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ORIGINAL ARTICLE

Effects of excessive irrigation of date palm on soil salinization, shallow groundwater properties, and water use in a Saharan oasis

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Abstract In arid oases, soil salinity and a rise in shallow groundwater are serious threats to long-term sustainability of irrigated agriculture. Understanding the impacts of irrigation practices on soil salinity and shallow groundwater dynamics is critical for improving soil conditions and water efficiency. In this study, the impacts of excessive irrigation of date palms with low-quality water on soil salinization and shallow groundwater properties (depth and electrical conductivity) were evaluated for a 10-year period (2005–2015) in a Saharan Tunisian oasis. The study included three phases: (1) assessment of the suitability of groundwater for irrigating date palms; (2) quantification of the long-term water use of date palm plantations; and (3) quantification of dynamic patterns of soil electrical conductivity and shallow saline groundwater in the studied oasis for a 10-year period (2005–2015). Results of this study indicated that under high evapotranspiration conditions, the identified low-quality water resources (leading to high soil salinization risk) coupled with rapidly rising shallow groundwater at critical depths (<1.5 m) (resulting from the high water use) were key factors of the rapid increase in soil salinization within the oasis. The soil electrical conductivity built up to levels that exceeded the salt tolerance of date palms, estimated at 4 dS m^{-1}. Although the excessive use of irrigation water dilutes the groundwater, and its salinity decreases, the risk of increasing soil salinity is greater because of rising water table.

Keywords Arid oases · Excessive irrigation · Shallow groundwater · Soil salinization

Introduction

The soil quality degradation is a serious problem in many arid agricultural regions (Li et al. 2016). Soil salinization, assessed as the increase in concentration of dissolved salts in soil, is a serious cause of this degradation (Nachtergaele et al. 2011). The arid countries affected by this environmental problem are mainly located in Australia, China, North and South America, India, Mediterranean countries, and Southeast Asia.

On a global scale, the loss of arable land through soil salinization and alkalization is estimated at 10 million ha each year (e.g., in Jalali 2007). The capacity of crop roots to take up water is decreased with soil salinization, leading to reduced crop production (Kijne 2003). Given this problem, there has been much research in arid regions to investigate the effects of soil salinization on crop production in Tunisia (Askri et al. 2010), Egypt (Matinfar et al. 2011), Spain (Aragüés et al. 2014), Australia (Bhuiyan et al. 2015), and China (Wang et al. 2015). These studies suggest that soil salinization is the consequence of several factors including use of saline water for irrigation (due to the shortage of freshwater resources), inappropriate irrigation regimes (i.e., irrigation frequency and water volume,

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rise of shallow groundwater (average depth <1.5–3 m)), and inappropriate drainage.

Saharan oases located in south of Tunisia, in which date palms (*Phoenix dactylifera*) are the main crop cultivated, are recognized as one the agricultural areas most affected by soil salinization. Date palms in Tunisia have a traditional importance in local diets and hence are economically crucial to local economies (Askri et al. 2014). Date palms are naturally adapted to arid conditions of the southern region of the country which is known as a low rainfall zone (less than 80 mm per year) with high evapotranspiration rate (up to 2000 mm per year).

Date palms need sufficient water in order to produce commercial yields (Tripler et al. 2011; Sperling et al. 2014). Unfortunately, the excessive irrigation of date palms (often with saline waters) coupled with the unfavorable properties of soil (sandy soil with high infiltration) makes shallow saline groundwater rise up to low depths (<2 m), therefore leading to chronic soil salinization throughout the oases (Askri et al. 2010). The salinization is usually worsened whenever upward fluxes of water and salts rise from the water table to the root zone of date palms (capillary rise) and when solutes are excluded by roots (Salama et al. 1999). Therefore, the control of shallow groundwater plays a key role in sustainable agriculture in the oases.

Most of the works regarding the soil salinization in Saharan Tunisian oases have focused on main causes and prevention approaches (e.g., Marlet et al. 2009; Askri et al. 2010, 2014). However, few studies have considered the effects of excessive irrigation of date palms (often with low water quality) on soil salinization and shallow groundwater properties (depth and electrical conductivity).

In this study, the effects of excessive irrigation of date palms with saline water are quantified based on the identification of major changes (changes in soil salinization and in shallow groundwater properties) that have taken place over a 10-year period (2005–2015) in a Saharan Tunisian oasis (Douz oasis). The main objective of this study was to quantify the dynamic patterns of soil salinization and shallow saline groundwater properties in the oasis for the period of 2005–2015. The aim was to provide an information base for the sustainable agriculture in arid oases by improving fields suffering soil salinization.

Case study

The present work was carried out at the Douz oasis, one of the important oases ecosystems in Tunisia. Douz is a small town located in Kebili governorate, southwestern Tunisia. The oasis is located between 33.27°–33.29°N latitude and 8.55°–8.59°E longitude (Fig. 1). The study area is characterized by hyper-arid climate with a mean annual rainfall less than 80 mm and a mean annual potential evapotranspiration of 1860 mm year^{-1}. The mean monthly temperature varies between 16.4 °C in December and 39.8 °C in August. Also, the oasis is marked by strong winds. The wind speed can reach 4.5 m s^{-1} in September (Table 1). The data presented in Table 1 are provided by the Tunisian meteorological service collected from the weather station of Kebili governorate. The open water evaporation is about 2500 mm year^{-1} (Zammouri et al. 2007). Because of the extreme arid climatic conditions, the improper management of irrigation waters, and the reduced discharge of drainage water, soil salinization is common in the oasis (Askri et al. 2010).

The cultivated land covers 800 ha. The soils are sandy with a fluctuating saline shallow groundwater at less than 2 m. The dominant cropping system (>95%) is the date palms (*Phoenix dactylifera*). Surface irrigation by flooding is the only irrigation method used to supply the needs of these plants. According to the results reported by Askri et al. (2014) and Haj-Amor et al. (2016), the actual evapotranspiration of date palms ranges between 1.2 and 12.6 mm day^{-1}. This variation is a function of climatic factors, shallow groundwater depths, and irrigation water salinities (Askri et al. 2014). The high evapotranspiration is the main condition observed in Saharan Tunisian oases (Askri et al. 2010, 2014).

Hydrogeological setting and irrigation water resources

From 1970 to 2005, the irrigation water supply of the Douz oasis was provided by three aquifers: the deep Continental Intercalaire (CI) aquifer, the Complex Terminal (CT) aquifer which contain large water reserves, and the shallow Plio-Quaternary (PQ) aquifer which is considered of secondary importance (Zammouri et al. 2007; Kraiem et al. 2012; Fig. 2). The CI aquifer (artesian waters), one of the largest confined aquifers in the word, is formed by three sub-aquifers which are 1100–2400 m deep. It is mainly found within a succession of clastic sediments (sands and sandstone) with frequent gypsum intercalations separated by clay-rich strata belonging mainly to the Neocomian series. The thickness of this aquifer, which reposes on the Jurassic carbonate substratum, varies from 150 to 400 m (Edmunds et al. 2003). The CT multilayered aquifer (200–600 m deep) is lodged in Miopliocene sands. The thickness of this aquifer is around 160 m, and its substratum is constituted of the Lower Senonian marly limestone. The PQ aquifer (pumped waters) is stored in the superficial

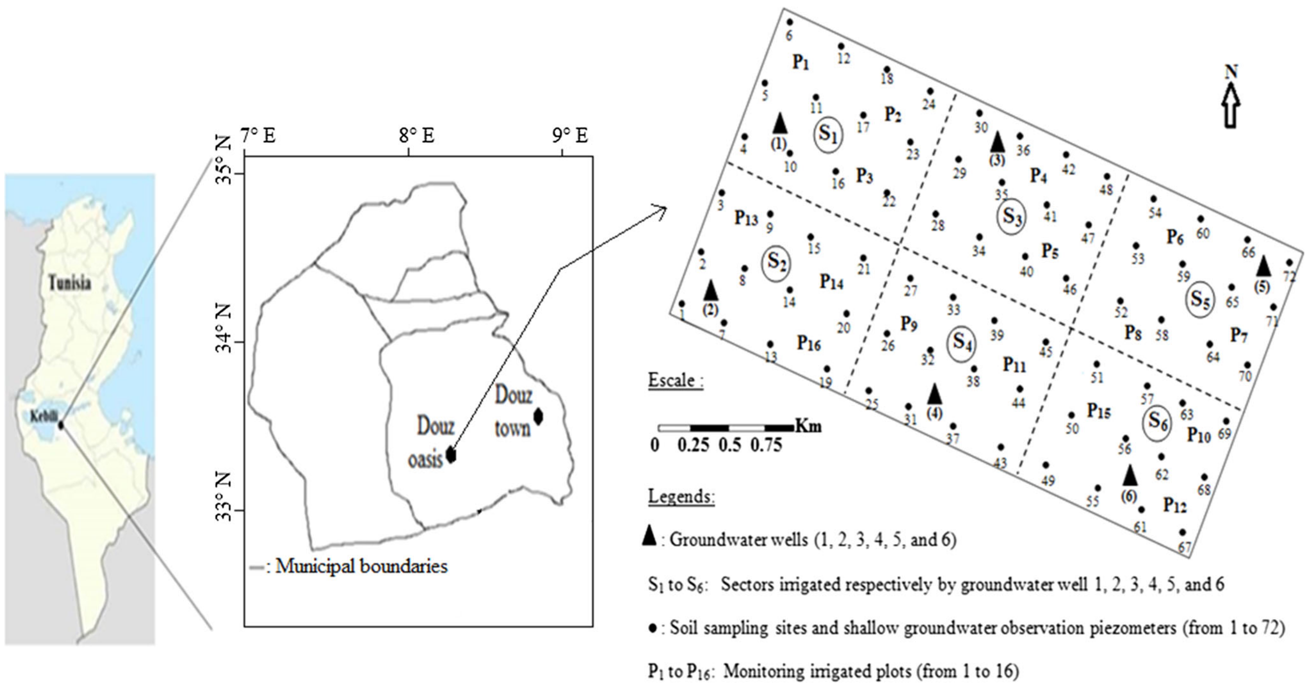

Fig. 1 Location map of Douz oasis and distribution of sampling sites

Table 1 Average monthly temperature (T), wind speed (U), rainfall (R), and potential evapotranspiration (ET_0) for the period 1985–2015 in Douz region

Month	Parameter			
	T (°C)	U (m s^{-1})	R (mm)	ET_0 (mm day^{-1})
January	16.7	3.6	14.1	2.2
February	18.3	3.1	10.2	3.1
March	21.5	4.1	10.1	4.2
April	26.7	4.2	8.4	5.1
May	29.4	4.3	7.1	7.1
June	34.8	4.4	0.3	8.2
July	37.7	4.2	0.4	8.5
August	39.8	4.1	0.5	9.2
September	33.6	4.5	0.1	6.1
October	28.8	4.1	7.8	4.1
November	21.5	3.5	7.6	2.1
December	16.4	3.6	12.4	2.1

fillings (depth <100 m), essentially with clayey sand formations (Kraiem et al. 2012). The over-exploitation of the deep groundwaters (CI and CT) throughout southern Tunisia has resulted in reductions in water levels and had led to depletion of these aquifers and degradation of their water quality (Zammouri et al. 2007; Tarki et al. 2016). For this reason, since 2005, a large increase in PQ aquifer use for agricultural purposes was recorded in the Douz oasis. Therefore, there is a critical need to assess the quality of this aquifer with references to its suitability for irrigation, which is the overall objective of this study.

Data acquisition

Groundwater data (sampling and analyses)

Six groundwater samples were collected from the pumping wells tapping PQ aquifer in January 2005 (Fig. 1). The sampling was carried out after 5 h of pumping operation in order to remove stagnant waters stored in the wells. Field parameters [temperature (T, °C), electrical conductivity (EC_{iw}, dS m^{-1}), and pH] were measured in situ with a portable field kit (Consort C535 multi-parameter analyzer). Water samples were stored in clean polyethylene bottles that were pre-treated with diluted nitric acid and rinsed with distilled waters. The samples were then transported to the laboratory. In the laboratory, the collected samples were filtered through a 0.45-µm filter and were then kept at 4 °C for chemical analyses. Chemical analyses of major elements (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and HCO_3^-) were performed with the ion chromatography technique using a Dionex DX 100 ion chromatograph equipped with a CS12 and an AS14A-SC Ion Pac columns and an AS-40 auto-sampler. The reliability of the resulting chemical analyses (Table 2) was checked according to the charge balance errors proposed by Freeze and Cherry (1979). The

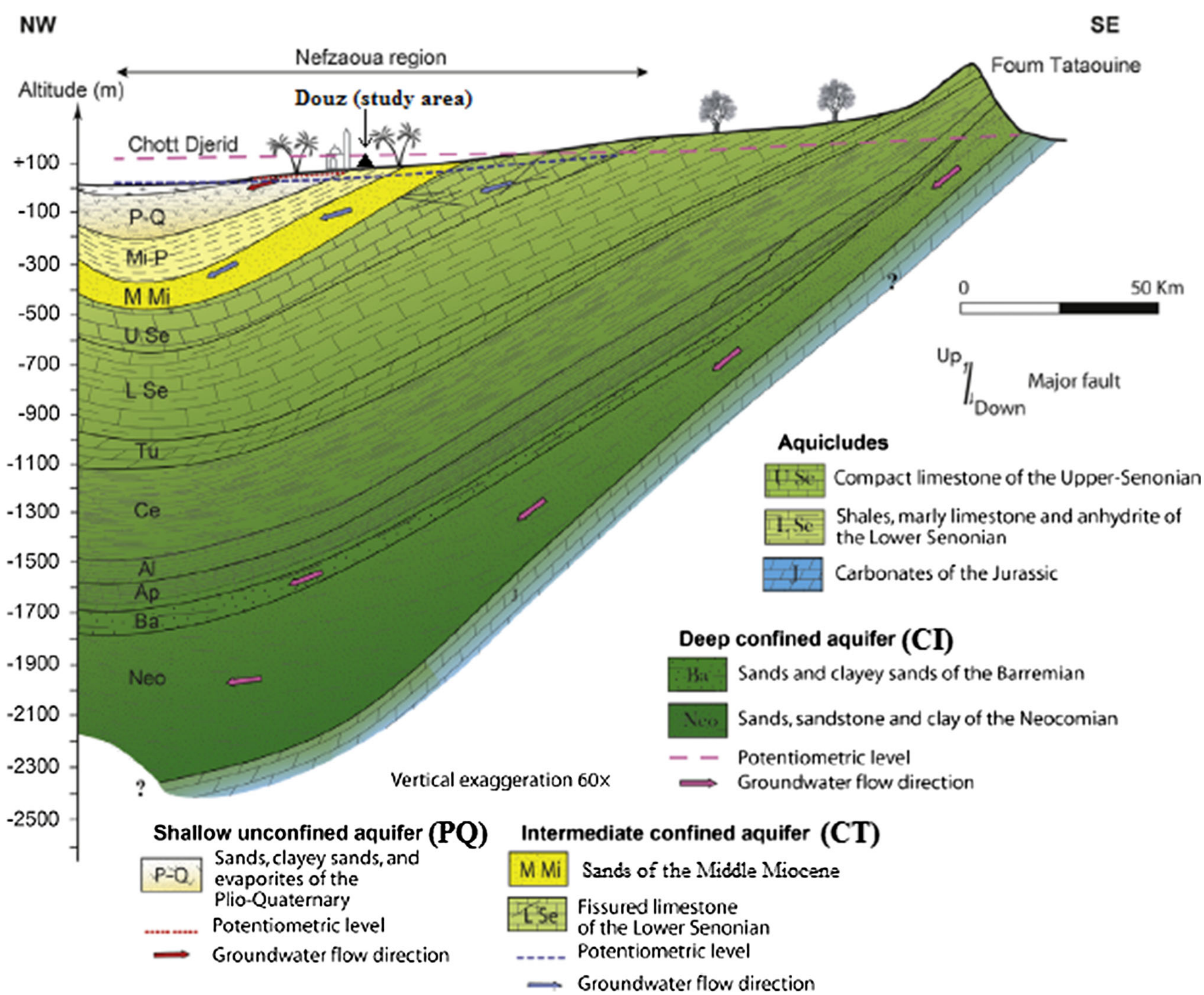

Fig. 2 Hydrogeological cross section of the Kebili aquifer system

Table 2 Geochemical properties of the analyzed groundwater samples in the study area (year: 2005)

Well N°	Depth (m)	Aquifer	T° (°C)	EC_{iw} (dS m^{-1})	pH	Cations and anions (meq l^{-1})							SAR
						Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-	
1	67	PQ	18.3	3.140	7.7	12.1	20.9	5.6	0.1	16.9	16.4	2.1	3.32
2	59	PQ	19.2	3.300	7.6	13.2	22	6.7	0.2	18	16.9	3.2	3.48
3	70	PQ	18.1	3.605	7.5	14.3	23.1	7.8	0.3	19.1	18	4.3	3.64
4	98	PQ	18.9	3.710	7.4	15.4	24.2	8.9	0.1	20.2	19.1	5.4	3.79
5	80	PQ	19.1	3.840	7.8	16.5	25.3	10	0.5	21.3	20.2	6.5	3.93
6	86	PQ	19.6	3.995	7.6	17.6	26.4	11.1	0.6	22.4	21.3	7.6	4.06

SAR sodium adsorption ratio

calculated errors (values <5%) showed an acceptable uncertainty for the purpose of this study. Piper diagram was used to identify the water type (chemical facies), while the USSL diagram was used to evaluate the expected salinity and alkalinity soil risks.

Soil salinization data

Top soil (0–30 cm) sampling was performed over the entire oasis (4.25 km length and 2.25 km width) in November of each study year during which no irrigation

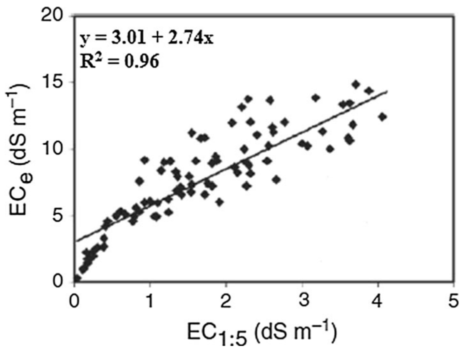

Fig. 3 Relationship between electrical conductivity of 1:5 soil to water extract ($EC_{1:5}$) and saturated past extract (EC_e) for 100 soil samples collected from Douz oasis

was performed. The soil sampling was done on a rough 0.4-km-spaced sampling grid (Fig. 1). The coordinates (longitude and latitude) of soil sampling sites were measured by a handheld GPS. In each sampling, a total of 72 soil samples were collected. Soil samples were bagged and transported to the laboratory to measure electrical conductivity. Before this measurement, the soil samples were dried, ground, and sieved (0.4-mm screen). A filtrate was extracted from a 1:5 mixture of soil:water to measure the electrical conductivity ($EC_{1:5}$). Then, $EC_{1:5}$ values were converted into the electrical conductivity of saturated paste (EC_e) based on a relationship (Eq. 1) established between $EC_{1:5}$ and EC_e for 100 soil samples collected from Douz oasis (Fig. 3).

$$EC_e = 3.01 + 2.74 \times EC_{1:5} \quad (1)$$

Shallow groundwater data

The shallow groundwater properties [depth (D) and electrical conductivity (EC)] were determined in November of each year at the same 72 sample locations. The depths were measured using a water-level sensor (Diver DI240, Van Essen Instrument) with 72 hand-augured piezometers. The piezometer consisted of 3-m-long plastic pipe with a diameter of 10 cm which was filtered at a depth of 50 cm to allow water penetration from the shallow groundwater. The (EC) was measured by a portable field kit (AQUAVIA SX723 Portable Conductivity Meter Kit) with standard conditions of temperature ($T = 25$ °C) and expressed in dS m^{-1}.

Water use data

During the entire period of the study, agricultural data related to timing and amounts of irrigation (irrigation supply) were obtained from the Regional Office for Agriculture Development of Kebili (Tunisia).

Mapping

For each year, the spatial variation of soil electrical conductivity (EC_e) and shallow groundwater properties (D and EC) in the oasis were identified based on geostatistical analyses of the measured data. In soil science, geostatistics were applied to estimate the soil attributes at unsampled locations (Goovaerts 1999). In this study, the experimental semivariogram, which is a measure of the degree of spatial dependence between samples, was calculated by averaging one half the difference squared of the parameter values over all pairs of observations with specified separation distance and direction. Then, various models (namely linear and exponential) were fitted to each field dataset in order to obtain the theoretical semivariogram parameters (nugget, sill, and range). Finally, the modeled semivariogram was exploited to compose the contourmaps of data (EC_e, D, and EC) based on kriging geostatistical approach (details of kriging procedure available in Liao et al. 2013). ARCGIS version 9.3 (Johnston 2004) was used to do geostatistical analyses in this study.

Results and discussion

Suitability of PQ groundwater for irrigation purpose

The analytical results of the PQ groundwater samples collected in January 2005 in the studied oasis are presented in Table 2. The water temperature averaged 19 °C, and the pH values ranged between 7.4 and 7.8. In the studied oasis, interactions with surrounding lithological formations (especially the limestone) allowed the dissolution of carbonates and thus the increase in pH values (Kraiem et al. 2014). The electrical conductivitiy values (EC_{iw}) ranged from 3.14 to 3.99 dS m^{-1} (i.e., TDS from 2010 to 2557 mg l^{-1}). The variation in EC_{iw} was mainly attributed to the anthropogenic activities prevailing in the oasis. The use of these saline waters (TDS $>$ 2000 mg l^{-1}) for irrigation of date palms could pose degradation risk for the soil agriculture potential (Ayers and Westcot 1985). Date palms irrigated with saline waters must necessarily be well drained, so that the accumulation of salts in the soil renders it not sterile. Therefore, water must be applied in excessive amounts in order to ensure adequate leaching requirement (USSL 1954).

The plotting of chemical analyses (ion concentrations) on Piper diagram (Fig. 4) showed that the irrigation water had sodium bicarbonate geochemical facies. The ionic composition was dominated by Ca^{2+} (20.9–26.4 meq l^{-1}), Cl^- (16.9–22.4 meq l^{-1}), SO_4^{2-} (15.8–21.3 meq l^{-1}), and Na^+ (12.1–17.6 meq l^{-1}). By contrast, concentrations in

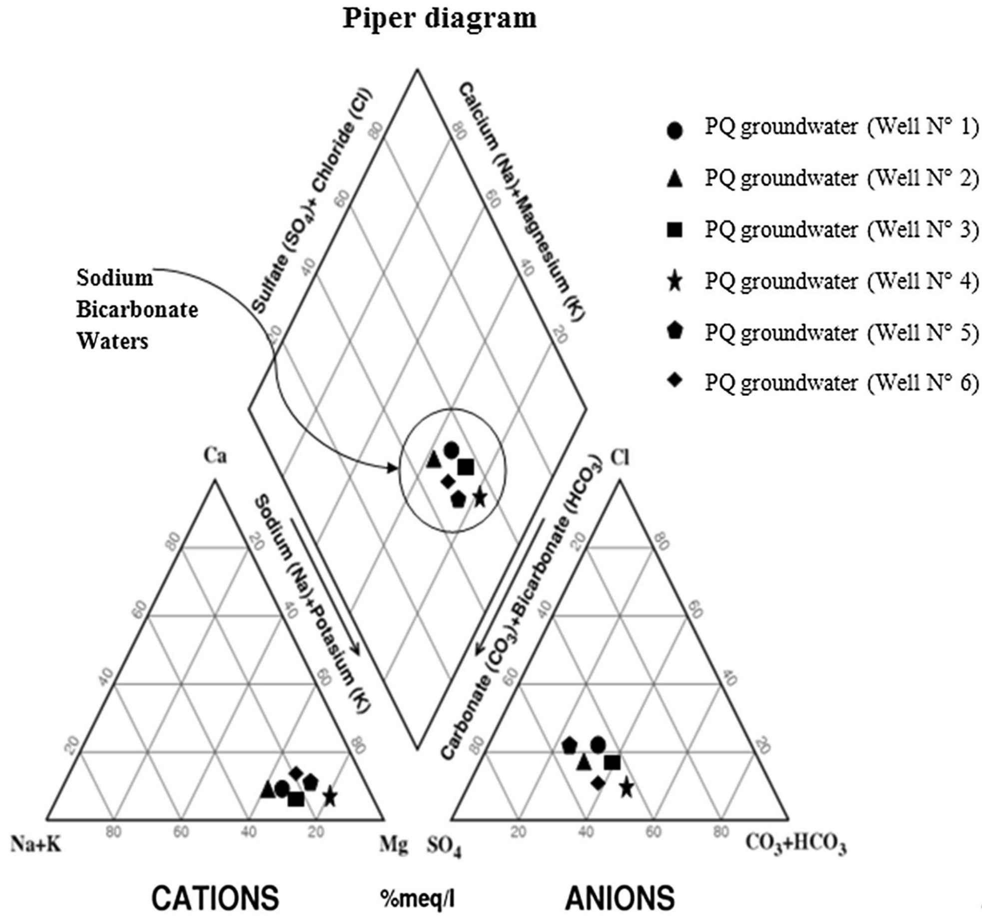

Fig. 4 Geochemical facies of groundwater water (PQ aquifer)

Mg^{2+} and K^{+} were relatively lower (Tables 2). To evaluate how the interaction of different ions affects the water suitability for irrigation uses, the sodium adsorption ration (SAR) values was plotted with the measured EC_{iw} on the USSL classification diagram (USSL 1954) (Fig. 5). As shown in this figure, all groundwater (PQ aquifer) fit in the C4–S1 class, which indicates a high salinity hazard and low to medium sodium content. It is an unfavorable class which means that irrigation water has a high potential risk of soil salinization and a medium expected risk of soil sodification. The control of salinity hazard is required for irrigation. In Saharan oases of Tunisia, like the study area, the use of these waters with low quality for irrigation is a necessity due to the rarity of freshwaters, the progressive extension of irrigated areas and the relative tolerance of the practiced cultures (date palms) to the soil salinity.

Long-term water irrigation water use of date palm plantations

In the context of the present work, irrigation performance in Douz oasis was analyzed in detail by calculating the relative water supply (RWS) indicator, which is the ratio of the sum of precipitation plus irrigation water to potential evapotranspiration (Perry 1996). In this analysis, the theoretical water requirements of date palms and their differences to farmers' actual water demands were evaluated in 16 plots in the study area during 4 years (2005, 2006, 2007, and 2008). The results (Table 3) showed an excess supply of water given that the mean value of the RIS indicator was greater than 1 (RWS = 2.6). Therefore, the practiced irrigation in Douz oasis was described as excessive irrigation.

Irrigation water use in the oasis showed a progressive increase during the study period. It increased from 12.6 Mm^3 in 2005 to 18.9 Mm^3 in 2015 (Fig. 6). The expansion of irrigated plantation area (by 110 ha, since 2009) constitutes one of the causes of the water use increase. Implementation of the project "Improvement of Irrigated Areas in Southern Oases" within the study oasis has led to the development of the water distribution network and consequently to the noted expansion of the total irrigated area. Private plots created by individual farmers were supplied with water by illegal wells that were drilled without any approval from the development authorities. This contributed to the rise of water demand and accentuated the severe pressure on the exploited PQ aquifer (Omrani and Dieter 2012). The rapid increase in numbers

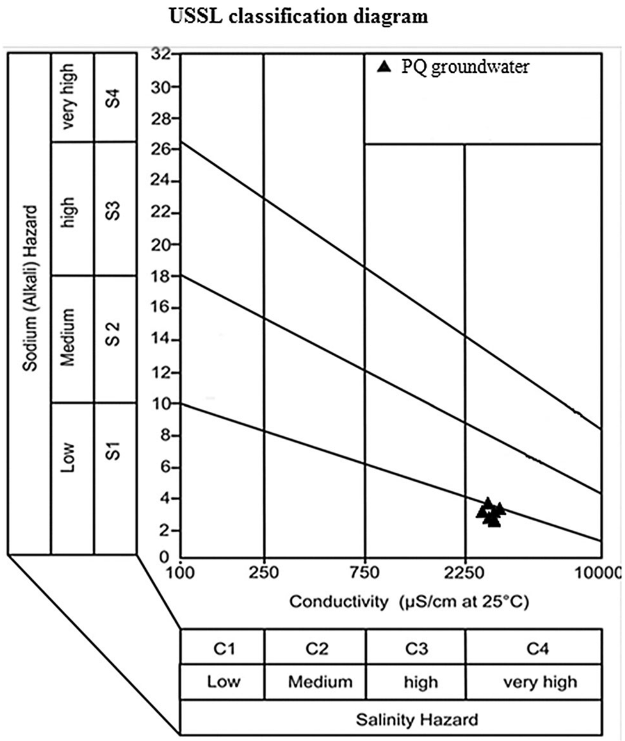

Fig. 5 Groundwater water class according to USSL classification diagram

Table 3 RWS values for date palms during 2005, 2006, 2007, and 2008

Plot N°	2005	2006	2007	2008	Mean RWS
Plot 1	2.3	2.1	1.8	1.7	1.9
Plot 2	3.5	3.4	3.3	3.1	3.3
Plot 3	2.1	2	1.7	1.5	1.8
Plot 4	2.5	2.6	2.2	2.1	2.3
Plot 5	3.7	3.5	3.6	3.2	3.5
Plot 6	2.7	2.5	2.4	2.1	2.4
Plot 7	2.9	2.5	2.1	2.3	2.4
Plot 8	3.9	3.7	3.4	3.3	3.5
Plot 9	2	1.8	1.6	1.5	1.7
Plot 10	4.1	3.9	3.6	3.5	3.7
Plot 11	2.2	2.1	1.9	1.6	1.9
Plot 12	4.3	4.1	3.9	3.7	4.1
Plot 13	1.9	1.7	1.5	1.4	1.6
Plot 14	3.1	2.9	2.7	2.5	2.8
Plot 15	3.3	3.1	2.9	2.6	2.9
Plot 16	1.8	1.4	1.6	1.3	1.6
Mean RWS	2.8	2.7	2.5	2.3	***2.6***

of the illegal wells, especially since 2010 (5 wells), was the key contributor to the water use increase during the period 2010–2015 (Fig. 6).

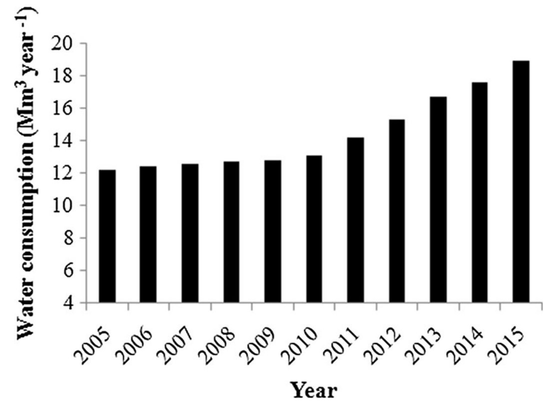

Fig. 6 Water used for irrigation during 2005–2015 in Douz oasis

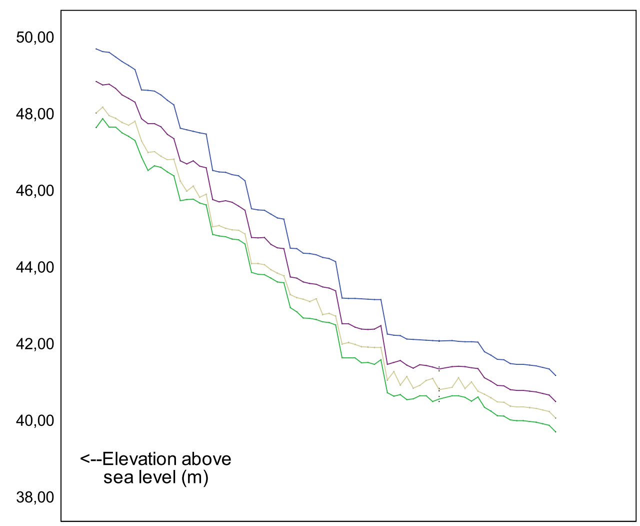

Fig. 7 Elevation of shallow water table of the monitoring points arranged in decreasing order of soil surface elevation (*blue line*). *Green line* indicates water table level measured in 2005, *gray line* same in 2009, and *purple* same in 2015. The distance between the highest northwestern and lowest southeastern points is more than 4 km

The water table level follows closely the original surface elevation (Fig. 7). It is evident that there is an abrupt rise of water table level during the last 10 years. The rise is much higher during the last 5 years than before.

In addition to this factor, the pricing of irrigation water is also a contributor to excess supply of water. Indeed, in Douz oasis, the water is charged on the basis of field size. The current annual irrigation water price is 150 € per ha. This price is quite low compared to international standards and does not encourage the farmers to avoid the excess supply of water during applications. Thus, implementation of an effective pricing program for irrigation waters can be a potential solution for water conservation. As reported by Burt (2007), the acceptable water charge for a new

Table 4 Pearson correlation analysis between shallow groundwater level under the surface and water use from the PQ aquifer in Douz oasis during 2005–2015 ($n = 1590$)

	WC	*R*	*E*	MP_1	MP_2	MP_3
WC (m^3)	1					
R (mm)	0.174	1				
E (mm)	−0.031	−0.485*	1			
MP_1 (m)	0.037	0.042	0.143	1		
MP_2 (m)	−0.023	−0.101	0.184	0.857**	1	
MP_3 (m)	−0.129	−0.033	0.425*	0.848**	0.830**	1

WC water use, *R* annual rainfall, *E* annual evaporative demand, *MP* shallow groundwater level under the surface (at monitoring piezometers 1, 2, 3)

* Significant at 0.05 level; ** significant at 0.01 level

program will depend upon the politics, level of water delivery service provided and benefits to farmers.

From 2005 to 2015, the rise in the shallow groundwater level at three monitoring piezometers was positively correlated ($P < 0.01$) with the water extraction from the PQ aquifer and negatively correlated ($P < 0.05$) with the evaporative demand (Table 4). Therefore, the massive irrigation of date palms directly relates to the rise in shallow groundwater. The area of plantations where the groundwater table was above the critical depth (1.5 m) extended, and this directly caused higher soil salinization.

Maps of soil salinization and shallow groundwater properties

The soil salinization and the shallow groundwater properties were monitored with yearly frequency during 2005–2015. Our study focused on the years 2005, 2009, and 2015 (Figs. 8, 9a, b).

The spatial similitude noted between soil electrical conductivity (Fig. 8) and shallow groundwater properties (Fig. 9a, b) confirms that water table is a major contributor to soil salinization within the oasis. A deep water table ($D > 2$ m) with low electrical conductivity (EC < 16 dS m^{-1}) was associated with low values of soil salinization. It is mainly through *capillary rise* (i.e., upward movement of water and salts) that the shallow groundwater has contributed to the soil salinization increase and has resulted in the salt accumulation at the top soil. Many authors (e.g., Bouksila et al. 2013; Yang et al. 2011; Askri et al. 2010) have shown that this capillary rise is directly proportional to the salinity and shallowness of water table.

Under high evapotranspiration of date palms, as observed in the study oasis, the increased water table salinity results in more dissolved salts within the cropped soil. Therefore, shallow groundwater management should be considered parallel to monitoring the soil salinization in arid irrigated areas. As reported by Haj-Amor et al. (2016) and Askri et al. (2014), better management in Saharan Tunisian oases requires regulating the irrigation frequency, the irrigation amount, and the drainage discharge. Also, they reported that the best water management for minimizing soil salinization combines the use of high irrigation frequency with small amounts of water (often saline) and intensifying drainage activities.

During the study period (2005–2115), the soil electrical conductivity (EC_e) varied from 3 to 9 dS m^{-1} in 2005 and from 4 to 12 dS m^{-1} in 2009, and it ranged from 6 dS to 12 dS m^{-1} in 2015 (Fig. 8). In all maps, the characteristic pattern showing increase in EC_e and water table electrical conductivity, as well as decreasing depth of water table, was closely linked to the slope of the oasis toward southeast, as indicated in Fig. 7. The long-term increase in EC_e (temporal increase) is remarkable in the field. The low impact of soluble salt leaching by rains in the study area (Saharan oasis with an average annual rainfall <80 mm) is the main cause of this increase between the years (Marlet et al. 2009). During the monitoring period, it was clear that EC_e can build up to levels that exceed the salt tolerance of date palms which is estimated at 4 dS m^{-1} (Mass and Hoffman 1977). These levels indicated that there was a high salinity stress for date palms. The initial saline condition of the irrigated soil (saline soils), the low quality of applied irrigation water (PQ aquifer), the high evaporative demand, the low rainfall ($\approx$80 mm $year^{-1}$), and especially the rising of shallow saline groundwater (Fig. 9a), resulting from the excessive irrigation of date palms (Table 3), all contributed to the progressive salinization increase in the irrigated area.

The observed soil salinization in Douz oasis corroborates and confirms the soil salinization trend recorded in the majority of Saharan oases of Tunisia (e.g., Marlet et al. 2009; Askri et al. 2010, 2014). Irrigation from 2005 to 2015 has lead to a notable rise of shallow water table below the critical depths (fixed at 1.5 m) (Askri et al. 2010, 2014). In 2015, the minimum (min) and maximum values of shallow groundwater depth (min = 0.6 m and max = 0.9 m) clearly indicated that in the whole irrigated areas (100%) the threshold level was highly exceeded. In 2005, the percentage of irrigated areas where the depths of water table exceeded the critical value (1.5 m) was lower than 5%. The recorded shallow depths of the water table were indicators of a growing problem: a dangerous buildup of salts in the soil outside downward irrigations exists especially in sandy soils noted in the oasis, where the capillary rise is high.

At spatial scale, the low slope of land the southeast part of the oasis coupled with the high density of plantation (130 palms/ha instead of 100 palms/ha in the other parts) could be the main factors of the very clear increasing soil electrical conductivity pattern toward southeast.

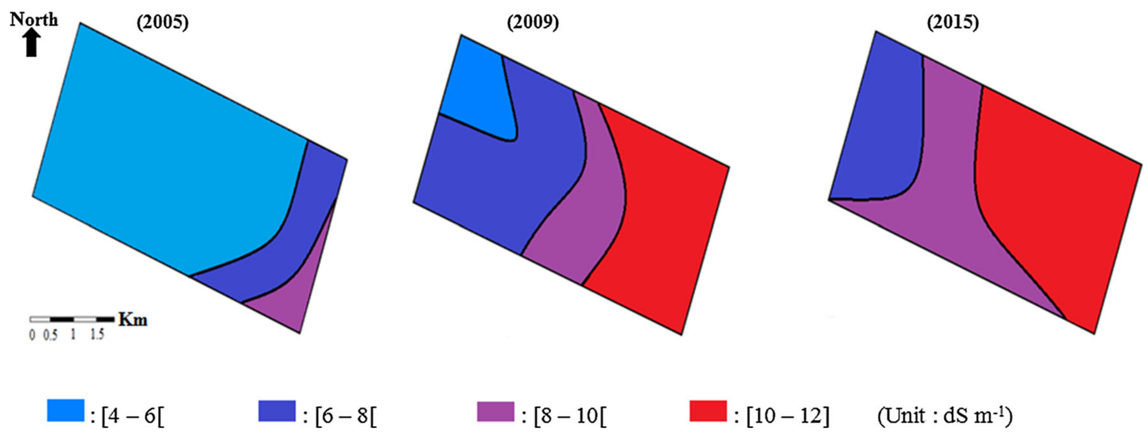

Fig. 8 Temporal change in soil electrical conductivity (years: 2005, 2009, and 2015)

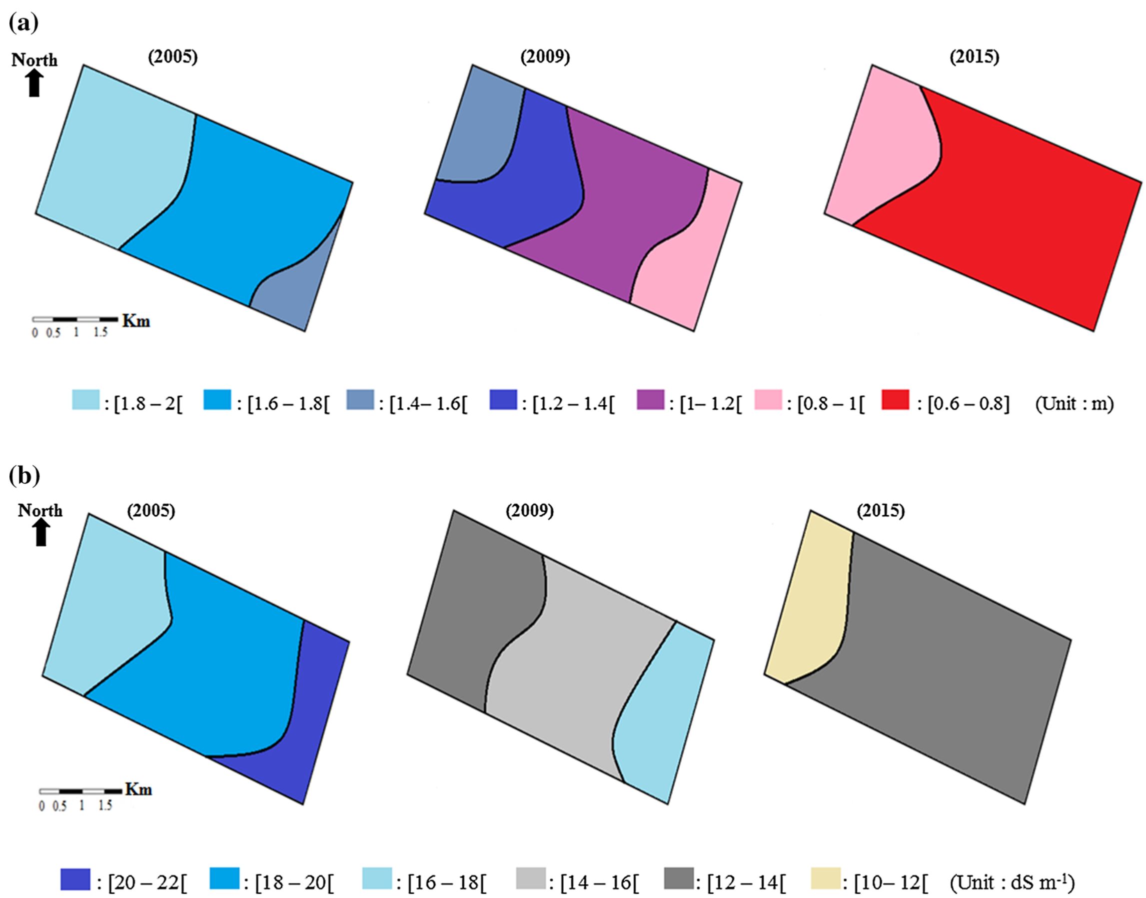

Fig. 9 **a** Temporal change in shallow groundwater depth (years: 2005, 2009, and 2015). **b** Temporal change in shallow groundwater electrical conductivity (years: 2005, 2009, and 2015)

In contrast to results with soil electrical conductivity, a desalinization trend was noted for the water table (decreasing of electrical conductivity) (Fig. 9b). High infiltration capacity of sandy soils coupled with the excessive irrigation frequencies has led to deep seepage and decreases the electrical conductivity of shallow water tables. Indeed, the electrical conductivity of shallow groundwater has decreased with continued irrigation with waters that have a lower electrical conductivity than the water table. In these cases, the shallow groundwater has been diluted by the irrigation waters.

At the spatial scale, assessment of soil salinization leads to distinguishing vulnerable areas that require urgent intervention for soil conservation (Nunes et al. 2007;

Table 5 Regression coefficients of the stepwise regression equations ($EC_e = B1 \times EC - B2*D$) for the prediction of the soil electrical conductivity (EC_e) and mean values of the variables of the same equation

Year	Adj R^2	B2_D	B1_EC	EC_e average (dS m^{-1})	*D* average (m)	EC average (d*S* m^{-1})
2005	0.973	−2.3	0.47	5.42	1.64	19.52
2009	0.993	−5.3	1.01	8.47	1.31	15.29
2015	0.989	−8.1	1.21	9.29	0.75	12.75

EC is the electrical conductivity of the groundwater (dS m^{-1}), and *D* is the depth to water table (m)

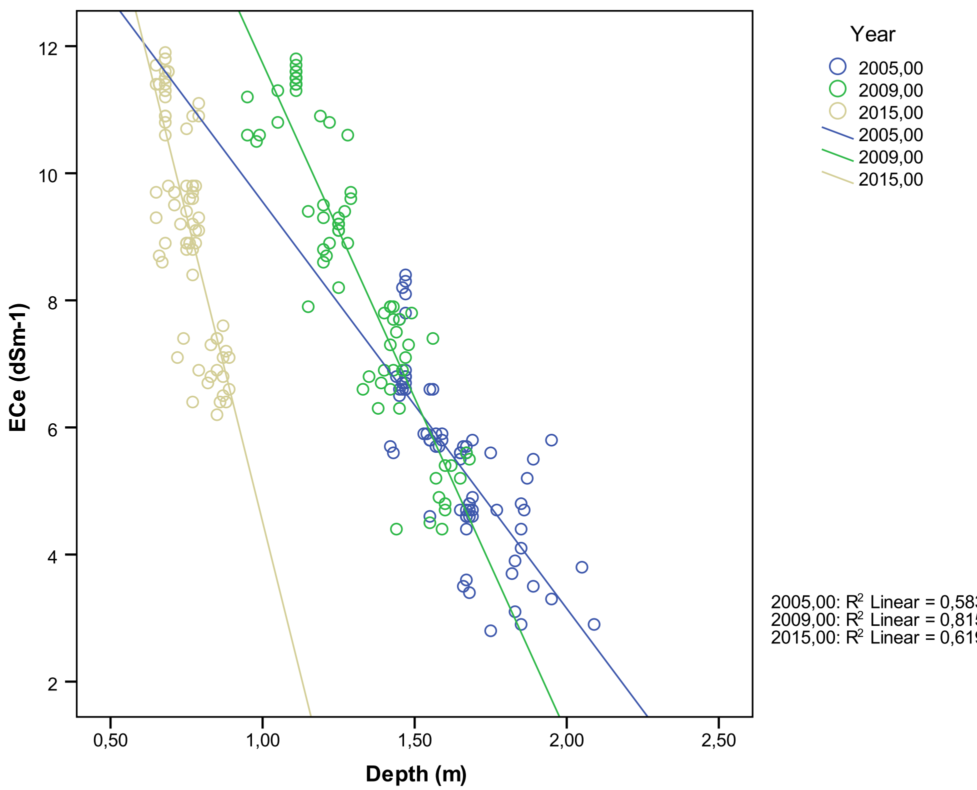

Fig. 10 Scatter of water table depth (*D*) versus soil electrical conductivity (EC_e) for the three monitoring years. The *fitted lines* show the relationship between the two variables only

Bouksila et al. 2013). The fact that saline shallow groundwater typically exceeds the critical depths during the observation years (especially 2015) indicates need for urgent intervention by improving the drainage conditions to decrease the soil salinization levels in Douz oasis. The mapped data from our study will assist the development of an efficient drainage system in the study oasis.

In order to compare the importance of the two main independent variables, that is water table depth and its electrical conductivity, determining the soil electrical conductivity (dependent variable), linear regression equations were calculated without intercept. Similar equations for soil salinization have been previously reported (Tóth and Várallyay 2001). In our study, the changes of the regression coefficients B1 and B2 of the two independent variables from year to year (Table 5) show the varying importance of these variables. As irrigation becomes more excessive and as water table depth and electrical conductivity decrease, soil electrical conductivity increases (see averages in Table 5), and the relative importance of the independent variables continuously shifts from the first monitored year to the third one.

The importance of water table salinity increases, and the importance of its depth decreases. This is the consequence of a new groundwater composition present in each year as shown in the two following figures: Figs. 10 and 11. Figure 10 shows that as irrigation becomes more excessive, the slope of the line fitted to the points becomes steeper. This means that the rise of the water table is expected to cause even higher salinity. There is a shift toward higher salinity; especially, 2015 is characterized by very shallow water table and high EC_e. Similarly, Fig. 11 shows that the slope of the line fitted between the values of water table and soil salinity becomes steeper every monitoring year. The rise of the water table is expected to cause higher salinity. In 2005, a water table electrical conductivity of

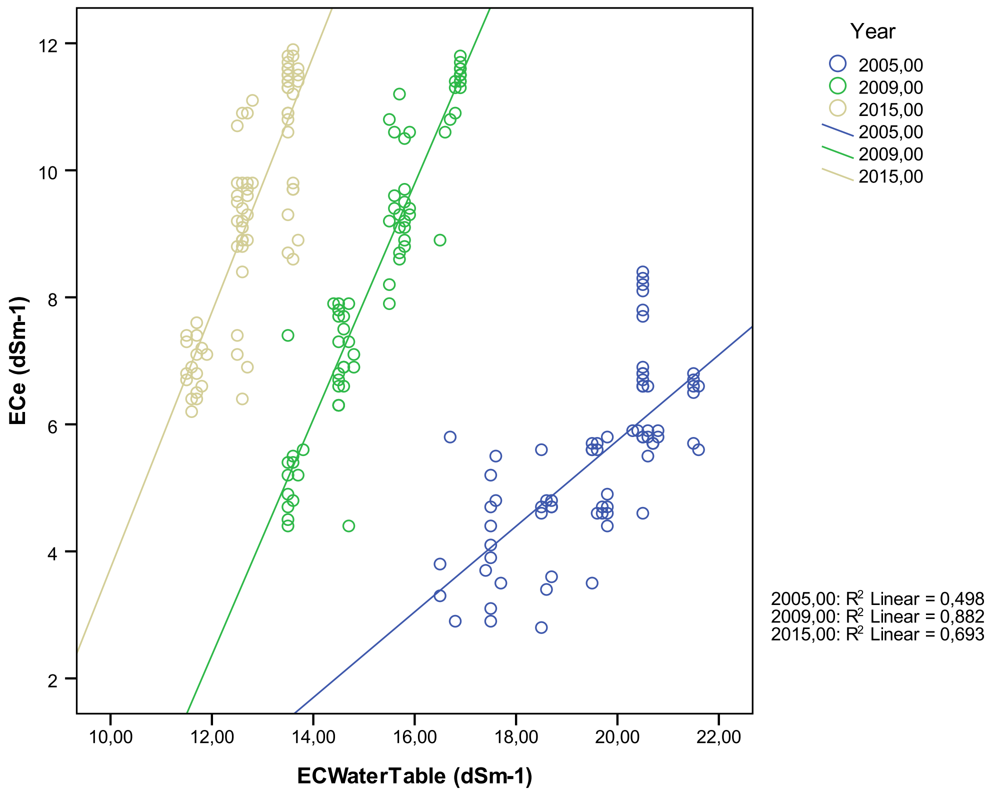

Fig. 11 Plot of water table electrical conductivity (EC) versus soil electrical conductivity (EC_e) for the three monitoring years. The *fitted lines* show the relationship between the two variables only

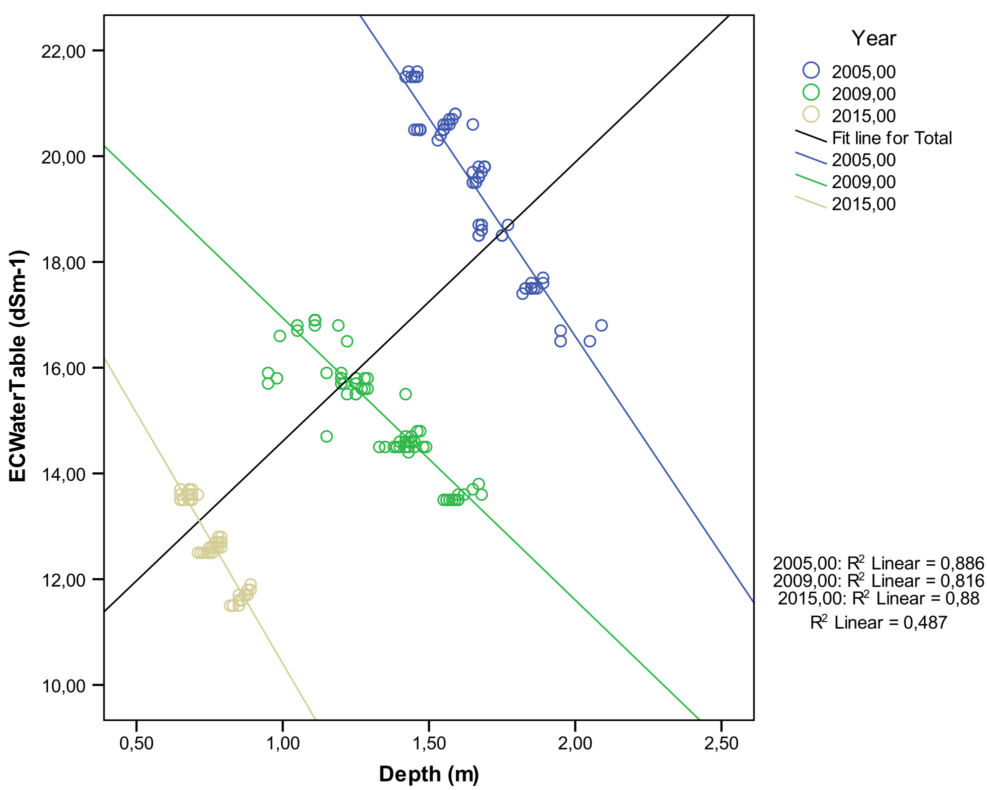

Fig. 12 Plot of water table depth (*D*) versus water table electrical conductivity (EC). The *black line* shows the overall regression covering all 3 years. The *blue*, *green*, and *yellow lines* show the regression lines of the particular monitoring years shown in the legends

21 dS m^{-1} caused EC_e of 7 dS m^{-1}. But in 2009, a water table electrical conductivity of 14 dS m^{-1} and in 2015 a value of 11 dS m^{-1} caused the same effect.

The relationship between the depth and electrical conductivity of the water table is illustrated by each monitored point in all 3 years in Fig. 12. The scatter of the points shows clustering inside a particular year. These small clusters are related to the separate irrigation waters (wells) used in the particular sets of plots. As the water table continues to get shallower, the effect of irrigation water becomes stronger compared to the original soil salinity, there is a homogenization, and the number of clusters declines. There is a negative relationship between water table depth and water table electrical conductivity (EC) in each year, which confirms the common experience of growers. The shallower the water table, the greater will be its electrical conductivity due to strong evapotranspiration. But there is an overall (mixing all 3 years) positive relationship between water table depth and water table electrical conductivity (EC), see the line from the left lower corner to the right upper corner, which is contradicting common experience. This is an artifact of mixing the different, separately regular situations of the individual years, because the large amount of irrigation water dilutes the water table and shifts yearly distribution toward shallower depths.

Conclusion

In this study, we mapped spatiotemporal soil salinization in the Douz oasis and identified the major changes that have taken place over a 10-year period (2005–2015) in irrigated date palms within an oasis where groundwater is at shallow depths (<2 m). Key factors contributing to soil salinization in the oasis from 2005 to 2015 included low quality of water resources (high soil salinization risk) and the rapid rise of shallow groundwater at depths less than 1.5 m which resulted from the high water use of date palm plantations. The identified spatial variation of soil electrical conductivity and shallow groundwater properties (depth and electrical conductivity) can be used by both land planners and farmers to develop effective strategies for managing soil and irrigation water. Such strategies should take into account the degradation of irrigation water quality (waters of PQ aquifer), the properties of sandy soils, the excessive irrigation of date palms, and the sustainability of plantations. Finally, future work should focus on the importance of the evaluation of long-term effects of the identified saline areas on date palm production (yields). Modeling can be a useful tool to understand crop performance in relation to the saline conditions of the Saharan oases. Indeed, the modeling results by Haj-Amor et al. (2016) have shown that irrigation with saline water is sustainable if rising water table is not a threat. Based on this study, the modeling must be expanded to include the presence of water table, various agronomic factors, and rational options of drainage. Such research will be capable of suggesting practical management options to avoid further aggravation of salinization.

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