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Environmental sensitivity and risk assessment in the Saharan Tunisian oasis agro-systems using the deepest water table source for irrigation: water quality and land management impacts

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Abstract
In dry-hot areas, such as southern Tunisia, the availability of good water is very limited by the low scanty rainfall, the long dry periods and the high evaporation rate. Thus, to deal with these issues, information concerning the quality of irrigation water and the variability of groundwater quality across the oasis system from water well to the final runoff released into the natural environment, is required to evaluate the potential impacts on agricultural soil fertility and to assess the effects of land-use and agricultural practices in environmental conservation and natural resources exploitation. In the current study, 28 water samples have been collected from public wells along the irrigation scheme and drainage canals and have been analyzed. The obtained data prove that groundwater has large spatial variability (EC between 2.93 and 10.05 ms/cm and TDS between 1.95 and 8.15 g/L) caused by different influencing factors such as aquifer water quality, overexploitation, distribution system and evaporation processes. According to the used ionic ratios (SAR, KR, PI, MH, TH, SSP, ESP, etc..), the used waters are locally of permissible quality, while the majority fall unsuitable class to be used in irrigation with a maximum SAR of 18 at El Hamma region. The findings indicate that, besides the severe restrictions required for the use of these high mineralized resources, CI water quality shows a slight variability along irrigation scheme, which may provide additive water resources that may be reused in agriculture, the runoff released into the environment and the excess of irrigation water lost to evaporation process. The evaluation of chemical quality of drainage water may provide a scientific basis for the reuse of these waters to more efficient land management aiming to the sustainable development of oasis agriculture and the prevention of land degradation.

Keywords Irrigation water quality · Environmental sensitivity · Salinization · Land management · Tunisian Saharan oasis

Abbreviations

EC Electrical conductivity

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SAR	Sodium adsorption ratio
KR	Kelly's ratio
PI	Permeability index
MH	Magnesium hazard
TH	Total hardness
SSP	Soluble sodium percent
ESP	Exchangeable sodium percentage
CI	Continental intercalaire
CT	Complex terminal
SASS	Système Aquifère du Sahara Septentrional
TDS	Total dissolved solids
WQI	Water quality index
HCA	Hierarchical cluster analysis
CA	Correlation analysis
PCA	Principal component analysis
PDES	Plan Directeur des Eaux du Sud
APIOS	Amelioration des Perimètres Irrigués dans Les Oasis du Sud
CES	Conservation des Eaux et du Sol
IWQI	Irrigation water quality index
CWQI	Canadian water quality index
OWQI	Oregon water quality index

1 Introduction

The groundwater is of significance importance in most areas of the world (Ahamed et al., 2013; Shahid et al., 2006) as about one-third of the world's population depends on groundwater resources for different purposes with or without treatment (Nickson et al. 2005). This major environmental parameter, which was formerly of good quality, is currently threatened by various sources (punctual or diffuse) of quality degradation (Besser & Hamed, 2019; Besser et al., 2018; Hamed, 2015; Hamed et al., 2018; Mokadem et al., 2016).

Groundwater quality is of international concern regarding its environmental and socio-economic repercussions (Apello and Postma 1994). This quality constitutes, consequently, a limited factor for the sustainable development and reveals a huge challenge to water management strategies (Bahaj et al., 2013; El Khoumsi et al., 2014; Giridharan et al., 2007; Raju, 2007). It is of determining effect on the utilization of groundwater for agricultural purposes In fact, irrigation is by far the biggest consumptive sector of water resources, especially in semiarid and arid regions where the rapid expansion of irrigated agriculture is closely related to the availability of groundwater resources at sufficient quantity and suitable quality (El Khoumsi et al., 2014; Sarathbabu and Jihn 2015; Besser et al., 2017, 2018, 2019).

Water development allocation to different consumption sectors without appropriate management and well-defined quality is detrimental to the environment and endangers the eco-sustainability. Hence, irrigation water quality assessment is a critical element in the maintenance of sustainable irrigated agriculture (Ben Brahim et al., 2012; Haj-Amor et al. 2017; Dhaouadi et al., 2020; Besser & Hamed, 2021). Thus, it is advisable to monitor groundwater chemistry, to follow the evolution of its quality in response to natural factors, and anthropogenic interventions to evaluate the suitability of these resources for agriculture (El Khoumsi et al., 2014; Raju, 2007). Consequently, a number of criteria and indices have been used for the classification of water quality for particular purposes, which should be carried out prior to any agriculture project implementation as a baseline study (Rao et al., 1982; Shahid et al., 2006; Mohammed, 2011;Bahaj et al., 2013; El Khoumsi et al., 2014; Dluzewski et al. 2017; Giridharan et al., 2007; Raju, 2007).

In the study area of Tozeur region (southwestern of Tunisia), groundwater constitutes the main source to supply the increasing demands of the expansion tourism and of agricultural activities. These competitive sectors and this development of water-dependent economy lead to overexploitation of groundwater resources in the area. Apart from the decline of quantity, groundwater quality deterioration is also a major concern (Besser & Hamed, 2019, 2021; Besser et al., 2017, 2018, 2019; Hamed, 2015; Hamed et al., 2014). In spite of the socioeconomic repercussions and the environmental challenges that represent these vital resources in Tozeur area, the management of groundwater resources is still insufficient and the monitoring of the suitability of these resources to particular uses is not the objective of any specific program. In fact, successions of land actions and water conservation programs in the study area and in southwestern Tunisia in general have been used for years since 1980s, besides a number of rehabilitation programs included in the development measures for the whole country systematically reviewed. The most important strategies largely discussed by previous published works in terms of efficiency, social accessibility and economic acceptability are the general plan of water in southern Tunisia (PDES), the actions of amelioration of irrigated perimeters in Tunisian oases agro-systems (APIOS), the programs of conservation of water and soil resources (CES), and the measures taken to inhibit damages related to extreme events (Gharbi, 2009). Although the variety of alternative water resources have been sought and numerous soil conservation plans have been adopted previously in the region of interest (local irrigation techniques, reuse of waste water, Mkayel system, installing of drainage system, applying of more irrigation water, etc.), the feasible alternatives available for local farmers for mitigation water scarcity and land degradation, in both terms quantity and quality, are exhausting croplands, lowering crop yields and increasing farm production costs.

The evaluation of water degradation as a subset of water management entails two closely related elements, which are the maintenance and the development of adequate quantities of water at adequate quantity (Apello and Postma 1994; Larsen & Ipsen, 1997; Sarathbabu and John 2015). Thus, this hydrochemical study aims to determine the groundwater quality and to map their spatial variation in terms of the degree of suitability for irrigation purposes and the response of the continental Intercalaire (CI) aquifer to natural (climate) factors and anthropogenic (overexploitation) stimulations. It attempts to determine the mineral origin of different parameters and to evaluate the influence of the various factors and mechanisms controlling groundwater chemistry in the area on their degree of purity and suitability for irrigation purposes using hydrochemical, hydrogeological and statistical approaches.

2 Site description

The study was conducted in Tozeur area (SW Tunisia), between the longitudes 33°47′37'' and 34°00′27'' and the latitudes 8°17′30″ and 7°31′43″. The area is known for the production of high-quality dates and the tourism activities in the Sahara desert. The climate is arid to desert with annual precipitations of 58.8 mm in 2018 (CRDA 2018) and a temperature that exceeds the 48 °C in June, July and August (CRDA 2019). The desert climate and the lack of surface water increase the exploitation of groundwater resources to meet the increasing supply of different competitive sectors of water consumption (Fig. 1).

The hydrogeological basin of the area is filled by a complex secondary to quaternary deposits with two major hiatuses containing three principal aquifers made up of several aquifer horizons separated by semipermeable sediments (Edmunds et al., 2003; OSS 2003; Hamed, 2015; Besser et al., 2017, 2019): the shallow aquifer logged in the plio-quaternary clayey and sandy deposits, the complex terminal aquifer (CT) hosted in the heterogeneous sequence from the Upper Cretaceous to the Miocene and represented by three main productive levels and the continental Intercalaire (CI) and the deepest aquifer made up of the mega sequence of the Lower Cretaceous continental formations (OSS 2003). In southern Tunisia, the increasing scarcity of good water quality coupled with aquifer overexploitation leads to a number of environmental impacts during the last two decades. The growing population is strain, continuously, on the water sector. Increasing water demands coupled with expansion of high-aquifer-dependent irrigated agriculture have induced an overdraft of SASS aquifers depending upon accessibility, resulting in the decrease in piezometric level, drying up of springs, increasing of water salinity, groundwater quality degradation taking into account the likely consequences of on soil fertility and agricultural production which is of great social and economic value in the study area (Kamel 2013; El Khoumsi et al., 2014; Sarathbabu and Jihn 2015; Besser et al., 2017, 2018, 2019).

The region is devoted principally to agricultural activities, namely date palm cultivation. It is characterized by the expansion of oasis agro-systems in net contrast to the desert outfit of chotts salt depressions and Great Erg sand dunes. The soil potential, in the study area, is very limited under the effect of bioclimatic conditions, the influence of Chotts and the extension of gypsum. The common irrigation system applied in the region is the surface irrigation one, knowing that during this last decade some farmers start to introduce the localized irrigation systems to adapt with water scarcity (Dhaouadi et al. 2015).

3 Materials and methods

3.1 Sampling and laboratory work

A total of 28 samples intended for the chemical analyses were collected from six different locations across the agricultural lands of Tozeur oasis region during the winter period of 2018, out of which, 11 were collected from deep wells (private and public), 11 from water cooling systems and irrigation scheme and 6 from the irrigation runoff released into the environment. Geographical coordinates and elevation of each sampling location were recorded using a handheld global position system (Fig. 1). Physical parameters, namely pH, T, and EC, are measured in situ with multiparameter.

The samplings are carried out and conditioned in plastic bottles. The water samples were immediately stored with 4 °C in a refrigerator containing the ice. The concentrations of major and minor elements were measured in Natural Water Treatment Laboratory (The Center for water Researches and Technologies, Borj Essedria Tunisia). These analyses were carried out using the volumetric method for determining the concentrations of HCO_3, Cl, Mg and Ca; UV spectrophotometer for evaluating the contents of trace elements, namely NO_3 and Fe; and flame spectrophotometer used for assessing the presence of K, Na and SO_4.

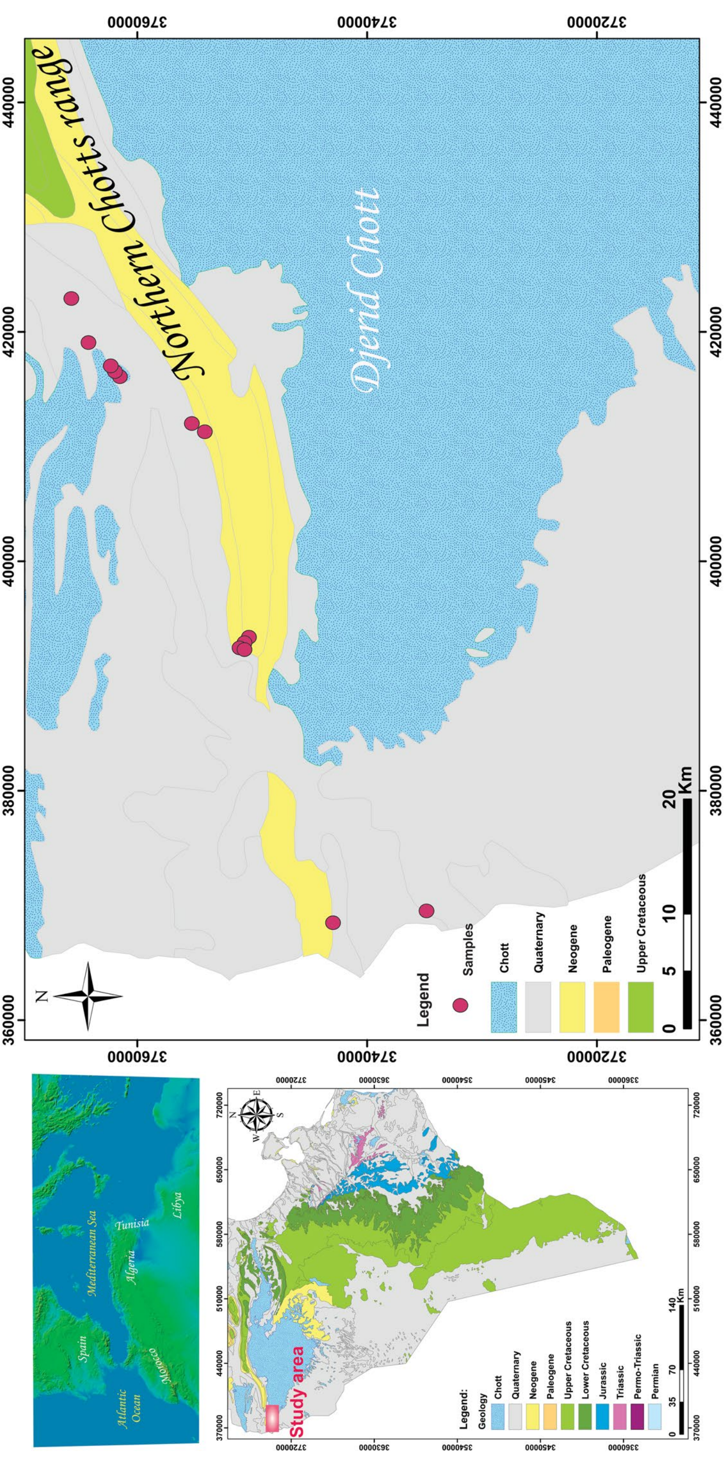


Fig. 1 Sampling map

3.2 Data analysis

Data analysis involves processes of characterization, examination and interpretation for a detailed resolution of causal relationships between the obtained data and the investigated variables and the research problematic. Thus, the evaluation of the integrity of the used qualitative and quantitative data (biological, chemical and physical parameters, standards and thresholds) follows different steps in the current study. The treatment of the physico-chemical parameters of the sampled waters was carried out using diagram, AquaChem and PHREEQ C software. Then, the sampled waters are classified on the basis of a number of quality parameters considering for judging water suitability for irrigation purposes, using the most common ionic ratios and indices to delineate the areas prone to increasing risks of salinization and alkalization (Table 1). Besides individual classification, the quality of the sampled waters is evaluated using the water quality index (WQI), which is a mathematical relation that transforms several physicochemical parameters of water into a single number categorizing the water according to its degree of purity and suitability for agricultural purposes (Table 2). The WQI, a rating that reflects the composite influence of different parameters, facilitates the common of the global state of the water in the given area (Gold et al. 2003; Guettaf et al. 2014).

The obtained results from different aforementioned hydrochemical analysis are treated using multivariate statistical analysis, the principal components analysis (PCA), the hierarchical cluster analysis (HCA) and correlation analysis (CA) widely applied in environmental studies as they provide a thorough examination of various factors governing the evolution of the investigated system, namely natural and anthropogenic processes, by reducing and summarizing a large data set in a restricted number of variables explaining the variance observed in the original data set without overlooked suppressed variables (Farnham et al. 2003; Anazawa and Ohmori 2005). These classical statistical analyses were performed using XLSTAT software.

4 Results

The measured physicochemical parameters of the analyzed waters are given in Table 3. The analytical precision of the total ions was checked by calculating the ion error balance, and it was within 0.09 and 7.6.

4.1 Physicochemical characterization of groundwater samples

For the different samples, the measured pH values range between 6.5 and 7.8, while the measured EC values vary between 2.93 and 10.05mS.cm^{-1}. The salinity varies correspondingly between 1.9 and 8.15 with a mean of 3.33 g/L (Table 3). Waters with high salinity levels are attributed to El Hamma CI_1 well, while the low mineralized waters are those of Mazaraa region.

The cation chemistry in all stations of Tozeur region is Na > Ca > Mg > K, while the anions are mainly dominated by the sulfate (Table 3). According to the Piper diagram, waters of the groundwater of the zone of study are rich in Ca, Na and SO_4 with a spatial variability. The waters are confined in permanent hardness category to saline waters class (Fig. 2).

Table 1 Summary of the mathematical expressions used to calculate different ratios and potential risks

Criteria		Expression	Classification	Risks	References	Max. acc. level
EC		Measured EC values (µs/cm)	USSL (1954)	Reduction of soil permeability; Increase of osmotic potential; Inhibition of plants to take nutriments Physiological drought	Thorne and Peterson (1954); Ayers and Westcot (1985); Michael (1992); Subramani et al. (2005); Bauder et al. (2007)	750
Sodium hazard	% Na	$\%Na = (Na^{+}*100)/(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})$	Richards (1954); Wilcox (1955)	Particles dispersion; Instability of aggregates; Deterioration of soil structure; Sealing of soil pores; Reduction of water infiltration and aeration; Toxic conditions	Todd (1980); Tiwari and Manzoor (1988); Oster (2001); Gupta (2005); Dhirendra et al. (2009); Nahid et al. (2009); Ishaku et al. (2011); Ogunfowokan et al. (2013)	60
	SAR	$SAR = Na^{+}/ [(Ca^{2+} + Mg^{2+})^{1/2}/2]$	Richards (1954); Wilcox (1955)			10
	ESP	$ESP = (Na^{+} / CEC) * 100$; CEC refers to cation exchange capacity $ESP = 100 * [(b (SAR) - a] / 1 + [b (SAR) - a]$; $a = 0.0126$; $b = 0.01475$	Richards (1954); Wilcox (1955)			6
	SSP	$SSP = 100 * Na/(Ca + Mg + Na + K)$	Richards (1954); Wilcox (1955)			60
	KR	$KR = Na^{+} / (Ca^{2+} + Mg^{2+})$	Kelly (1951)			1
RSC		$RSC = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+})$	Eaton (1950); Gupta and Gupta (1987)	Destruction of soil structure; Affecting plant growth	Ayers and Westcot (1985); Aghazadeh and Mogaddam (2010); Wadie and Abduljalil (2010)	2.5
RSBC		$RSBC = HCO_3^{-} — Ca^{2+}$	Eaton (1950); Gupta and Gupta (1987)			
MH		$MH = 100 * Mg^{2+} / (Ca^{2+} + Mg^{2+})$	Szabolcs and Darab (1964); Paliwal (1972)	Increasing soil alkalinity; Decreasing soil productivity	Nagaraju et al. (2014); Dhirendra et al. (2009); Ramesh & Elango (2012)	500
PI		$PI = 100 * (Na + + (HCO_3^{-})^{1/2} / (Ca^{2+} + Mg^{2+} + Na^{+})$	Doneen (1964)	Reduction of soil permeability for a long-term utilization	Nagaraju et al. (2014); Vasanthavigar et al. (2010)	75
TH		$TH (ppm) = 2.497\ Ca^{2+} + 4.115\ Mg^{2+}$	Todd (1980); Hem (1989)	Reduction of soil fertility; Clogging of water distribution networks	Hosseinifard and Aminiyan (2015)	50

Table 1 (continued)

Criteria	Expression	Classification	Risks	References	Max. acc. level
PS	$PS = Cl^{-} + (SO_4^{2-} / 2)$	Doneen (1964)	Reduction of soil fertility; Affecting plant growth	Mass (1990)	35
CR	$CR = ((Cl/35.5 + 2*SO_4))/(2(CO_3 + HCO_3/100))$	Handa (1964); Karanth (1987)	Reduction of soil productivity; Clogging of water distribution networks	Karanth (1987) Srivastava et al. (2012)	2

Table 2 Summary of the mathematical expressions of the used indexes

Calculated index	Formula	Parameters	References
IWQI	$IWQI = \sum Q_i * W_i$; $Q_{i =} Qi_{max} - [(X_{ij} - X_{inf}) * Q_{i\,amp} / X_{amp}]$	Q_i = non-dimensional number depending 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 upper most border (limit) as the maximum value obtained the highest value determined) in the physical and chemical analysis of water sample; Wi = weight of the ith parameter	Ayers and Westcot (1999); Meireles et al. (2010)
CWQI	$CWQI = 100 - ((F_1^2 + F_2^2 + F_3^2)^{1/2} / 1.732)$ $F_1 = 100$ * Number of failed variables / Total number of variables; $F_2 = 100$ * Number of failed tests / Total number of tests; $F_3 = nse / (0.01\, nse + 0.01)$; $Nse = \sum_{i-1}^{n} \frac{excurions}{number\ of\ tests}$ Excursion $_i$ = (Failed test value $_i$ / Objective $_j$) – 1; if the variable is greater than the objective; Excursion $_i$ = (Objective $_j$ / Failed test value $_i$) – 1; if the test value falls below the guideline	$F_{1=}$ Scope; F_2 = Frequency; F_3 = Amplitude; Nse = normalized sum of excursions;	CCME (2001); Ayers and Westcot (1999)
OWQI	$OWQI = \sqrt{N} / (\sum_{i=1}^{n} \frac{1}{Si} 2)$; $S_i = W_i * Q_i$	S_i = sub-index calculated; N = number of variables	Cude (2001); Dunnette (1979)

Table 3 Descriptive variables of the geochemical variables

Variables	Minimum	Maximum	Mean	SD
pH	6.560	7.800	7.071	0.404
T (°C)	22.200	76.000	48.936	17.604
EC (mS/cm)	2.930	10.050	4.490	2.110
RS (g/L)	1.950	8.150	3.337	1.743
Ca (meq/L)	14.080	32.800	18.039	5.063
HCO_3 (meq/L)	2.360	3.300	2.756	0.208
Mg (meq/L)	2.920	13.600	5.469	2.964
Cl (meq/L)	9.000	84.000	19.614	22.527
Na (meq/L)	9.320	84.750	25.556	19.303
SO_4 (meq/L)	16.847	35.820	26.347	5.167
NO_3 (meq/L)	0.000	0.001	0.000	0.000
K (meq/L)	1.403	2.755	1.739	0.351
Fe (meq/L)	0.006	0.023	0.008	0.003

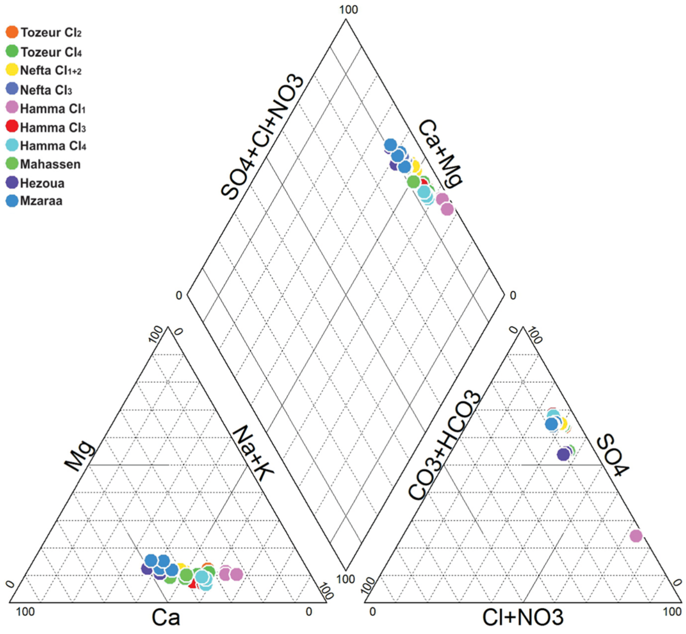


Fig. 2 Piper diagram

The distribution according to the Stuyfzand classification indicates that the samples are brackish and dominated by $NaSO_4$ and $CaSO_4$ water types. Groundwater is impaired to evaporation weathering processes as illustrated by the Gibbs chart (Fig. 3).

These results are consistent with the outputs of the statistical methods. In fact, the Pearson matrix (Table 4) illustrates good relationships between the major elements and the TDS values and the EC on the one hand and between the major elements on the other hand. The dissolution and the leaching of the hosted formations seem to be the major factors

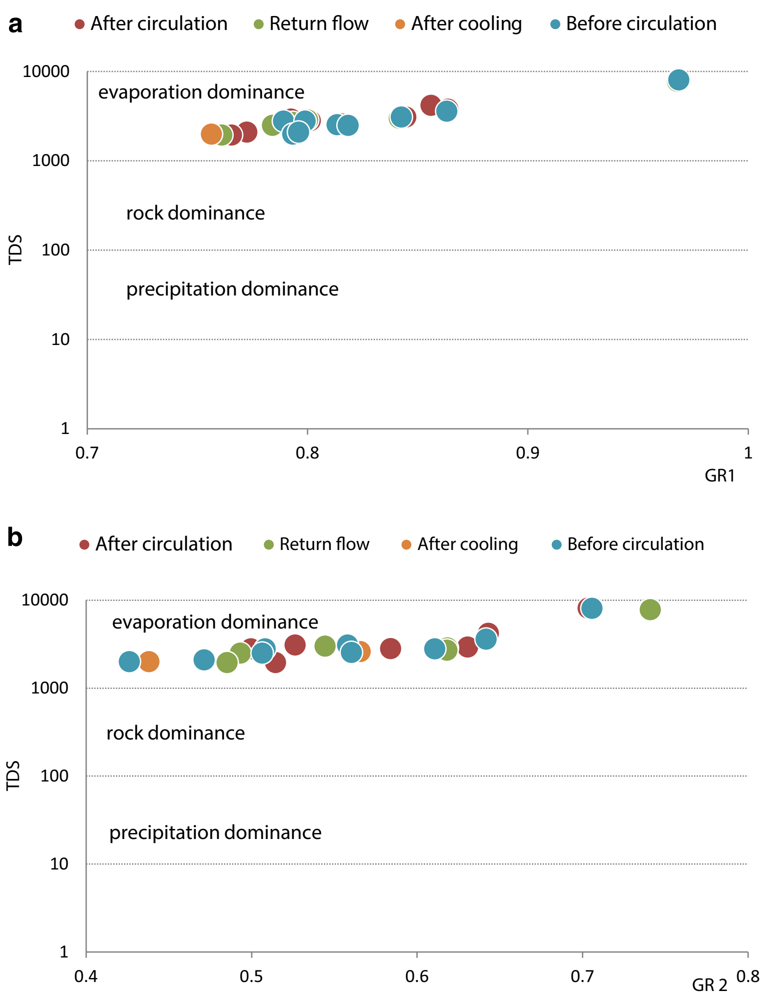


Fig. 3 Gibbs chart

controlling the groundwater mineralization in the study area. The sulfate, however, did not demonstrate any good correlation with major elements. Besides the major elements, the analyses of the water samples in Tozeur region have nitrate concentration ranging between 9.22 0.10^{-4} and 0.03 mg/L. The absence of a good correlation between sulfate and major elements and NO_3-SO_4 and NO_3-Cl, NO_3-Na, NO_3-Ca and NO_3-Mg show a medium relationship indicate an intrusion of salt waters and/or indicate anthropogenic pollution of the wells (Fig. 4).

The three first factors resulting from the application of PCA on the physicochemical parameters of the studied samples account more than 78% of total variability (Fig. 5). The first factor F1 illustrates a good relationship with EC, Cl, Mg, TDS, Na and Ca, moderate loading with SO_4, K and NO_3 and negative loading with T, HCO_3, pH and Fe, which have a strong relationship with the second factor that accounts about 17% of the total variability. Three different groups are observed from the distribution of the

Table 4 Correlation matrix of the geochemical variables

Variables		pH	T °C	EC (mS/cm)	RS (g/L)	Concentrations (meq/L)								
						Ca	HCO3	Mg	Cl	Na	SO_4	NO_3	K	Fe
pH		1												
T ° C		−0.636	1											
EC (mS/cm)		−0.167	0.069	1										
RS(g/l)		−0.074	−0.064	0.965	1									
Concentrations (meq/L)	Ca	−0.050	−0.081	0.926	0.937	1								
	HCO_3	−0.200	0.182	−0.054	−0.148	−0.101	1							
	Mg	−0.110	−0.057	0.927	0.942	0.940	−0.132	1						
	Cl	−0.126	−0.040	0.951	0.968	0.952	−0.035	0.949	1					
	Na	−0.116	−0.065	0.954	0.987	0.920	−0.137	0.924	0.968	1				
	SO_4	0.087	−0.026	0.308	0.349	0.201	−0.499	0.257	0.133	0.317	1			
	NO_3	−0.030	−0.292	0.443	0.529	0.444	−0.208	0.473	0.437	0.501	0.429	1		
	K	−0.146	0.096	0.475	0.446	0.498	0.233	0.474	0.547	0.451	−0.315	0.270	1	
	Fe	−0.279	0.403	−0.124	−0.122	−0.118	−0.046	−0.120	−0.165	−0.154	0.037	−0.110	0.013	1

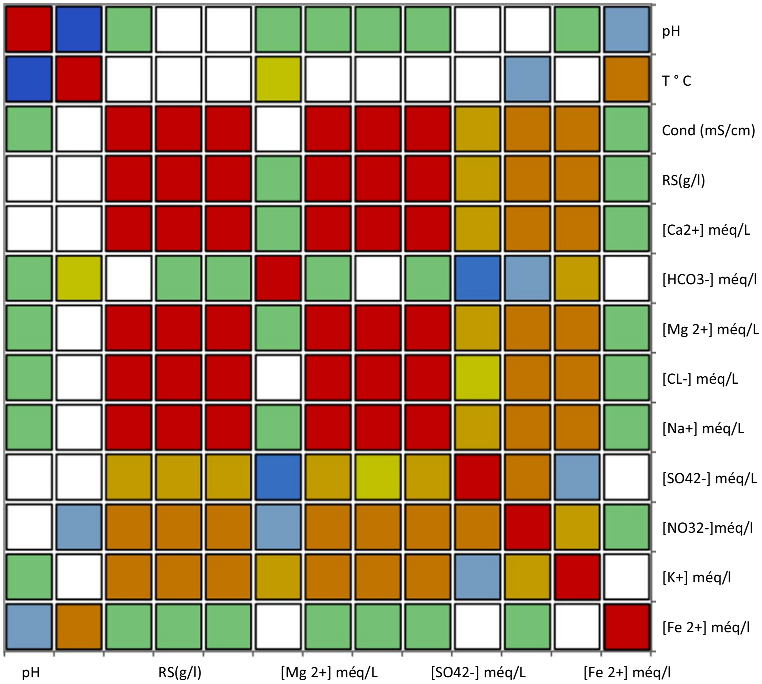
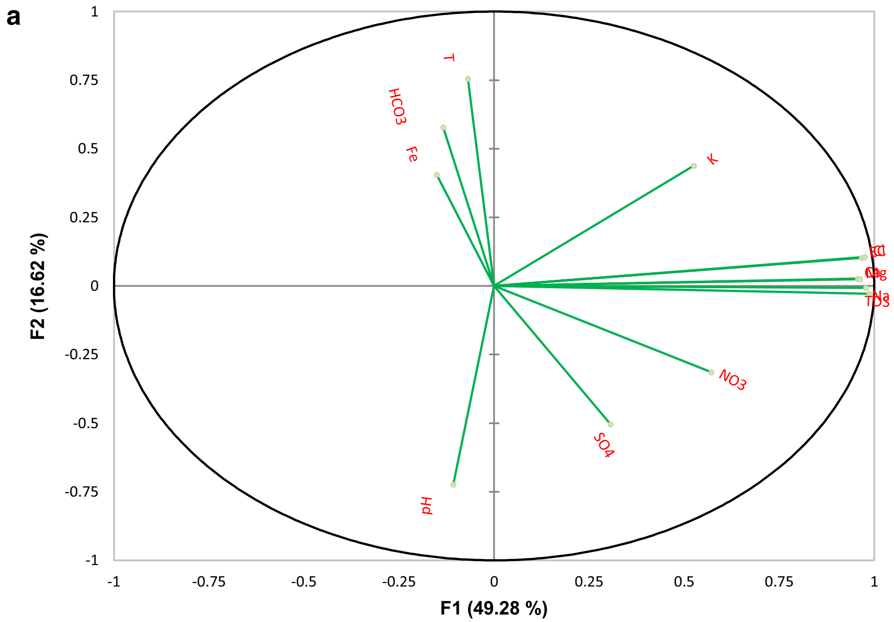


Fig. 4 Correlation chart

variables in the factorial plan: the first seems to be related to the mineralization processes (ion exchange, dissolution, weathering, etc.). The second, with a good correlation with temperature, HCO_3 and opposite variation with pH, may be attributed to the dissolution of carbonates minerals, while the third group clusters K, SO_4, NO_3 and may reflect the inputs of anthropogenic processes (return of irrigation water, fertilizer contamination, etc.). The distribution of the analyzed samples according to F_1 and F_2 illustrates four different groups. The waters of El Hamma CI_1 well form a separated group referring to high mineralized waters with strong positive loading for F_1. The second group shows a good correlation with the second factor and contains the samples with high measured temperatures. The third group illustrates the dominance of sulfate, while the fourth clusters the low mineralized waters of Mzaraa, Mahacen and Hazoua regions (Fig. 5).

The application of HCA on the basis of the geochemical data of the analyzed samples indicates that the mineralization of CI groundwaters in the study area is governed by two different processes that differ from natural weathering and carbonate dissolution and anthropogenic origin related to water-back flow from irrigation (Fig. 6). The dissolution of the hosted formations is enhanced by the elevated temperature (thermal waters of the CI aquifer) that forms the third class.

The distribution of the observations in the factorial plan illustrates four different clusters in consistence with the results of the PCA. The first cluster refers the influence of high temperature in the dissolution of the hosted formations and groups the samples that illustrate the highest temperature levels. The second and the third groups reveal



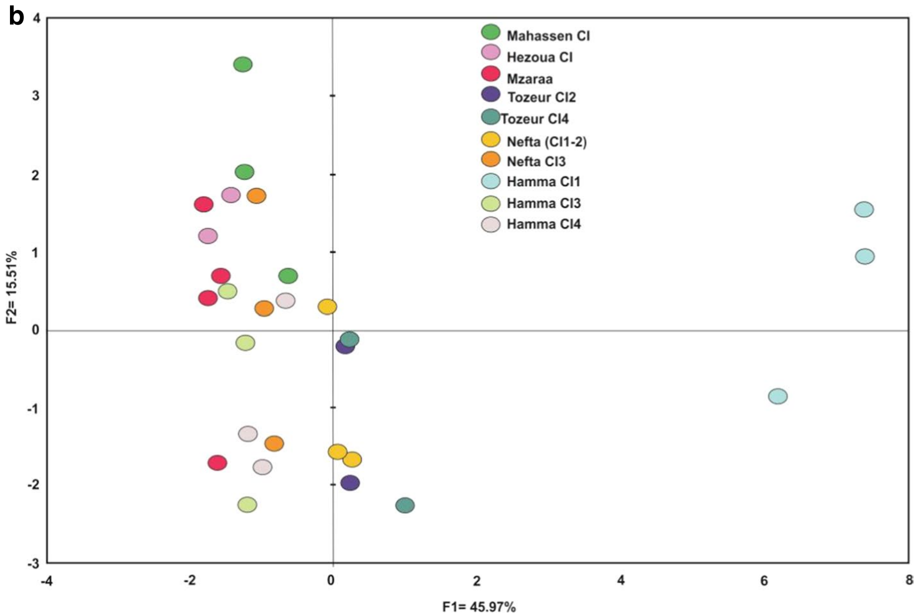


Fig. 5 **a** Distribution of physicochemical variables; **b** distribution of observations

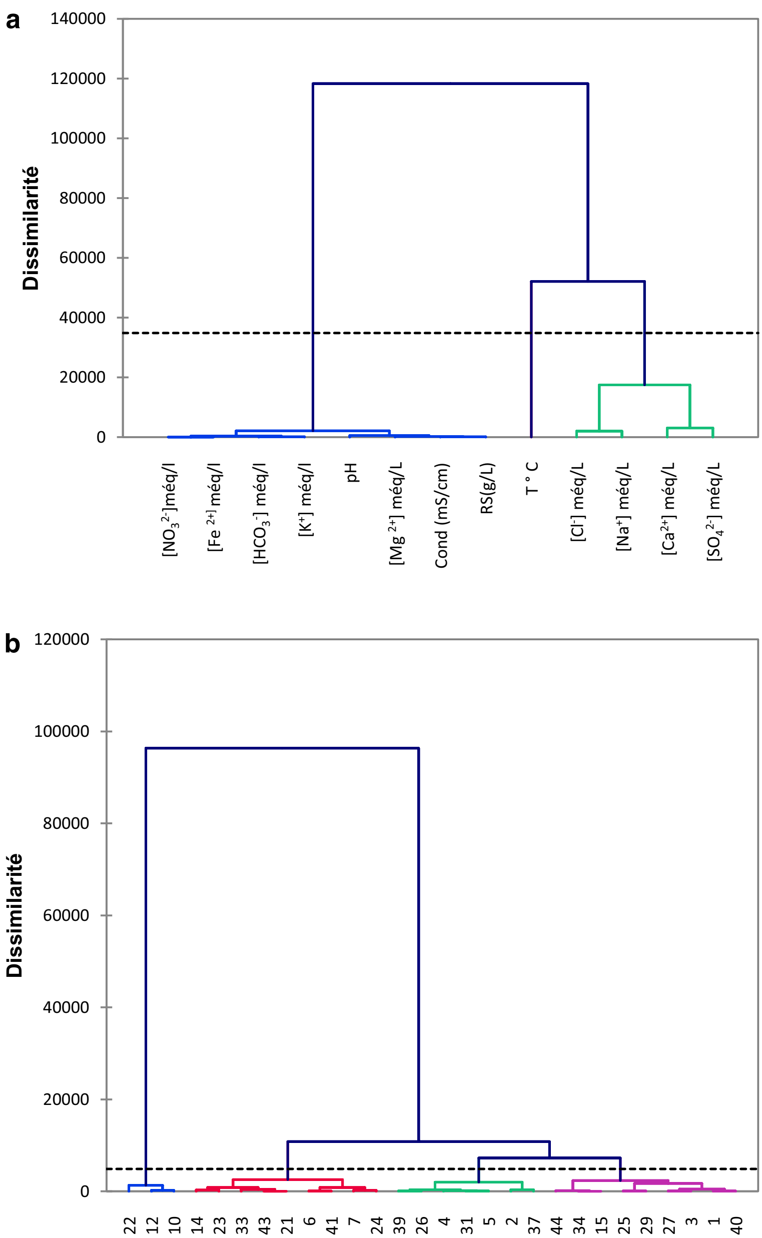


Fig. 6 **a** Dendrogram of physicochemical variables; **b** dendrogram of observations

the contribution of the dissolution processes in groundwater mineralization. The fourth group, however, clusters the contaminated waters by the water-back flow and the excess of irrigation (Fig. 6).

Table 5 Descriptive variables of the ionic ratios

Variable	Minimum	Maximum	Mean	SD
% Na	31.472	64.544	46.941	8.971
SAR	3.053	18.069	7.081	3.705
ESP	3.141	20.250	8.206	4.262
SSP	31.472	64.544	46.941	8.971
RSC	– 42.900	– 14.560	– 20.751	7.942
RSBC	– 30.100	– 11.180	– 15.282	5.089
MH	16.044	30.636	22.292	4.269
PI	39.368	67.111	52.709	7.832
TH	952.58	2561.15	1266.36	462.15
PS	19.624	97.668	32.788	23.014
KR	0.500	1.926	1.011	0.365
RS (g/L)	1.950	8.150	3.337	1.743
CR	20.196	107.269	40.315	24.351

4.2 Evaluation of CI water quality for irrigation

Different indices may be used to evaluate the suitability of the used water for irrigation, among them the ionic ratios are calculated indices based on the physicochemical parameters of the analyzed waters. The statistic descriptions of the calculated ionic ratios on the basis of the measured proprieties of the sampled waters are synthesized in Table 5; the used indices do not show great standard deviation, which indicates that the CI water quality is governed, generally, by the same processes in the Tozeur region.

The evaluation of the salinity hazard of the analyzed waters according to the classification of USSL (1954) indicates that the CI waters are of doubtful to unsuitable quality to be used in irrigation. Only few samples are below the maximum acceptable limit and show a good quality with low salinization risks. The highest risks are attributed to the El Hamma region. The classification of the CI groundwater according to Na-based indices is presented in Fig. 7. The CI samples show different classifications. In fact, the calculated sodium percentage shows that the majority of the sampled waters have doubtful quality that may induce adverse effects for soil fertility and products quality, especially with inappropriate drainage system for long-term use; however, El Hamma CI samples show inappropriate quality to be used for irrigation. The highest quality according to this index is observed in Mzaraa and Hazoua wells. Correspondingly, the spatial distribution of SAR values demonstrates the difference between the sampled waters from Mahacen, Hazoua, Mzaraa and Nefta regions where the water is of good quality and the unsuitable water for particular uses in the other regions especially for El Hamma CI_1 where the SAR reaches 18. The classification of ESP, SSP ratios illustrates similar classifications.

A more detailed analysis, however, with respect to irrigation suitability of the CI groundwater is made by plotting the data on the diagram of Wilcox and Riverside (Fig. 7). Overall, the samples fall in the class of C_1S_3 and C_1S_4, which restrict their suitability for agricultural activities in Tozeur oasis areas. The hydrochemical analyses reveal that sodicity and salinity problems are expanded and the excess of Na, Ca, and Mg makes the water in some locations unsuitable for irrigation. In fact, the average value of the parameters illustrates similar classification on the basis of the calculated corrosivity ratio (CR), Kelly's ratio (KR), magnesium hazard (MH) and total hardness (TH) index (Table 4).

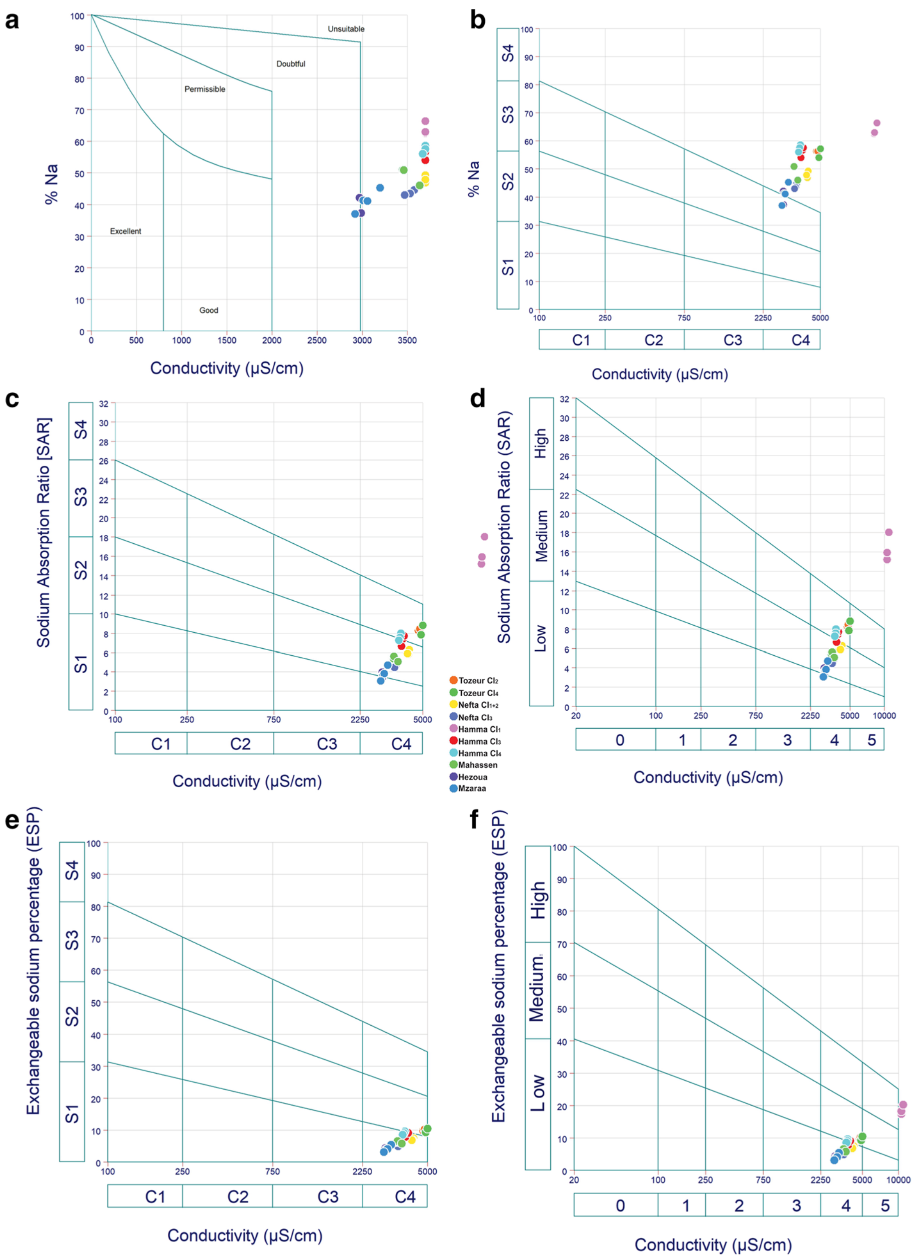


Fig. 7 **a, b** Classification according to %Na; **c d** classification according to SAR values; **e,f.** classification according to ESP values

The reliability of the obtained results and the influence of the calculated ratios are confirmed by the strong correlation between the TDS and the different ionic indices according to the Pearson correlation matrix. The application of PCA on the calculated ionic ratios indicates that the quality of the sampled waters is influenced by two principal factors that

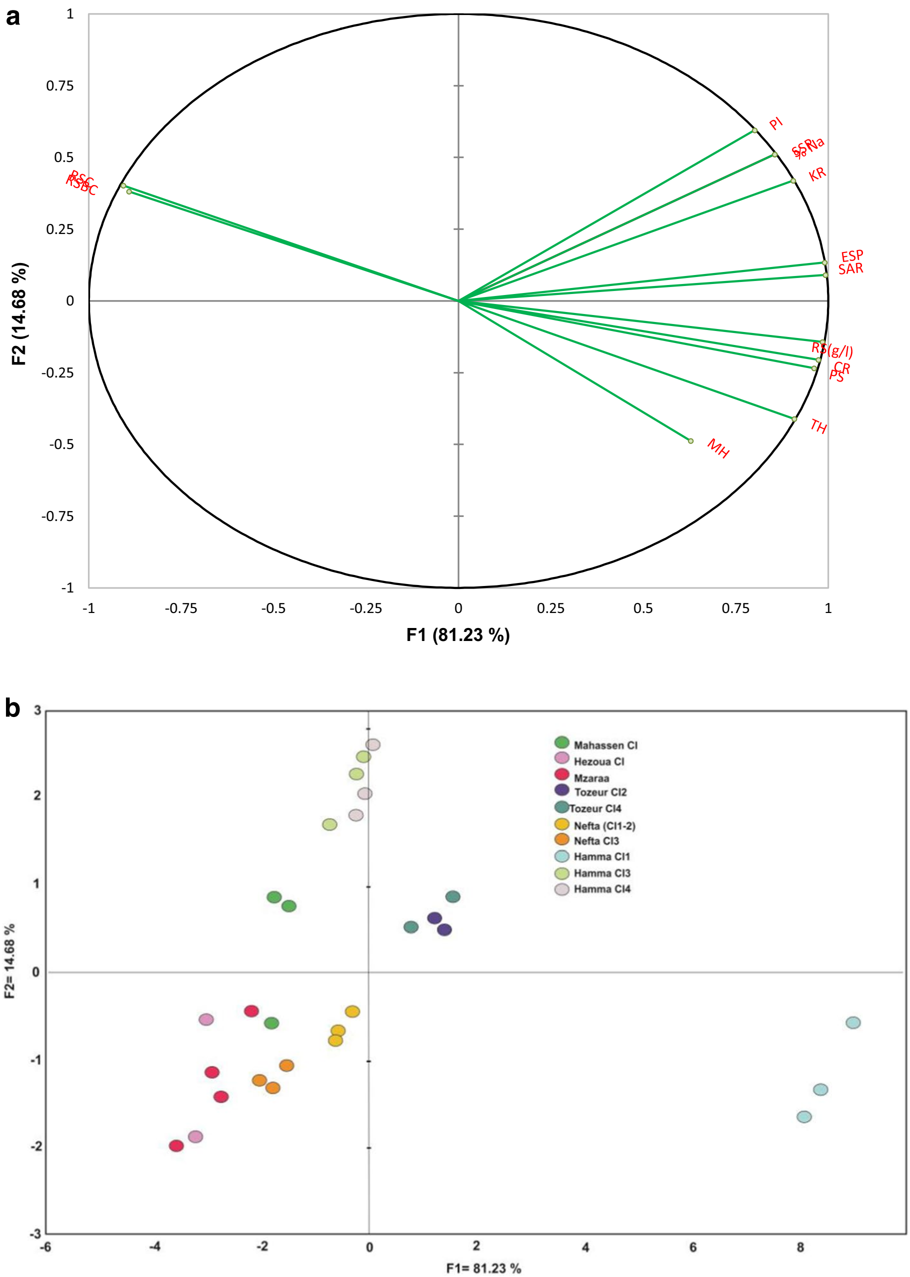


Fig. 8 **a** Distribution of ionic ratios; **b** distribution of observations

account more than 96% of the total variability. The first factor shows a strong loading, positive with the majority of the ionic ratios as well as with the salinity and negative for carbonates and bicarbonates residual ratios. It may refer to the risks of salinization of water and soils. The second factor, however, does not show any significant correlation with salinity, but it exhibits moderate-to-good correlation with % Na, SSP, PI, RSB, RSCB, and it may indicate the influence of the sodic conditions. The distribution of the sampled waters in the factorial plan illustrates four separated groups. The first group is made up of the high

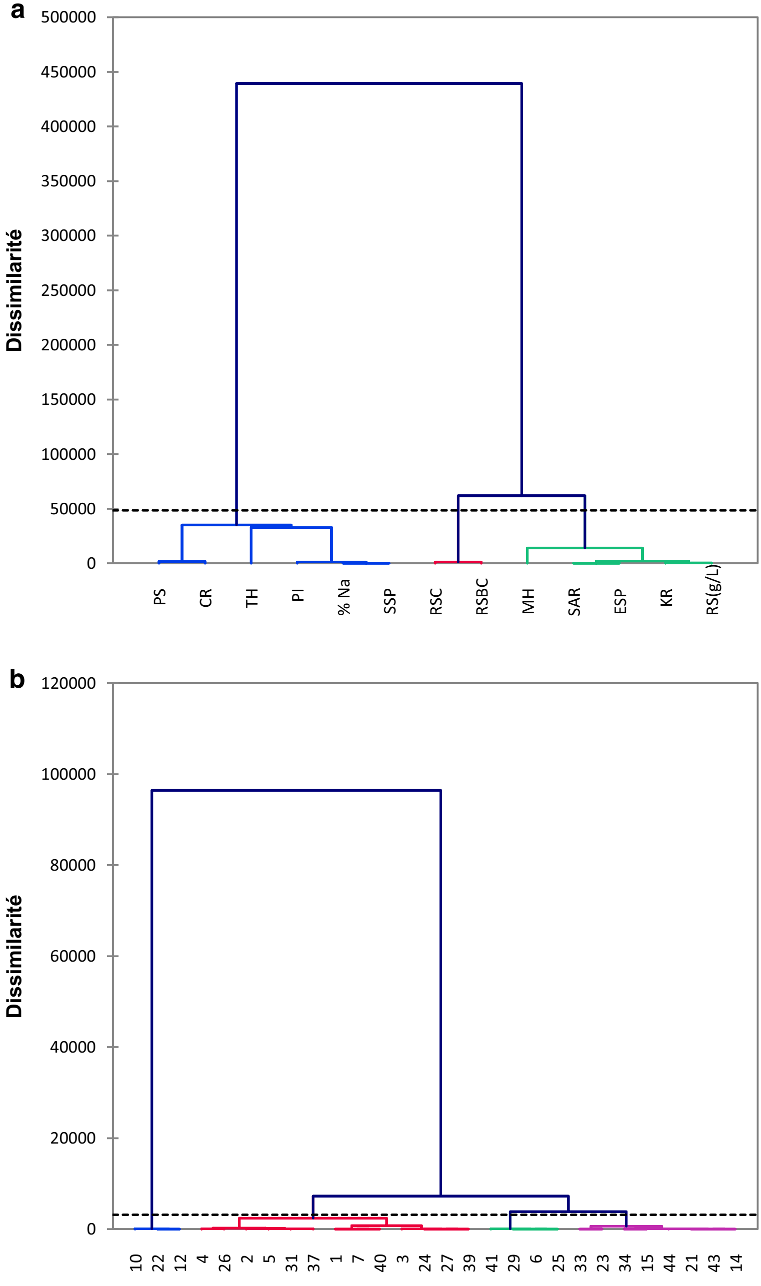


Fig. 9 **a** Dendrogram of ionic ratios; **b** Dendrogram of observations

mineralized El Hamma CI_1 water (Fig. 8). It indicates the highest risks of soil salinization. The second group is formed by Tozeur wells illustrating equivalent influence of the two factors. The third group clusters El Hamma CI_3 and CI_4 and Mahacen wells, which show a strong positive loading with F_2. The fourth group demonstrates a weak correlation with both factors and clusters the highest water qualities of Mzaraa and Hazoua. The application of the HCA on the basis of the calculated ratios illustrates different clusters confirming the

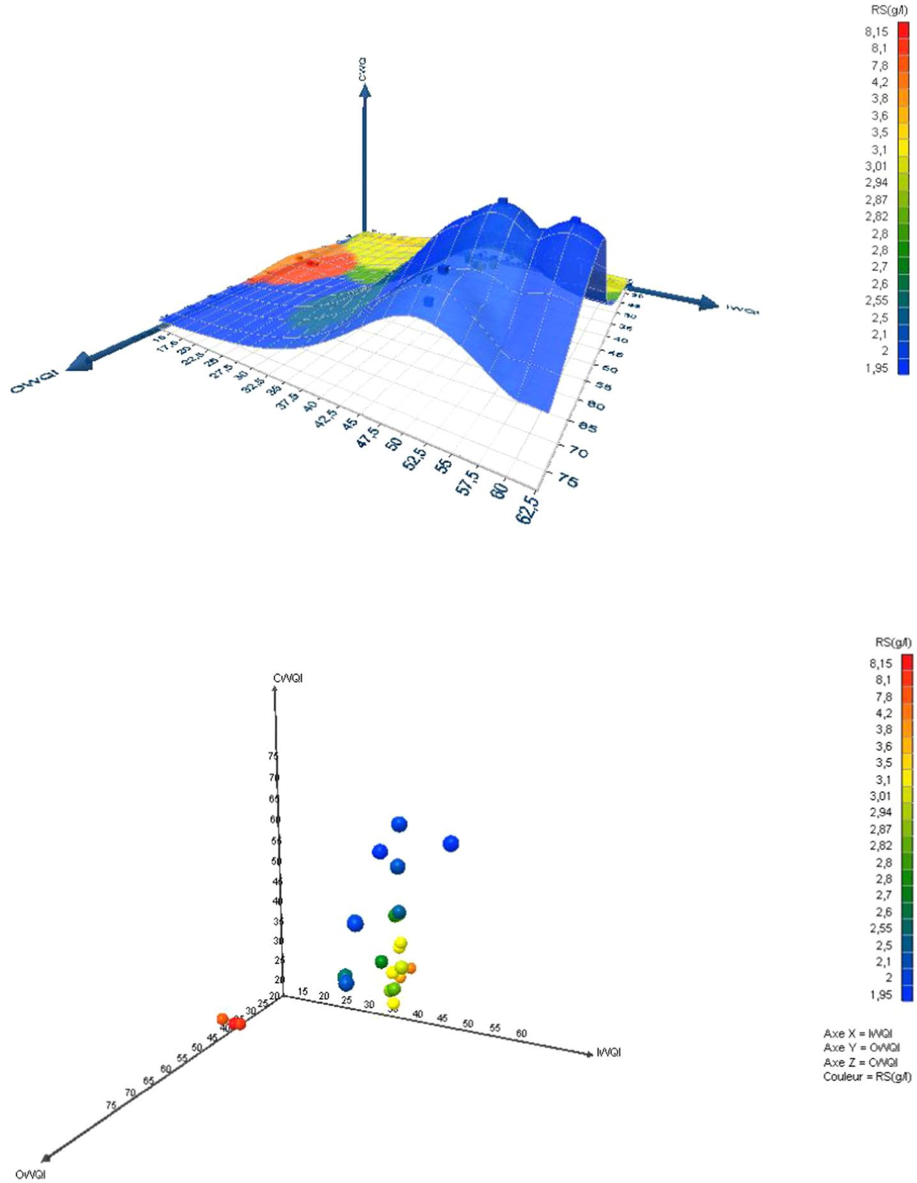


Fig. 10 Distribution of WQI indexes

aforementioned classification, resulting in four different groups of samples that cluster the waters according to the potential impacts on soil fertility and crops quality (Fig. 9).

Besides the ionic ratios, the suitability of the used waters is evaluated according to the most common water quality indexes (Fig. 10). The obtained results are illustrated in Fig. 10. The obtained results IWQI, CWQI and OWQI indicate that all the sampled waters have bad-to-unsuitable quality to be used for irrigation purposes. The distribution of the sampled waters shows that, in consistent with previous results, EL Hamma CI_1 waters exhibit the lowest quality, while Hazoua and Mzaraa waters may be used for irrigation with restricted utilization and appropriate drainage system. The degree of risks and the likely consequences are different according to the measured salinity and the type of salts (Fig. 10).

5 Discussion

5.1 Water chemistry of CI samples

The obtained data indicate that the sampled waters, whether they were collected from water wells, drainage-irrigation scheme or from the released runoff, are characterized by high amount of dissolved salts for which the hydrochemical facies is saline to brackish, especially El Hamma and Tozeur regions, where the salinity values attain the maximum of 8.1 g/L. Despite the common trend, the sampled waters show large spatial variability of the physicochemical parameters. It results on a wide range of the calculated ratios and indices. This variation suggests that the water chemistry in the study area is heterogeneous and regulated by distinguished mechanisms, namely dissolution process, identified by the good correlation between the major elements and between the major elements and the salinity and the evaporation factor by Gibbs chart and by the binary plot Na/Cl *vs.* EC since the area of the interest experiences semiarid and dry climatic conditions (Ben Brahim et al., 2012; Besser & Hamed, 2021; Hamed, 2015; Zammouri et al., 2007) enhancing the evaporation of the distributed water and concentrations of the dissolved salts along the irrigation and drainage schemes (Haj-Amor et al. 2017; Besser et al., 2017, 2018; Dhaouadi et al., 2020; Besser & Hamed, 2021). Moreover, given the low renewable rate of the investigated CI aquifer that embodies water resources recharged mainly during the humid periods of Holocene and Pleistocene (Edmunds 1997, 2003; Guendouz et al., 1997; OSS 2003; Hamed, 2015…), the continuous exploitation of these resources with an increasing coefficient from 57.72 to 99.66% in 2010 and 2016, respectively, corresponds to 9 Mm^3 of exploitation from 17.4 Mm^3 of available resources in 2010 and 17.94 Mm^3 of exploitation from 18 Mm^3 of available resources in 2016 according to the published synthetic reports of CRDA in 2010 and 2016. This uncontrolled abstraction may modify the natural flows of groundwater enhancing lateral and vertical leakage from different water-bearing strata (Swezey 2003; Hamed et al. 2014; Mokadem et al., 2016), and it may induce the mixing from deep water circulation from deeper reservoirs below the SASS system (Besser & Hamed, 2021; Besser et al., 2018, 2019; Hamed, 2015).

Besides major ions, the distribution of the concentrations of the minor elements such as Fe and NO_3 illustrates a spatial variability. The increasing nitrate concentrations illustrate the impact of leaching of soil-mineralized nitrogen, while the elevated iron concentrations are mainly explained by the enhanced dissolution of the formation by the thermal CI waters. The slight variability of the content of trace elements between the different types of samples (well, drainage and runoff) is resulted from the leaching of agricultural lands, and it highlights the influence of farming practices relative to the excessive use of fertilizer (nitrogen, potassium and phosphate excess in drainage and runoff water) and the distribution of high water amount that induces the creation of gypsum crusts at the upper soil layers (Besser et al., 2017; Zammouri et al., 2007). The cumulative content of the dissolved elements along the irrigation drainage schemes attains its maximum in the final basin of runoff collect released directly into the environment.

The dynamic nature of CI water chemical composition retraces the multiple interactions between the different environmental components and reflects the impact of different natural (lithology, groundwater flow movement, residence time, recharge rate, salt solubility, dissolution, ion exchange, mineral weathering, etc..) and anthropogenic (exploitation, pollution, pumping, land-use impacts, etc.) factors. The perpetually changing chemical composition of CI water needs closer attention to predict and to assess the long-term effects of the continuous use of this irrigated quality on soil fertility and soil structure and crop yield, especially for an increasingly freshwater stress region.

5.2 Water quality of CI samples

The sustainable development of the agro-systems is closely related to the used irrigation water quality coupled with the restrictions relative to the adopted irrigation method and the implemented drainage network. Indeed, irrigated agriculture with poor water quality reduces soil productivity and changes soil physicochemical proprieties (Talukdar et al. 1988), which affects the agricultural production. The continuous irrigation of highly mineralized waters may induce increasing risks of soil salinization which, in dry-hot area, constitutes a real threat of the productivity of agricultural lands. The development of gypsum crust in the upper layers of irrigated lands reduces significantly the infiltration and the aeration along the profile, which may induce progressively physiological droughts of the cultivated crops. The high amount of some elements, namely sodium, bicarbonate and magnesium, may bring about alkalization, hardness, impermeability and corrosion issues for agricultural soils and canal distribution (Zied Haj-Amor et al. 2017; Besser et al., 2018, 2019; Mokadem et al. 2018). Thus, the evolution of water chemistry and the evaluation of water quality for irrigation purposes are, consequently, of paramount importance in the environment sustainability development and that provide decisive information of water management if relevant and periodic data are available.

The classification system to assess the quality of water suitability for particular uses can be ascertained as expressed by certain chemical characteristics that may affect the water suitability for irrigation. In the current study, to comprehensively judge the irrigation water quality of CI samples and to quantitatively assess the relationship between water chemical components and soil salt content, both ionic ratios and water quality indexes have been used.

Irrigated agriculture depends on sufficient water supply of usable quality, which has been plentiful in southern Tunisia until the nineties (Edmunds et al. 1997; OSS 2003). Presently, the limited water availability and the multiple water uses have been experiencing ecological problems that elicit widespread public concern about its impacts on crop yield and land productivity of the key economic activity of the region and may impact as well the livelihood of the local population. The physicochemical priorities of the analyzed waters classified the samples mostly as doubtful class to unsuitable category, and very few samples fall in permissible to good class. The results indicate high to very high

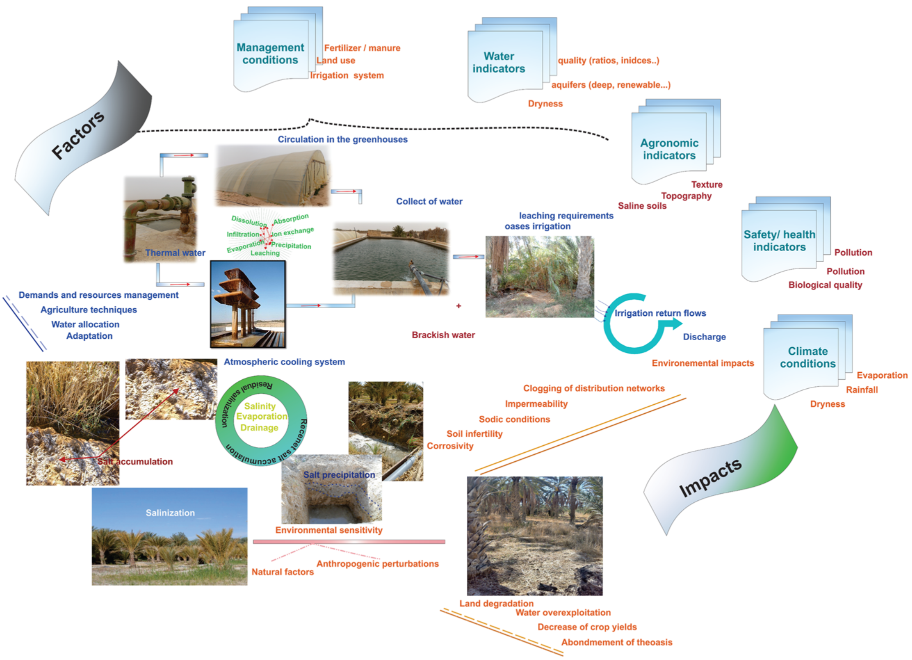


Fig. 11 Environmental impacts of water quality and management factors

saline and alkaline risks, especially with the textural families of the soils in the study area which ranges between silty clay to clay loam having sodic to slightly alkaline reactions. The soils, initially gypsiferous and poorly cemented, are generally insufficiently drained, which creates gypsum crusts in the upper layer of the horizon and induces the water logging problems (Fig. 11).

The distribution of the obtained results may reflect the influence of both natural processes and anthropogenic activities. In fact, the highly mineralized waters are characterized by the elevated temperature. These thermal waters enhance the dissolution of evaporative strata frequently intercalated within the sandy formations of the continental Intercalaire. The general tendency of bad water quality of the CI samples may indicate as well the paleo-recharge of these fossil low renewable waters. The long residence time and the low renewable rates increase water salinity and enrich the solution by soluble elements. The lithology variation and the hydraulic connectivity of different water bearing strata influence in turn water salinity.

The variation of water quality reflects, furthermore, the impact of exploitation of the CI aquifer. In fact, the zones with high risks of soil infertility are characterized by the highest value of piezometric-level decrease. The continuous exploitation exceeding the renewability rate of the resources leads to an overdraft of the groundwater resources.

The variation of the CI chemistry, salinity and salt content along the irrigation system indicates the influence of farm practices; that is why we find that the structure with three floors in the traditional oases of southern Tunisia has been degraded and only the date palm tree remains, which can withstand to 7 g /L of salinity (Zammouri et al., 2007, Haj-Amor et al. 2017) but other arboriculture and forage farming were practiced only by some farmers who have illicit water sources (Karbout et al. 2019).

Saline sols leaching and overall system operators in water quality are used for irrigation. The increase in sodium, calcium and magnesium concentrations along the drainage channels illustrates the impacts of salt leachate from the irrigated lands where the high rate of evapotranspiration contributes to the increase of ionic content, while the decrease of some concentrations in the irrigation return flows demonstrates the influence of mixing and dilution between different water bodies. It indicates as well surface contamination by manure and fertilizers' excessive use as it retraced by the increase of nitrate contamination; to reduce the risk of contamination, with the quality of the irrigation water, the farmers must be careful for the choice of fertilizer. The EC and TDS do not show any variation. It suggests that water quality is not impacted by the amount of salts only but by the type of dissolved salts as well.

The spatial variation of the CI groundwater quality and the evaluation of the potential impacts on irrigated system, on soil fertility and on crop yield make the difference between water resource capacity and environmental requirements defining, consequently, by the utilizable capacity for the CI aquifer Tozeur area, the portion that may be used in irrigation activities. This distribution indicates, furthermore, that in some localities, the water quality has already reached the levels that are hardly compatible with environmental thresholds. With regard to salt loading and increasing sodic and saline conditions, more than half to three-quarters of the basin is classified as saline and reveal high risks of water logging and soil salinization. This salinization may result from both residual soil salinity and new formed salt accumulation. These circumstances require the leaching of a quantity of dissolved salt in the drainage system by the application of a large quantity of water in order to maintain salt balance (Besser & Hamed, 2021; Dhaouadi et al., 2020). The proper leaching requirements (Table 6), which consider the irrigated crop type, irrigation system and adopted management strategies, should be addressed in a flexible way for finding the optimal conditions and the likely rehabilitation measures of the used low-quality water for the coexistence of environmental function balance and irrigated agriculture in the future.

The necessity of intervention of the regional agricultural development commissioners in the oasis region is crucial to correct the irrigation schedule of the farmers and the fraction of leaching for the different oases to reduce the risk of salinization and degradation of soil irrigated by these waters.

5.3 Impacts on irrigation system

The bad water quality used for irrigation may induce continuous impacts on the sustainability and the performance of the irrigation system with increasing calcium, magnesium and bicarbonate contents. Since individual classification is generally infallible, the application of numerous indexes may be of crucial importance. Various indexes may be used to provide indication of scale forming and the corrosive potential of the water.

The calculated Langelier index (LI) of the CI samples ranges from −0.18 to 0.67, the majority of the samples indicate no major problems with corrosion and scaling and according to the Langelier classification (1936) they are classified as slightly scale forming and corrosive based on Carrier (1956) quality distribution. Few samples, referring mainly to El Hamma waters and the irrigation return flows, show increasing problems with scaling of irrigation pipes and emitters and serious corrosion issues according to the aforementioned class. Correspondingly, the obtained distribution on the basis of

Table 6 Correlation matrix of the ionic ratios

Variables	% Na	SAR	ESP	SSP	RSC	RSBC	MH	PI	TH	PS	KR	RS(g/L)	CR
% Na	1												
SAR	0.888	1											
ESP	0.912	0.998	1										
SSP	1.000	0.888	0.912	1									
RSC	−0.568	−0.863	−0.843	−0.568	1								
RSBC	−0.562	−0.850	−0.831	−0.562	0.992	1							
MH	0.324	0.567	0.551	0.324	−0.703	−0.614	1						
PI	0.992	0.845	0.870	0.992	−0.481	−0.475	0.246	1					
TH	0.564	0.863	0.843	0.564	−0.999	−0.985	0.729	0.478	1				
PS	0.691	0.938	0.922	0.691	−0.968	−0.954	0.664	0.626	0.971	1			
KR	0.985	0.940	0.954	0.985	−0.646	−0.636	0.384	0.973	0.645	0.770	1		
RS(g/L)	0.765	0.963	0.954	0.765	−0.952	−0.938	0.660	0.701	0.953	0.987	0.828	1	
CR	0.722	0.947	0.934	0.722	−0.967	−0.952	0.679	0.653	0.967	0.993	0.792	0.990	1

Table 7 Distribution of CAI, LI, RI and AI indices

Samples	CAI 1	CAI 2	LI	RI	AI
6	– 0.79590645	– 0.36014505	0.11	0.067	12.11
25	– 0.84957618	– 0.38890226	0.42	0.2	12.42
41	– 0.70016276	– 0.30724756	0.29	– 0.17	12.29
29	– 0.88252733	– 0.38786247	– 0.09	0.85	11.91
7	– 0.71980869	– 0.30544095	0.06	0.081	12.06
1	– 0.61688865	– 0.26208577	0.18	0.37	12.18
40	– 0.61715155	– 0.25823739	– 0.47	1.2	11.53
24	– 0.89829194	– 0.30576491	0.01	– 0.12	12.01
27	– 0.7710764	– 0.26495715	0.36	0.37	12.36
39	– 0.69218966	– 0.23495684	– 0.35	0.8	11.65
22	0.10957815	0.30603124	0.03	0.071	12.03
12	0.05867962	0.16136895	0.12	0.62	12.12
10	– 0.05696174	– 0.15643243	– 0.58	1.1	11.42
43	– 1.21879302	– 0.41121232	0.30	– 0.35	12.30
44	– 1.02249672	– 0.34541129	0.33	0.42	12.33
14	– 1.29193202	– 0.43616129	– 0.05	0.35	11.95
21	– 1.58032611	– 0.5509141	0.07	0.08	12.07
34	– 1.46534587	– 0.51047729	0.13	0.78	12.13
15	– 1.36694616	– 0.47209405	– 0.63	1.6	11.37
33	– 0.35327542	– 0.20401979	– 0.05	– 0.037	11.95
23	– 0.38262179	– 0.22134.383	– 0.31	0.62	11.69
3	– 0.44706877	– 0.26097165	0.67	– 0.15	12.67
2	– 0.16456806	– 0.09324252	0.13	– 0.021	12.13
4	– 0.24135377	– 0.13416825	0.01	0.37	12.01
31	– 0.4340716	– 0.16505386	0.54	0.068	12.54
26	– 0.79710433	– 0.29744231	– 0.33	0.77	11.67
37	– 0.44765185	– 0.16817645	0.24	– 0.3	12.24
5	– 0.21925123	– 0.07977683	0.10	0.39	12.10

the aggressiveness index indicates that these waters are moderately aggressive, while few samples are classified as aggressive waters with AI> 1. The distribution of Ryznar index shows in turn homogenous classification and indicates, according to Ryznar (1942) and Carrier (1965) quality distribution, that heavy scale may be formed and that the corrosion is intolerable (Table 7).

5.4 Impacts of irrigation runoff

Chronic scarcity of freshwater is experienced in Tozeur area, and the continuous use of low-quality water is expected. Irrigation will become more dependent on poorly characterized and virtually monitored sources of water. This quality is expected to have adverse impacts not only on the upstream parts of the basin (agricultural land and greenhouses) but also in the downstream. Continuous damage of the ecosystem caused by the low quality of irrigation return flow represents also a serious concern. In fact, the distribution of the chemical composition of the sampled waters indicates that the runoff waters are enrich in mineral content and contaminated generally by surface pollutants, land use and farm

Fig. 12 Discharge of irrigation return flows

Table 8 Summary of the characteristics of the different water types

Water type		Phys-icochemical proprieties		Calculated ionic ratios						Water quality index		
		EC	RS	SAR	SSP	MH	PI	PS	KR	IWQI	CWQI	OWQI
Well water	Min	3.01	2	3.45	32.68	16.47	39.63	19.62	0.52	19.36	23.84	21.01
	Max	10.05	8.1	15.22	60.23	30.35	63.07	97.66	1.6	52.98	64.39	72.15
	Mean	4.81	3.36	7.06	47.2	21.9	52.95	32.94	1.01	43.64	41.4	47.63
Drainage water	Min	2.93	1.95	3.98	37.29	16.34	44.97	19.62	0.64	18.25	23.74	20.84
	Max	10.01	8.15	15.95	61.77	28.47	63.91	96.26	1.67	50.62	66.52	72.00
	Mean	4.41	3.44	7.22	47.97	22.39	53.63	32.83	1.03	43.66	41.98	47.77
Runoff water	Min	3	1.95	3.82	36.22	16.04	43.57	20.21	0.61	44.81	34.57	39.67
	Max	4.04	3.01	7.72	54.24	25.03	60.1	28.57	1.29	59.99	68.78	62.72
	Mean	3.4	2.6	5.83	45.7	21.78	51.28	24.01	0.93	49.28	48.83	49.34

manure. The discharge of these uncontrolled flows in terms of both quality and quantity induces undoubtedly huge eco-impacts that increase land degradation and desertification processes (Fig. 12). Improving the environmental quality of irrigation runoff is important for the long-term agricultural sustainability.

The important volume lost to the evaporation by the direct released runoff may constitute, moreover, additive alternative resources of water that may be reused in different sectors. In fact, according to Table 8, the chemical composition of both drainage water and runoff show a slight variation with respect to the primary source of exploitation, the public and private wells. The narrow range of concentrations of major and minor elements guarantee a similar classification of the different sampled types, which raises the potentiality of the reuse of these resources after a preliminary treatment, especially within the context of climate change and the lack of fresh and conventional resources.

5.5 Socioeconomic and environmental impacts

The irrigation performance is evaluated by different social, economic and environmental aspects, namely natural resources exploitation, water quality, irrigation system sustainability, irrigation rates, type of amendments, crop yield and production, in Tozeur area; the environmental impacts of irrigation may be detected by various effects. In fact, the evolution of the agricultural production and the superficies of the irrigated lands demonstrate that more than 600 ha are abandoned in the Tozeur area between 2016 and 2017 (9008 ha in 2016 to 8444 ha in 2017) (CRDA). This abandonment is due to various factors that are principally related to the irrigation water quality and land-use practices that increase soil salinization and water logging problems; the oasis become infertile and the dates palm are no longer rentable. Correspondingly, the variation of the superficies of agricultural lands and thermal projects reflects the progressive endoreisation of these areas.

The continuous exploitation of fertile soils with bad water quality increases alkalization and salinization issues. Thus, periodically, large parts of greenhouses land reveal the increased permeability issues. Thus, they are turned on oasis since the date palm is more adaptable to severe climate and salinity conditions. Taking the example of El Hamma region where the cultivated greenhouses decreased from 8.55 to 6.55 ha in 2016–2017 (CRDA), and correspondingly the areas covered by the oases increased. The expansion of the new agricultural lands is limited by the geomorphologic features of the region (the sandy dunes and the salt depressions), by the climatic conditions (high evaporation and low rainfall) and by the quality irrigation waters (deep low renewable water from SASS aquifers). These new lands will be abandoned as well after 5 to 10 years with regard to current practices and in the absence of treatment of irrigation water quality. These scenarios of this continuous deterioration will impact progressively the lifestyle of the local population and may lead to eco-migration of these farmers since the agriculture is the unique economic activity of the region.

The rehabilitation of contaminated sites in large areas can be ensured through several measures. The following are the common measures: (1) bioremediation (i.e., use of microorganisms to decontaminate surface and subsurface soils, and details are in Zhao and Poh (2008)); (2) land farming (i.e., it involves the application of contaminated material that has been excavated onto the soil surface and periodically tilled to mix and aerate the material, and details are in Harmsen et al. (2007)); and (3) phytoremediation (i.e., it involves plants in soil and groundwater remediation; details and case studies are in Schnoor et al. (1995)).

6 Conclusions

This study highlights the physicochemical quality of CI water in the region of Tozeur on the one hand. On the other hand, this study identified the impacts of irrigation water quality on soil salinization and the potential management plans of the runoff and excess drainage water to optimize the exploitation of low renewable deep water in these arid lands. The assessment of water mineral content is crucial for the estimation of the percentage of different salt, ions, and other pollutants, which may affect soil fertility and crop yield. This study aimed to provide a scientific basis for improving oasis ecosystem, sustainable development of agriculture, maintain healthy production, manage available water resources, and prevent soil land use and land degradation.

This paper drafted with the intention to evaluate the impacts of the cultural practices on water quality. It assesses the efficiency of the used irrigation system to create awareness about the range of environmental challenges and problems that pertain the maintenance of the irrigated agriculture and the ecological aspects of agricultural development. Although the article discusses classical and traditional irrigation water quality concerns (salinization and alkalization), it highlights continuous quality issues and emerging environmental problems. The present work emphasizes the need of further development of water-saving plans based on a critical review of the annual lost water to evaporation from drainage and runoff resources required to evaluate the potential additive resources that may be conserved and reused. The future development scenarios of competing water needs using water management models may be used in accordance with conventional–non-conventional resources counterbalancing the water deficit supporting the hierarchical water demands with regard to the implications of water resources operational management and technical capacity clear to policy makers.

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