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GIS-based evaluation of groundwater quality and estimation of soil salinization and land degradation risks in an arid Mediterranean site (SW Tunisia)

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Abstract Southwestern Tunisia is known for its high-quality date palm production. The agricultural activity supports the social and economic pressure. Considering prolonged drought conditions and surface water insufficiency, increasing supplies rely on deep aquifers in spite of the critical status of the water quality used. Intense agriculture development has placed oases durability and crop quality to high risks of soil fertility loss, land degradation, and water availability issues, due to severe climate conditions, overexploitation of groundwater resources, intense desertification, overuse of soil, and poor land management. The recent contamination of the largest aquifer in southern Tunisia (Continental Intercalaire) by petroleum flows adds another dimension to the problem of water crisis and soil salinization in the region of interest. In this study, 41 water samples from CI wells were correspondingly collected for hydrochemical analyses. Major and minor element concentrations were evaluated by different standard methods. The obtained dataset indicates that the western side possesses low salinity hazard, whereas Nefzaoua and El Fedjej areas reveal highly mineralized water unsuitable for irrigation purposes. A number of assessment ratios (KR, TH, SAR, ESP, PS, etc.) and graphical methods (Riverside and Wilcox) confirm this classification. The combination of geochemical indicators with geographic information system permits the assessment of water quality on the basis of two different indexes. The resulted maps show, in turn, scattered classification between the western field with acceptable water quality and El Fedjej-Nefzaoua areas where the CI water is unsuitable for agricultural activities. Besides water chemistry evaluation, the assessment of soil composition, particularly toxic element concentrations, constitutes reliable criteria for monitoring the effectiveness of agricultural practices and the

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suitability of irrigation water. Hence, the concentrations of four heavy metals have been monitored along three soil profiles ranging from the surface to 80 cm of depth. The results are within permissible limits. The vertical distribution of Ni, Pb, Cu, and Zn is related mainly to physiochemical soil parameters, difference in moisture, and fine fraction distribution.

Keywords CI · Heavy metals · Land degradation · Groundwater quality · Chotts basin

Introduction

Soil salinization is a dynamic issue that constitutes a chronic threat to the physicochemical properties of soil. It negatively impacts agricultural production and greatly reduces soil fertility (Ben Aissa et al. 2004; Legros 2009). The salinization may derive from different origins. It can be natural related to arid climate and droughty hydrologic conditions or it can result from anthropogenic activities, signature of the combination of poor water quality and inappropriate irrigation practices (Szabolcs 1987; Blasko et al. 1995; Spoor 1998).

Despite the fact that it constitutes a worldwide issue largely discussed in many countries all over the world, soil salinization seems to be more pronounced in semiarid and arid countries where weathering conditions and human impacts have simultaneously lead to endless pressure on different natural resources. These distributions constitute a great challenge for their resilience to degradation and accentuate their vulnerability for various types of alteration (Floret and Potanier 1982; Chaieb and Zaâfouri 2000; Jauffret and Visser 2003; Ouled Belgacem and Louhaichi 2013; Ben Abdellatif et al. 2016). In consequence, the cumulative impacts of human abusive consumption, desert environment, and severe climate change effects have strongly induce land degradation expressed by overexploitation of water resources and intense soil salinization (Besser 2015; Besser et al. 2016; Hamed 2016).

Although it is of critical economic and social significance, ensuring water supply in accordance with quality criteria has received for a long time less consideration. Undoubtedly, the intense use of groundwater resources to sustain human needs (agriculture, industry, etc.) leads to man-made contamination of these limited resources well observed in different regions in Tunisia (Ben Alaya et al. 2013; Hamed et al. 2014; Mokadem et al. 2016; Mtibaa and Irie 2016; Re et al. 2017) owing to serious repercussions on population livelihood, the economic sector, and the environment. The reduction of yield quality and soil fertility gives rise to the importance of water quality assessment issues for irrigation purposes.

In Tunisia, 50% of the irrigated perimeters are largely sensitive to soil salinization issues and about 25% are affected by water logging (Rhoades et al. 1992; Bouksila et al. 2010; Hamed 2016). Subsequently, the delineation of areas highly affected or more vulnerable to land degradation is of great concern especially in the southern part of the country where the oases systems are mainly concentrated around Chotts salt lakes (Bouksila and Jelassi 1998; Nunes et al. 2007; Kamel et al. 2006; Ben Hassine et al. 2016).

The study area in SW Tunisia (Fig. 1) is particularly devoted to high-quality "Deglet Enour" production. The geothermal resources of SASS aquifers in low enthalpy Chotts field are essentially used for oases systems' irrigation and greenhouses' heating. These highly mineralized thermal waters exhibit low irrigation water quality to be used in agriculture activities. Undesirable results, expressed mainly by increasing soil salinization and gypsum crust formation in upper soil layers, are commonly observed in the oases of the study area. Although groundwater resources reveal increasingly undesirable quality (Besser 2015; Hamed 2016b), the desertic features of the area give few options for irrigation and define a great challenge for farmers to buffer drought conditions, to ensure safe productivity and to avoid soil deterioration and salinization problems. In this regard and as the successful agricultural production depends on appropriate land management, irrigation water quality, soil type, plant tolerance, climate conditions, and drainage system (Michael 1990), the contamination of the Continental Intercalaire, the largest aquifer system in southern Tunisia, by hydrocarbons flows (Besser 2015; Besser et al. 2016; Hamed 2016) places the groundwater resources at greater risks of usualness for different uses. Consequently, the paper aims, first, to delineate regions where the CI water is suitable for irrigation purposes and to evaluate the effects of its chemical composition in soil productivity and plant growth. Second, it attempts to assess the impact of the contaminated water by petroleum substances used for irrigation in soil composition and to estimate its risks for soil and yield degradation. In order to enable GIS environment to identify CI water quality types, different approaches have been used relative to the collected data. The hydrogeological, pedological, and geological particularities of the studied area develop interactive relations within GIS platform owing to groundwater quality classification (Fig. 2).

Presentation of the study area

Geographic setting

The study area is a flat basin situated in southwestern Tunisia, limited by the endoreic salt depressions of "El Fedjej, Djerid, and El Gharsa" in the north and by the sand dunes of the Great Oriental Erg in the south (Tunisian territory). It is bounded by the Dahar plateau to the east and by the dunes of the Great Occidental Erg (Algerian Territory) to the west. It lies between 33°–34°30′ N and 7°30′–10° E. Tectonically, the succession of different extensive and compressive tectonic activities leads
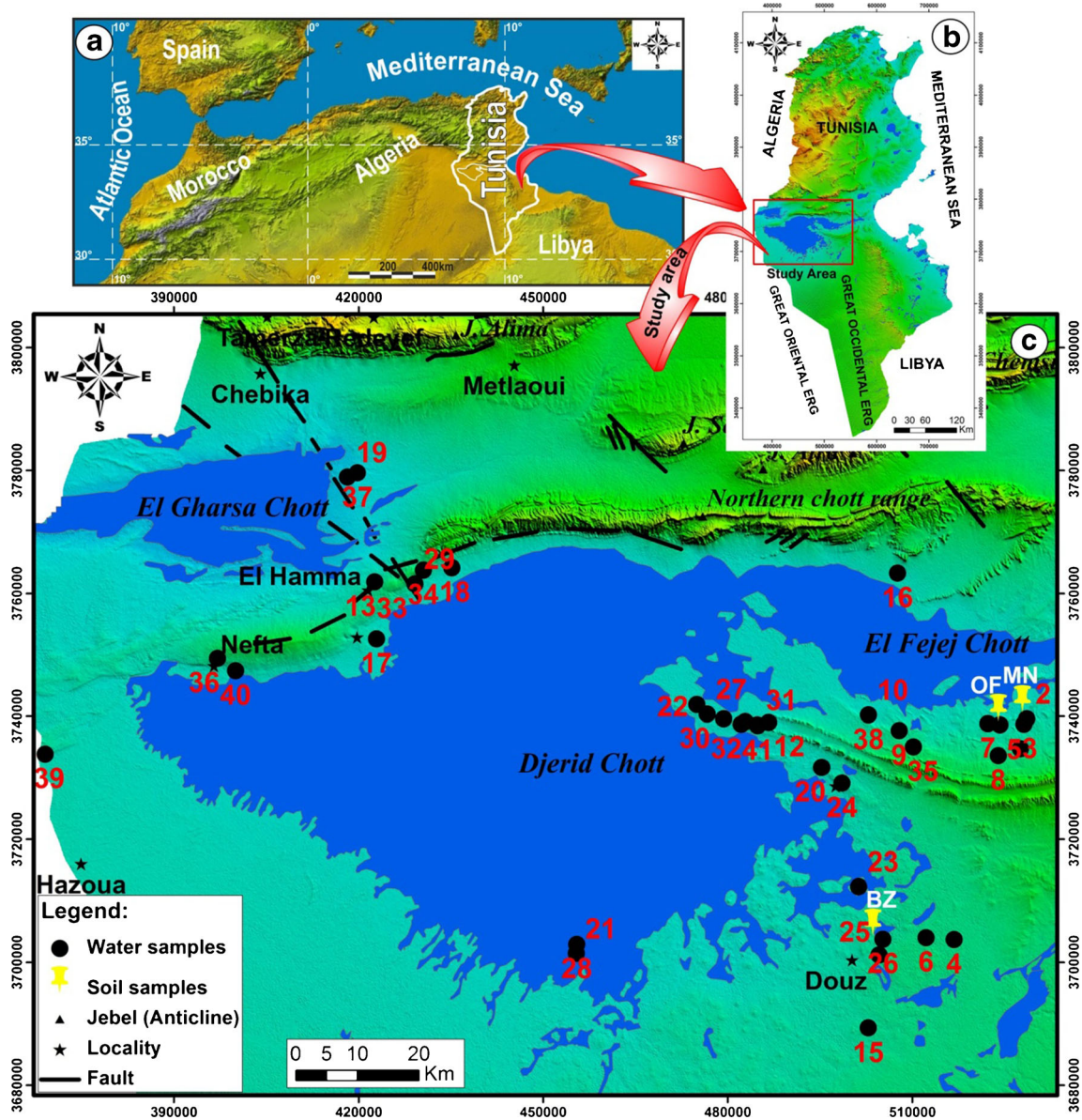
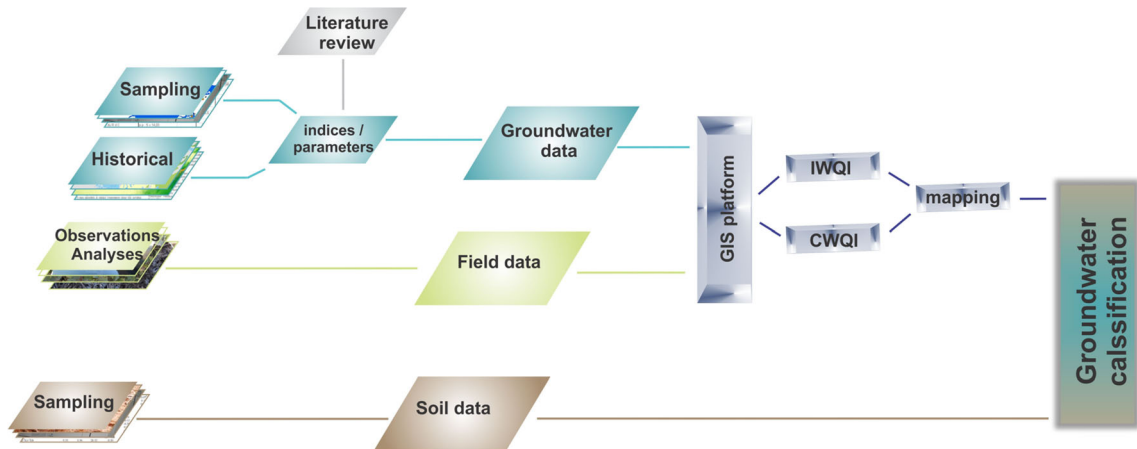**Fig. 1** **a**, **b** Localization of the study area. **c** Sampling map

Fig. 2 Flowchart of the different approaches used

to a complex architecture of the study area which occupies a hinge position between two different domains: the Saharan platform in the south and the Atlassic structures in the north. It constitutes a converge zone of several structures (Ben Youssef 1999; Zargouni and Biely 1986; Lazzez et al. 2008): the most Atlassic southern structure represented by the E-W Chotts features, the NW-SE Gafsa strike-slip, and the Negrine-Tozeur accident (Rouatbi 1967; Mekrazi 1975; Bouaziz 1995; Lazzez et al. 2008; Said et al. 2011; Zouaghi et al. 2011).

The study area is characterized by a semiarid climate with southward transition to desertic conditions. The rainfall potential has an average of 80 to 90 mm/year. These low precipitations show an interannual and interseason irregularity. The abundant rainfall, that occasionally reaches 100 and 120 mm/year, is mainly expressed by extreme events (Bryant et al. 1994; Ferchichi 1996; Kadri and Van Ranst 2002). The wettest period is between December and February with an average temperature below 12 °C (Kadri and Van Ranst 2002). The driest months are June, July, August, and September that have an average temperature of 31.8 °C (Kadri and Van Ranst 2002). The high-temperature values are associated with high evapotranspiration potential about 2000 to 2500 mm/year (Bryant et al. 1994; Agoun 2010) and that may reach 264 mm during July (Kadri and Van Ranst 2002). The surface water deficit reveals a huge challenge for groundwater resources to sustain agricultural production which assumes a crucial role in the economic activity of the region and for the whole country as well (Mamou and Hlaimi 1999; Kadri and Van Ranst 2002; Belloumi and Matoussi 2007; Agoun 2010).

Hydrogeological setting

Regarding droughty conditions, water needs are essentially supplied by groundwater resources. Freshwater and low saline resources are allocated in priority to drinking purposes. Thus, agriculture draws most of their needs from highly mineralized waters from deep aquifers. Shallow aquifers, logged in MPQ formations and alluvial fillings and fed by leakage from deepest levels or by return flows of irrigation water, exhibit high salinity levels and low potential to be permanently used in agriculture. The expansion of oases is directly linked to SASS aquifer resources. Thus, the study area hosts a great number of deep wells exploiting the Complex Terminal "CT" and the Continental Intercalaire "CI" aquifer system.

The CT, hosted in Upper Cretaceous-Tertiary sediments, and the CI, the deepest aquifer (from 300 to 2800 m of depth) and the largest one in southern Tunisia logged in the continental series of Lower Cretaceous, embody a huge stock of low renewable water (Cornet 1964; Castany 1982; M'Rabet 1987; OSS 2003). Their recharge coincides with the humid period of Pleistocene and Holocene. The scanty rainfall contributes little in the groundwater renewal in recharge areas (Edumds et al. 1997; Kamel 2011; Hamed et al. 2014).

The overexploitation of these aquifers leads to the extinction of artesianism and springs, except in some mountain oases in Tamerza (Hachicha and Ben Aissa 2014). Increasing salinity and decreasing quality become the major features of deep water resources in Chotts basin. Recently, the overdraft of the CI aquifer, the most exploited aquifer in Kebili field (Hachicha and Ben Aissa 2014; Besser 2015), induces a severe contamination of these thermal resources by HC pollution. Thus, the reassessment of the quality of these waters for irrigation purposes seems to be crucial taking into account the major defects of petroleum pollution for soil fertility plant growth and oases durability.

Pedological setting

Soils covering oases land in the studied region are gypsiferous, and they are covered by gypsiferous and sandy materials and encrusted by alluvial deposits (Kadri and Van Ranst 2002; Hachicha and Ben Aissa 2014; Ben Hassine et al. 2016). They are classified as poorly evolved alluvial soils or wind-borne parent materials (Mtimet 2001). The surface horizon is generally thick formed by sandy loam texture as periodically a fertile sand dune layer with 20 to 100 cm of thickness is applied as a traditional treatment to increase water infiltration and to avoid gypsum crust formation (Hachicha and Ben Aissa 2014). It is covered by a crust of gypsum limestone type (Kadri and Van Ranst 2002; Ben Hassine et al. 2016). It grades downward to a more salty texture admitting frequent gypsum accumulations in deep horizons (El Fekih and Pouget 1966; Association Française pour l'Etude du Sol (AFES) 2008). These soils are classified as aridisols or halpic GYPSOSOL limestone (Commission de Pédologie et de Cartographie des Sols (CPCS) 1967; AFES 2008).

The extension of oases occurs in plat low-lying areas, and they are released near Chotts salt lakes; gravity underground water flows may be slow and insufficient. Hence, stagnation and water logging lead to an engorgement of soil by the brackish water. The lack of possibility of water evacuation leads to a creation of new lakes commonly observed in several oases in Kebili field (Hachicha and Ben Aissa 2014). The high evaporation potential and the lack of accumulated salt leaching induce a sealing of soil pores by salt deposits in surface horizons and an accentuation of soil salinization (Ben Aissa et al. 2004; Marlet et al. 2007), besides shallow aquifer fluctuations that can be involved in salt concentrations at soil downstream part (Hachicha and Ben Aissa 2014; Ben Hassine et al. 2016).

The combination of climate conditions, water quality, and agriculture practices induces increasing risks of land degradation. The excessive uncontrolled use of natural resources and the oases renovation cause a mismanagement of the grouped oases in Chotts field characterized by very complex and

interconnected drainage systems owing to problems of under-ground water flows (Hachicha and Ben Aissa 2014). In consequence, and as the sustainability of soil fertility and the safeguarding of the oases system depend strongly in the water quality used, the assessment of the soil salinization and alka-linization status and risks has been widely studied (Côte 1998; Kadri and Van Ranst 2002; Ben Aissa et al. 2004; Marlet 2004; Belloumi and Matoussi 2007; Marlet et al. 2007; Zammouri et al. 2007; Legros 2009; Kraiem et al. 2012; Ben Hassine et al. 2016). Currently and according to farmers, a huge reduction of yields and quality has been noticed since 2014 with an early wilting of many hectares observed especially in the Djemna region. Thus, the regular assessment of the irrigated water quality in Chotts basin is necessary for a lose intervention corresponding to fields' observations and obtained results.

Materials and methods

Figure 1 shows the 41 sites of water sampling that have been chosen for hydrochemical analyses. The samples were collected from a number of wells at depths ranging from 300 to 2774 m across the study area. The EC and pH were determined in the fields immediately after sampling using multiparameter measurements. The samples were transported to the Laboratory of Fertilizer and Phosphate in the Tunisian Chemical Group of Gabes (Tunisia) and to the Integrated Laboratory of Water at the High institute of Sciences and Technologies of Water of Gabes (Tunisia) to perform different hydrochemical analyses following the standard guidelines. The salinity was determined by total dissolved salts (TDS) measured by evaporation process until dryness to weigh the residue. The major ions were determined according to standard methods: volumetric titration methods (HCL, EDTA), spectrometric technique, chromatography liquid phase, and flame photometer. The obtained results were used as input data of different key parameters to calculate irrigation water quality indexes (IWQI) taken in the GIS environment. ArcGis 9.3 spatial analyst was used to generate spatial distribution of different chemical parameters and to produce the final IWQ maps.

Three soil profiles have been realized and 12 soil samples were collected from different areas in southwestern Tunisia irrigated by the CI water polluted by petroleum substances in Kebili region (Fig. 1). The analyses of heavy metals were carried out in the Water Researches and Technologies Center Borj-Cedria (CERTE-Tunisia) following the ICP-AES method. The samples were dried, sieved, and reground to obtain fine material with 200 µm fraction. One gram of the sample was digested in a mixture of high purity water, concentrated nitric acid, and concentrated hydrochloric acid. The sample extract was digested at a temperature of 120 °C for 4 h. It was then filtered using 0.45 µm and diluted with HNO$_3$ (0.5 M) to 50 ml.

Results and discussion

The suitability of water for irrigation purposes is not only related to the total amount of dissolved salts, but it depends also on the types of salt. In consequence, a number of guidelines are generally used to define permissible limits of different water components for a particular use. The evaluation of the risks of alkalinization and salt accumulation requires, generally, a water classification based on the most commonly used criteria for estimating. Consequently, a large spectrum of indices and parameters traditionally discussed in the literature has been used, in the current study, for a refined delimitation of safe, vulnerable, and affected areas taking into account the soil type distribution and the local pedological, hydropedological, and morphologic context.

Water type

The identification of water facies is crucial for a better understanding of predominant geochemical factors controlling water chemistry (Mondal et al. 2010; Ramesh and Elango 2012). Different diagrams could be used, among them the Chadha (1999) diagram which represents a modified version of the Piper (1944) plot. The Chadha diagram evaluates the contribution of a number of processes in groundwater chemistry such as cation exchange, water mixing, and rock weathering (Chadha 1999). It is based on the calculated difference expressed in milliequivalent percentage between alkaline earths (Ca + Mg) and alkali metals (Na + K) for the X axis and between weak acidic (HCO$_3$ + CO$_3$) and strong ones (Cl + SO$_4$) in the Y axis. As seen in Fig. 3, the studied water samples fall closely to the Y axis revealing the excess of strong acidic anions over weak acid anions for the majority of sampled points while the remaining exhibits a marginal contribution of Ca-Mg-Cl-SO$_4$ and Na-Cl water type.

Evaluation of risks of water quality for soil salinization

Salinity hazard

The total dissolved salts and electric conductivity are the most reliable useful criteria for water quality judging (Michael 1992; Silva 2004). Saline conditions increase osmotic potential and inhibit plants' ability to take up water and nutriments causing physiological drought and reduction of soil permeability (Thorne and Peterson 1954; Ayers and Westcot 1985; Michael 1992; Subramani et al. 2005; Bauder et al. 2007). For irrigation purposes, the permissible limits are evaluated based on use duration, soil structure, and plant tolerance.

Fig. 3 Classification of CI water type according to the Chadha diagram
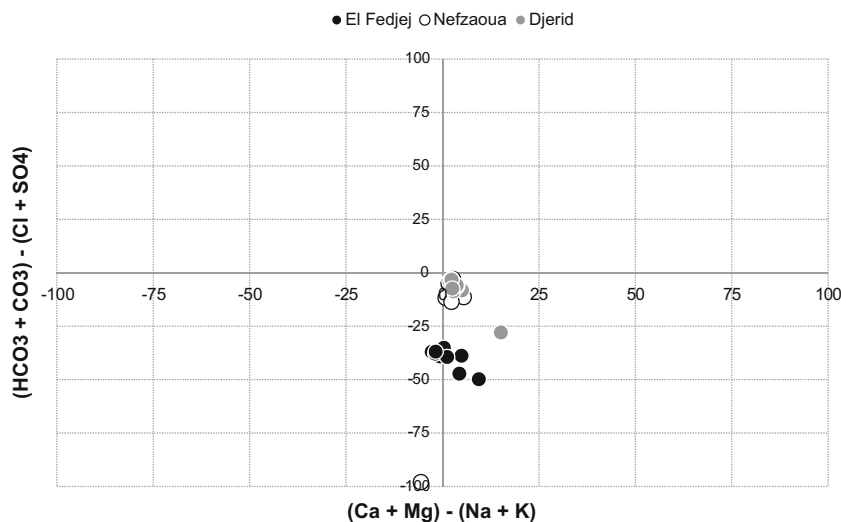
The studied samples reveal a wide range of EC values (Table 1). According to FAO (1985) classification, CI water has moderate to high salt content, and based on US Salinity Laboratory (1954) guidelines, 31.70% is unsuitable water for irrigation purposes. In the field, these samples represent 100% of El Fedjej water points, 15.78% of Nefzaoua samples, and only 8.33% of Djerid samples. Correspondingly, the salinity reveals a minimum of 0.6 and a maximum of 20 g/l found at Djemna region (Fig. 4). The EC and TDS values increase from the west to the east (Fig. 4). These results are in agreement with enhanced rock-water interactions along the flow paths and the prolonged storage of water in the hosted aquifer and indicate a mixing between different water bodies in the contaminated area.

Sodium hazard

Sodium is among the major water constituents that may adversely affect soil texture and plant growth due to high sodium contents above the recommended limits. Sodium accumulation changes the physicochemical properties of soil . It induces

Table 1 Classification of CI water based on the US salinity hazard index

EC (μS/cm)	Salinity hazard	Samples (%)	Samples by basin (%)
< 250	Low	0	0
250–750	Medium	0	0
750–2250	High	65.85	91.66% of El Djerid samples
			84.21% of Nefzaoua samples
> 2250	Very high	34.14	8.33% of El Djerid samples
			15.78% of Nezaoua samples
			100% El Fedjej samples

particle dispersion, aggregate instability, structure deterioration displacement of Ca and Mg from clays units, and replacement by Na from water. This ion exchange leads to soil pore sealing and reduces soil permeability, aeration, and water infiltration. The diminution in the downward movement of interdraining water can be toxic for sensitive plants (Todd 1980; Matthess 1982; Tiwari and Manzoor 1988; Ayers and Westoct 1999; Department of Environment (DOE) 1997; Oster 2001; Gupta 2005; Dhirendra et al. 2009; Nahid et al. 2009; Nata et al. 2009; Tiri and Boudoukha 2010; Ishaku et al. 2011; Ogunfowokan et al. 2013). Hence, several parameters for water quality evaluation were defined based on sodium concentration.

Sodium percent It is denoted in percent following the empirical formula below (1):

$$\%NA = \left(Na^{+*}100\right)\Big/\left(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}\right); \quad (1)$$

All concentrations are measured in milliequivalents per liter.

For the current study, the classification on the basis of sodium level is shown in Table 2. The samples exhibit medium to high sodium contents ranging from 29.64 to 50.21%. These scattered results indicate the relative enrichment in sodium following the flow path from the western side toward El Fedjej depression; 65.85% of samples show good water quality with low alkalinization risks. In the field, they correspond to 91.66% from Djerid water points, 78.94% from Nezaoua area, and only 10% from El Fedjej basin. However, for permissible quality with % Na from 40 to 60, 90% of samples of the eastern side fall in this field.

These Na percentages were plotted vs. EC values in Wilcox (1955) and Riverside (Richards 1954) diagrams. The obtained plots illustrate different classifications. According to the
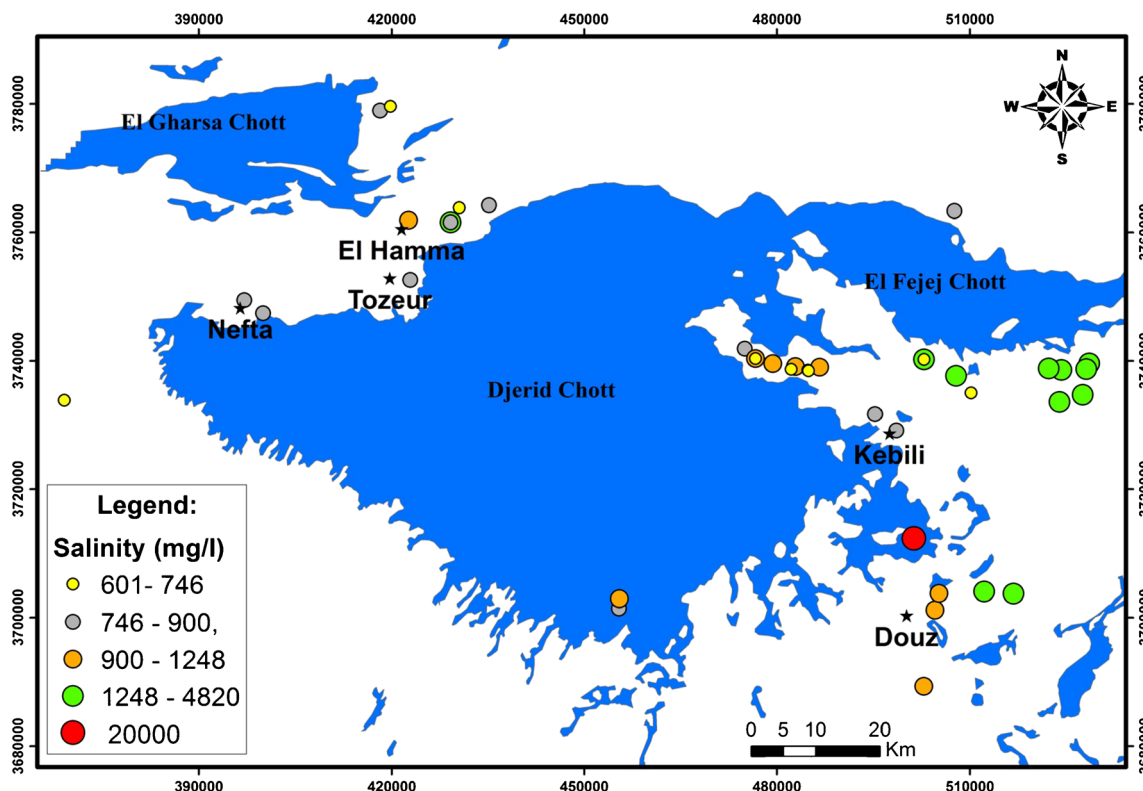
Fig. 4 Salinity map

Wilcox diagram (Fig. 5a), CI samples show three separated groups. The majority of Djerid and Nefzaoua samples (65.85%) reveal good water quality with little risks for developing harmful impacts on soil fertility and plant growth; 7.31% of samples referring to the Nefzaoua area are confined to doubtful quality for a particular use that cannot be used for irrigation under ordinary circumstances. These waters should be used in particular conditions with a special soil

management and an adequate drainage system. For the remaining (26.82%) representing El Fedjej basin, Djemna, and El Hamma 2 wells from the western part, the water has unsatisfactory quality to be used for oases irrigation.

However, according to the Riverside plot (Fig. 5b), the majority of CI samples fall in the high sodium level field, while El Fedjej water points, two wells in Nefzaoua basin, and only one borehole from the western side show very high risk related to elevated sodium content. In general, the CI samples exhibit poor water quality unsuitable for irrigation for the entire Chotts basin.

Sodium absorption ratio Sodium absorption ratio is a reliable criterion for the assessment of sodium detrimental impacts. It evaluates soil alkalinization risks and assesses the tendency of sodium absorption, following the expression below (2):

$$SAR = Na^+ \left/ \left[\left(Ca^{2+} + Mg^{2+} \right)^{1/2} \middle/ 2 \right]; \right. \qquad (2)$$

The concentrations are expressed in milliequivalents per liter.

The classification of CI groundwater with respect to sodium absorption ratio (SAR) is given in Table 3. All water samples show SAR values lower than 10 meq/l,
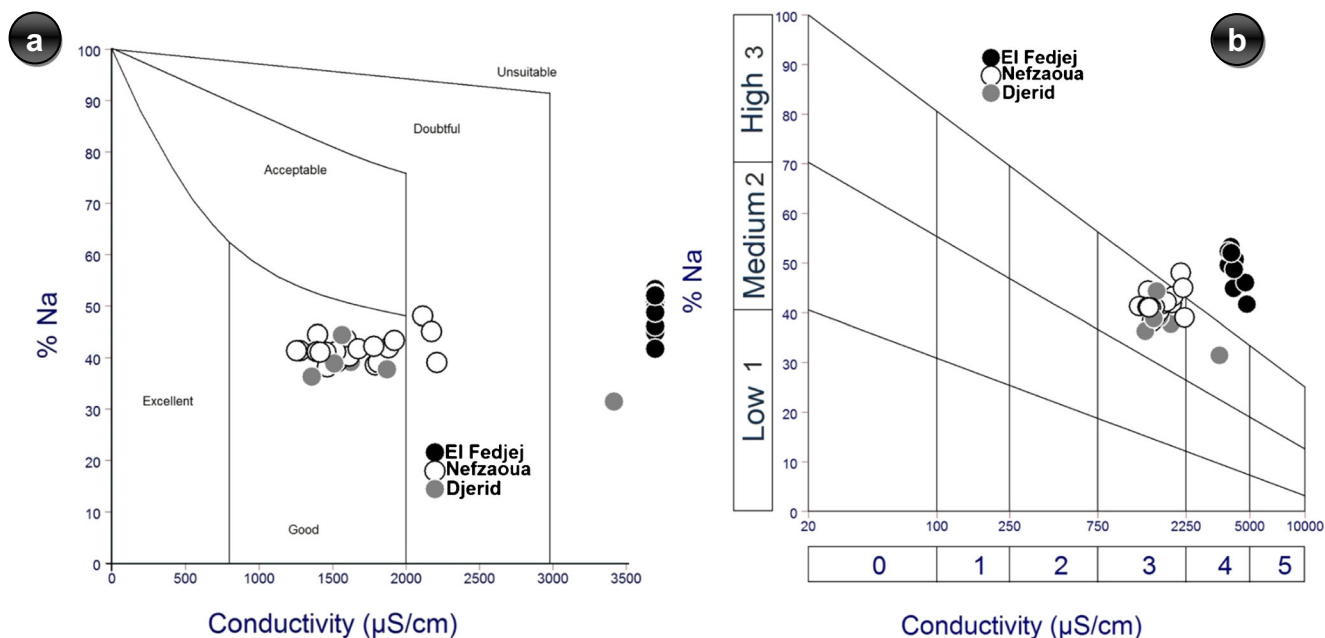
Table 2 Classification of CI water based on sodium percentage

Sodium percentage (% Na)	Water quality	Samples (%)	Samples by basin (%)
< 20	Excellent	0	0
20–40	Good	65.85	10% of El Fedjej samples
			78.94% of Nefzaoua samples
			91.66% of El Djerid samples
40–60	Permissible	34.14	90% of El Fedjej samples
			21.05% of Nefzaoua samples
			9.09% of El Djerid samples
60–80	Doubtful	0	0
> 80	Unsuitable	0	0

Fig. 5 Water quality in relation to electrical conductivity and percent sodium: **a** Wilcox diagram, **b** Riverside diagram

suggesting a good quality for irrigation, except Djemna well in Nefzaoua area.

In this regard, according to the Wilcox and Riverside plots shown in Fig. 6, the groundwater in the study area illustrates scattered groups with different soil salinization and alkalinization risks; 73% fall in the S_1C_3 field corresponding to low alkalinization dangers and limited EC harmful effects for soils with restricted drainage. A systematic monitoring for this acceptable water quality may be required. In the fields, these samples represent Djerid and Nefzaoua basins. The second group refers to all samples of El Fedjej area and some samples of the western side. It shows high salinity levels associated with high alkalinization risks. These samples are unsuitable for irrigation purposes as they may adversely affect soil structure and plant growth.

Exchangeable sodium percentage It is closely related to SAR and it depends on the cation exchange capacity (3). As it is extremely difficult to evaluate the CEC for various soil

types, exchangeable sodium percentage (ESP) can be calculated based on the following empirical formula (4):

$$\left(ESP = \left(Na^+ \big/ CEC \right)^* 100; \text{with CEC } referring \right. \tag{3}$$
$$\text{to } cation \ exchange \ capacity$$

$$ESP = 100^* \left[\left(b\,(SAR) - a \right) \big/ 1 + [b\,(SAR) - a]; with \ a \right.$$
$$= 0.0126; b = 0.01475 \tag{4}$$

For the studied samples, ESP values are ranging between 2.99 and 9.19; 75% fall in the S_1C_3 field with low sodium percentage (Fig. 7). These waters can be used for irrigation with routine checks of the salinity levels. The remaining (25%) show an ESP greater than 6% indicating sodic soils and poor water quality leading to an alteration of soil dispersibility and structure (Trivedy and Geol 1984; Saleh et al. 1999). These waters are unsuitable for irrigation and animal consumption. In the fields, they correspond to the El Fedjej boreholes and Djemna well.

Soluble sodium percentage It evaluates, in turn, risks of sodium accumulation in soils. It is defined by the following expression (Todd 1980; Gupta and Gupta 1987) (5). For soluble sodium percentage (SSP) values greater than 60%, the water is considered unsuitable.

$$SSP = 100^* \, Na \big/ (Ca + Mg + Na + K); \tag{5}$$

All concentrations are expressed in milliequivalents per liter.

Table 3 Summary statistics of principal criteria of evaluation of the suitability of CI water

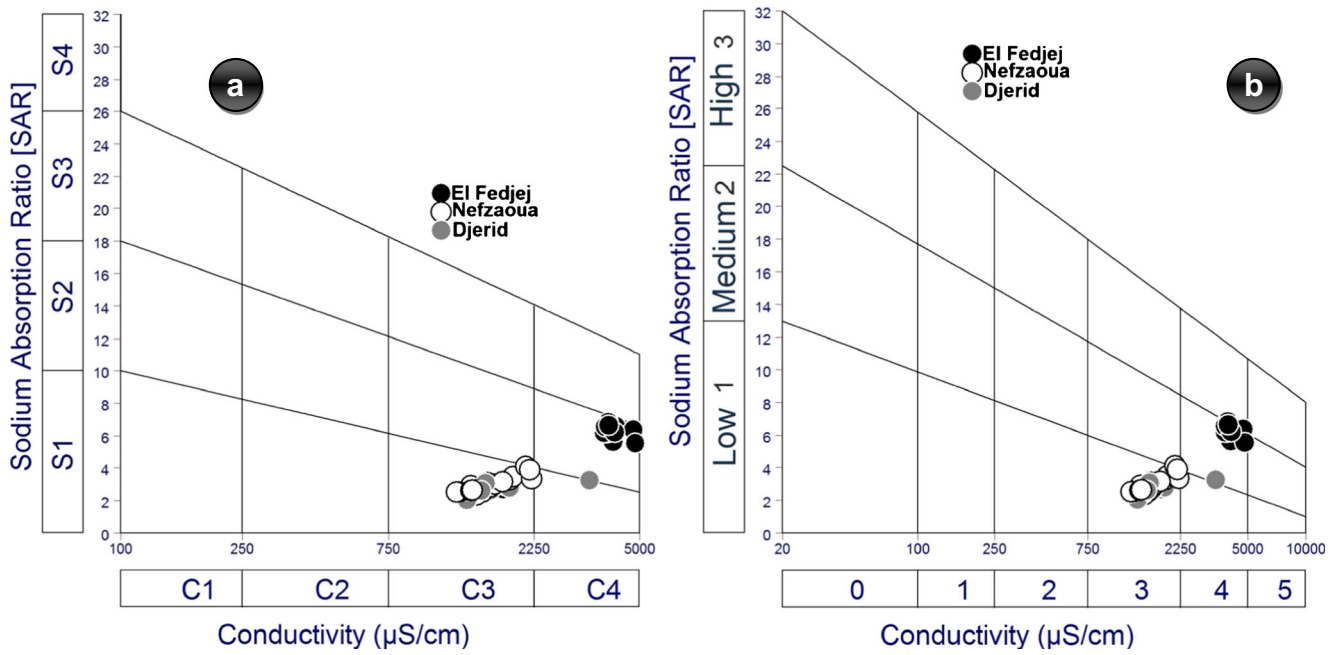| Criteria	Good (%)	Permissible (%)	Unsuitable (%)
% Na	63.42	36.58	0
SAR	73.17	24.39	2.43
RSB RSBC	100	0	0
TH	0	43.90	56.10

Fig. 6 Comparison of the evaluation of the suitability of CI for irrigation based on SAR ratio in: **a** Wilcox diagram, **b** Riverside diagram

The studied samples show an SSP ranging from 29.64 to 50.22 largely below the maximum acceptable limit.

Residual sodium carbonate and residual sodium bicarbonate

Besides sodium, carbonate and bicarbonate are considered as detrimental elements for soil structure and plant growth. High concentrations may significantly alter water quality and affect water's suitability for irrigation. Thus, the excess of these elements is evaluated by the residual sodium carbonate and

residual sodium bicarbonate recognized by the following expressions (Eaton 1950; Gupta and Gupta 1987) with all concentrations expressed in milliequivalents per liter (6 and 7):

$$RSC = \left(HCO_3^- + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right); \qquad (6)$$

$$RSBC = HCO_3^- - Ca^{2+}. \qquad (7)$$

For values less than 1.25, the water quality is considered safe for irrigation. This utilization is used to be marginal for residual sodium carbonate (RSC) ranging between 1.25 and
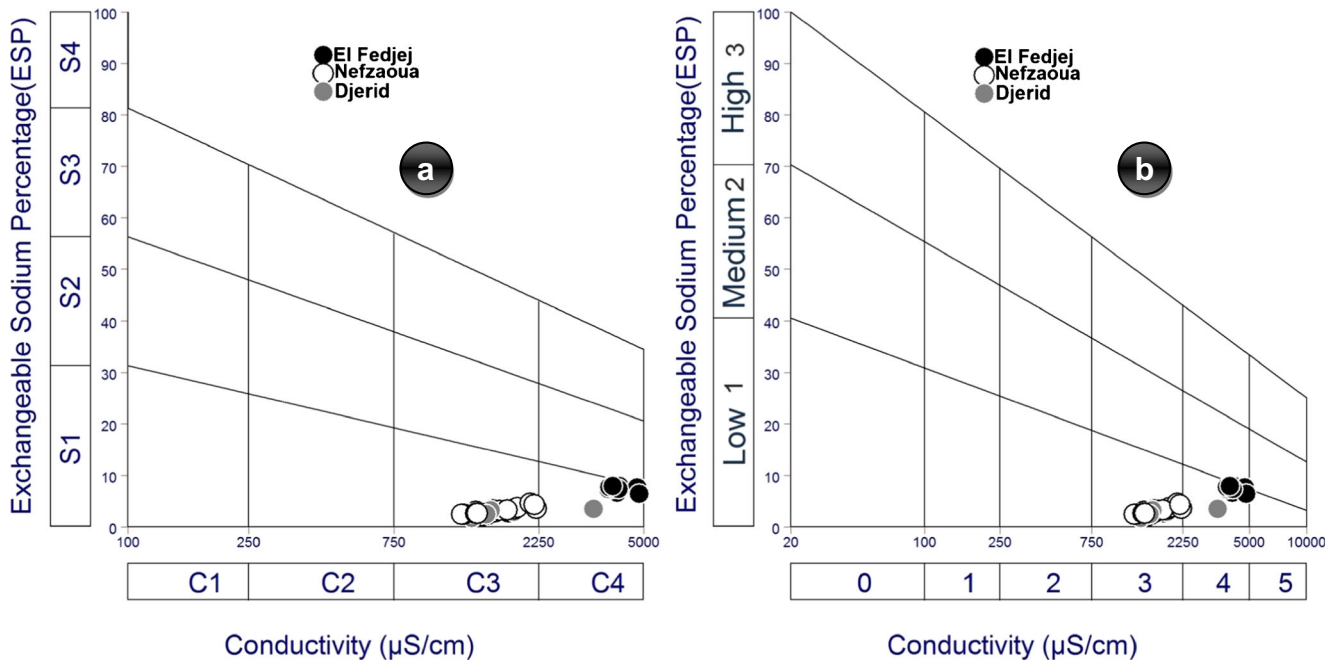

Fig. 7 Water quality classification in relation to ESP ratio: **a** Wilcox diagram, **b** Riverside diagram

2.5 meq/l. However, for values greater than 2.5, the water is unsuitable (Ayers and Westcot 1985; Domenico and Schwartz 1990; Aghazadeh and Mogaddam 2010; Wadie and Abduljalil 2010). The studied samples have RSC and residual sodium bicarbonate (RSBC) levels largely below the safe threshold for irrigation (Table 3).

Magnesium hazard

The usefulness of water for agriculture activities can be evaluated as well by the magnesium hazard (MH) (8) (Szabolcs and Darab 1964, Paliwal 1972). Magnesium and calcium are among the essential elements for maintaining the equilibrium state. However, the Mg excess in water may significantly affect soil quality increasing its alkalinity and decreasing its productivity (Paliwal 1972; Ayers and Westcot 1985; Nagaraju et al. 2014; Dhirendra et al. 2009; Ramesh and Elango 2012). For MH above 50, the water is considered unsuitable for irrigation.

$$MH = 100^* \, Mg^{2+} \Big/ \left(Ca^{2+} + Mg^{2+} \right); \qquad (8)$$

The CI water samples show a MH varying between 24.26 and 54.83 with a mean of 42.76; 78% of samples have MH values between 42 and 54 meq/l. The CI water exhibits undesirable quality for irrigation purposes.

Permeability index

Long-term use of poor irrigation water quality may significantly reduce soil permeability for high Na, Ca, Mg, and HCO_3 concentrations (Nagaraju et al. 2014; Vasanthavigar et al. 2010). Thus, Doneen (1964) defined the permeability index (9) given by the following expression for finding the water suitability for irrigation:

$$PI = 100^* \Big(Na^+$$
$$+ \left(HCO_3^- \right)^{1/2} \Big/ \left(Ca^{2+} + Mg^{2+} + Na^+ \right) \qquad (9)$$

All concentrations are measured in milliequivalents per liter.

According to permeability index (PI) values, three classes were differentiated: PI > 75% for excellent water quality, 25 < PI < 75% for good to permissible water quality, and PI less than 25% for unsuitable water. For the studied CI samples, the PI is ranging between 35.38 and 58.29% referring to permissible to good water quality with low risks related to inadequate soil management and inappropriate drainage.

Kelly ratio

The Kelly ratio (KR) (Kelly 1951) is employed to assess water quality based on Na excess over Ca and Mg following the expression below (10):

$$KR = Na^+ \Big/ \left(Ca^{2+} + Mg^{2+} \right); \qquad (10)$$

The concentrations are expressed in milliequivalents per liter.

For values above a unity, the water is considered unsuitable; 7.31% of the CI samples are above a unity. In the fields, they correspond to El Fedjej water points and Djemna well. These waters cannot be used in irrigation; 14.63% of the samples show a KR between 0.8 and 1%, revealing a marginal undesirable quality. The remaining reveals good irrigation water quality.

Total hardness

Water is classified based on its hardness expressed by Ca and Mg content recognized by the following Eq. (11) (Todd 1980; Hem 1985; Sawyer et al. 2003):

$$TH \, (ppm) = 2.497 \, Ca^{2+} + 4.115 \, Mg^{2+}; \qquad (11)$$

Concentrations are expressed in milliequivalents per liter.

For total hardness (TH) values greater than 100, the water exhibits undesirable quality for irrigation, while above 500 ppm, it is considered unsuitable. Despite the fact that 43.90% of the samples are below the maximum acceptable limit (Table 3), CI water indicates high level of hardness leading to many plumping and scaling problems (World Health Organization 2004; Hosseinifard and Aminiyan 2015).

Potential salinity

Water suitability for irrigation is not related only to the concentrations of soluble salts in water, but it also depends as well in the percentage of solute accumulation in soils after irrigation. Thus, Doneen (1964) defined the potential salinity index based on chloride and sulfate concentrations (12):

$$PS = Cl^- + \left(SO_4^{2-} \Big/ 2 \right); \qquad (12)$$

All concentrations are expressed in milliequivalents per liter.

The CI samples reveal a potential salinity more pronounced in El Fedjej basin and in Djemna region exceeding 35 meq/l and a minimum of 5.49 meq/l in the western side.

Chloronity index

High chloride concentrations in irrigation water may lead to hazardous impacts for soil fertility and plant growth (Mass 1990). Thus, chloronity index is among the most important ratios used to find the suitability of water for irrigation purposes especially for long-term use. For the current study, CI samples exhibit a wide range of chloride index referring to low mineralized water in the western side and to unsuitable resources for agricultural activities toward the east, particularly in El Fedjej and Djemna areas.

Irrigation water quality index

The assessment of water quality for irrigation purposes and its vulnerability to different types of pollution has been evaluated according to a great number of indexes and parameters as there is no single criteria that can provide sufficient information or give a clear classification. In this regard, water quality indexes are considered as useful tools for judging the usefulness for irrigation purposes and constitute an efficient method for water classification. Water quality index (WQI) gives a general idea as it summarizes groups of criteria and expresses their variability in one term. It combines a series of parameters referring to physical, chemical, and biological water characteristics and simplifies their representation for a better understanding of the evolution tendency. It is based on the combination of a number of criteria used for assessing water quality that have been recognized as the most reliable factors controlling the water quality. For each determinant, there are a rating scale and weightings corresponding to its impact for water degradation (Couillard and Lefebvre 1985; Hu et al. 2005; Debels et al. 2005; Asadi et al. 2007; Yogendra and Puttaiah 2008; Meireles et al. 2010; Rokbani et al. 2011; Khalaf and Hassan 2013; Jahad 2014). The first index was mentioned by Horton (1965) and numerous further works constitute a reevaluation of the initial version according to different regional and local conditions (Babiker et al. 2007).

The WQI is a model established through the integration of GIS (Meireles et al. 2010) platform for a comparison of the spatial distribution of different key parameters. To assess CI water quality in the studied region, two indexes have been used: IWQI and CWQI.

IWQI IWQI is established based on collecting data of different factors. The first step involves the choice and the identification of several criteria considered more influential for soil fertility and plant growth. The second step witnesses defining quality measurement values Q_i, estimated based on each parameter value (13), according

to the criteria recognized by Ayers and Westcot (1999) established in Tables 4 and 5:

$$Q_i = Q_{i\,max} - \left[\left(X_{ij} - X_{inf} \right) * Q_{i\,amp} \big/ X_{amp} \right]; \qquad (13)$$

Q_i is a nondimensional number; it depends on tolerance limits;

$Q_{i\,max}$ maximum value of the category;

X_{ij} parameter spotted value;

X_{inf} minimum border category;

$Q_{i\,amp}$ category ampleness;

X_{amp} category ampleness for each parameter; estimated by considering the uppermost border (limit) as the maximum value obtained the highest value determined in the physical and chemical analysis of water sample.

The general suitability map showing the spatial distribution of the variation in concentrations of combined parameter series at different locations is given by Fig. 8. According to the classification defined by Meireles et al. (2010) (Table 6), the obtained values, ranging from 34.44 to 85.85%, indicate that the water points have irrigation index that spreads more or less uniformly across the study area (Fig. 8); 4.87% fall in the excellent water quality field, 43.90% have good quality that required restrictions for use at the long term, 24.39% refer to moderate quality, 12.19% exhibit poor water quality, and 14.63% correspond to unsuitable water for irrigation requiring high to severe restrictions.

In Djerid and Nefzaoua areas, groundwater is generally suitable for short-term use with some restrictions, except El Hamma and Djemna regions, where some wells indicate very poor water quality. The remaining presents water quality index categorized under high to severe classes. CI samples with poor water quality are located essentially in the aquifer discharge area in the eastern part near El Fedjej Chott depression referring to the contaminated area by HC seepage. These quality fluctuations can happen due to long residence time, formation weathering, overexploitation of water resources, and up/down leakage from different reservoirs. Although most of the water samples are classified under low to moderate restrictions indicating a satisfactory

Table 4 Weights of different IWQI parameters (Meireles et al. 2010)

Parameter	Weight (W_i)
EC	0.211
Na	0.204
HCO₃	0.202
Cl	0.194
SAR	0.189
Total	1

Table 5 Limits of tolerance of different parameters controlling water quality (Ayers and Westcot 1999; Meireles et al. 2010)

Q_i	EC (µS/cm)	SAR (meq/l)	Concentrations (meq/l)		
			Na	Cl	HCO$_3$
85–100	200–750	< 3	2–3	< 4	1–1.5
60–85	750–1500	3–6	3–6	4–7	1.5–4.5
35–60	1500–3000	6–12	6–9	7–10	4.5–8.5
0–35	< 200 or > 3000	>= 12	> 9	> 10	< 1 or > 8.5

quality for irrigation purpose, a more refined assessment of different individual parameters related to water quality index may reveal high index according to reference values owing to soil alteration especially for high content of Na, SO$_4$, HCO$_3$, and Cl.

CWQI It is one of the principal indexes widely used in the evaluation of water quality. It is developed by the Canadian Council of Ministers of the Environment (CCME) (2001). It consists of three different factors and its classification is based on water quality guidelines and standard values. The selected parameters will be combined in three variances (scope, frequency, and amplitude) with values spanning between 0 and 100 resulting in water index classed into five different categories (CCME 2001).

- Scope F_1: It refers to the percentage of variables that did not meet the standard values relative to the total number of selected variables during the time period (failed variables). It is expressed by the following formula (14):

$$F_1 = 100^* \; Number \; of \; failed \; variables \Big/ Total \; number \; of \; variables \tag{14}$$

- Frequency F_2: It witnesses the percentage of individual tests that do not meet the standard values (failed tests), expressed by (15):

$$F_2 = 100^* \; Number \; of \; failed \; tests \Big/ Total \; number \; of \; tests \tag{15}$$

- Amplitude F_3: It represents the amount by which the failed test did not meet the standard value. It is calculated in three different steps.
- The first step is to calculate the excursion which refers to the number of times by which an individual concentrations is greater or less than the standard values at it is expressed by (16 and 17):

$$Excursion_i = \left(Failed \; test \; value_i \Big/ Objective_j \right) - 1;$$
$$if \; the \; variable \; is \; greater \; than \; the \; objective; \tag{16}$$

$$Excursion_i = \left(Objective_j \Big/ Failed \; test \; value_i \right) - 1;$$
$$if \; the \; test \; value \; falls \; below \; the \; guideline. \tag{17}$$

- The second step refers to the estimation of the collective amount by which individual tests are out of compliance, by summing the excursions of individual failed tests divided by the total number of tests (18):

$$Nse = \sum_{i-1}^{n} \frac{excurions}{number \; of \; tests} \tag{18}$$

Fig. 8 Distribution of IWQI values
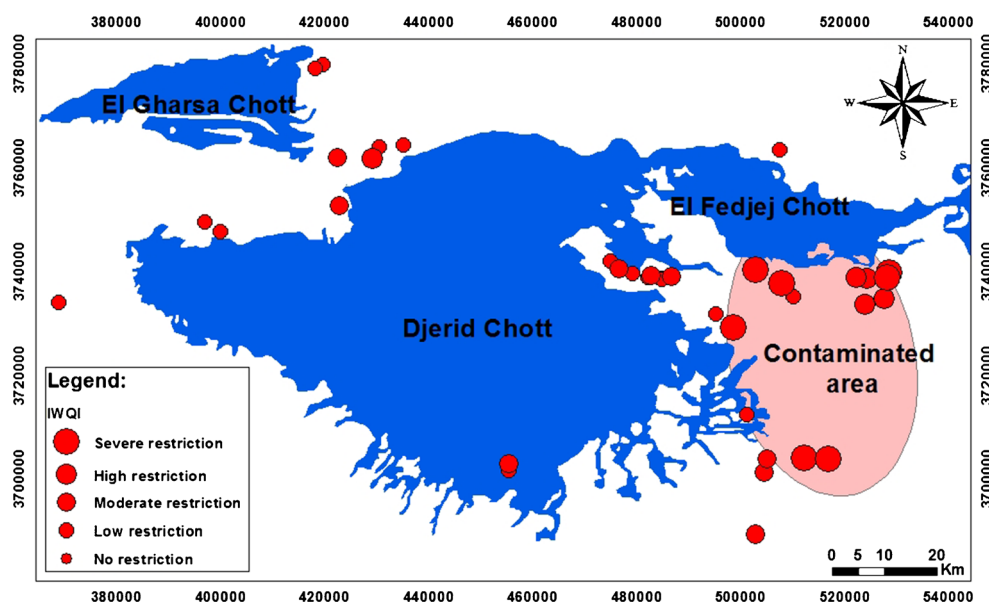
Table 6   Classification of irrigation water quality index and recommendations (Meireles et al. 2010)

IWQI (%)	Water use recommendations	Recommendations	
		Soil	Plants
85–100	No restriction (NR)	May be used for the majority of the soils with low probability of causing salinity and sodicity problems, being recommended leaching within irrigation practices, except for soils with extremely low permeability	No toxicity risk for most plants
70–85	Low restriction (LR)	Recommended for use in the irrigated soils with light texture or moderate permeability, being recommended salt leaching. Soil sodicity in heavy texture soils may occur, being recommended to avoid its use in soils with high clay.	No toxicity risk for most plants
55–70	Moderate restriction (MR)	May be used in soils with moderate to high permeability value being suggested moderate leaching of salts	Plants with moderate tolerance to salts may be grown
40–55	High restriction (HR)	May be used in soils with high permeability without compact layers. High-frequency irrigation schedule should be adopted for water with EC above 2000 μS/cm and SAR above 7.	Should be used for irrigation of plants with moderate to high tolerance to salts with special salinity control practices except water with low Na, Cl, and HCO$_3$ values
0–40	Severe restriction (SR)	Should avoid its use for irrigation under normal conditions. In special case may be used occasionally water with low salt levels and high SAR require gypsum application. In high saline content water, soils must have high permeability and excess water should be applied to avoid salt accumulation.	Only plants with high salt tolerance, except for waters with extremely low values for Na, Cl, and HCO$_3$ values

The F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursion from objection to yield a range between 0 and 100 according to the following expression (19):

$$F_3 = \mathrm{nse} \Big/ \left(0.01\ \mathrm{nse} + 0.01\right) \quad (19)$$

The CWQI is then calculated by the sum of square of three factors divided by 1.732 as shown in the following expression (20):

$$CWQI = 100 - \left(\left(F_1{}^2 + F_2{}^2 + F_3{}^2\right)^{1/2} \Big/ 1.732 \right). \quad (20)$$

As seen in Fig. 9 and according to CWQI values obtained based on World Health Organization (2008) and Ayers and Westcot (1999) guidelines, the entire CI samples in Chotts basin exhibit a poor quality unsuitable for irrigation purposes revealing a huge challenge for the maintenance of soil productivity and crop production.

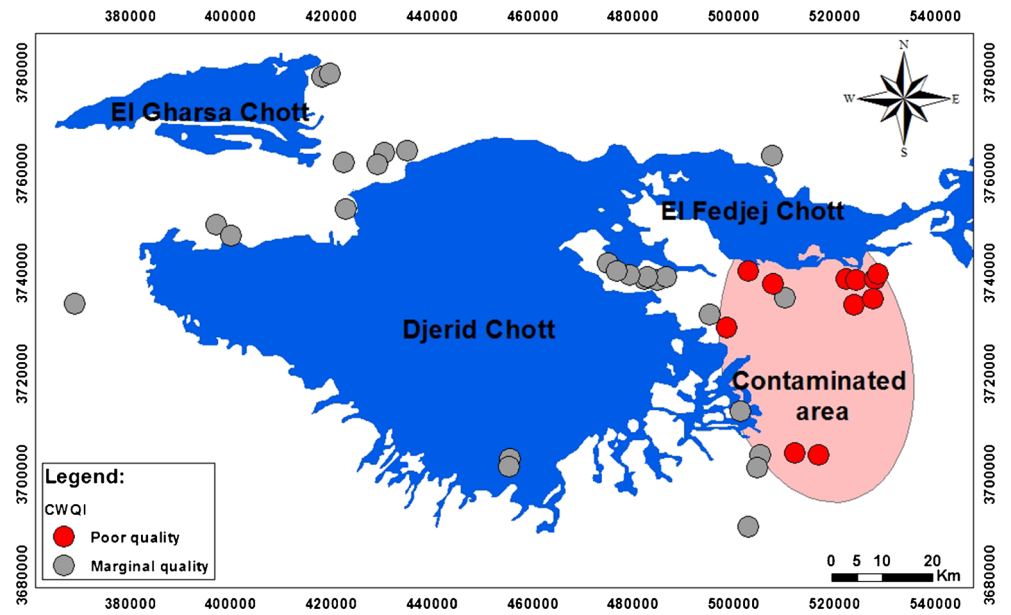**Assessment of heavy metal concentrations in soil profiles**

Besides solute accumulation, heavy metals are among the most toxicological pollutants that can significantly adversely affect soil composition and productivity. Despite their natural concentrations in soil, they constitute a major threat especially with the increasing anthropogenic activities. Scattered literature has defined permissible limits for heavy metals in agricultural soils, and a constant review of the maximum acceptable concentrations takes place systematically depending essentially on soil nature and texture and on the duration of soil exposition to heavy metal concentrations.

In the study area, the CI-contaminated water by petroleum substances (Fig. 10a) (Besser 2015; Besser et al. 2016; Hamed 2016) is permanently used for oases irrigation owing to a number of harmful environmental consequences shown in Fig. 10 b: a concentration of petroleum substances in the root zone, an early wilting of small trees, and a concentration of salt in upstream part of soil, common in field observations in different oasis in Kebili field. Consequently and in order to get a more detailed assessment of the poor irrigation water quality effects in cultivated soils, Cu, Zn, Pb, and Ni concentrations are monitored for four different depths ranging between the surface and the 80-cm depth in Mazraa Neji (MN), Oum El Fareth (OF), and Bazma (BZ) regions in the contaminated area (SW Tunisia).
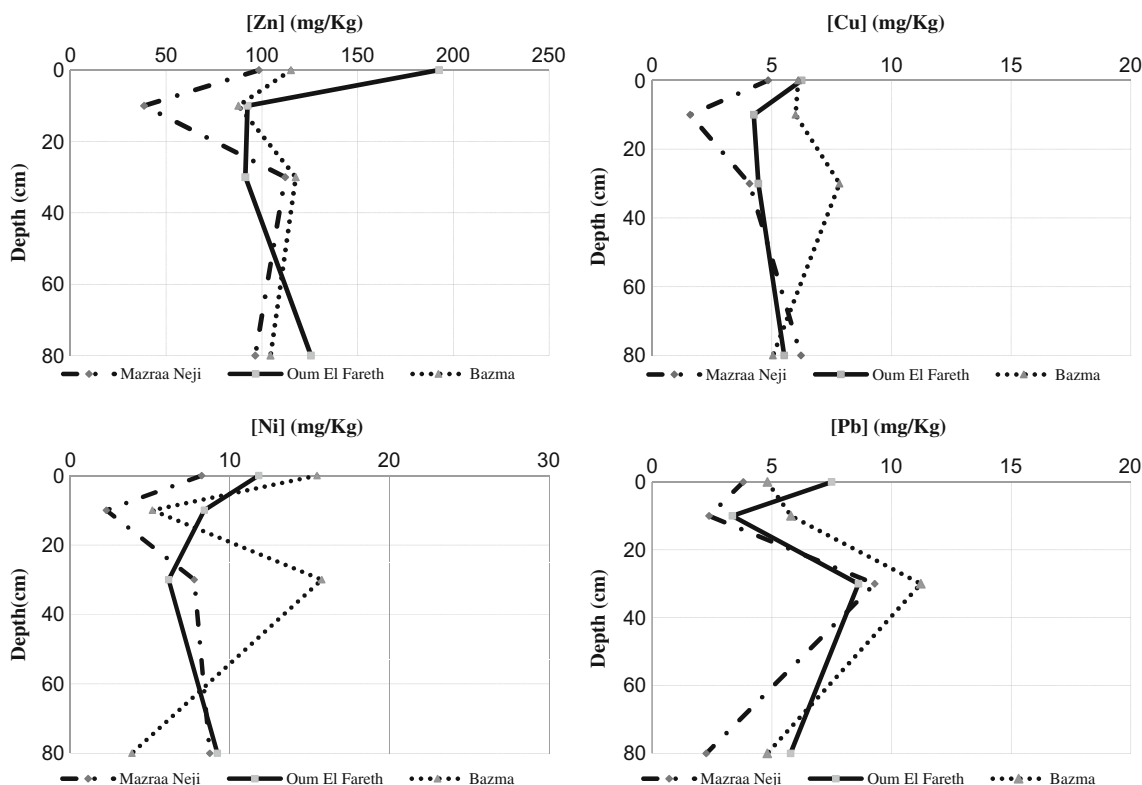
The results are shown in Fig. 11. Cu has a minimum of 1.59 mg/kg, a maximum of 7.83 mg/kg, and a mean of 5.18 mg/kg. Zn concentrations range between 38.48 and 192.59 mg/kg with a mean of 106.07 mg/kg. Ni content varies

Fig. 9 Distribution of CWQI values

Fig. 10 **a–c** Contaminated CI water by petroleum substances. **d–f** Environmental impact of contaminated water for soil and plant

Fig. 11 Distribution of heavy metal concentrations vs. soil depths

from 2.25 to 15.75 mg/kg leading to a mean of 8.57 mg/kg, while Pb concentrations spanned between a minimum of 2.26 mg/kg, a maximum of 15.18 mg/kg with a mean of 5.80 mg/kg. The different concentrations are within the permissible limits for agriculture soils (Malik et al. 2010). The profile of heavy metal concentrations vs. depth did not show any statistically significant correlation. These variations strongly depend on the soil physicochemical characteristics such as soil cation exchange capacity, pH variation, difference in moisture, abundance of organic matter, and fine fraction distribution (Iwegbue et al. 2006). This vertical distribution does not appear to be related to a man-made contamination.

As seen in Fig. 11, these four elements reveal similar correlation patterns with higher concentrations found at the surface and a decreasing trend of heavy metal content in the sublayer soils. Previous researches concluded that heavy metals are mainly concentrated in the top soil (0–15 cm) for the agricultural cultivated soils (Liu and Chen 2006) as higher concentrations are generally derived from the parent materials or leached from the upper layer of the halomorphic soil (Floret and Pontanier 1982) covering the oasis land and rich in organic matter. They may be related to anthropogenic input: fertilizing frequency, agrochemical compounds, manure application, and homogenous added airy overturned soil rich in organic matter commonly observed in the oasis of southwestern Tunisia. They may be attributed as well to the poor quality of the irrigation water that reveals higher concentrations of trace

elements and currently contaminated by petroleum substances.

Furthermore, these elements exhibit a similar trend expressed by rapidly dropped concentrations in the 0–10-cm range. This abrupt decrease may be related to the sandy loam texture of the upper overturned soil layer. The higher permeability leads to a rapid mobilization in the upper 10 cm and the heavy metals have migrated downward through the soil profile.

The increase of concentrations of heavy metals in the 10–30-cm depth range exceeding surface concentrations for Ni and Pb may be accompanied by a degradation of organic matter, a diminution of pH value, and a reduction in cation exchange capacity. The abundance of the clayey fine fraction may significantly increase the adsorption of heavy metals that can strongly adhere to the oxyhydroxy surfaces (Drever 1997; Ekosse 2001). Hence, these elements are trapped in this fine horizon.

In the upper 30 cm, the concentration of the four elements slightly decreases. For most sampling sites, heavy metal concentrations decrease at deeper sections, except nickel and copper for Mazraa Neji and Oum el Fareth regions, and these elements show relocation for 30–80-cm depth range. The correlation between their concentrations reveals a high correlation coefficient ($R^2 = 0.83$) suggesting a common origin related to natural parent material and subaerial weathering. The mobility of HM along with the soil profile in the study area

is classed as Cu > Zn > Ni > Pb, directly linked to soil composition, formation process, and mobile forms of these elements.

## Impact of climate variability on groundwater in the study area

The study area belongs to an arid climate where only groundwater resources are available to meet growing needs of water especially for agriculture. Despite the low renewable rate of these deep aquifers, the SASS system embodies a huge stock of water that is often not considered affected by extreme events or gradual climatic changes as deep aquifers appear less prone to seasonal and interannual climate variability. Nevertheless, deep aquifers' response to multiyear climatic changes is identifiable by increasing pumped and climate-induced effects on groundwater supplies owing to a mixing of different water bodies that may be relevant for geochemical changes (Russo and Lall 2017).

These effects on groundwater quantity and quality have been already noticed for CI aquifer in the study area, and the HC contamination constitutes the ultimate consequence and the most relevant impact of both overexploitation and decadal climate changes on groundwater pressure. This alarming situation gives rise to the discussion about the reliability of the current water management and the necessity of adaptive feasible practices correlated with ingoing scientific measurements to buffer droughty conditions and to ensure long-term freshwater resources.

Synthesis

The study area is characterized by harsh climate conditions, surface water scarcity, and desertic environment. The absence of industrial activities and tourism investment associated with increasing unemployment owns to an expansion of agriculture activities that constitutes a key environmental parameter supporting the socioeconomic pressure of the region and protecting the ecologic balance. Bordered by the Chotts salt lakes and the sandy dunes of the Great Oriental Erg, human activities were concentrated in restricted zones around the endoreic depressions. In the beginning of the 1960s, the creation of oases system in North Africa was primarily related to natural emergence of thermal water of SASS aquifers expressed by springs and foggaras, until the 1980s. The spatial distribution of springs identified distant groups of palm plantations with net contrast with droughty environmental conditions. Then, the frequent occurrence of artesian wells defined sufficient resources for expansion of cultivated perimeters of tolerant plant to arid conditions, high temperature, and elevated salt content (date palm). Permanent irrigation of gypsum soils with saline thermal waters induces fertility loss and owns to the abandonment of "mother" oases where renovation takes place in low-lying areas linked directly to water availability (Fig. 12). In the last decades and in order to increase yield production and date exportation, changes in agriculture policies adopt modern strategies based on maximizing land size, reducing tree density, adopting specialization culture (monoculture), and doubling the water quantity used for irrigation despite the critical status of groundwater resources in the southern province. These new projects have adversely

Fig. 12 Conceptual model of soil fertility evolution
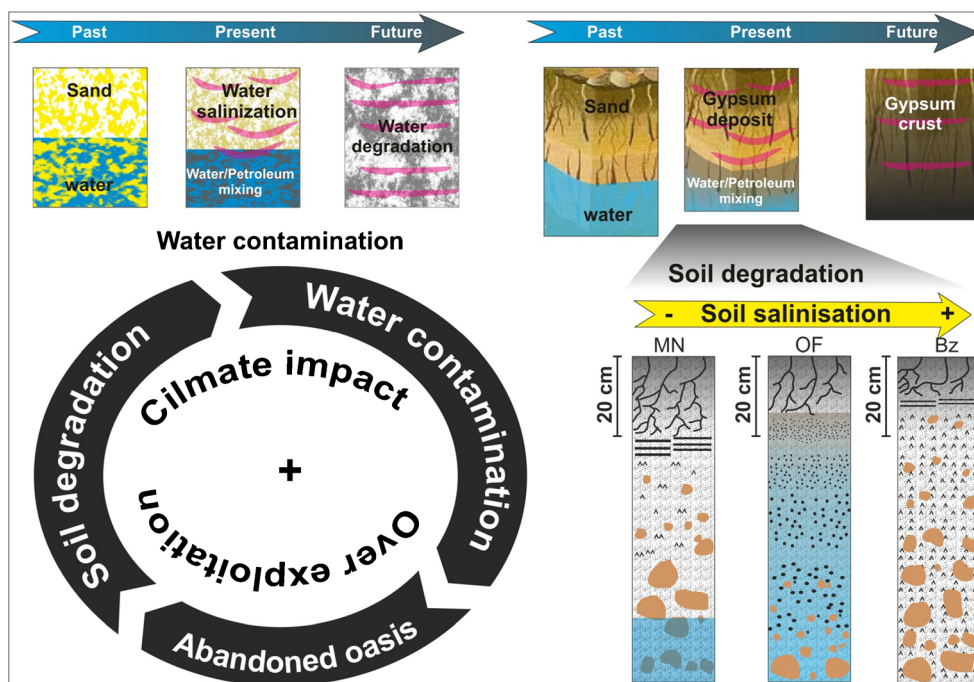
affected the soil physicochemical properties undergoing intensive degradation: increase of shallow water table, creation of new salt lakes in oases, clogging of irrigation network, and increase of soil salinization (Ben Aissa et al. 2004; Hachicha and Ben Aissa 2014).

In fact, in Kebili and Tozeur regions, 60% of oases are irrigated with highly mineralized geothermal water exhibiting more than 3 g/l of salinity (Hachicha and Ben Aissa 2014). Regarding the platitude of the area and to the proximity of salt depressions, an incomplete execution of irrigation water leads to an engorgement of poor water quality. Considering high evapotranspiration potential and elevated temperatures, the evaporation of stagnant water resulted in concentration of salts inducing sealing of soil pores in the upper layers of the soil (Ambroggi 1966) and the creation of gypsum horizon in the root zones preventing water infiltration and nutrient absorption (Job 1992; Ben Aissa et al. 2004; Ben Hassine 2005; Marlet et al. 2007). The fluctuations of shallow aquifer water table, strongly dependent on the return of irrigation of poor water quality, reduce soil porosity and induce salt concentrations at different soil depths (Ben Hassine et al. 2016). Hence, considering the reduction of the effectiveness of the drainage system, the crust formation and the water logging risks appear generally after 5 years from the beginning of irrigation resulting in increasing loss of soil fertility threatening the sustainability of the oases system (Fig. 12). Subsequently, older irrigated perimeters are mostly broken up every 10 years pushing farmers to extending their palm plantations generally stopping the restricted fertile lands of hypersaline depressions and sandy dunes and the limited water resources (Hachicha and Ben Aissa 2014; Ben Hassine et al. 2016). In brief, the drastic increase of production leads to uncontrolled spread of palm plantations and induces, consequently, overexploitation of water resources and soil fatigue (Fig. 12).

Currently, the palm production is facing a continuous reduction in yield and in its quality function of the fragile balance between man, water, and soil (Hachicha and Ben Aissa 2014). In Kebili field, actually nearly 16 ha is abandoned in Djemna region because of high salinity level and contaminated irrigated water by petroleum substances (Fig. 10). Different approaches converge to the unsuitability of CI water for agricultural purposes. Poor land management, gypsiferous crust formations, and intense soil fatigue place the safeguarding of oases at greater risks of progressive endoreisation (Mhiri et al. 1998).

Conclusions and perspectives

Groundwater in arid and semiarid regions is of critical social and economic importance. Its quality fluctuations constitute a limiting factor for particular uses.

In Chotts basin, the suitability of CI groundwater for irrigation purposes is evaluated based on the most reliable and common criteria. The results indicate that the eastern side processes high salinity hazard and alkalinity hazards. Agriculture activities are likely to face increasing soil permeability loss and reduction in yields, while in the Djerid and Nefzaoua areas, the soils are safe to vulnerable according to water guidelines. Generally, the CI water reveals permissible to doubtful quality with increasing rates of development of saline conditions with respect to the actual poor drainage system. The Djemna region with salinity greater than 20 g/l shows the highest expected risks which are already being observed according to the farmers with a loss of production of more than 16 ha of date palm.

The IWQI and CWQI GIS models illustrate W-E progressive alteration of CI water quality. The highest risks were estimated at the contaminated area. In this regard, the assessment of impacts of the contaminated water by petroleum substances used for irrigation in soil composition expressed by monitoring of heavy metal (Ni, Pb, Zn, Cu) concentrations along three soil profiles reveals that these concentrations are currently within permissible limits reflecting a natural origin of these elements without any impact on anthropogenic pollution.

The maintenance of the oases system and the safeguarding of the region's economic and population income are currently threatened by a huge challenge: continuous water degradation, increasing soil salinization, and current hydrocarbon contamination. The actual level of knowledge needs further evaluations of the CI aquifer resources regarding its vulnerability and needs estimations of water degradation quality by a multidisciplinary approach owing to risk mapping of the aquifer's groundwater quality for a better understanding of the feasible alternative of remediation and adaptation. Effective use of outcomes of hydrogeological investigations should be carefully taken into account for the planning of different water management strategies that may be based essentially on the promising alternative of "unconventional" water resources. New projects for seawater desalination should be placed as soon as possible to offer an additive source of water especially for agriculture activities. Additionally, risks evaluation not only at one country's scale but for the whole transboundary hydrogeological system should be reexamined taking in account climate variability, supply insufficiency, and permanent water contamination.

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