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REVIEW ARTICLE

Assessment of natural resources in tunisian Oases: degradation of irrigation water quality and continued overexploitation of groundwater

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Abstract
Given the arid climatic conditions and the frequent long dry episodes in southwestern Tunisia, the sustainability of agricultural activities in this region depends entirely on the presence of sufficient quantities of accessible groundwater of suitable quality for agriculture. Hence, preserving the agrosystems that cover more than 7% of the fertile area of this region, which are of huge socioeconomic value, requires a critical assessment of the groundwater available to these systems. In this context, the present study was performed to determine whether deep groundwater resources are suitable for irrigating more than 54,000 ha of the Nefzaoua Oasis in southern Tunisia. The calculated values of ionic indices (SAR: 3.83–23.6; TH: 17.39–147.65; PI: 35.57–74.81; PS: 5.–79.29) and quality indices (IWQI: 17.14–83.39; CWQI: 17.64–63.96) for these highly mineralized waters indicate that they are unsuitable for irrigation purposes. The risk of land degradation in the Nefzaoua Oasis due to the use of unsuitable irrigation water are being amplified by inappropriate agricultural practices (inefficient drainage and excessive irrigation), mismanagement (the utilization of traditional irrigation techniques, irregular water distribution, and uncontrolled expansion of irrigated lands and water exploitation), and the harsh natural conditions present. The combined impact of these natural and anthropogenic constraints on the local environment necessitate the implementation of a detailed management scheme that utilizes detailed and flexible planning of rehabilitation activities to preserve the ecological and economic value of the agrosystems in this region.

Keywords Water quality · Irrigation · Oasis · Soil degradation · Southern Tunisia

Introduction

Water scarcity is a major problem that continuously threatens human survival, especially in semi-arid and arid regions, where increasing water demand from the local population and industries in the area tends to lead to uncontrolled abstraction from deep confined and semiconfined aquifers. Hence, ensuring the availability of a sufficient permanent water supply of suitable quality for particular uses in hot, dry regions represents a huge challenge, given the unpredictable climate variability in these areas (Cudennec et al. 2008; Hamed 2015). Careful management of the resources that are available in such regions is therefore necessary to suppress water stress due to the degradation of water in terms of both quality and quantity. Indeed, in agricultural areas, the livelihoods of residents and economic development greatly depend on the ability to maintain agricultural production and preserve crop quality, which in turn require the systematic assessment of numerous factors such as irrigation water

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quality, agricultural practices, and drainage systems (Zammouri et al. 2007; Dhaouadi et al. 2015, 2020).

Tunisia, like most arid and semi-arid regions of the Mediterranean Basin, is facing a growing crisis over water resources, especially in the southern province, which is characterized by a dry continental climate and a scarcity of surface water (Guendouz et al. 1997; Hamed 2015; Besser et al. 2018; Dhaouadi et al. 2020). Hence, there is a steady linear rate of exploitation of semiconfined and confined aquifers in this region in order to buffer drought conditions, regardless of any interannual and interseasonal climatic disturbances. This ongoing abstraction generally exceeds the capacity of the aquifers for sustainable exploitation, leading to irreversible water withdrawal (Edmunds et al. 2003), progressive quality degradation (Hamed 2015; Besser et al. 2017), and a high risk of pollution (Besser et al. 2019; Besser and Hamed 2019), making the water resources in the region unsuitable for agricultural activities. This is hugely important considering that most of the population in southern Tunisia depend on the agricultural sector for work, and that this region principally produces high-quality Deglet Ennour dates.

In addition to its social and economic importance in the development of this region of Tunisia (Carpentier 2017), the cultivation of date palms has major religious and cultural value, especially during the month of Ramadan. This value encourages farmers to invest in this agricultural sector, despite the multiple natural, institutional, and political constraints on date palm cultivation in this region, especially the scarcity of high-quality groundwater resources, the length of time that it takes to develop irrigated areas, and the considerable investment required (Hamed 2015; Mokadem et al. 2016; Besser et al. 2017; Haj Ammar et al. 2014). It should also be noted that date palm cultivation has an ecological benefit, since the expansion of irrigated land suppresses soil degradation due to desertification in southern Tunisia (Dhaouadi et al. 2015, 2017, 2020).

However, agricultural sustainability in southern Tunisia is increasingly being challenged by the threat of soil infertility and degradation (Hachicha and Ben Aissa 2014; Ben Hassine et al. 2016). Various rehabilitation measures (Stratégie Nationale sur le Changement Climatique (SNCC), conservation des eaux et des sols (CES)) have been implemented that mainly relate to the amount of irrigation water used in a plot, the area of a cultivated plot, and institutional and financial actions. However, the suitability of water for irrigation purposes still receives relatively little attention despite its multiple effects on the development of agrosystems. Thus, assessing the irrigation water in the Chotts Basin (Nefzaoua region, southwestern Tunisia) is a crucial step towards determining the optimal method of safeguarding the oasis system in this region and thus maintaining the livelihoods of the local population. Therefore, in the study reported here, the effects of natural and anthropogenic constraints on the state of water resources in the Chotts Basin were investigated, as were the impacts of various environmental factors on soil fertility and the economic value of the agrosystems in this region (which produce three types of agricultural crops with various tolerance limits). More specifically, based on data obtained from sampling campaigns, field investigations, and hydrogeological and other data analyses, this work aimed to (1) assess the suitability of the water in the study area for agricultural purposes, (2) estimate the detected and/or potential impacts of water quality on water resources and oasis-based agrosystems in the study area, (Edmunds et al. 1997, Hamed et al. 2018) and (3) highlight the natural resource management actions required to optimize crop production and ensure economic, social, and environmental stability in the Nefzaoua region (Ben aissa et al. 2013; Ncibi et al. 2020).

Data analysis

Site description

The study area is located in southwestern Tunisia (Fig. 1), and covers an area of 22.454 km^2. It corresponds to a vast plain bounded by the endoreic depressions of the Chotts Basin (El Fedjej, Djerid, and El Gharsa) to the north, the Dahar plateau to the east, and the sand dunes of the Grand Erg Oriental (Tunisian territory) and the Occidental (Algerian territory) to the south and west, respectively. It is characterized by a semi-arid to arid climate with low and irregular rainfall that exceptionally exceeds 100 mm, a high evapotranspiration rate of around 2500 mm, and high temperatures that exceed 40 °C by 6/7 °C during the summer period (Bryant et al. 1994; Ferchichi 1996; Kadri and Van Ranst 2002; Ben Boubakar 2007).

Given the dry climatic conditions in the region, the expansion of irrigated cultivation (the oasis system, greenhouse cultivation) and, consequently, economic and environmental stability are closely linked to the abundance and accessibility of groundwater resources.

Groundwater resources. As well as a shallow aquifer in Plio-Quaternary deposits (lumino-clayey and marly sands) that is fed by the rare precipitation in the region and ascending flows from deep water tables and is characterized by low water quality, the hydrogeological system in the study area includes one of the largest aquifer systems in the world, the SASS, with an area of 1 million km^2 and a depth exceeding 3 km (OSS 2014). This transboundary system, which is shared between Libya, Tunisia, and Algeria, is a multi-aquifer system consisting of two main aquifers: the Terminal Complex hosted in Upper Cretaceous carbonate deposits, and the sandy formations of the Miocene and

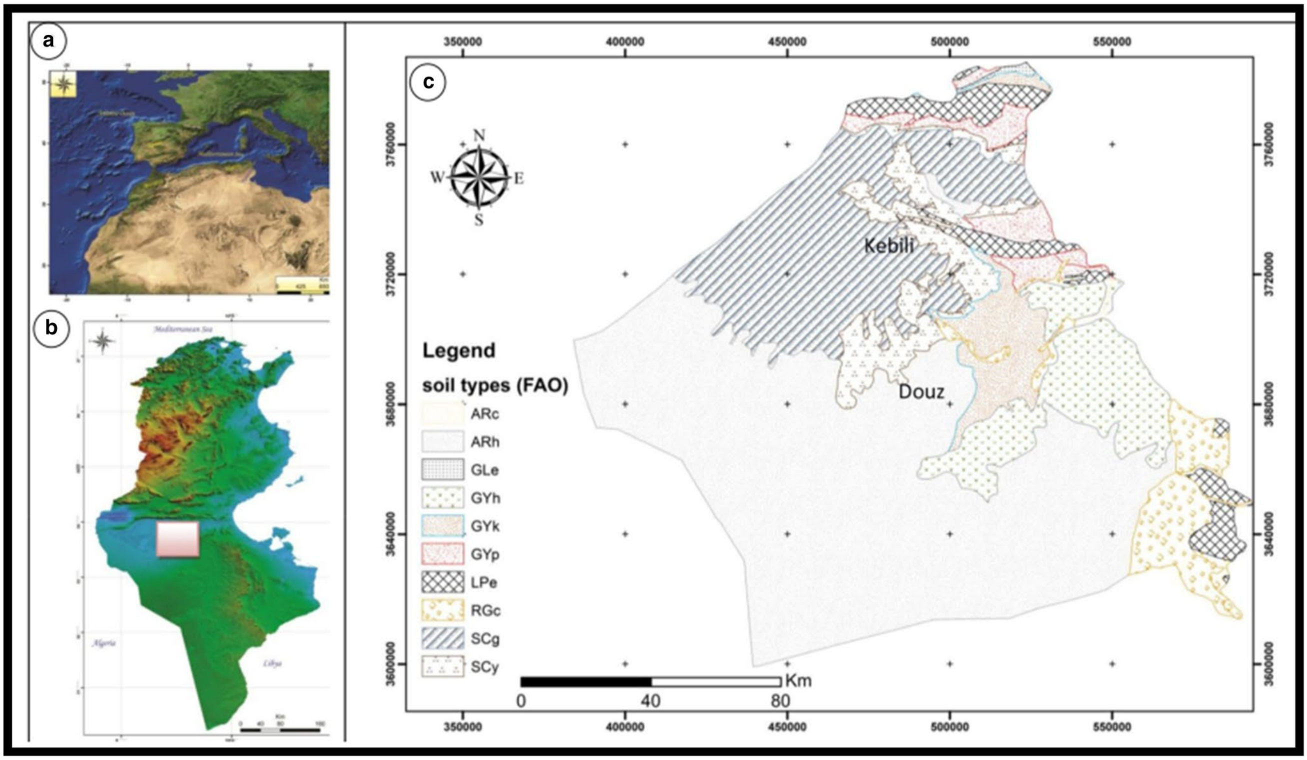

Fig. 1 **a**, **b**: Localization of the study area; **c**. Soil types of the study area

the Continental Intercalaire in Lower Cretaceous deposits. These aquifers were mainly charged during humid periods of the Quaternary (Hamed et al. 2015; Besser et al. 2019).

Soil resources. The soils covering the oases consist of gypsum, gypsum sands, and alluvial deposits. They are often capped with gypsum crusts. These soils are classified as poorly evolved alluvial soils (Mtimet 2001), also known as aridisols or halpic gypsosol limestone (AFES 2008). To maintain the fertility of these lands and increase water infiltration, a sandy layer 20–100 cm thick is periodically added. Agriculture in the study area focuses on three main types of products: date palms (high-quality Deglet Ennour), fruit trees, and vegetables (Ben Mohammed 2015). There are almost 24,897 ha of cultivable land and 479 ha of forest in the region of interest (CRDA 2018).

Data collection

During field investigations, a detailed survey of farmers and government institutions responsible for agricultural activity was performed across the study area to identify the main problems that are imposing constraints on sustainable regional development and negatively impacting the environment. The survey focused in particular on the agricultural techniques practiced and the remediation and rehabilitation methods employed by the local population. The findings of this survey were used to evaluate the individual practices of local farmers, institutional control (insufficient vulgarization, inefficient control), landowner satisfaction with local services (e.g., conflict assessment, investment-to-benefits ratio, irrigation water scheduling, irrigation network disruption, traditional distribution methods, and traditional control and maintenance techniques), indigenous knowledge, and water quality. A literature review was also carried out to evaluate the suitability of the water in this region for agricultural activities and to estimate its potential impacts on soil fertility and land productivity based on various ionic ratios for the water, water quality indices, and graphical representations of the region. The data collected and the results from field investigations and the questionnaire along with published data obtained from Haj Ammar et al. (2014), OSS (2014), and Dhaouadi et al. (2020) on samples from deep groundwater wells were analyzed and interpreted using spatial data distribution software, hydrochemistry, and statistics.

Results and discussion

Water chemistry

According to water samples, the electrical conductivity (EC) of groundwater resources in the Nefzaoua region range from 2.78 to 8.53 ms cm^{-1}. The lowest total dissolved solids (TDS) values are on the order of 2000 mg/L, while the highest exceed 5 g/L. In the two sampled aquifers, saline waters were mainly found in the discharge zones (Chott depressions), consistent with the groundwater flow direction, the long residence times, the water–rock interactions, and the vertical and lateral transfer of water between aquifer levels. This variation in salinity between neighboring boreholes may be explained by the presence of hypersaline water that circulates in deep reservoirs below the hydrogeological system after entering the aquifer system through particular lithological and/or tectonic pathways (Besser et al. 2017, 2018, 2019). The analyzed waters present a mixed facies characterized by permanent hardness. Cl^- and SO_4^{2-} dominate over calcium and sodium, although there is relative enrichment in Na^+ or SO_4^{2-} for some boreholes (Fig. 2).

Quality of the irrigation water Omrani et al. (2011)

Assessment of the suitability of the water for irrigation

Classification based on ionic ratios: The groundwater samples analyzed in previous works were categorized based on selected ionic indices.

- *Salinity hazard.* The studied samples showed a wide range of electrical conductivity values. According to guidelines from Richards (1954) and the FAO (2007), not all of the samples analyzed in previous works were suitable for irrigation purposes. The spatial distribution of electrical conductivity values showed good agreement with the TDS distribution, which peaked in the southern part of the study area. The salinity hazard was also evaluated on the basis of the potential salinity (PS) index. The results showed that, in the short and medium term, the soil salinization risk was generally moderately low, but it was significant in some localized areas (PS values of around 79 and 41 meq/L). For continuously irrigated areas, the estimated values showed a progressively increasing risk of lost soil fertility.
- *Alkalinity hazard.* The water samples contained moderately high levels of sodium in comparison to the total cations, or high sodium levels in some localized areas. This indicates that the water is only suitable for irrigation under certain conditions of use, since irrigation with this water could lead to increasing relative enrichment in sodium in the direction of the depression of El Fedjej. Figure 3 presents the distribution of water samples in Wilcox (1955) and Riverside (Richards 1954) diagrams. The figure indicates that these waters should only be used to irrigate plants with a high sodium tolerance, and only

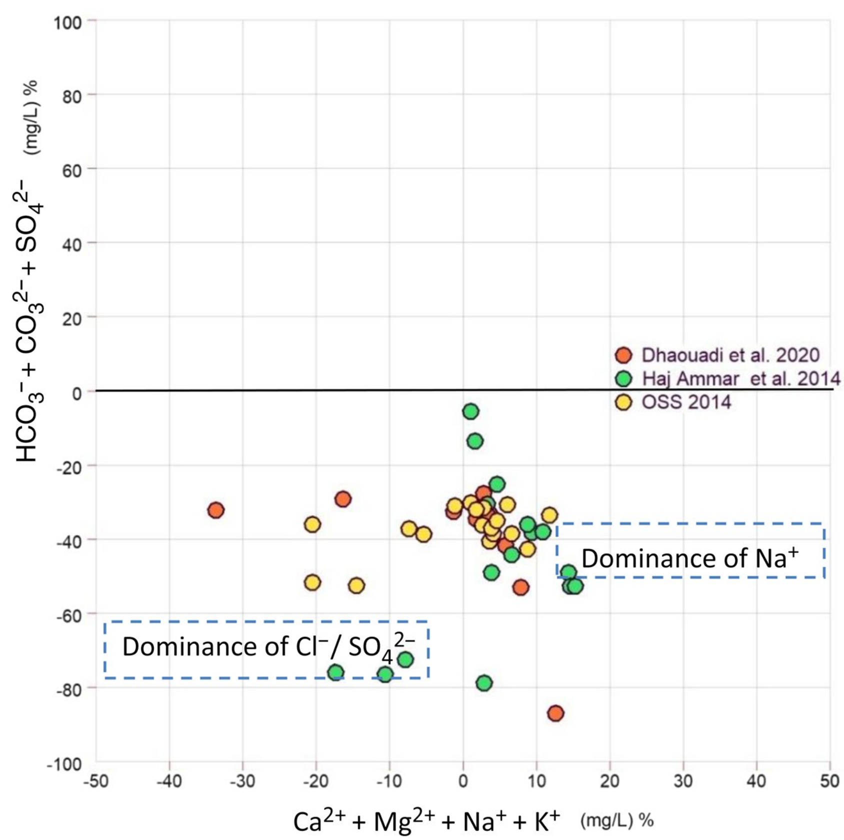

Fig. 2 Chadha diagram

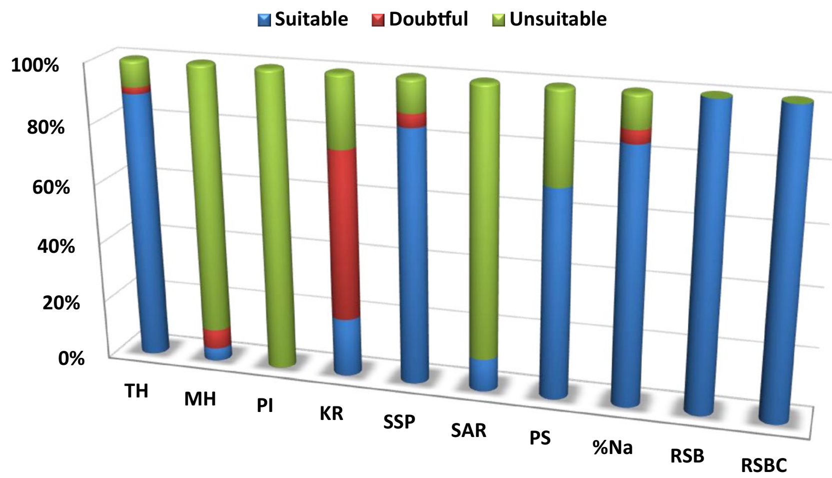

Fig. 3 Distribution of the calculated ionic ratios

when there is a special soil management scheme and an adequate drainage system. Likewise, the exchangeable sodium percentage (ESP) and soluble sodium percentage (SSP) values indicate that the samples are of doubtful quality and that systematic salinity monitoring is required. On the other hand, the sodium adsorption ratio (SAR) values of the groundwater in the Chotts Basin range between 3.83 and 23.6, greatly exceeding the acceptable range of SAR values, even for the most tolerant plants (FAO 2007). Thus, irrigation with the groundwater in the Chotts Basin will lead to a high risk of soil salinization and alkalinization. According to the Wilcox and Riverside classifications, a gradual loss of permeability, pore clogging, crop toxicity, and impermeability of the topmost soil horizons are the main challenges that would result from the continued use of this groundwater. These cumulative and progressive negative impacts on the productivity of the agricultural land in the study area were also confirmed by the values of Kelly ratio (KR) (between 0.46 and 2.67) and potential permeability observed for soils in this region.

– *Residual sodium carbonate and residual sodium bicarbonate.* According to the published data, the waters had residual sodium carbonate (RSC) and residual sodium bicarbonate (RSBC) levels that were well below the safety thresholds for irrigation (Fig. 3).
– *Magnesium hazard.* The groundwater samples had total hardness and corrosivity ratios values that far exceeded the maximum limits, indicating the need for a preliminary examination of groundwater treatment before use.

Multivariate statistical results. Water quality was also classified by agglomerating a wide spectrum of water quality indices using statistical methods. Table 1 shows the correlation matrix of the various criteria considered in this combined classification scheme. The matrix indicates that the salinity and ionic indices are well correlated. The first two factors resulting from the application of the principal component analysis (PCA) method (Fig. 4) to the data were found to represent about 85% of the total variance. Consistent with previous results, the results obtained here for the Nefzaoua samples point to an increasing risk of soil degradation. The distribution of the calculated ionic ratios on the factorial plane reveals the presence of two principal factors that govern the chemistry of the water and its suitability for agricultural purposes. The first refers to the alkalinity hazard and the related permeability and infiltration issues, while the second relates to the influence of increasing magnesium and

Table 1 Pearson correlation matrix

	HCO_3^-	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}	TDS
HCO_3^-	1								
Cl^-	0.709**	1							
NO_3^-	0.342	− 0.148	1						
SO_4^{2-}	0.201	0.367	− 0.577**	1					
Na^+	0.742**	0.806**	− 0.174	0.614**	1				
K^+	− 0.285	0.158	− 0.142	− 0.391*	− 0.178	1			
Mg^{2+}	0.435*	0.635**	− 0.341	0.599**	0.783**	0.167	1		
Ca^{2+}	0.668**	0.668**	− 0.256	0.715**	0.900**	− 0.296	0.790**	1	
TDS	− 0.255	0.205	− 0.191	− 0.272	− 0.148	0.964**	0.222	− 0.215	1

**Significant correlation

calcium concentrations on soil fertility and the clogging of the irrigation network. The strong correlation of the measured salinity values of the sampled waters with the second factor indicates that water hardness is the parameter that has the greatest impact on soil fertility in the study area. Likewise, the results of hierarchical cluster analysis (HCA; Fig. 5) prove that there is a hierarchy of influences on the risk of salinization (Tables 2, 3, 4).

Classification according to quality indices. Aggregating multiple physicochemical parameters into a single water quality index is a more rigorous method of judging the suitability of water resources for particular purposes. The spatial distribution of the resulting integrated water quality index (IWQI) values coincides with the spatial distribution of the previous water quality classification based on ionic ratios, and indicates that water quality decreases in a southerly direction in the study area. IWQI was found to range between 17.39 and 83.39. More than 92% of the samples were categorized into the IWQI classes corresponding to water that should be highly or severely restricted for use in irrigation (69.57 and 23.91%, respectively), indicating poor water quality. The utilization of such water for irrigation requires systematic monitoring and appropriate practices, especially when it is used for long periods. The water samples were also classified according to another aggregated water quality parameter, the Canadian Water Quality Index (CWQI). Based on their CWQI values, about 97% of the water samples in the Nefzaoua area were unsuitable for use in irrigation. The spatial distributions of these indices illustrate the variability in water quality in the study area according to these two indices. The similarity of the distributions obtained for the two indices is due to the fact that both indices are constructed from many of the same variables; in particular, the total salinity of the water defines its suitability for various uses, and the elements dissolved in the water as well as the ionic ratios of these components are important influences on the fragile water–soil–climate equilibrium.

Table 2 PCA results

	Principal component		
	1	2	3
HCO_3^-	0.165	− 0.103	0.389
Cl^-	0.181	0.140	0.210
NO_3^-	− 0.062	− 0.170	0.522
SO_4^{2-}	0.169	− 0.047	− 0.377
Na^+	0.219	0.007	0.080
K^+	− 0.055	0.413	0.121
Mg^{2+}	0.188	0.170	− 0.039
Ca^{2+}	0.218	−0.028	− 0.029
TDS	− 0.038	0.419	0.087

Table 3 IWQI and CWQI values for water samples in the study area, as reported in the literature

Data source	CWQI		IWQI	
	Min.	Max.	Min.	Max.
Dhaouadi et al. (2020)	27.15	49.33	33.93	48.8
OSS (2014)	17.64	63.96	17.14	83.39
Haj Ammar et al. (2014)	20.65	27.54	25.13	50.27

Table 4 Water quality classification based on IWQI and CWQI values (CCME 2001; Meireles et al. 2010)

Water quality indices	Range	Water usage recommendations or water quality
IWQI	85–100	No restriction
	70–85	Low restriction
	55–70	Moderate restriction
	40–55	High restriction
	< 40	Severe restriction
CWQI	95–100	Excellent quality
	60–75	Poor quality
	0–59	Very poor quality

Suitability and impact of the quality of the irrigation water

Upon reviewing the published data on groundwater resources in southern Tunisia, it became clear that the spatial variability of the water chemistry in this region can be explained by the influences of various processes that control the chemistry—dissolution, water–rock interactions during long residence times, drainage, and evaporation—as well as the effects of the overexploitation of the aquifers in this region. Reviewing the data also highlighted that the groundwater used for irrigation in the study area was almost poor in quality, and was saline or of medium alkalinity, so it was unsuitable for agricultural purposes. In fact, using this warm saline groundwater for irrigation leads to the neoformation of salt layers (gypsum screens) in the soil (Hamed 2015). Thus, the soils in the study area are saline soils. This salt accumulation constitutes a physiological threat that hinders the development of agricultural activity in cultivated areas (Nezli et al. 2007) and has repercussions for the entire ecosystem: the osmotic potential of the soil solution decreases, the soil structure deteriorates, the properties of the soil are heavily influenced by the high sodium content, the surface layers become impermeable, oxygen levels in the soil decrease, and certain ions in the salts are toxic (Person 1978; Beradaï 2009; Ben Hassine 2005; Marlet 2004). These characteristics suppress or even impair the productivity of the soil by reducing the uptake of nutrients by vegetation, thus disrupting their development. Salt stress exerts its effects,

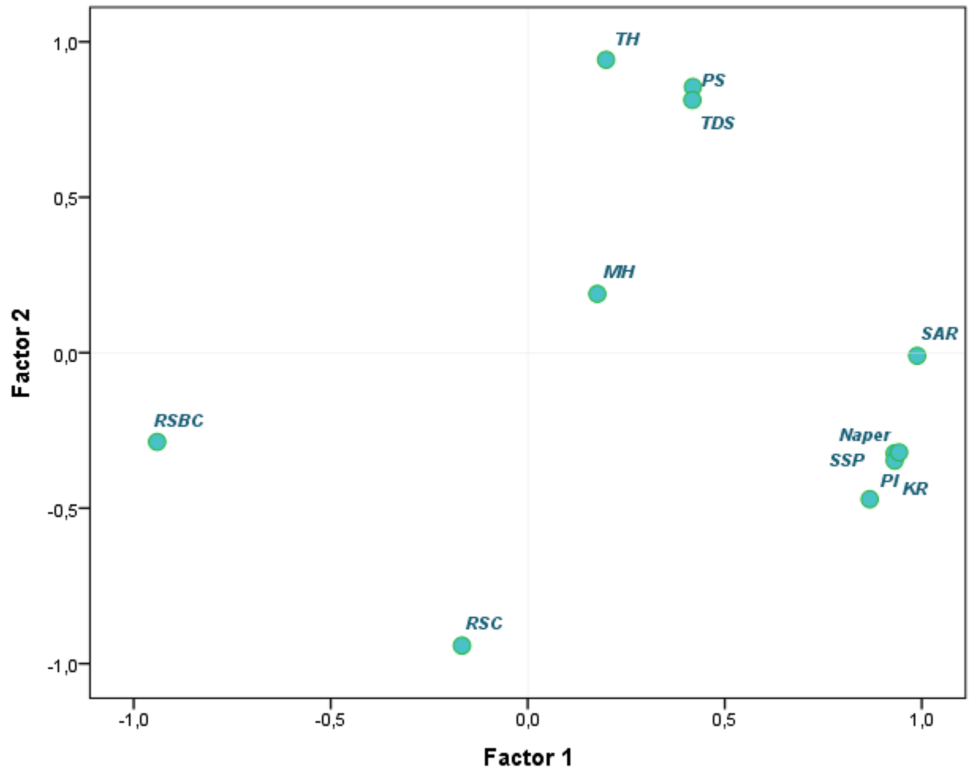

Fig. 4 Statistical analysis using PCA. *Naper* Napercentage

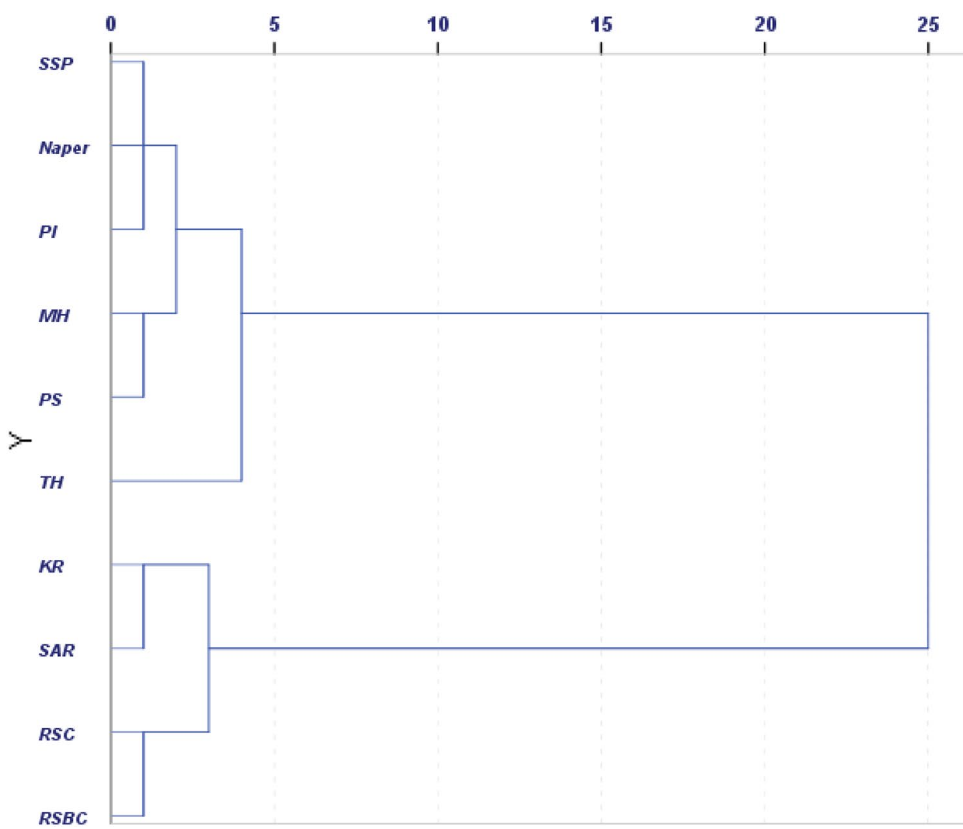

Fig. 5 Statistical analysis using HCA. *Naper* Napercentage

and the soil gradually becomes infertile (Ben Hassine 2005). The irrigated area will then be abandoned in favor of new plots and/or the type of crop cultivated will be changed, most likely making the plot unprofitable, especially considering the severe weather conditions in this region (Hamed 2015).

Agricultural practices and the irrigation system

In addition to the climatic conditions of the region and the agricultural practices used there, soil fertility depends on the quality of the irrigation water available. The use of highly mineralized water that is enriched in salts along with an insufficient drainage system and inappropriate farming practices will lead to increased soil degradation, loss of soil fertility, waterlogging, the formation of gypsum crusts, and an increasing risk of alkalinization and salinization in an oasis-based agrosystem, challenging the survival of the local population. However, since water policy is closely linked to regional socioeconomic challenges, the sustainable management of water resources can play a leading role in solving problems relating to rural poverty, unemployment, and environmental issues, as these issues are directly linked to the degradation of the quality of the water used for irrigation and/or its indirect impacts on water productivity and soil fertility (and consequently on agricultural yields) (Fig. 6).

In the study area, a combination of the effects mentioned above has resulted in a progressive loss of landscape and a reduction in its economic and ecological value. The traditional techniques used in irrigation (e.g., flooding and gravity) have enhanced the development of gypsum crusts, reducing soil aeration and water infiltration. These issues are amplified by the poor quality of the water used for irrigation, which necessitates adequate drainage and respect the crop water requirements. Given the individual behavior of landowners and the inefficient institutional control in this region, the poor quality of the irrigation water has led to increasing overexploitation of aquifers and progressive degradation of natural water resources, threatening the environmental sustainability and the socioeconomic security of the area. Figure 7 presents photographs that illustrate the observed impact of the low-quality irrigation water on various oasis-based agrosystems. A number of water management plans have been adopted since the end of the 1990s, including the Tunisian Decennial Strategy for Mobilizing Water Resources and the Regional Master Plan for the Use of Southern Waters (Hamdane 2015), but the predicted benefits of these plans in terms of water productivity are yet to materialize at the oasis farm level (Dhaouadi et al. 2020).

To combat land degradation, a sustainable management scheme for natural resources is required. In such a

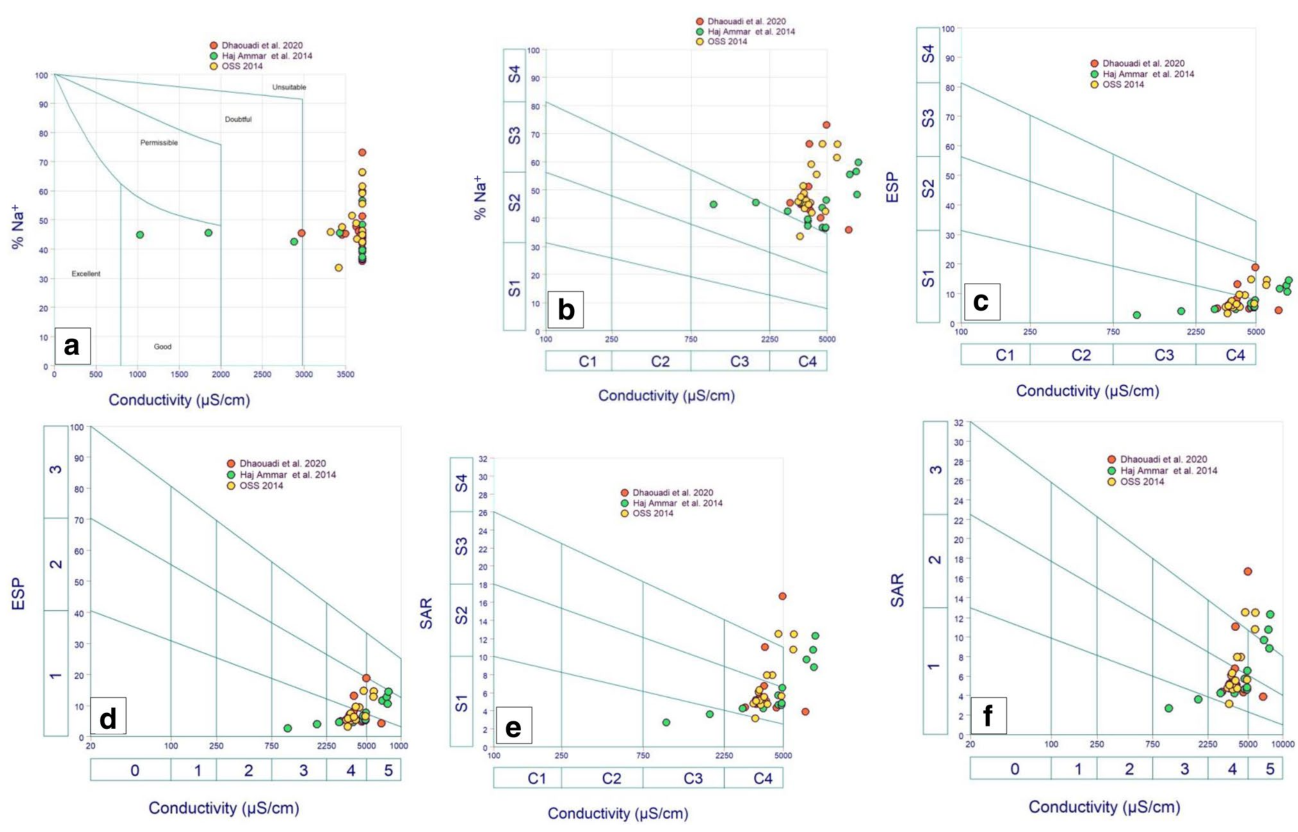

Fig. 6 Water quality classification according to the Riverside and Wilcox diagrams

Fig. 7 Photos illustrating the observed land degardation issues in the study area

scheme, certain measures are implemented to protect natural resources from various sources of contamination and/or degradation. In fact, even though the region is greatly influenced by its natural and geomorphologic features, the data collected show that factors relating to human pressure on resources are the main influences on the intensity of progressive land degradation and, in particular, the development of illegal oases and the uncontrolled expansion of private wells. Rehabilitation efforts should target severely degraded areas as well as non-high-risk areas in order to minimize the devastating effects of soil salinization and alkalization, which can increase desertification.

Akbari et al. (2016) developed a series of remediation plans for agricultural lands in semi-arid and arid regions in order to reduce vulnerability to desertification processes. The land was categorized according to the plant cover and farming practices applied. Data collected from field investigations and a literature review suggest that remediation plans for the studied area should focus on risk minimization (II-b/III-a) and control measures (III-b/III-c) (Akbari et al. 2016). These plans involve two main activities to bring soil degradation under control in the study area. The first activity is to intensify vegetation cover by cultivating plants that are resistant to high salinity and frequent droughts. The second activity is to implement comprehensive technical management and institutional control. Indeed, systematic investigation and monitoring at the plot scale limits uncontrolled expansion and illegal practices. Implementing scientifically based management along with technical tools and governmental supervision should improve drainage systems and water infiltration and reduce gypsum crust formation, thus increasing agricultural production. Over the last few decades, in order to increase the yield of dates and the amount of dates exported, agricultural policies have been modified according to modern strategies based on maximizing the land area, reducing tree density, crop specialization (monoculture), and doubling the quantity of water used for irrigation (Besser et al. 2017). This new approach has adversely affected the physicochemical properties of the soil and caused intensive degradation: fluctuations in the shallow water table, the creation of new salt lakes in the oases, clogging of the irrigation network, and increased soil salinization (Ben Aissa et al. 2004; Hachicha and Ben Aissa 2014). Irrigated plots are generally abandoned after 10 years, while the creation of new oases is limited by the scarcity of fertile land between the salty depressions and sand dunes and the limited water resources available (Hachicha and Ben Aissa 2014; Ben Hassine et al. 2016). The drastic increase in production without considering the environmental stability of the region has caused the uncontrolled proliferation of palm groves, leading to overexploitation of water resources and soil fatigue, thus exposing the oases to an increased risk of endorisation (Besser et al. 2017).

Soil degradation in the study area

In southwestern Tunisia, about 50% of the agricultural land is irrigated with water with a salinity of more than 3 g L^{-1}, and about a third of the agricultural land is affected by surface fluctuations in the saline water table (Hachicha and

Ben Aissa 2014; Ben Hassine et al. 2016). In a large part of the study area, the original environment has already been degraded by the climatic conditions, the proximity of salt depressions, the overexploitation of water resources, poor irrigation practices, and because most of the water sources have dried up (Mtimet 2001; Zammouri et al. 2007; Hachicha and Ben Aissa 2014; Ben Hassine et al. 2016). Indeed, the application of the farrow and basin technique, an irrigation method in which water is directed to flow through narrow channels between rows of palm trees, has adversely affected land productivity. Although this method is less expensive and easy to manage in flat landscapes, it is not well suited to sandy soils as it results in high water losses due to leaching and evaporation processes. The depletion of water resources is clearly a major problem in the southern oases of Tunisia. Private initiatives to illegally extend oases and increase access to water by digging wells has led to the overextraction of renewable groundwater and an acceleration of saline water intrusion from saline areas (e.g., Chott Djerid in Kebili) (Omrani and Ouessar 2008). Developed on sandy clay and gypsum soils (AFES 2008; Ben Hassine et al. 2013, 2016) near salt lake depressions, the oases of southwestern Tunisia suffer from salinization and increasing congestion (Zammouri et al. 2007; Ben Hassine et al. 2013, 2016; Hachicha and Ben Aissa 2014). In addition, the stagnant water used for irrigation is laden with salts, leading to increasing salt concentrations in the soil. Such conditions make it more difficult for plants growing in the soil to absorb moisture and nutrients, so they eventually die from dehydration (Marlet et al. 2009). As well as these problems due to the soil type present in the study area and the cumulative effects of applying highly mineralized water to the soil for irrigation purposes, the maintenance of the oasis system and soil productivity are also threatened by the rapid deterioration of the environment caused by the contamination of the main regions of the IC aquifer with hydrocarbons (the water from this aquifer is extensively used for agricultural activities in the Kebili field; see Fig. 5).

Drainage problems

The impact of the irrigation water on soil fertility and the chemical composition of the agricultural lands in the region of interest was monitored in the winter and summer of 2018. This monitoring also examined the effects of development by assessing oasis quality based on the quantity of drainage water. Salinity levels in the water showed a significant seasonal variation, which is obviously due to climatic variations in addition to the irrigation scheme implementation and the quality of the water used. The distribution of salinity in the winter showed two separate groups. The first group showed increasing salinity despite the amount of water drained from the plot. This group demonstrates that the land is becoming highly salinized, and that the frequency of gypsum crusts in the soil is independent of the proportion of the irrigation water that was leached and drained. These are signs of deep degradation of the oases. The second group shows a clearly visible correlation between the salinity content and the quantity of water; a proportional change was also discerned for the summer measurements. This interdependence shows the strong enhancing effects of the climatic conditions in the region of interest and human activity on the risk of salinity. While this salinity risk can be explained by high evapotranspiration in summer, it is due to insufficient irrigation water drainage in winter. The two problems are amplified by the poor quality of the water used for irrigation. Governmental institutions must deal with various aspects of water contamination, including land use, biological diversity, the disruption of natural cycles, the need to reduce greenhouse gas emissions, and the production of products and toxic by-products (Miquel 2001).

Despite the spatiotemporal variability of the published data, a general trend for water quality degradation in the region of interest is indicated by various calculated indices, field investigations, and by the cumulative impacts of the irrigation systems and farming practices used in the study area. A steady decrease in land productivity leading to a continuous drop in crop quality is predicted. About 407.3 Mm^3 per year of groundwater are exploited, but there are only 236.7 Mm^3 of available resources, which corresponds to an exploitation rate of > 172%. Consequently, any water management plan for this region must be based on a diagnosis of the factors that affect the environment in the study region, as well as on guidelines for treatment based on environmental responsibility.

Reasonable accommodation of sustainable development

The degradation of groundwater resources in the study area remains a major concern given the sensitive nature of the deep aquifer system, which is closely linked to the vulnerability of rural farmers in the region, as their livelihoods mainly depend on agricultural activities (greenhouses, palm trees, etc.). However, the possibility of developing an accurate and relatively rapid preparation and response system depends on the local specifics of exploitation-conservation factors. More work is needed to assess the most feasible alternative water management schemes for the study area (Wong et al. 1997; Bass et al. 1999; Ishaku et al. 2011; Kuppi 2011). It should be noted that the results of this study fill an important gap in the characterization of a serious environmental problem in Nefzaoua that is strongly linked to water consumption. This study has also generated very precise data for those interested in proposing a concrete remediation project, especially for water degradation. Certain actions could be proposed to improve irrigation water quality and reduce risks to human health. Certain management project, instead of amelioration of the current situation of natural resources, may adversely affect their resilience and sustainability.

Conclusions and recommendations

Groundwater resources in the Nefzaoua region show a chemical facies that is dominated by chloride, sulfates, and sodium, suggesting that irrigating the land with these resources leads to a high risk of salinization. A review of relevant published works indicated that there has been a progressive degradation of water quality in the study area, such that water resources are now of doubtful quality or are locally unsuitable for agricultural purposes. The continuous use of these waters along with inappropriate farm practices can explain the progressive degradation of land productivity and soil fertility in the Nefzaoua region. A field survey indicated that natural resource exploitation in this region is not sufficiently controlled, as illegal oases were found to be much larger in number and extent than legal oases. The exploitation of water resources was found to have been underestimated, which—along with the number of private wells—further highlights the degradation of groundwater resource quality. These waters are also unusable for agricultural purposes, as they have harmful effects on soil fertility, vegetation development, agricultural profitability (dates), and on the ecosystem in general (and therefore on human health). The area is suffering from an irreversible loss of natural resources, economic value, and cultural heritage, and the landscape will be lost to desertification and soil infertility unless a scientifically based remediation plan is adopted.

This study highlights the need to utilize interesting methodological approaches to perform detailed analyses rather than to use a large number of them superficially to manage the current situation and/or prevent further water resource degradation due to intense exploitation that jeopardizes the sustainability of local agrosystems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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