |

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**Table 6** | Classification of samples according to their water hardness

| Total hardness (°F) Water qualification | | 0–7 Very soft | 07–14 Sweet | 14–22 Moderately soft | 22–32 Quite soft | 32–54 Hard | >54 Very hard |
|---|---|---|---|---|---|---|---|
| (%) of samples | Wet period 2012 | 0 | 1 | 0 | 5 | 18 | 76 |
| | Dry period 2012 | 0 | 0 | 1 | 4 | 13 | 82 |
| | Wet period 2017 | 0 | 2 | 10 | 8 | 8 | 72 |
| | Dry period 2017 | 4 | 0 | 6 | 5 | 12 | 73 |
| Domestic Use | | Good water for drinking | | Permissible water for drinking | | Doubtful to water unsuitable for drinking | |

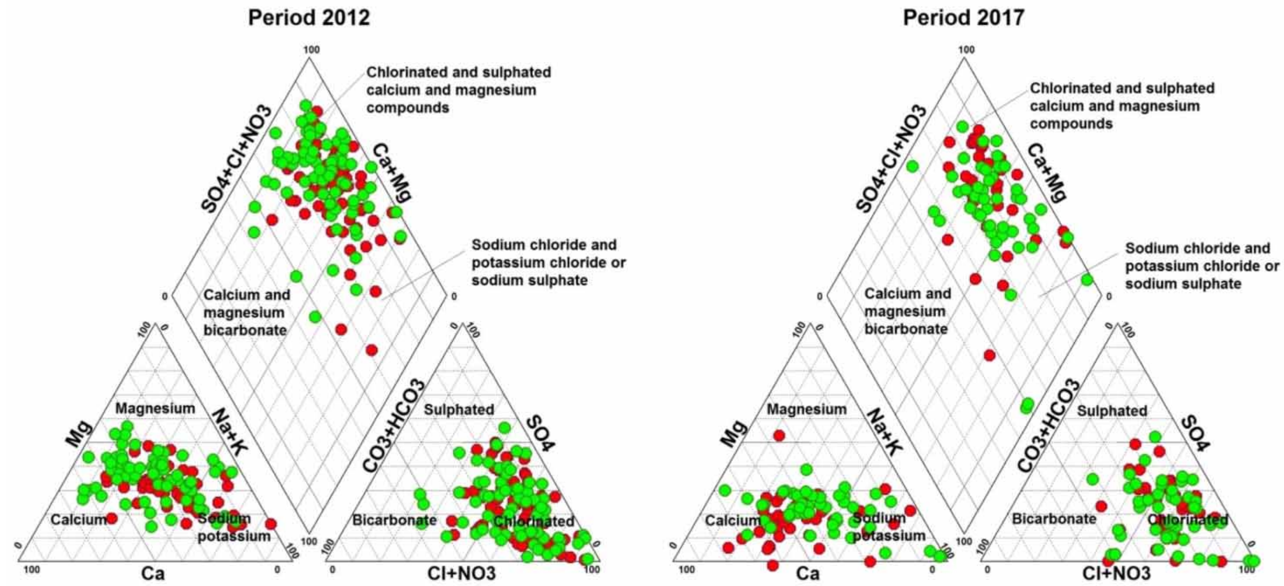


**Figure 6** | Presentation of Upper and Middle Cheliff alluvial aquifers on the Piper diagram (Red points: wet period 2012 and 2017; Green points: dry period 2012 and 2017).

The GWQI values were calculated for each sample (Table 3) and it is presented in Table 7.

The results analysis provided us with the following information:

– Four quality classes (Good quality, Permissible, Doubtful and Unsuitable for consumption and irrigation) were identified in the year 2017 while five classes with the addition of the Excellent quality class in the year 2012 (dry period).
– 1.40% of water points analyzed, specifically only 1 point out of 132 in 2017, has been characterized with Excellent water quality (Pz 5) for human consumption.
– From 16.90% to 21.31% in 2012 and from2.63 to 4.16% in 2017 presents the Good quality water for consumption, respectively.
– It is noted that most of the points are above the limit of Good quality: 80% in 2012 and 95% in 2017.

For example, the monitoring of groundwater quality has shown deference in the number of quality classes in the two campaigns from the same period (dry period). We note that the 2017 campaign has 4 classes while the 2012 campaign has 5 classes. This is due to the following reasons:

– The effect of precipitation and evaporation on groundwater mineralization: rainfall in 2012 was marked as a wet year (450 mm) and 2017 was marked as a dry year (360 mm), compared to 2012.

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**Table 7** | Groundwater quality statistics using the GWQI

| Periods | | Type of water: Excellent | Good | Permissible | Doubtful | Water unsuitable for drinking |
|---|---|---|---|---|---|---|
| Wet period 2012 | Number of samples | 00 | 13 | 26 | 15 | 07 |
| | % | 00 | 21 | 43 | 25 | 11 |
| Dry period 2012 | Number of samples | 01 | 12 | 30 | 16 | 12 |
| | % | 02 | 18 | 39 | 23 | 18 |
| Wet period 2017 | Number of samples | 00 | 01 | 16 | 15 | 06 |
| | % | 00 | 03 | 42 | 39 | 16 |
| Dry period 2017 | Number of samples | 00 | 02 | 22 | 19 | 05 |
| | % | 00 | 04 | 46 | 40 | 10 |

– Socio-economic development in the year 2017 compared to 2012 causing the increase in water needs, the increase in the discharge of domestic wastewater and industrial and the degradation of groundwater quality.
– The return of salty irrigation water to the aquifer (increasing groundwater concentrations).

Figure 7 shows the spatial distribution of GWQIs of the Upper and Middle Cheliff alluvial aquifers for the wet and dry periods years of 2012 (Figure 7(a)) and 2017 (Figure 7(b)).

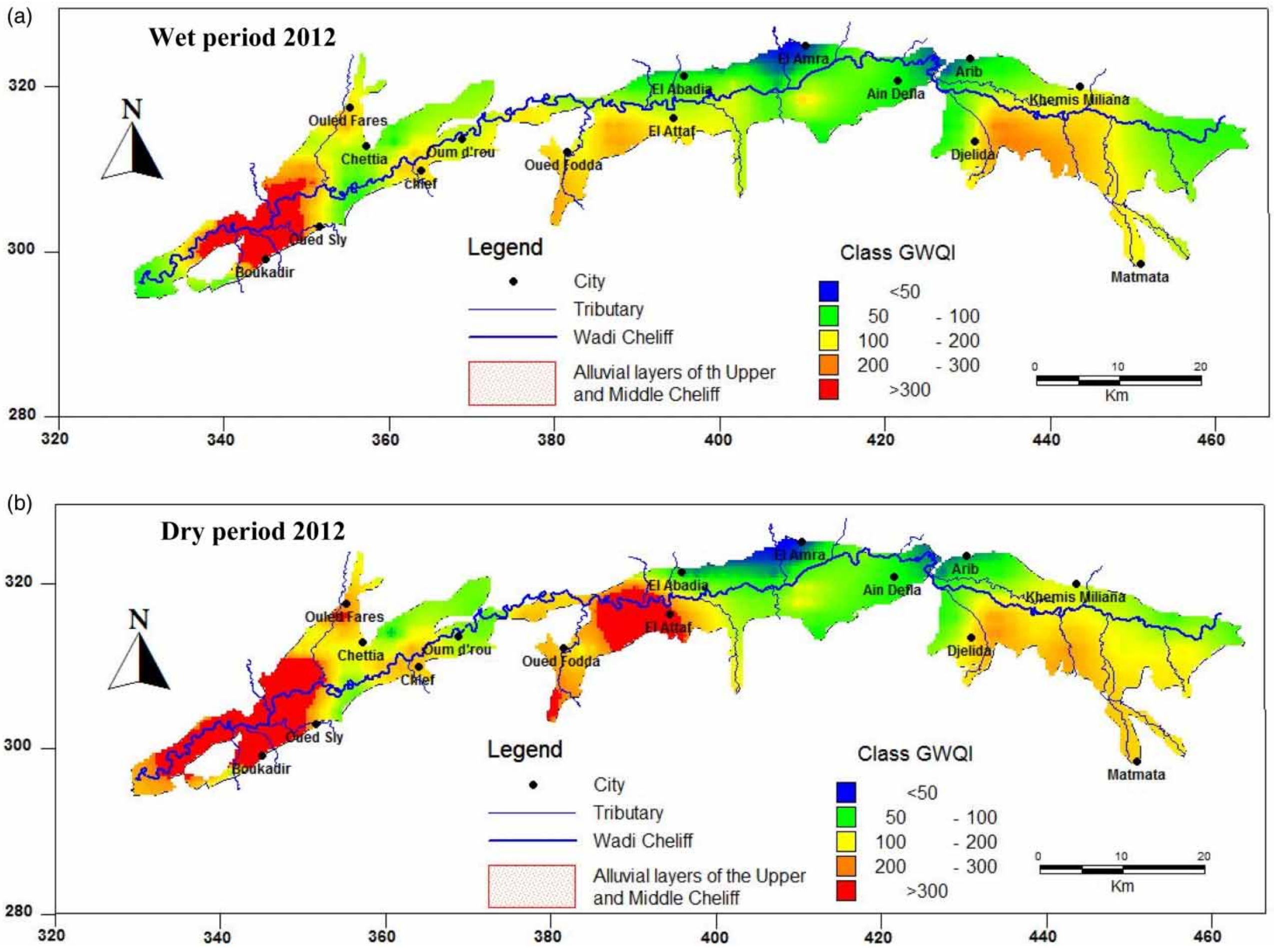


**Figure 7** | Index map (GWQI) of the groundwater quality in the Upper and Middle Cheliff alluvial aquifers in 2012.

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The analysis of the four maps (Figures 7 and 8) shows that the overall water quality was better in 2012 compared to 2017. The water points with very low quality are located in: (1) the south-east of the Haut Cheliff plain; exactly in the regions of Bir Ouled Kalifa, Khemis Miliana and Djendal, (2) the west of the plain of Middle Cheliff; precisely in the region of El Attaf, near to Djebel Témoulga, and (3) the center of the Middle Western Cheliff plain, near the cities of Chlef and Boukadir. This deterioration can be due to (i) the leaching of Triassic formation outcropping in the southern part of the plain of Khemis Miliana, (ii) the loaded water with $SO_4^{2-}$ and $Cl^-$ transported by Massine and Deurdeur wadis and (iii) the ascent of the deep salted water in the El Attaf region. Only the northern part of the Middle Cheliff plain, between El Amra and El Abadia is characterized by the Good to Excellent water quality.

The spatial analysis of the GWQI map of the Upper and Middle Cheliff alluvial aquifers showed that:

- 65 km$^2$ of the area is classified with from Good to Excellent quality. These areas are located in the northern and northeastern part of the Middle Cheliff plain and west of the city of Arib. This area is decreasing in 2017.
- More than 450 km$^2$ of the area is characterized by a Doubtful groundwater quality (observed almost in all the part of the plain in 2017) in particular around the points located in the region of Khemis Miliana, Djendal, El Attaf and Chlef cities.
- We note an increase in the area of non-drinking water quality (Unsuitable for drinking) from 2012 to 2017, indicating exposure of groundwater in the Upper and Middle Cheliff alluvial aquifers to several natural and anthropogenic pollutants over the five years.
- Finally, we can conclude that some wells located in El Abadia and El Amra cities have Good quality water for drinking.

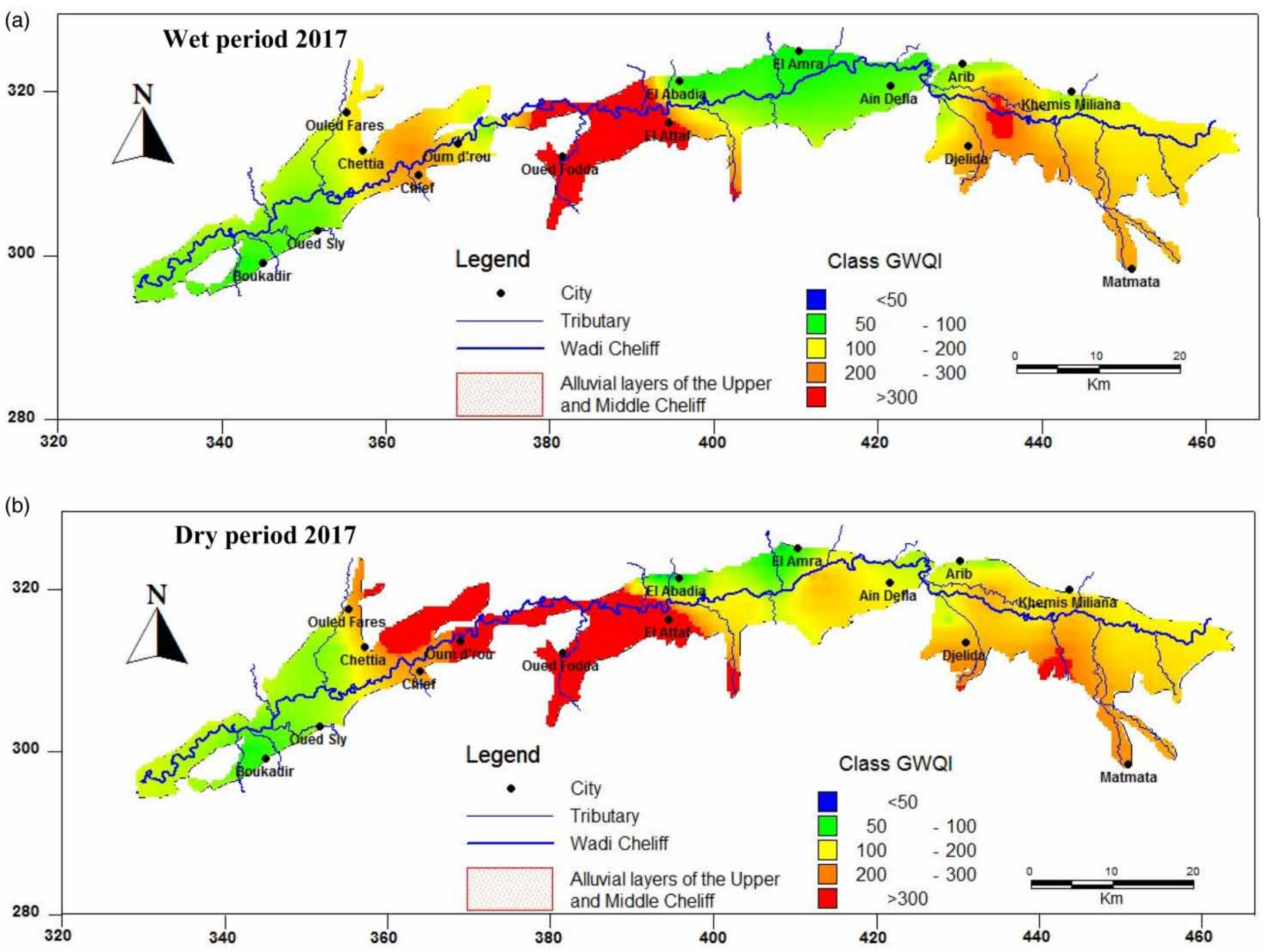


**Figure 8** | Index map (GWQI) of the groundwater quality in the Upper and Middle Cheliff alluvial aquifers in 2017.

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### Water quality for irrigation uses

As discussed before, groundwater is the main resource of irrigation in semi-arid areas and salinity can cause significant adverse effects due to the binding of $Na^+$ and $Cl^-$ salts by soil colloids.

The water suitability for a specific use depends on the types and quantities of dissolved salts. The accumulation of these chemical elements in the water, in the form of water-soluble salts, can negatively affects the characteristics of the soil. Moreover, they cause disorders in the metabolism of plants and in the osmotic process (Todd 1980). Indeed, these salts cause the risk of soil salinization.

– The SAR values of the groundwater samples (Table 8) range from 0.20 to 20.39 in 2012 and 0.19 to 42.93 in 2017.
– For the EC values (Table 8), more than 56 and 31% of the groundwater samples exceed a value of 3,000 μS/cm, for years 2012 and 2017, respectively. In addition, all water samples fall into the Permissible to Doubtful/Unsuitable categories for irrigation.
– According to the Richards diagram (Figure 9), the water samples belong to the following classes:

a- C3-S1: Average to poor quality, used with caution; requires drainage with leaching and/or whitewash application.
b- C4-S1: Poor to mediocre water quality, used with caution for heavy soils and sensitive plants, use for light and well-drained soils requires a leaching dose and/or whitewash contribution.
c- C4-S2: Very bad quality water used only for light and well-drained soils and for resistant plants with necessity of leaching doses and/or whitewash contribution.
d- C4-S3: Very bad quality used only for exceptional circumstances. Water not recommended for irrigation.

**Table 8** | Classification of groundwater quality for irrigation

| | | | Wet period 2012 | | Dry period 2012 | | Wet period 2017 | | Dry period 2017 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Classification pattern** | **Categories** | **Ranges** | **Nbr** | **%** | **Nbr** | **%** | **Nbr** | **%** | **Nbr** | **%** |
| Sodium absorption ratio (SAR) | Very low | < 2 | 18 | 29 | 28 | 39 | 06 | 16 | 08 | 17 |
| | Low | 2–12 | 43 | 68 | 41 | 58 | 30 | 79 | 35 | 73 |
| | Medium | 12–22 | 02 | 03 | 02 | 03 | 02 | 05 | 01 | 02 |
| | High | 22–32 | 00 | 00 | 00 | 00 | 00 | 00 | 03 | 06 |
| | Very high | > 32 | 00 | 00 | 00 | 00 | 00 | 00 | 01 | 02 |
| Electrical conductivity (EC) | Excellent | < 250 | 00 | 00 | 00 | 00 | 00 | 00 | 00 | 00 |
| | Good | 250–750 | 00 | 00 | 01 | 01 | 01 | 03 | 00 | 00 |
| | Permissible | 750–2,250 | 22 | 35 | 20 | 28 | 15 | 39 | 20 | 42 |
| | Doubtful | 2,250–5,000 | 27 | 43 | 32 | 46 | 18 | 47 | 23 | 48 |
| | Unsuitable | > 5,000 | 14 | 22 | 18 | 25 | 04 | 11 | 05 | 10 |
| Chloride (meq/L) | Excellent | < 4 | 02 | 03 | 05 | 07 | 01 | 03 | 02 | 04 |
| | Good | 4–7 | 09 | 14 | 07 | 10 | 04 | 11 | 07 | 15 |
| | Permissible | 7–12 | 14 | 22 | 13 | 18 | 13 | 34 | 16 | 33 |
| | Doubtful | 12–20 | 16 | 26 | 18 | 25 | 14 | 26 | 16 | 33 |
| | Unsuitable | > 20 | 22 | 35 | 28 | 40 | 06 | 16 | 07 | 15 |
| Sodium percentage (% Na) | Excellent | 0–20 | 08 | 13 | 22 | 31 | 02 | 05 | 02 | 04 |
| | Good | 20–40 | 34 | 54 | 30 | 42 | 25 | 66 | 23 | 48 |
| | Permissible | 40–60 | 13 | 20 | 16 | 23 | 06 | 16 | 16 | 34 |
| | Doubtful | 60–80 | 07 | 11 | 03 | 04 | 05 | 13 | 04 | 068 |
| | Unsuitable | > 80 | 01 | 02 | 00 | 00 | 00 | 00 | 03 | 06 |
| Residual sodium carbonate (RSC) | Permissible | < 1.25 | 61 | 97 | 70 | 99 | 37 | 97 | 46 | 96 |
| | Unsuitable | ≥ 1,25 | 02 | 03 | 01 | 01 | 01 | 03 | 02 | 04 |
| Permeability index (PI) | Suitable | < 75 | 60 | 95 | 70 | 99 | 35 | 92 | 43 | 90 |
| | Unsuitable | ≥ 75 | 03 | 05 | 01 | 01 | 03 | 08 | 05 | 10 |
| Magnesium adsorption ratio (MAR) | Permissible | ≤ 50 | 36 | 57 | 30 | 42 | 34 | 89 | 38 | 79 |
| | Unsuitable | > 50 | 27 | 43 | 41 | 58 | 04 | 11 | 10 | 21 |
| Kelly's ratio (KR) | Suitable | < 1 | 49 | 78 | 62 | 87 | 32 | 84 | 34 | 71 |
| | Unsuitable | ≥ 1 | 14 | 22 | 09 | 13 | 06 | 16 | 14 | 29 |

Nbr: Number of samples; (%): Percentage of samples.

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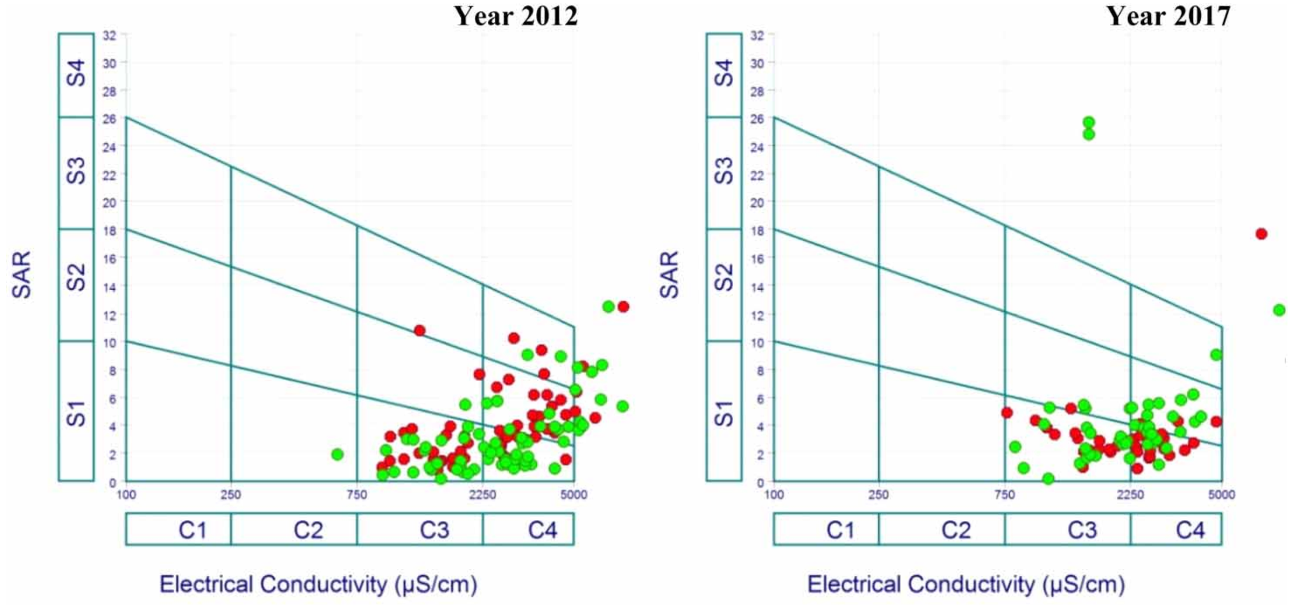


**Figure 9** | Richards diagram (Riverside) representation of the groundwater samples in the Upper and Middle Cheliff alluvial aquifers (Campaigns 2012 and 2017).

In the Upper and Middle Cheliff alluvial aquifers the same water quality for irrigation is found, during the entire observation period where the lithology influence (geological formations) is observed. For example, near El Attaf city, the high salinity is explained by a saltwater invasion of deep origin (as a result of the the NW-SE fault replay that truncates the eastern zone of Djebel Témoulga) and by the Triassic or Permo-Triassic formations rooted on the massif (IFES 2002). Also, near Bir Ouled Khlif (Massina wadi) and Boukadir cities, the salinity is influenced by the dissolution of evaporite formations (gypsum formations).

– 60, 66, 50 and 46% of the water samples are unsuitable for irrigation with Cl higher than 12 meq/l in the wet and dry periods of 2012 and 2017, respectively (Table 8). The high concentration may be related to halite dissolution and wastewater infiltration (Madene *et al.* 2020). The higher Cl content in Oued Massin and Attafs regions (near Djebel Témoulga) could be explained by the saltwater invasion of deep origin (as a result of the the NW-SE fault replay that truncates the eastern zone of Djebel Temoulga) and by the Triassic or Permo-Triassic formations rooted on the massif (IFES 2002) and presence of the domestic wastewater discharge from the agglomerations on the left bank of the Chlef wadi.
– The %Na varies from 3.70 to 84.15 in 2012 and from 4.06 to 96.23 in 2017 (Table 8). However, a percentage of 11, 04, 13 and 15% of the water samples analyzed in the wet and dry periods of 2012 and 2017, respectively, are Unsuitable for irrigation.
– The ESP values of groundwater samples range from −0.98 to 38.21 in 2012 and from 0.97 to 22.31 in 2017 (Table 8).
– The water samples classification considering the parameters %Na and ESP in relation to the EC indicates that more than 50% of water samples were classified as an Unsuitable water for irrigation (Figure 10). It can be seen that the groundwater is undergoing degradation through the effect of the lithology on its quality.
– According to the Wilcox diagram (Figure 10), the water samples belong to the following classes:

* – The Good class: it gathers the water which is weakly mineralized. It occurs in the center and northeast of the El Abadia-El Amra plain and west of the Khemis Meliana plain near the Arib city and in the southwest of Chlef plain near the edges of the Ouarsenis massif (dissolution of evaporite formations of Triassic ante-nappes of Ouarsenis) with a percentage of 33 and 25% of water points analyzed in 2012 and 2017, respectively.

* – The Admissible class: it includes water slightly mineralized. It is presented in the North of the El Abadia-El Amra plain with a percentage of 10% of water points analyzed for the dry period of 2017.

* – The Mediocre (poor) class: it includes the water located in the east of the Khemis Meliana plain and the west of the Chlef plain near the Boukadir city. While, this class represents only a percentage of 40 and 25% during the years of 2012 and 2017, respectively, for the analyzed water points.

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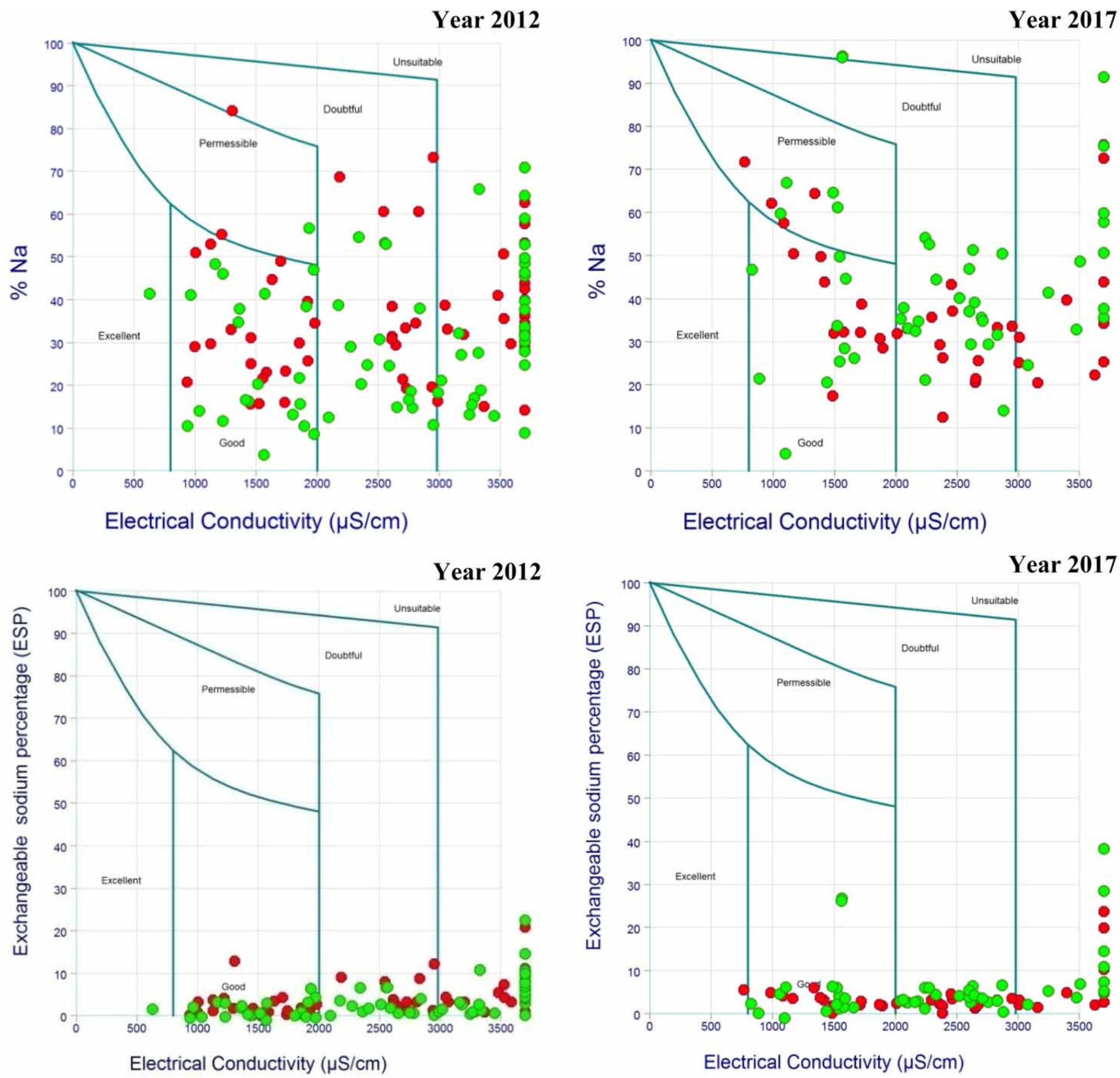


**Figure 10** | Wilcox diagram representation of the groundwater samples in the Upper and Middle Cheliff alluvial aquifers (Campaigns 2012 and 2017).

* – The Doubtful class: It includes water located in the south of the Khemis Meliana plain near the Oued Massin and in the northeast of the Chlef plain near Djebel Témoulga. While, this class represents a percentage of 25% in the periods of observation (2012 and 2017) of the water points analyzed.

– The RSC values ranges between 3.81 and −151.33 in year 2012 and 7.22 and −56.20 in year 2017 (Table 8). It revealed that the Upper and Middle Cheliff aquifers represent 95 to 98% of the groundwater samples where the RSC values less than 1.25. The following classes were found to be present:

* – Type 01 water (RSC >1.25) with a percentage of 01 to 03% in 2012 and 03% in 2017. They present a major degradation risk of the physical soils properties by sodization. Two water points (Pz 13 and Pz 15) fall into the RSC >1.25 class showing a very high risk of residual Alkalinity, indicating an Unsuitable water quality for irrigation.

* – Type 02 water (RSC <1.25) with a percentage greater than 96%. They present a low degradation risk compared to the previous class (Sumner 1993; Marlet & Job 2006). They can be used for irrigation without any problem (permissible).

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– Groundwater PI values range between 13 and 100 in 2012 and 20 to 116 in 2017 (Table 8). Based on the PI results, the water samples found in class II are categorized as Permissible to Good for irrigation with the percentage varying from 90 to 95%.
– For the MAR, the calculated values of groundwater samples vary between 24.29 and 100 in 2012 and 2.43 to 87.36 in 2017 (Table 8). Over 49% in 2012 and 16% in 2017 of groundwater samples exceed the limit (MAR >50).
– For the Kelly's Index, over 17% in 2012 and 23% in 2017 of groundwater samples exceeded the value 1 (Table 8).

The groundwater quality assessment for irrigation was carried out by estimating the Groundwater Quality Index for Irrigation (GWQII). This index is an important parameter to assess groundwater quality and suitability (Avvannavar & Shrihari 2008). In the study area, the GWQII values of groundwater samples range from 28.27 to 808.93 in 2012 and 46.36 to 544.23 in 2017.

For the periods 2012 and 2017, the GWQII indicated poor quality for the majority of points. It is 50% in 2012 and 60% in 2017. We also note that 2% to 4% of the water points analyzed present an unsuitable water quality for irrigation.

The Figures 11 and 12 show the spatial distribution of the GWQII during the two years of study (2012 and 2017). The low values are observed in the downstream of the study area between El Amra and El Abadia cities; and Ain Defla and Arib cities (Figure 8(a) and 8(b)). However, the high values are observed in the regions of El Attaf (Djebel Témoulga), Boukadir and Massine wadi.

In the study area, the relationship between the GWQII and the classical parameters (SAR, EC, Cl, RSC and ESP) indicates a good correlation (Table 9) where the GWQII gives a satisfactory classification of water quality for irrigation.

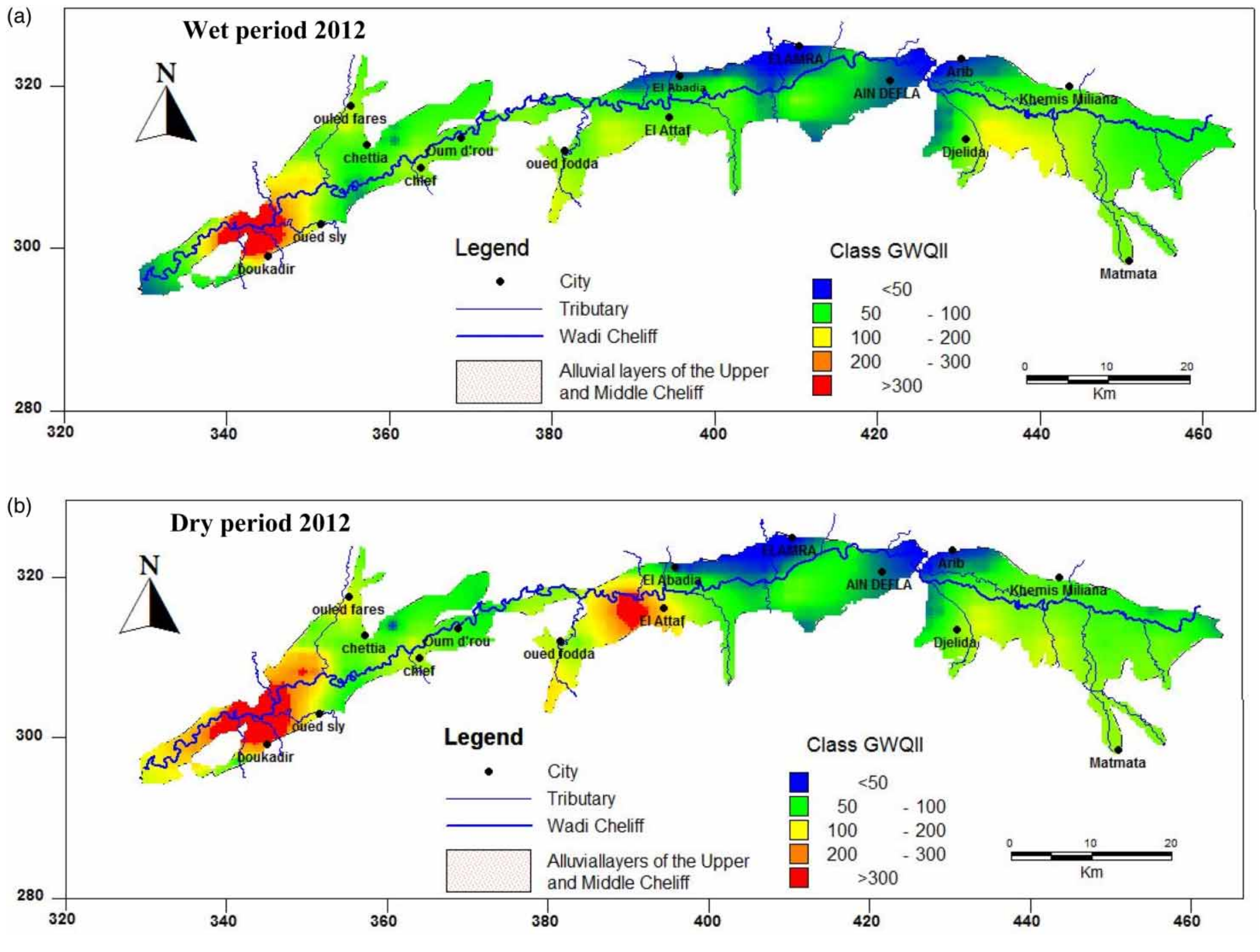


**Figure 11** | Index map (GWQII) of the irrigation groundwater quality in the Upper and Middle Cheliff alluvial aquifers in 2012.

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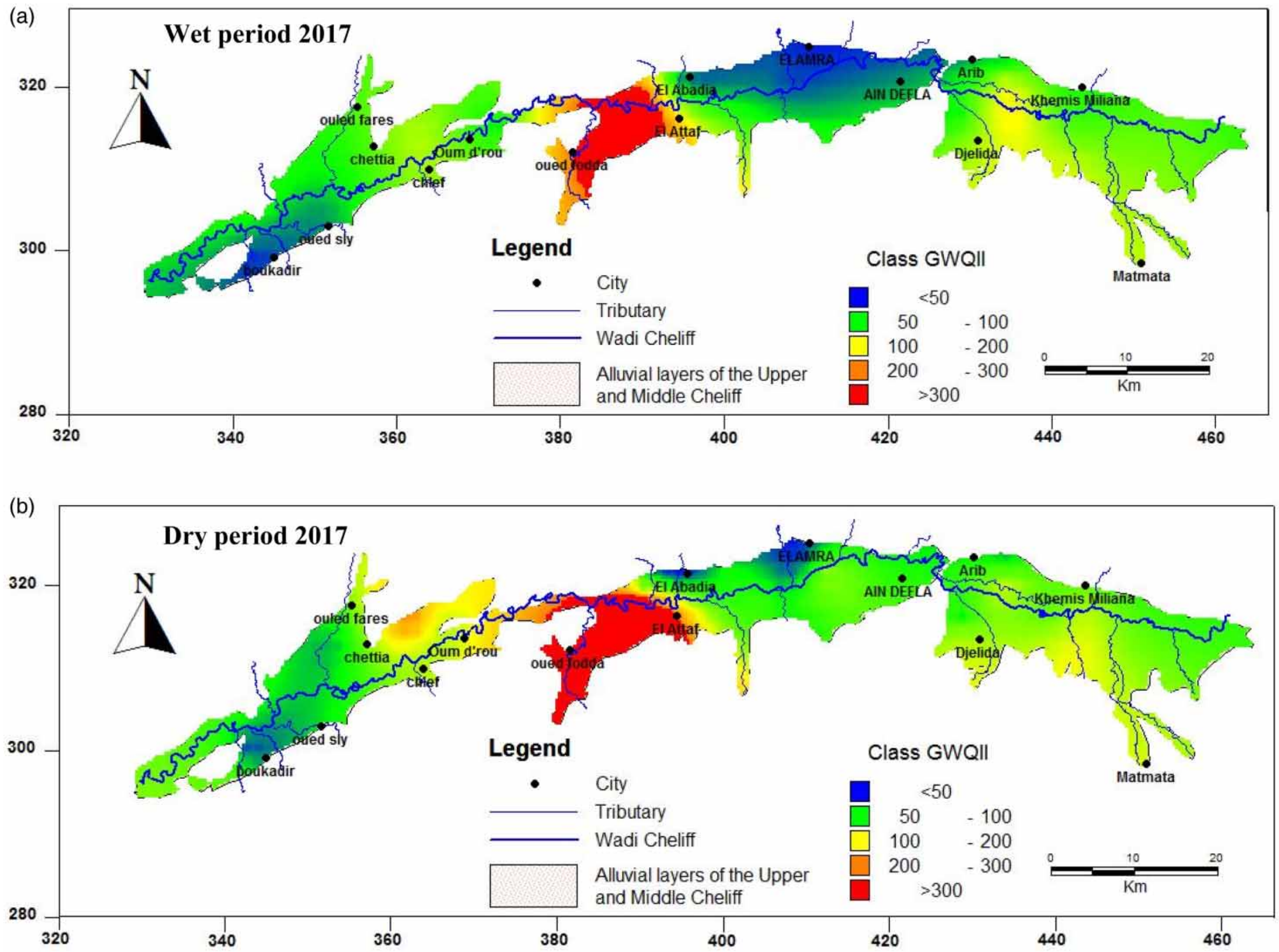


**Figure 12** | Index map (GWQII) of the irrigation groundwater quality in the Upper and Middle Cheliff alluvial aquifers in 2017.

**Table 9** | Correlation coefficient between the irrigation water quality index (GWQII) and the parameters used to assess irrigation water quality

| | | **Correlation coefficient** | | | |
|---|---|---|---|---|---|
| **Parameters** | **Relationship with GWQII** | **Wet period 2012** | **Dry period 2012** | **Wet period 2017** | **Dry period 2017** |
| SAR | GWQII | 0.48 | 0.59 | 0.73 | 0.70 |
| EC | | 0.99 | 0.99 | 0.98 | 0.98 |
| Cl | | 0.94 | 0.94 | 0.92 | 0.95 |
| RSC | | 0.93 | 0.93 | 0.87 | 0.68 |
| ESP | | 0.49 | 0.59 | 0.72 | 0.61 |
| %Na | | 0.08 | 0.24 | 0.19 | 0.36 |
| PI | | 0.11 | 0.02 | 0.03 | 0.19 |
| MAR | | 0.02 | 0.31 | 0.17 | 0.28 |
| KR | | 0.01 | 0.24 | 0.33 | 0.11 |

## CONCLUSION

The results obtained showed that the majority of the analyzed chemical elements exceed the standards fixed by the WHO. Moreover, the high contents of $Ca^{2+}$ and $Mg^{2+}$ contribute in increasing total hardness.

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According to the GWQI, the results show that the groundwater quality has been Permissible to Doubtful utilization. However, the analysis of the spatial distribution map of the GWQI shows that the downstream part of the study area is characterized by an Excellent to Good water quality presenting 20% in 2012 and 5% in 2017 of the points analyzed.

Results based on the parameters of SAR, EC, Cl, RSC, %Na, MAR, PI, KR and Richards and Wilcox classifications indicate that the groundwater quality ranges from Good to Unsuitable for irrigation purposes. The salinity risk reveals that 20% of the water samples fall into the C4-S3 class, which is considered unsuitable for irrigating. Two types of water were recognized by the Richards method, namely poor to mediocre. The use of its waters could have a negative effect on the soil evolution. The estimation of the GWQII in the wet and dry periods for 2012 and 2017 shows the predominance of the Good to Permissible groundwater quality class in most of the plains. However, soil type as well as proper selection of plants should be taken into consideration. Also, this study suggested that groundwater is Unsuitable for drinking purposes without treatment and quality measures should be considered while cropping in its irrigation use. Finally, this study demonstrates the flexibility of the proposed approach to assess groundwater quality for irrigation and drinking water supply as to reduce the risk of their use. Moreover, it provides significant information necessary for the management and sustainability of groundwater in a semi-arid region. It can be applicable too in humid and arid regions.

## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## REFERENCES


Abboud, I. A. 2018 Geochemistry and quality of groundwater of the Yarmouk basin aquifer, North Jordan. *Environmental Geochemistry and Health* **40**, 1405–1435.

ABH-CZ 2004 River Basin Agency, Cheliff Zahrez, Hydraulic cadastre of the Cheliff hydrographic basin – Downstream of the Boughzoul dam, 2004.

Achour, F. 1997 *Hydrological Conditions and Water Availability in Semi-Arid Regions: Application of new Methodologies to the Cheif Basin. Algeria*. PhD thesis, University of Franche Comté, France, p. 261.

Achour, F., Bouzelboudjen, M. & Pieyns, S. A. 1998 Spatio-temporal variability of water resources in semi-arid regions: application to the Chéliff basin, Algeria. Water Resources Variability in Africa during XXth Century (Proceedings of the abidjan'98 Conference. held at Abidjan, Cote d'Ivoire, November 1998). *IAHS Publ* **252**, 225–234.

Aher, D. N., Kele, V. D., Malwade, K. D. & Shelke, M. D. 2016 Lake water quality indexing to identify suitable sites for household utility: a case study Jambhulwadi Lake; Pune (MS). *Journal of Engineering Research and Applications* **6** (5), 16–21.

An, Y. & Lu, W. 2018 Hydrogeochemical processes identification and groundwater pollution causes analysis in the northern Ordos Cretaceous Basin, China. *Environmental Geochemistry and Health* **40**, 1209–1219.

Arveti, N., Sarma, M. R. S., Aitkenhead-Peterson, J. A. & Sunil, K. 2011 Fluoride incidence in groundwater: a case study from Talupula, Andhra Pradesh, India. *Environmental Monitoring and Assessment* **172**, 427–443.

Asadi, S. S., Vuppala, P. & Anji, R. M. 2007 Remote sensing and GIS techniques for evaluation of groundwater quality in Municipal Corporation of Hyderabad (Zone-V), India. *International Journal of Environmental Research and Public Health* **4** (1), 45–52.

Avvannavar, S. M. & Shrihari, S. 2008 Evaluation of water quality index for drinking purposes for river netravathi, Mangalore, south India. *Environmental Monitoring and Assessment* **143** (1–3), 279–290.

Ayers, R. S. & Westcot, D. W. 1988 Water quality in agriculture. *FAO Irrigation and Drainage Bulletin* **29** (1), 165.

Bakalowicz, M. 1979 *Contribution de la Géochimie des Eaux à la Connaissance de L'aquifère Karstique et de la Karstification. Thèse de Doctorat*, Université Pierre et Marie Curie, Paris 6, France.

Bekkoussa, S., Bekkoussa, B., Taupin, J. D., Patris, N. & Meddi, M. 2018 Groundwater hydrochemical characterization and quality assessment in the Ghriss Plain basin, northwest Algeria. *Journal of Water Supply: Research and Technology* **67**, 458–466.

Benjamin, B. 2007 *Cartographie Agroclimatique à Meso-échelle : Méthodologie et Application à la Variabilité Spatiale du Climat en Gironde Viticole: Conséquences Pour le Développement de la Vigne et la Maturation du Raisin. Thèse de Doctorat*, Université de Bordeaux, France.

Bernard-Jannin, L., Sun, X., Teissier, S., Sauvage, S. & Sánchez-Pérez, J. M. 2017 Spatio-temporal analysis of factors controlling nitrate dynamics and potential denitrification hot spots and hot moments in groundwater of an alluvial floodplain. *Ecological Engineering* **103**, 372–384.

Bodrud-Doza, M. d., Towfiqul Islam, A. R. M., Ahmed, F., Das, S., Saha, N. & Safiur, R. M. 2020 Characterization of groundwater quality using water evaluation indices, multivariate statistics and geostatistics in central Bangladesh. *Water Science* **30** (1), 19–40.

Bouderbala, A. 2017 Assessment of water quality index for the groundwater in the upper Chéliff plain, Algeria. *Journal Geological Society of India* **90**, 347–356.


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by guest

Busico, G., Cuoco, E., Kazakis, N., Colombani, N., Mastrocicco, M., Tedesco, D. & Voudouris, K. 2018 Multivariate statistical analysis to characterize/discriminate between anthropogenic and geogenic trace elements occurrence in the Campania plain, southern Italy. *Environmental Pollution* **234**, 260–269.

Busico, G., Ntona, M. M., Carvalho, S. C. P., Patrikaki, O., Voudouris, K. & Kazakis, N. 2021 Simulating future groundwater recharge in coastal and inland catchments. *Water Resources Management* **35** (11), 3617–3632.

Chitsazan, M., Aghazadeh, N., Mirzaee, Y. & Golestan, Y. 2019 Hydrochemical characteristics and the impact of anthropogenic activity on groundwater quality in suburban area of Urmia city, Iran. *Environment, Development and Sustainability* **21** (1), 331–351.

Djeda, F. 1987 *Etude Hydrogéologique et Simulation par Modèles Mathématiques de la Nappe de Khemis-Miliana (Bassin du Haut Chelif, Algérie). Thèse de Doctorat*, Université de Franche-Comté, Besançon, France.

Doneen, L. D. 1964 *Notes on Water Quality in Agriculture*. Published as Water Science and Engineering Paper 4001, Department of Water, Science and Engineering, University of California, Davis.

Dwivedi, S. L. & Patha, V. 2007 A preliminary assignment of water quality index to Mandakini river, Chitrakoot. *Indian Journal of Environmental Protection* **27**, 1036–1038.

Eaton, F. M. 1950 Significance of carbonates in irrigated waters. *Soil Sci* **69**, 127–128.

El Jihad, M. D. & Taabni, M. 2019 *Water in the Maghreb: What Water 'Mix' in the Face of Climate Change Effects?* Water and climate in North Africa and the Middle East, Editions Transversal, pp. 11–25.

FAO 2016 Available from: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=fr

Gapon, E. N. 1933 On the theory of exchange adsorption in soils. *Zhurnal Osshchei Khimii (Journal of general chemistry)* **3**, 144–152.

Girard, P. & Hillaire-Marcel, C. 1997 Determining the source of nitrate pollution in the Niger discontinuous aquifers using the natural ratios. *Journal of Hydrology* **199** (3/4), 239–251.

Glangeaud, L. 1955 *Plio-quaternary Deformations of North Africa-Geol*. Rundsch. Mendig 1, pp. 180–187.

Gorine, M., Benkhelifa, M., Gacem, F. & Bellague, D. 2020 Evaluation of the quality of groundwater used for irrigation in the Mina plain, Algeria. *Journal of Water Science* **32** (3), 223–234.

Gouaidia, L. 2008 *Influence de la Lithologie et des Conditions Climatiques sur la Variation des Paramètres Physico-Chimiques des Eaux D'une Nappe en Zone Semi Aride, cas de la Nappe de Meskiana Nord-est Algérien*. Doctoral thesis, Université d'Annaba, Algeria.

Gouaidia, L., Guefaifia, O., Boudoukha, A. & Hemila, M. L. 2013 Assessment of the groundwater salinity used for irrigation and risks of soil degradation: example of the plain of Meskiana, Northeastern Algeria. *Geo-Eco-Trop* **37** (1), 81–92.

Hameed, A., Alobaidy, M., Mukheled, J., Al-Sameraiy, A., & Kadhem, A. J. & M, A. A. 2010 Evaluation of treated municipal wastewater quality for irrigation. *Journal of Environmental Protection* **1**, 216–225.

Hamouche, S., Sebai, K. & Mokhtari, E. 2021 *Apport de la Télédétection et des SIG Pour le Suivi de la Qualité Physico Chimique des Eaux de Surface. Cas de Barrage de Béni Haroun (W. de Mila)*. Master's mémoire, Université de M'Sila, Algeria.

Hceflcd 2006 Study on fish farming at Almassira dam, CR dar Chafaai, Cercle d'Elbrouge, Province of Settat, p. 201.

IFES (Icosium Forages Engineering Services) 2002 *Bureau D'études, Miliana, Rapport D'étude Géophysique par Prospection électrique du Moyen Chélif (El Attaf)*. Ain Defla, Algeria.

Kelly, W. P. 1963 Use of saline irrigation water. *Soil Science* **95**, 355–391.

Khodabakhshi, N., Asadollahfardi, G. & Heidarzadeh, N. 2015 Application of a GIS-based DRASTIC model and groundwater quality index method for evaluation of groundwater vulnerability: a case study, Sefid-Dasht. *Water Science and Technology: Water Supply* **15** (4), 784–792.

Kireche, O. 1977 *Geological and Structural Study of the Schistose Massifs of the Cheliff*. Thesis Doctorate 3rd cycle in geology, USTHB, Algiers, Algeria.

Kireche, O. 1993 *Geodynamic Evolution of the Maghrebian Tellian Margin From the Study of the Parautochthonous Shistose Domain; Chp: Massif du Chéliff Oranaie*. Doctoral thesis, Es-Science USTHB, Algiers, Algeria.

Koussa, M. & Berhail, S. 2021 Evaluation of spatial interpolation techniques for mapping groundwater nitrates concentrations: case study of Ain Elbel, Sidi Makhlouf syncline in the Djelfa Region (Algeria). *Larhyss Journal* **45**, 119–140.

Krishan, G., Singh, S., Kumar, C. P., Gurjar, S. & Ghosh, N. C. 2016 Assessment of water quality index (WQI) of groundwater in Rajkot District, Gujarat, India. *Journal of Earth Science and Climatic Change* **7**, 341.

Kumar, A. & Dua, A. 2009 Water quality index for assessment of water quality of river Ravi at Madhopur (India). *Global Journal of Environmental Science* **8** (1), 49–57.

Leduc, C., Pulido-Bosch, A. & Remini, B. 2017 Anthropization of groundwater resources in the Mediterranean region: processes and challenges. *Hydrogeolgy Journal* **25**, 1529–1547.

Lepvrier, C. 1971 *Data Relative to Schistosity and Metamorphism in the Chéliff and Bou Maad Massifs (Autochthonous North and Meso-Tellian)*. C.R.Acad-Sci, Paris, pp. 285–296.

Lepvrier, C. 1978 The synschist folds of the Chéliff massifs (tell algérois, algérier). *Geog-phys. Geol-Dynam* **20** (1), 119–136.

Leulmi, M. S., Aidaoui, A., Djoudar, H. D., Khelfi, M. A., Lobo Ferraira, P., Ammari, A. & Aziez, O. 2021 Spatio-temporal analysis of nitrates and piezometric levels in groundwater using geostatistical approach: case study of the Eastern Mitidja Plain, North of Algeria. *Arabian Journal of Geosciences* **14**, 386.

Machiwal, D., Cloutier, V., Güler, C. & Kazakis, N. 2018 A review of GIS-integrated statistical techniques for groundwater quality evaluation and protection. *Environmental Earth Sciences* **77**, 681.

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Madene, E., Meddi, H., Boufekane, A. & Meddi, M. 2020 Contribution of hydrogeochemical and isotopic tools to the management of Upper and Middle Cheliff Aquifers. *Journal of Earth Science* **31** (5), 993–1006.

Margat, J. & Van Der Gun, J. 2013 *Groundwater Around the World*. CRC Press/Balkema EH Leiden, Netherlands, 343.

Marlet, S. & Job, J. O. 2006 Processes and management of soil salinity. In: *Traitéd' irrigation*, 2nd edn (Tiercelin, J. R. ed.). Tec & Doc, Lavoisier, p. 822.

Mattauer, M. 1958 *Étude Géologique de L'Ouarsenis Oriental (Algérie)*. Doctoral thesis, Université de Paris, France.

Meena, A. L. & Bisht, P. 2021 Assessment of water quality for irrigation purpose: a case study of Bassi and Chaksu Tehsils, Jaipur District, Rajasthan, India. *Sustainability, Agri, Food and Environmental Research* **9** (4), 480–490.

Meghraoui, M. 1982 *Etude Néotectonique de la Région NE D'El Asnam. Relation Avec le Séisme du 10 Octobre 1980. Thèse de doctorat*, Université de Paris 7, France.

Meghraoui, M., Cisternas, A. & Philip, H. 1986 Seismotectonics of the lower Chéliff basin: structural background of the El Asnam (Algeria) earthquake. *Tectonics* **5**, 809–836.

Mehdaoui, R., Mili, E. M. & Mahboub, A. 2019 Using physico-chemical and bacteriological parameters to characterize the quality of groundwater in the Ziz Valley (Errachidia province South-East of Morocco). *La Houille Blanche* **105** (5–6), 5–15.

Mehreen, A., Rafia, M. & Syed, M. 2021 Analysis of water quality indices and machine learning techniques for rating water pollution: a case study of Rawal Dam, Pakistan. *Water Supply* **21** (6), 3225–3250.

Nagaraju, A., Kumar, K. S. & Thejaswi, A. 2014 Assessment of groundwater quality for irrigation: a case study from Bandalamottu lead mining area, Guntur District, Andhra Pradesh, South India. *Applied Water Science* **4** (4), 385–396.

Njitchoua, R., Dever, L., Fontes, J. C. & Nah, E. 1997 Geochemistry, origin and recharge mechanisms of groundwaters from the garoua sandstone aquifer, northen Cameroon. *Journal of Hydrology* **190** (1/2), 123–140.

Papazotos, P., Koumantakis, I. & Vasileiou, E. 2019 Hydrogeochemical assessment and suitability of groundwater in a typical Mediterranean coastal area: a case study of the Marathon basin, NE Attica, Greece. *HydroResearch* **2**, 49–59.

Perrodon, A. 1957 *Étude Géologique des Bassins Néogènes Sublittoraux de L'Algérie*. Doctoral thesis, Université de Paris, France.

Pradhan, S. K., Patnaik, D. & Rout, S. P. 2001 Water quality index for the groundwater in and around a phosphatic fertilizer plant. *Indian Journal of Environmental Protection* **21**, 355–358.

Raghunath, H. M. 1987 Ground water: hydrogeology, ground water survey and pumping test, rural water supply and irrigation systems. Book, 2nd Edition, New York, J. Wiley & Sons, 563.

Ramachandran, A., Sivakumar, K., Shanmugasundharam, A., Sangunathan, U. & Krishnamurthy, R. 2020 Evaluation of potable groundwater zones identification based on WQI and GIS techniques in Adyar River basin, Chennai, Tamilnadu, India. *Acta Ecologica Sinica* **41** (4), 285–295.

Rezig, A., Saggai, S., Baloul, D., Dahmani, S., Bouamria, M. & Djafer Khodja, H. 2021 Groundwater pollution risk in the region of bouira (north center of Algeria): origin and consequences on health. *Journal of Fundamental and Applied Sciences* **13** (1), 58–74.

Richards, L. A. 1954 *Diagnosis and Improvement of Saline and Alkali Soil*. USDA Agricultural Handbook 60, Washington, p. 160.

Rufino, F., Busico, G., Cuoco, E., Darrah, T. H. & Tedesco, D. 2019 Evaluating the suitability of urban groundwater resources for drinking water and irrigation purposes: an integrated approach in the agro-aversano area of southern Italy. *Environmental Monitoring and Assessment* **191**, 768.

Rufino, F., Busico, G., Cuoco, E., Muscariello, L., Calabrese, S. & Tedesco, D. 2021 Geochemical characterization and health risk assessment in two diversified environmental settings (southern Italy). *Environmental Geochemistry and Health*.

Sahu, P. & Sikdar, P. K. 2008 Hydrochemical framework of the aquifer in and around East Kolkata wetlands, West Bengal, India. *Environmental Geology* **55**, 823–835.

Siebert, S., Burke, J. M., Faures, K., Frenken, J., Hoogeveen, P., Doll, P. & Portmann, F. T. 2010 Groundwater use for irrigation – a global inventory. *Hydrology and Earth Systems Science* **14** (10), 1863–1880.

Smith, M., Cross, K., Paden, M. & Laban, P. 2016 *Spring – Managing Groundwater Sustainably*. IUCN, Gland, Switzerland.

Srinivasamoorthy, K., Vijayaraghavan, K., Vasanthavigar, M., Sarma, V. S., Rajivgandhi, R. & Chidambaram, S. 2011 Assessment of groundwater vulnerability in Mettur region, Tamilnadu, India using drastic and GIS techniques. *Arabian Journal of Geosciences* **4**, 1215–1228.

Stadler, S., Osenbrück, K., Knöller, K., Suckowa, A., Sültenfuß, J., Oster, H., Himmelsbach, T. & Hötzl, H. 2008 Understanding the origin and fate of nitrate in groundwater of semi-arid environments. *Journal of Arid Environments* **72** (10), 1830–1842.

Sumner, M. E. 1993 Sodic soils- new perspectives. Australian. *Journal of Soil Research* **31**, 683–750.

Szabolcs, I. & Darab, C. 1964 The influence of irrigation water of high sodium carbonate content of soils. In *Proceedings of 8th International Congress of Isss*, Vol. 2, pp. 803–812.

Talhaoui, A., El Hmaidi, A., Jaddi, H. & Ousmana, H. 2020 Calculation of the water quality index (WQI) for the evaluation of the physico-chemical quality of the superficial waters of the oued Moulouya (NE, Morocco). *European Scientific Journal* **16** (2), 64–85.

Todd, K. 1980 *Groundwater Hydrology*. 2nd Edition. New York, J. Wiley & Sons, 510.

Touhari, F., Meddi, M., Mehaiguene, M. & Razack, M. 2015 Hydrogeochemical assessment of the Upper Cheliff groundwater (North West Algeria). *Environmental Earth Sciences* **73** (7), 3043–3061.

USSL 1954 *Diagnosis and Improvement of Saline and Alkaline Soils*. U.S.D.A. Handbook, VIII, Vol. 60, U.S. Government Print Office, Washington 160.

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Varol, S. & Davraz, A. 2015 Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey). *Environmental Earth Sciences* **73** (4), 1725–1744.

Venkatramanan, S., Chung, S. Y., Ramkumar, T., Rajesh, R. & Gnanachandrasamy, G. 2016 Assessment of groundwater quality using GIS and CCME WQI techniques: a case study of Thiruthuraipoondi city in Cauvery deltaic region, Tamil Nadu, India. *Desalination and Water Treatment* **57** (26), 12058–12073.

Wilcox, L. V. 1955 *Classification and use of Irrigation Water*. USDA, Circular 969, Washington, DC, p. 19.

Yidana, S. M., Ophori, D. & Banoeng-Yakubo, B. 2008 A multivariate statistical analysis of surface water chemistry data- The Ankobra Basin, Ghana. *Journal of Environmental Management* **86**, 80–87.

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