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Soil salinisation and irrigation management of date palms in a Saharan environment

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Abstract The continuance of agricultural production in regions of the world with chronic water shortages depends upon understanding how soil salinity is impacted by irrigation practises such as water salinity, irrigation frequency and amount of irrigation. A two-year field study was conducted in a Saharan oasis of Tunisia (Lazala Oasis) to determine how the soil electrical conductivity was affected by irrigation of date palms with high saline water. The study area lacked a saline shallow water table. Field results indicate that, under current irrigation practises, soil electrical conductivity can build up to levels which exceed the salt tolerance of date palm trees. The effects of irrigation practises on the soil electrical conductivity were also evaluated using model simulations (HYDRUS-1D) of various irrigation regimes with different frequencies, different amounts of added water and different water salinities. The comparison between the simulated and observed results demonstrated that the model gave an acceptable estimation of water and salt dynamics in the soil profile, as indicated by the small values of root mean square error (RMSE) and the high values of the Nash–Sutcliffe model efficiency coefficient (NSE). The simulations demonstrated that, under field conditions without saline shallow groundwater, saline irrigation water can be used to maintain soil electrical conductivity and soil water content at safe levels (soil electrical conductivity <4 dS m^{-1} and soil water content >0.04 cm^3 cm^{-3}) if frequent irrigations with small amounts of water (90 % of the evapotranspiration requirements) were applied throughout the year.

Keywords Arid lands · Irrigation practises · Saline water · Soil salinisation

Introduction

Irrigation has significantly contributed to increased crop production worldwide, but it has also led to salinisation of agricultural lands and has caused the destruction of these lands in many regions (Van Schilfgaarde 1994). Zeng et al. (2014) estimated that 2×10^7 to 3×10^7 hm^2 of irrigated land have been seriously damaged and degraded by salinisation and that approximately 1.5 % of this land could be permanently unusable for agricultural production. In Tunisia, the important saline areas (about 20,000 ha) are mainly located in the south of the country where date palms (*Phoenix dactylifera*) constitute the main crop. The date palm tolerates extreme adverse

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environmental conditions and is one of the most important plants in the oases ecosystems. In southern Tunisia, date palm is the principal richness of the Saharan oases. These arid regions, which are favourable to growing date palm, are characterised by long, hot summers, with or very little to no rainfall and low relative humidity during the ripening period. Therefore, yield levels largely depend on irrigation (Askri et al. 2014). Unfortunately, approximately 50 % of the oases conducive to cultivation of date palms in Tunisia are confronted with soil fertility problems and hence have deficient productivity (Bouksila et al. 2013). Water scarcity and soil salinisation are the main factors responsible for the low agricultural productivity of these oases (King and Thomas 2014). Soil salinisation is the consequence of several factors including the application of saline water for irrigation (due to the shortage of fresh water resources) and inadequate drainage activities (Askri et al. 2010).

The future of irrigated agriculture in Saharan Tunisian oases, as in other arid regions, will need to include the use of irrigation water containing high levels of soluble salts. The salinisation level of the root zone can be decreased by leaching, the process of flushing excessive soluble salts out of the root zone during the growing season or at the end of the season (Corwin et al. 2007). A better understanding of the interaction between irrigation practises (salinity of applied water and frequency of irrigation) and soil salinisation is needed for groundwater planning and management and a sustainable and safe use of soil resources (Malash et al. 2008).

The interactions between soil salinisation and irrigation practises are complex and are affected by many factors. Evaluating the interaction of these factors through field research is difficult and expensive because numerous uncontrolled factors may affect crop performance in addition to the controlled variables. In addition, the magnitude of salt accumulation in a single growth season is often small and may not be readily detectable by routine soil sampling in the field (Chen et al. 2010). Modelling in this regard provides an effective alternative (Xu and Shao 2002), as it can help to elucidate how temporal and spatial aspects of soil water and solute fluxes are affected by irrigation practises (Šimůnek et al. 2008).

In the Tunisian oases of the Kebili governorate, saline water is increasingly used for surface irrigation of date palm. Although the date palm is tolerant to salinisation, the irrigation practises are questionable with regard to their long-term sustainability in these regions where rainfall is insufficient to provide adequate leaching. Deficit irrigation with water of poor quality may cause “secondary soil salinisation” which will progressively decrease date palm yields and compromise soil resources (Ghazouani et al. 2009). Secondary soil salinisation in Tunisian oases has been studied by many authors (e.g. Ibrahimi et al. 2014). However, most of these studies are based on studying cropped soil salinisation independently of irrigation practises. The objective of our research was to evaluate the effect of irrigation practises on the temporal change in soil salinisation under the climatic conditions of the Saharan Tunisian oases. Field measurements of soil salinisation change were based on a 2-year field monitoring. The HYDRUS-1D model was used to simulate the effects of irrigation practises on the soil electrical conductivity under different irrigation frequencies, amounts and water salinities.

Materials and methods

Study area

The study was conducted in the Lazala Oasis (latitude 33° 2′ N and longitude 8° 2′ E) in the Kebili governorate of Tunisia. It is a modern oasis, representative of the Saharan oases of Tunisia, located about 5 km south of the town of Douz (Fig. 1). The annual rainfall is less than 100 mm, which is insufficient to support agricultural activities. The annual potential evapotranspiration can reach 2000 mm. The climate is also characterised by strong winds carrying sand in the spring and hot winds (sirocco) in the summer (Zammouri et al. 2007).

The oasis covers 75 ha and is divided into 150 equally sized plots of farmland. Each plot is rectangular in shape, typically 100 m long × 50 m wide, and consisting of 40–50 irrigation basins (series of small level basins), where date palms and some fodder crops are cultivated. The water used for irrigation flows from a deep geothermal artesian well drilled into the Continental Intercalaire aquifer. The depth of this well is 2020 m with a discharge rate of 60 $\mathrm{l\,s^{-1}}$ and a water temperature of 72 °C. Surface irrigation by flooding is the main irrigation method. Irrigation water has an average electrical conductivity (EC_{iw}) of about 6.5 $\mathrm{dS\,m^{-1}}$ and a pH of 7.79. The sodium adsorption ratio (SAR) is 11.5 and the dominant geochemical facies is sodium chloride (Table 1). Similar to other modern Saharan oases of

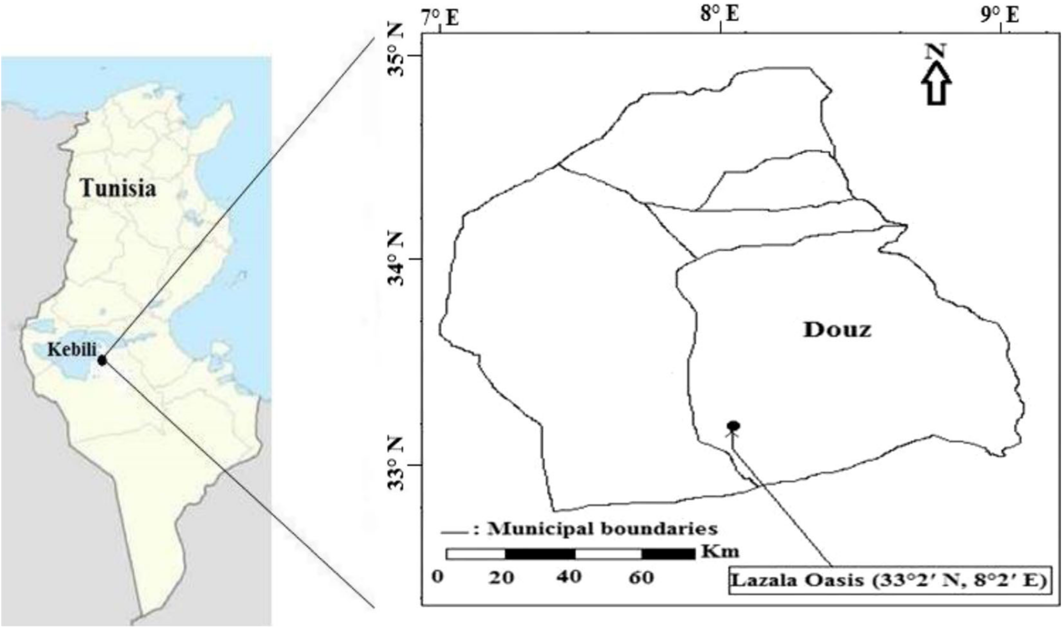


Fig. 1 Location of the study area (Lazala Oasis)

Tunisia, the water table (perched shallow groundwater) is absent in the study area due to the intensive drainage in the irrigated areas.

Field monitoring

During the 2 years of monitoring (2013 and 2014), various parameters needed to study the temporal change in soil salinisation were collected and measured in a 0.5-ha plot, representative of the oasis and only planted with mature date palms (180 palms ha^{-1}).

Soil properties measurement

Before the observations, the following soil properties of the plot were determined through a 1.5-m soil profile: soil texture, bulk density, field capacity, wilting point, saturated hydraulic conductivity (K_s) and electrical conductivity (EC_e). Soil samples were collected at depths of 0.3, 0.6, 0.9, 1.2 and 1.5 m according to the standard method 'ISO 10381–1:2002'. A total of 15 soil samples were collected, with three replications each. Samples were air-dried and ground to pass through a 2-mm mesh. Soil texture was measured in the laboratory using the laser diffraction method (Mastersizer-Model 3000, Malvern instruments). Three fractions were measured, clay ($d < 2$ μm), silt (2 μm $< d <$ 50 μm), and sand (μm 50 $< d <$ 2 mm). Soil bulk density was obtained by oven drying undisturbed soil samples of 100 cm^3 for 48 h. Field capacity and wilting point of all soil samples were measured by pressure-plate at −33- and −1500-kPa suctions, respectively. K_s values of the undisturbed soil cores were determined using the falling head method (Klute and Dirksen 1986). The electrical conductivity of the saturated paste (EC_e) was measured according to the standard method proposed by the US Salinity Laboratory Staff (1954).

Soil properties are presented in Table 2. The soil texture ranges from loamy sand to sandy. Since the EC_e was higher than 6 dS m^{-1} for all

Table 1 Physicochemical composition of irrigation water in the Lazala Oasis in 2013

Data									
pH	SAR	EC_{iw} (dS m^{-1})	Cations and anions (meq L^{-1})						
			Na$^+$	Ca^{2+}	Mg^{2+}	K$^+$	Cl$^-$	SO$_4^{2-}$	HCO$_3^-$
7.79	11.50	6.50	38.05	13.57	8.39	1.20	39.70	15.90	4.10

Table 2 Physical properties of the soil in the plot studied

Determination	Soil depth (cm)				
	00–30	30–60	60–90	90–120	120–150
Sand (%)	80.2	79.3	82.3	81.5	80.6
Silt (%)	14.6	16.8	13.7	14.9	15.5
Clay (%)	4.2	3.9	3.9	3.5	3.7
Soil texture	Sand	Silty sand	Sand	Sand	Sand
Bulk density (g cm^{-3})	1.58	1.44	1.55	1.57	1.52
Field capacity (−33 kPa) (cm^3/cm^3)	0.11	0.12	0.11	0.11	0.12
Wilting point (−1500 kPa) (cm^3/cm^3)	0.038	0.035	0.040	0.038	0.041
Electrical conductivity (dS m^{-1})	7.4	7.2	6.9	6.7	6.3
Saturated hydraulic conductivity K$_s$ (cm/day)	99.8	89.4	83.5	75.6	73.4

soil layers, the soil is classified a saline soil (US Salinity Laboratory Staff 1954).

Temporal change of soil electrical conductivity

In order to evaluate the temporal change of soil electrical conductivity during the 2 years of the monitoring, samples in five soil layers (0–30, 30–60, 60–90, 90–120 and 120–150 cm) were collected monthly in the 1.5-m soil profile (1.5 m represents the maximum depth of date palm root zone). For each soil sample, the electrical conductivity of the saturated paste (EC_e) was determined according to the standard method (US Salinity Laboratory Staff 1954) and expressed in dS m^{-1}.

Soil water content monitoring

The monitoring of water content was done by the time-domain reflectometry (TDR) method (Cichota et al. 2008), which allows for direct determination of soil moisture. The specific instrument used was Trase model 2001 from Soil Moisture Corporation Company. The TDR probes used was the 6005CL2 model adapted to salinisation and previously calibrated. During the 2 years of field observations, soil water content was measured every 10 days with a depth interval of 30 cm down to 150 cm.

Modelling

Model description

The HYDRUS-1D model (version 4.16) was used as a tool to investigate the impact of irrigation practises on land salinisation. HYDRUS-1D simulates the one-dimensional water flow and solute transport in incompressible, porous, variably saturated media, in a steady or transient regime, for a known metric system and various time steps (Šimůnek et al. 2008).

The model solves a modified version of the Richards' equation in order to simulate water movement:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right]-S \tag{1}$$

where θ is the volumetric water content of the soil (L^3 L^{-3}), t is time, z is the vertical coordinate (positive upward), K is the unsaturated hydraulic conductivity (L T^{-1}), h is the soil pressure head (L), and S is the root water uptake (L^3 L^{-3} T^{-1}). Richards' equation is solved numerically for given initial and boundary conditions and for specified soil hydraulic properties. The upper boundary and lower boundary conditions are set as atmospheric boundary condition and free drainage, respectively. The Van Genuchten-Mualem equations (Mualem 1976; Van Genuchten 1980) are used to describe the soil-water characteristic relationships as follows (Eq. 2 and Eq. 3):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s-\theta_r}{1+|\alpha h^n|^m} & for\ \ h<0\ \text{ with } m = 1-\dfrac{1}{n}\quad n>1 \\ \theta_s\quad for\quad h\geq 0 \end{cases} \tag{2}$$

where $\theta_r$and θ_s are the residual and saturated soil water contents(L^3 L^{-3}) respectively, h is the water pressure head (L), α(L^{-1}) and n are shape parameters.

$$K(\theta)=\begin{cases} K_s S_e^{\ell}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 & \text{for} \quad h<0 \quad \text{with} \quad m=1-\dfrac{1}{n} \quad n>1 \quad \text{and} \quad S_e=\dfrac{\theta(h)-\theta_r}{\theta_s-\theta_r} \\ K_s \quad \text{for} \quad h\geq 0 & \end{cases} \tag{3}$$

where K_s is the saturated hydraulic conductivity ($L\,T^{-1}$), S_e is the effective saturation (−), and ℓ is the pore connectivity parameter.

Salt movement in a homogeneous one-dimensional porous medium is governed by the convection–diffusion equation defined as follows:

$$\frac{\partial\theta c}{\partial t}=\frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z}-qc\right)-\varphi \tag{4}$$

where c is the solute concentration of the liquid phase ($M\ L^{-3}$), q is the volumetric flux density given by Darcy's law ($L\ T^{-1}$), φ is the sink or source for solutes ($M\,L^{-3}\ T^{-1}$) and D is a combined diffusion and dispersion coefficient ($L^2\ T^{-1}$). According to Mandare et al. (2008), the molecular diffusion under irrigated field conditions is insignificant relative to dispersion.

Root water uptake

The root water uptake was simulated as a function of depth and time and is a function of the pressure and osmotic heads to account for water and salinity stresses, respectively (Van Genuchten 1987):

$$S(h,h_0,z)=\alpha_1(h)\alpha_2(h_0)\beta(z)T_p \tag{5}$$

where α_1 is the root water uptake stress reduction function ($0\leq\alpha_1\leq 1$) depending on soil water pressure, h (L), α_2 is the root water uptake stress reduction function ($0\leq\alpha_2\leq 1$) depending on osmotic head, h_0 (L), β is the root spatial distribution (L^{-1}) depending on depth (z) and Tp is the maximum transpiration rate ($L\ T^{-1}$). For theα_1, Feddes et al. (1978) proposed a piecewise linear reduction function parameterized by four critical values of the water pressure head, $h_4 < h_3 < h_2 < h_1$:

$$\alpha_1(h)=\begin{cases} 0 \quad h\leq h_4 \quad \text{or} \quad h \geq h_1 \\ \dfrac{h-h_4}{h_3-h_4} \quad h_3 > h > h_4 \\ 1 \quad h_2 \geq h \geq h_3 \\ \dfrac{h-h_1}{h_2-h_1} \quad h_1 > h > h_2 \end{cases} \tag{6}$$

where h_1, h_2, h_3 and h_4 are threshold parameters such that the water uptake of date palm is at the maximum rate when the soil pressure head is between h_2 and h_3, decreases linearly when $h > h_2$ or $h < h_3$, and becomes zero when the soil pressure head is above the anaerobiosis point h_1 and below the wilting point h_4. For the α_2 (h_0)-function, the piecewise linear (threshold-slope) function proposed by Mass and Hoffman (1977) was used:

$$\alpha_2(h_0)=1-\frac{b}{360}\left(h^*{}_0-h_0\right) \tag{7}$$

where b is the yield reduction (expressed in %) resulting from the increase of soil water salinity (expressed in $dS\ m^{-1}$), and $h^*{}_0$ is the soil water osmotic head corresponding to the threshold salinity. This equation is valid for $h_0 \leq h^*{}_0$. β (z) denotes the dimensionless spatial root distribution with depth (z). Once S is calculated as part of a numerical solution of Eqs. (1) and (5), the actual transpiration rate T_a is calculated as follows:

$$T_a=\int_{L_R} Sdz \tag{8}$$

where L_R is the root zone depth.

Model parameters

The modelling was carried out for the selected plot considering a soil profile 1.5 m deep which was modelled by considering five layers corresponding to the soil samples, which were collected every 30 cm. The numerical simulation was conducted with a daily time step using a depth interval dz of 0.05 m. Hydrus-1D simulations were conducted from January 1, 2013 to December 31, 2014. Most of the input parameters required in the model were measured directly in the field or laboratory.

Meteorological data

The model works on a daily basis with daily weather data as inputs: rainfall, air temperature, wind speed, relative humidity and solar radiation (Table 3). These data were measured by an automatic weather station installed in the

Table 3 Average monthly temperature, solar radiation (R), relative humidity (RH), wind speed (U), rainfall and reference evapotranspiration (ET_0) in 2013 and 2014

Month	Data					
	Temperature (°C)	R (MJ m^{-2} day)	RH (%)	U (m s^1)	Rainfall (mm)	ET_0 (mm day^{-1})
January	15.6	11.8	59.8	3.8	15.2	2.4
February	17.2	14.6	53.7	3.2	11.3	3.4
March	20.4	19.9	46.4	4.8	10.4	5.1
April	25.6	24.5	45.1	4.4	9.5	7.1
May	28.3	25.8	36.5	4.7	8.0	10.3
June	33.9	28.1	31.8	4.6	0.4	10.6
July	36.6	28.6	31.4	4.4	0.7	11.1
August	36.9	29.5	35.1	4.3	0.3	11.2
September	32.5	16.8	44.8	4.8	0.1	7.1
October	27.9	14.1	49.7	4.3	8.9	5.4
November	20.4	12.7	57.6	3.8	8.7	3.1
December	15.3	10.1	68.4	3.8	14.5	2.1

oasis since September 2012. The monitoring of each weather parameter is done hourly, and daily data are obtained by determining the mean of data collected for 24 h. ET_0 software (Raes 2007) was used to estimate daily evapotranspiration (ET_0) from the collected data based on the FAO Penman-Monteith equation.

Soil hydraulic properties

The parameters describing soil hydraulic properties are presented in Table 4. The measured saturated hydraulic conductivity (K_s) was used in the simulation. The soil hydraulic parameters θ_r (residual water content) and θ_s (saturated water content) were determined from the particle size distribution and bulk density of the soil with the Rosetta model (Schaap et al. 2001) implemented in Hydrus-1D. The pedotransfer functions obtained were adjusted to the values of volumetric water content and electrical conductivity measured in the field by inverse modelling, as described by Šimůnek et al. (2005), an optimization method matching numerical results with field data. This method was used for determining the shape parameters (α and n), and the pore connectivity parameter (ℓ), which are the sensitive parameters to water flow according to Lu and Zhang (2002). One parameter at a time was optimized for each layer, the remaining parameters being kept fixed. This procedure was repeated for each parameter. The soil hydraulic parameters were determined by inverse modelling using measured data during the year 2013.

The agreement between the Rosetta output (Table 4) and the soil moisture-matric potential relationship

Table 4 Determined hydraulic parameters for different soil layers

Determination	Soil depth (cm)				
	00–30	30–60	60–90	90–120	120–150
Residual water content θ_r (cm^3/cm^3)	0.023	0.023	0.028	0.029	0.035
Saturated water content θ_s (cm^3/cm^3)	0.27	0.28	0.32	0.31	0.33
Saturated hydraulic conductivity K_s (cm/day)	99.8	89.4	83.5	75.6	73.4
α (cm^{-1})	0.25	0.19	0.18	0.18	0.16
n	2.81	2.65	2.65	2.40	2.41
ℓ	0.48	0.48	0.46	0.43	0.42

between −33 and −1500 kPa (Table 2) was verified, as shown in Fig. 2. (Fig. 2 shows only the results of the 00–30-cm soil layer, but a good agreement was also noted for the other soil layers).

Solute transport parameters

The parameters related to solute transport within the soil profile are presented in Table 5. The soil dispersion length α_L (a parameter characterising the longitudinal dispersivity of salts within the soil) was set to 8.35 cm, based on an inverse analysis by Hydrus-1D (using measured data during the year 2013). According to Mandare et al. (2008), the molecular diffusion under irrigated field conditions is less effective than hydrodynamic dispersion. In the Saharan oases of Tunisia, the water flow through soil layers caused by soil surface evaporation is of the order of a few millimetres per day. Therefore, the use of a diffusion coefficient is required in the simulations. The diffusion coefficient in soil is a function of volumetric water content (Hamamoto et al. 2010); for this reason, it was measured (using a transient state method described by Mehta et al. (1995)) over a wide range of water contents (just before irrigation event; immediately after irrigation; 5, 10, and 15 days after irrigation). The obtained diffusion coefficients were ranged from 0.16 to 0.26 $cm^2\ s^{-1}$. For the five soil layers, the initial profile of electrical conductivity measured at the beginning of study was used in the simulations.

Crop data

A summary of the HYDRUS-1D input data with regard to crop type is shown in Table 6. The thickness of the root zone layer, the root density and the spatial distribution of roots were measured through intensive sampling around the study date palm trees. The details reported by Munier (1973), Oihabi (1991) and Zaid and Jiménez (2002) were used during measurement. Roots are typically concentrated between 0.3 and 1.5 m with a density of 14 $cm^3\ cm^{-3}$. Therefore, the modelled thickness of the root layer (L_R) was set at 1.2 m. The spatial distribution of roots (β) was fixed at 0.008 cm^{-1}. The parameters for root water uptake are not available in the literature for date palms. The critical values of pressure head (h_1, h_2, h_{3high}, h_{3low} and h_4) required for calculating the root water uptake reduction function due to water stress ($\alpha_1(h)$) were selected from the data suggested by Feddes et al. (1976) for various vegetable crops. Root water uptake reduction function due to salinity stress ($\alpha_2(h_0)$) was described by adopting the following salinity threshold and slope function (reduction of plant yield caused by increasing of soil salinity): $h^*_0 = 4$ dS m^{-1} and $b = 3.6$ % per unit of electrical conductivity (Mass and Hoffman, 1977).

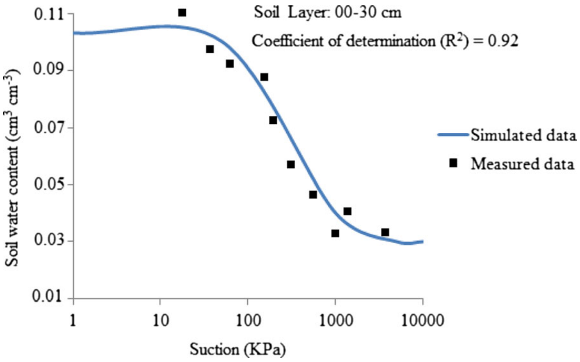


Fig. 2 Estimated and measured soil water content–matric potential relationship

Table 5 Parameters for the calculation of solute transport using the HYDRUS-1D model

Parameter	Value
Initial electrical conductivity (dS m^{-1})	
Soil layer 1 (00–30 cm)	7.4
Soil layer 2 (30–60 cm)	7.2
Soil layer 3 (60–90 cm)	6.9
Soil layer 4 (90–120 cm)	6.7
Soil layer 5 (120–150 cm)	6.3
Dispersion length, α_L, (cm)	8.35
Diffusion coefficient ($cm^2\ s^{-1}$)	0.16 to 0.26

Table 6 Crop data used in HYDRUS-1D model

Data	
Crop	Date palms (*Phoenix dactylifera*)
Maximum rooting depth (m)	1.5
Thickness of the root layer (cm)	1.2
Root density ($cm^3\ cm^{-3}$)	14
Spatial distribution of roots (β) (cm^{-1})	0.008
h_1, h_2, h_{3high}, h_{3low} and h_4 (cm)	0, 0, −500, −600, −15,000
Electrical conductivity threshold (dS m^{-1})	4
Slope (% per dS m^{-1})	3.6

Boundary and initial conditions

Given that the shallow groundwater was absent in the study area, the bottom boundary condition was considered as free drainage for water and zero concentration gradient for salt transport. The irrigated area was equipped with a drainage system consisting of 2-m deep open ditches spaced 50 m apart.

The upper condition of the soil profile was set as atmospheric boundary condition (BC). Implementing the atmospheric BC requires specifying water inputs (irrigation and rainfall), as well as potential evaporation and transpiration rates. The water inputs measured during the observation period (2013 and 2014) are summarized in Table 7. The irrigation duration in the monitoring field was set at 4 h for every irrigation event. Potential transpiration and potential evaporation were determined as the product of reference evapotranspiration (ET_0) by the basal crop coefficient (K_{cb}) and the evaporation coefficient (K_e), respectively (Allen et al. 1998). ET_0 software (Raes 2007) was used to estimate daily ET_0 from the collected weather data. K_e was determined as follows (Allen et al. 1998):

$$K_e = \min(K_r(K_{c\max} - K_{cb}), fK_{c\max}) \quad (9)$$

where K_{cmax} is the maximum value of the crop coefficient following rain or irrigation, f is the fraction of soil not covered by plants and exposed to evaporation, K_{cb} is the basal crop coefficient and K_r is the dimensionless evaporation reduction coefficient dependent on the moisture content of the upper soil layer (00–30 cm). According to Allen et al. (1998), K_{cmax} and K_{cb} were 1.20 and 0.85, respectively. f was determined and fixed at 0.38 based on the estimation suggested by Allen et al. (1998). K_r was calculated according to the equations proposed by Allen et al. (1998). During the simulation period, K_r showed always the maximal value (near 1) on the irrigation day, due to the full saturation of the soil, and the minimal value (near 0) after 15 days due to the dry condition of the topsoil. The calculated values of K_{cmax}, K_{cb}, f and K_r were introduced into Eq. (9) in order to determine the K_e coefficient, which varied from 0.18 to 0.27 during the 2 years of the study. In the HYDRUS-1D model, the potential transpiration was transformed into actual transpiration by means of the root water uptake reduction function (Eq. 5), whereas soil actual evaporation was estimated by the model, according to the moisture conditions at the topsoil. The initial conditions were derived from the measured soil moisture and salinity data. The initial soil water content was 0.066, 0.067, 0.071, 0.072 and 0.074 $cm^3\ cm^{-3}$, respectively, for the five soil layers downward. The salinity data are noted in Table 5.

Validation of the Hydrus-1D model

To validate the model under the current management of irrigation water in the oasis, field measurements (soil water content and soil electrical conductivity) in 2014 were used. The modelling results were graphically and statistically evaluated. In the graphical approach, the measured and simulated volumetric water contents and soil electrical conductivity were plotted as a function of soil depth. The statistical approach involved the calculation of the root mean square error (RMSE) and the Nash–Sutcliffe model efficiency coefficient (NSE). These indicators were defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum (S_i - M_i)^2} \quad (10)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} \left(M_i - \overline{M}\right)^2} \quad (11)$$

where S_i and M_i are the ith simulated and measured values respectively, n is the number of

Table 7 Amounts of rainfall and irrigation in the plot during the observations

Year	Rainfall (mm)	Irrigation			Total (mm)
		Irrigation amount (mm)	Irrigation frequency (days)	Number of irrigation events	
2013	88	160	35	10	1688
2014	79	150	–	12	1879

observations and *M* is the average of measured values. The closer to 0 the RMSE, the more accurate is the model. An NSE equal to 1 represents a perfect agreement between the measured and simulated results.

Simulation exercise

After proper validation of the model, different simulation scenarios were carried out to test the impact of the irrigation practises on the temporal changes in soil electrical conductivity and soil water content, as simulated by the HYDRUS-1D model with a daily time step during one study year. The field data of the year 2013 (rainfall, evapotranspiration, etc.) were used. The simulations were performed under field conditions without saline shallow groundwater. The aim was to identify the best irrigation practise (water salinity, irrigation frequency and irrigation amount) which allows maintaining the soil electrical conductivity at safe levels (<4 dS m^{-1}) (Mass and Hoffman, 1977) and provides adequate soil water content in the root zone, i.e. above a soil water content threshold of 0.04 cm^3 cm^{-3} (soil wilting point).

Eighteen scenarios of irrigation management were designed on the basis of irrigation treatment in the study oasis and irrigation practises observed in many Tunisian Saharan oases (Table 8):

- Selection of irrigation frequencies (number of irrigation events):

– The low number of irrigation events noted in the study area during the year 2013 (10 events) contributes to soil salinisation. In order to evaluate the effect of increasing this number (*N*) on soil electrical conductivity and soil water content, three irrigation frequencies (IF) were selected as follows:

– IF = 30 days (*N* increases 20 % of the 2013 reference value; *N* + 2 = 12);

Table 8 Irrigation scenarios simulated by the HYDRUS-1D model

Irrigation scenario (N°)	Water salinity (dS m^{-1})	Irrigation frequency (days)	Number of irrigation events	Water amount in 1 irrigation event (mm)	Annual irrigation water (mm)
1	4 (saline water)	30[a]	12	114 (100 % ET_c)	1368
2				103 (90 % ET_c)	1236
3		26[b]	14	100 (100 % ET_c)	1400
4				89 (90 % ET_c)	1246
5		22[c]	16	84 (100 % ET_c)	1344
6				75 (90 % ET_c)	1200
7	3 (moderate-saline water)	30	12	114	1368
8				103	1236
9		26	14	100	1400
10				89	1246
11		22	16	84	1344
12				75	1200
13	2 (low-saline water)	30	12	114	1368
14				103	1236
15		26	14	100	1400
16				89	1246
17		22	16	84	1344
18				75	1200

IF irrigation frequency)

[a] Short IF

[b] Moderate IF

[c] High IF

- IF = 26 days (N increases 40 % of the 2013 reference value; $N + 4 = 14$);
- IF = 22 days (N increases 60 % of the 2013 reference value; $N + 6 = 16$).

- Selection of irrigation amounts:

- Based on the average actual daily evapotranspiration of the year 2013 ($ET_c = 3.8$ mm day^{-1}), two irrigation amounts (I_1 and I_2) were selected for each irrigation frequency:

IF = 30 days:

- $I_1 = 100$ % of $ET_c = 30 \times 3.8 \times 1 = 114$ mm; $I_2 = 90$ % of $ET_c = 30 \times 3.8 \times 0.9 = 103$ mm

IF = 26 days:

- $I_1 = 100$ % of $ET_c = 26 \times 3.8 \times 1 = 100$ mm; $I_2 = 90$ % of $ET_c = 30 \times 3.8 \times 0.9 = 89$ mm

IF = 22 days:

- $I_1 = 100$ % of $ET_c = 22 \times 3.8 \times 1 = 84$ mm; $I_2 = 90$ % of $ET_c = 30 \times 3.8 \times 0.9 = 75$ mm
- Selection of irrigation water salinities:

- Different water salinities were selected on the basis of irrigation practices observed in Tunisian Saharan oases (CRUESI 1970)

Results and discussion

Field measurements of soil salinisation

Upward fluxes from a saline shallow groundwater can contribute significantly to soil salinisation in irrigated areas (Babajimopoulos et al. 2007) due to capillary rise, whenever the water table level reaches a critical depth, usually considered to be 1.5 m below the soil surface (Northey et al. 2006). Under field conditions without saline shallow groundwater (as the study area), the noted salinisation of the irrigated soil should be mainly attributed to irrigation management (Fig. 3).

Under the current management of irrigation water, a seasonal variation of electrical conductivity (EC_e) of the 00–30-cm soil layer was noted for both years of the monitoring (Fig. 3). This seasonal variation of soil salinity was characterized by an increased trend in the summer, due to irrigation with saline water, and a decreasing trend in the winter, due to salt leaching by rainfall (Chen et al. 2010). In 2013, EC_e varied from 7.4 dS m^{-1} in January to 11.8 dS m^{-1} in August, with an average of 9.8 dS m^{-1}. In 2014, the EC_e ranged from 10.1 dS m^{-1} in January to 14.9 dS m^{-1} in August, with an average of 12.8 dS m^{-1}. The long-term increase in EC_e,, which is the difference between the years, was very remarkable in the field. The low impact of soluble salt leaching by rains in the study area is the main cause of this increase between the years (Marlet et al. 2009). During the monitoring period, it is clear that EC_e can build up to levels that exceed the salt tolerance of date

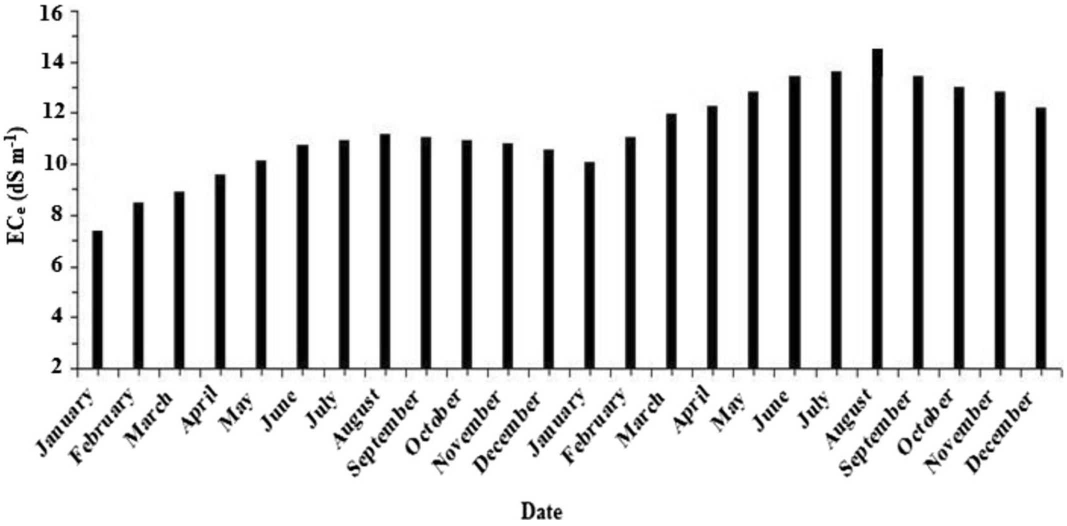


Fig. 3 Temporal change of the electrical conductivity (EC_e) measured in the 00–30-cm soil layer during 2013 and 2014

palms, estimated at 4 dS m^{-1} (Mass and Hoffman, 1977). Similar results (salinity >4 dS m^{-1}, seasonal and yearly variations of soil salinization) were also noted for the other soil layers (30–60, 60–90, 90–120 and 120–150 cm). The initial saline condition of the irrigated soil, the high salinity of irrigation water (EC_{iw} = 6.5 dS m^{-1}), the high evaporative demand, the low rainfall (≈80 mm $year^{-1}$) and especially the low irrigation frequency (≥35 days) all contribute to the progressive salinisation of the irrigated area. Studies have shown that frequent irrigation can leach salt effectively, thereby reducing the salt content of the root zone and resulting in salt tolerance of a given crop (Ramos et al. 2012).

The distribution of the electrical conductivity measured in the different layers of the soil profile at the end of summer of each year (2013 and 2014) is presented in Fig. 4. Under the current irrigation treatment, the electrical conductivity of all the soil layers was higher than 6 dS m^{-1}, making the irrigated soil a saline soil (US Salinity Laboratory Staff 1954). The electrical conductivity distribution throughout the soil profile was mainly attributed to the effects of the low irrigation frequency and the high evaporative demand especially at the surface soil layer (0–30 cm).

Actual soil evaporation and date palm transpiration

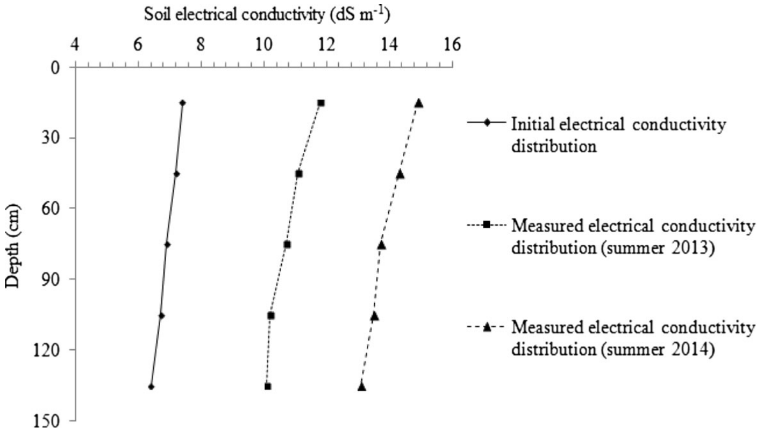
Daily actual soil evaporation and date palm transpiration, as simulated by the Hydrus-1D model for 2013 with the irrigation practises in the oasis, are illustrated in Fig. 5. Actual soil evaporation varied between 0.9 and 3.5 mm day^{-1} with an average of 1.7 mm day^{-1}. Actual transpiration varied from 1.1 to 4.4 mm day^{-1} with an average of 2.1 mm day^{-1}. For comparison, in another Tunisian Saharan oasis (ancient oasis with saline shallow groundwater), daily simulated transpiration rate of date palms ranged from 0.4 to 9.1 mm day^{-1}, with an average of 2.4 mm day^{-1} for a water table depth of 200 cm (Askri et al. 2014). This comparison reveals the contribution of shallow groundwater to the date palm water use (transpiration). In contrast to the modern oases of Tunisia (like the monitored field), in ancient Tunisian oases, the presence of water tables at shallow depths considerably increased the actual transpiration of date palms, especially during periods when no rainfall and no irrigation occurred (Askri et al. 2014). This reinforces the point that the date palm is able to meet its water needs with shallow groundwater despite its high salinity.

The variation of actual soil evaporation and transpiration of date palms throughout the year are related to the weather conditions and irrigation events. For example, in summer (from DOY 150 to 240), actual soil evaporation rate is very high due to high air temperatures (> 30 °C) and low relative humidity (<35 %). As to actual transpiration rates, the peaks observed in summer represent the responses of palms to irrigation events. This confirms that date palm responds quickly to the water inputs. During the winter season, the first 2 months of the year (from DOY 0 to 60) and the last 2 months (from DOY 300 to 360), the actual transpiration rate decreases in relation to weather factors, and hence, irrigation events have a lower effect.

Model validation

Figure 6 presents the time-series of the soil electrical conductivity and soil water content of the different soil layers, as measured and as simulated by the model,

Fig. 4 Measured electrical conductivity distribution at the summer end of each study year



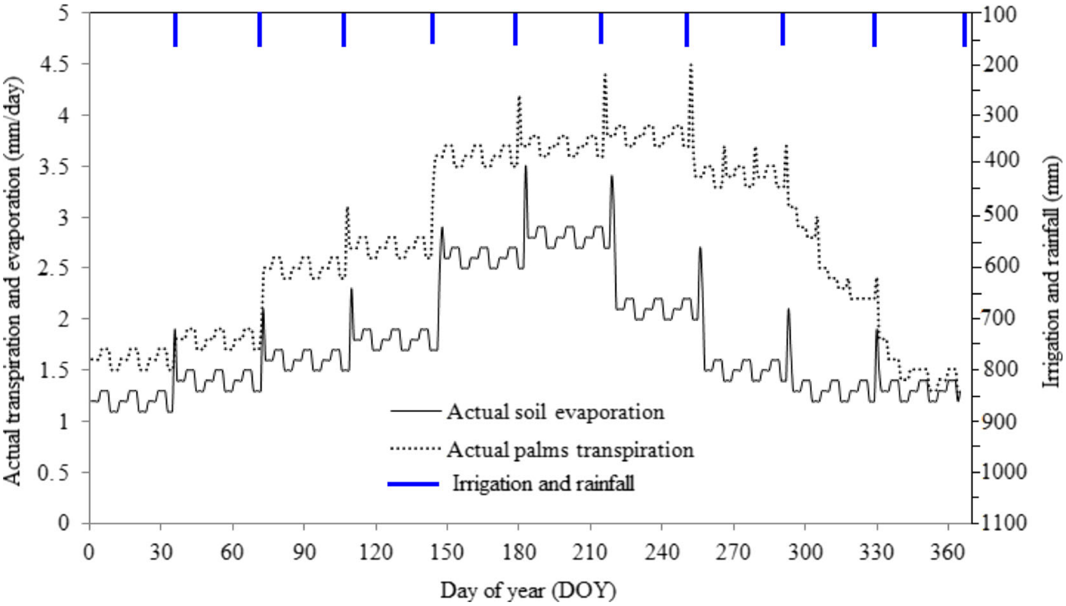


Fig. 5 Daily variation of actual soil evaporation and transpiration as simulated by the HYDRUS-1D model during 2013

during the validation period (2014) under the current irrigation practises. The agreement between the simulated and observed data was evaluated by the root mean square error (RMSE) and the Sutcliffe model efficiency coefficient (NSE). For the soil electrical conductivity, the RMSE varies from 0.58 to 0.91 dS m^{-1}, whereas the NSE ranges from 0.80 to 0.89 (Fig. 6a). For the soil water content, the RMSE varies from 0.012 to 0.02 cm^3 cm^{-3}, whereas the NSE ranges from 0.78 to 0.87 (Fig. 6b). The small values of RMSE (close to 0) and the good values of NSE (close to 1) indicate that the HYDRUS-1D model gives acceptable estimates of water and salt movements in the soil profile. The small discrepancy between the simulated and measured values may be attributed to experimental errors (such as the estimation of irrigation water amount) and to some physical processes, such as adsorption and hysteresis in the retention curve, which are not taken into account by the model. Furthermore, as the model works on a daily basis, it ignored the daily fluctuations of input factors, which could cause uncertainties in model results.

Soil salinisation under different irrigation scenarios

The effects of changes in irrigation water salinity, irrigation frequency and irrigation amount on the root zone electrical conductivity and on the soil water content at the root zone were simulated under field conditions without saline shallow groundwater (Table 8).

The maximum values of simulated soil electrical conductivity in the root zone for the different irrigation amounts are presented in Fig. 7a. With a water salinity of 2 dS m^{-1} (low-saline water) and an irrigation amount of 100 % of ET$_c$, where ET$_c$ is the evapotranspiration requirements, the maximum root zone electrical conductivity ranged from 2.3 to 2.7 dS m^{-1}. With a salinity of 3 dS m^{-1} (moderate-saline water), it ranged from 3.2 to 3.9 dS m^{-1}, and with a salinity of 4 dS m^{-1} (saline water), it ranged from 3.6 to 4.8 dS m^{-1}. As expected, root zone electrical conductivity increased with applied water salinity. Date palm is considered to be one of the most tolerant crops to salinisation, and it is slightly affected by salinisation stress. A previous study conducted in an Egyptian oasis (El-Bana and Ibrahim, 2008) showed that date palm can produce full yields if it is irrigated with saline water up to 2 g l^{-1}, but the yield is reduced by 10, 25 and 50 % if irrigation water salinity rises to 3, 5 and 8 g l^{-1}. The salinity of the irrigation water significantly affected the electrical conductivity of the root zone (Fig. 7a). However, this was not the case with a shallow water table. Indeed, the analysis of the interaction between water table depth and irrigation water salinity conducted in another Saharan oasis of Tunisia demonstrated that the salinity of irrigation water had a low impact on root zone salinisation when the saline groundwater was less than 1 m deep (Askri et al. 2014).

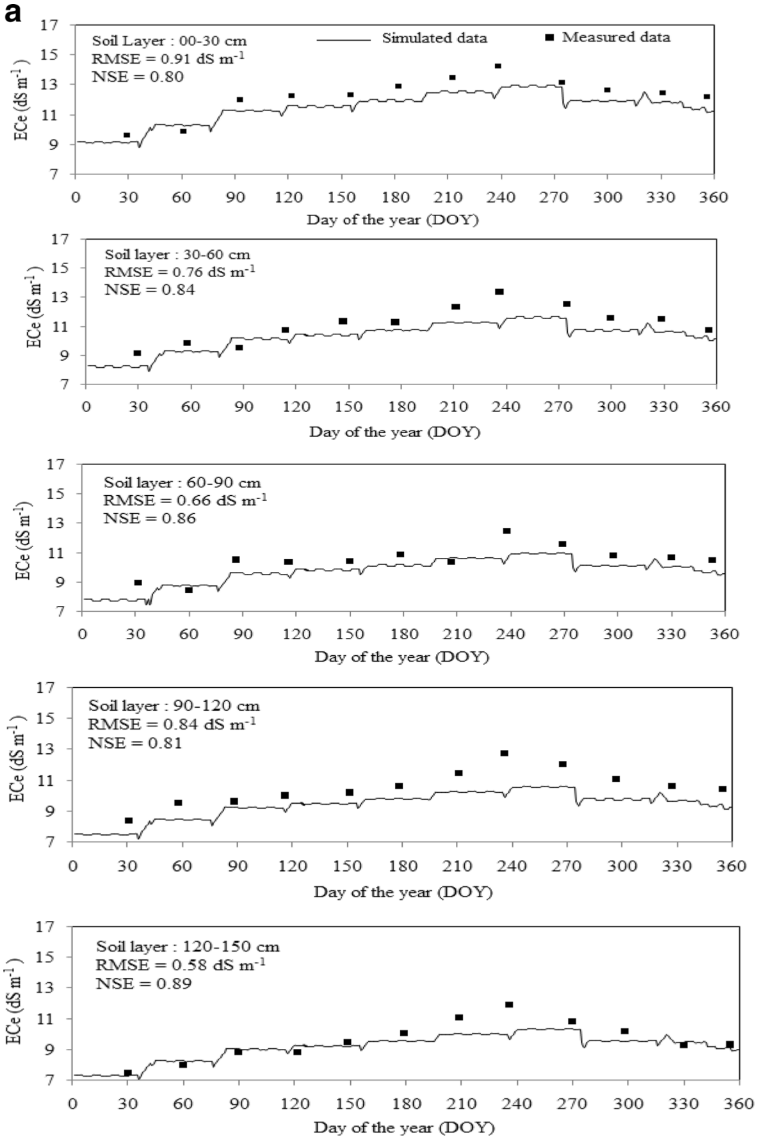


Fig. 6 **a** Comparison between simulated and measured soil electrical conductivity (EC_e) during the validation period (2014) for the different soil layers. **b** Comparison between simulated and measured volumetric water content during the validation period (2014) for the different soil layers

With both of the irrigation amounts (100 and 90 % of ET_c), the electrical conductivity threshold of 4 dS m^{-1} for date palms was not reached when irrigation water with low and moderate salinity (2 and 3 dS m^{-1}) was used. When irrigation water has a high salinity (4 dS m^{-1}), soil electrical conductivity is maintained below 4 dS m^{-1} only in the case of a high irrigation frequency (22 days). These results demonstrated that salt accumulation decreased when the amount of applied water increases. Indeed, as the amount of irrigation water increased consecutive to an increase of irrigation frequency, more salts were leached out of the soil profile and the soil electrical conductivity decreased. With saline water, a high irrigation frequency of 22 days (short duration between two successive irrigation events) significantly contributed to salt leaching and greatly reduced the electrical conductivity of irrigated soil. Therefore, under field conditions without saline shallow groundwater, saline irrigation water can be used to maintain the maximum soil electrical conductivity at safe levels (<4 dS m^{-1}) if an appropriate irrigation frequency (frequent irrigations) and an appropriate

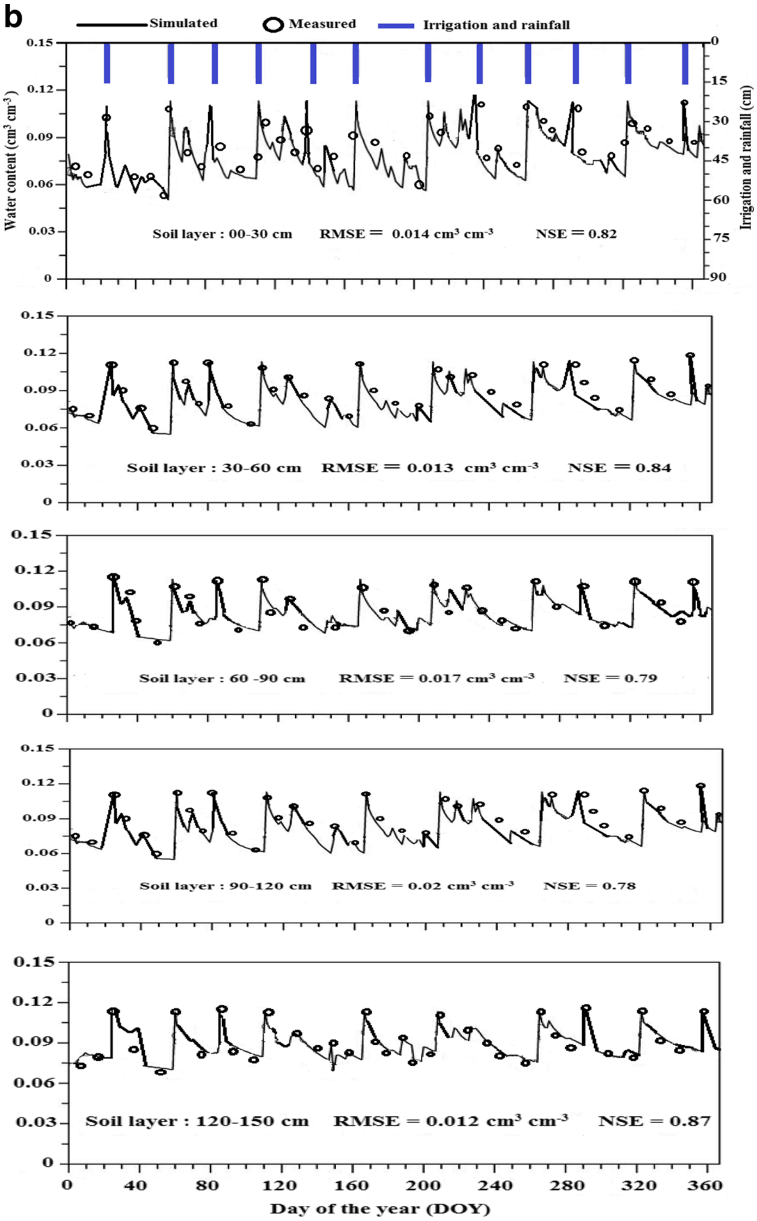


Fig. 6 (continued)

water amount (100 or 90 % of ET_c) are applied. This irrigation management is confirmed also by the results presented in Fig. 7b. Indeed, the minimum simulated soil water content in the root zone was higher than 0.04 cm^3 cm^{-3} (soil water availability) for an irrigation frequency of 22 days.

As expected, the simulation results (Fig. 7b) showed that the soil water content in the root zone was improved when the frequency and amount of irrigation were increased. The salinity of applied water also had a significant effect. Indeed, decreasing irrigation water salinity (from saline to low-saline water) can significantly contribute to decrease soil water content in the root zone. Decreasing irrigation water salinity will reduce the stress on plants, increase root water uptake and consequently decrease soil water contents.

Due to the shortage of water resources in the Saharan oasis of Tunisia, it is recommended to use the lowest irrigation amount (90 % of ET_c) among the two simulated amounts. Indeed, the simulation results presented

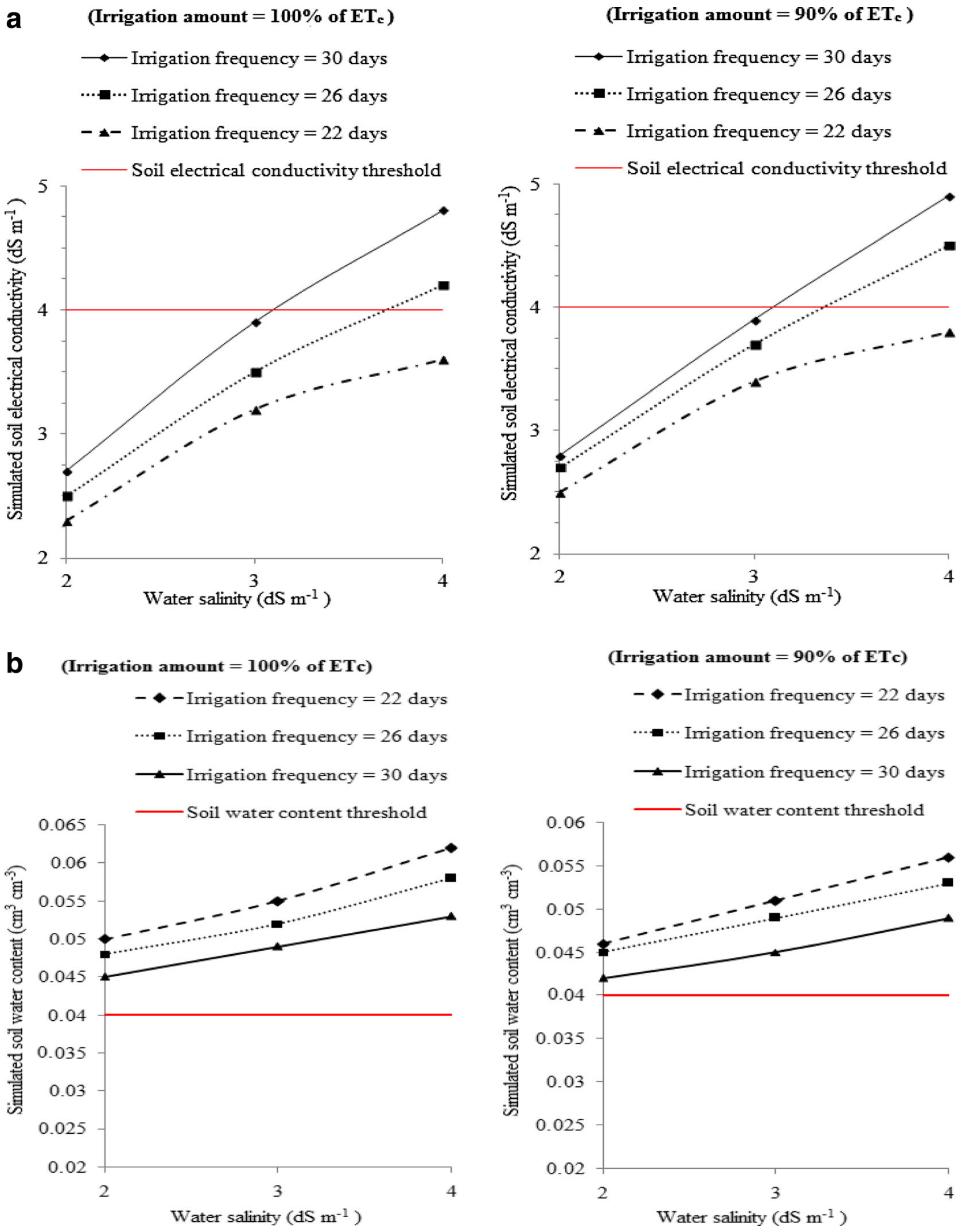


Fig. 7 **a** Maximum values of simulated soil electrical conductivity (at the root zone) for the different irrigation amounts (100 and 90 % of the evapotranspiration requirements). **b** Minimum values of simulated daily soil water content (at the root zone) for the different irrigation amounts (100 and 90 % of the evapotranspiration requirements)

in Fig. 7a, b showed that providing 90 % of the evapotranspiration requirements by irrigation will result in acceptable limits for soil electrical conductivity and soil water content.

Irrigation of date palms is necessary throughout the year, but the irrigation frequencies, irrigation amounts and water salinities must be taken into consideration. Pre-season irrigation has the potential to leach salt out of the root zone and maintain it at reduced levels (Marlet et al. 2009). Our simulation exercise provided insights into soil water and salt redistribution and their effects on soil salinisation and should help in the establishment of improved management practises for irrigated arid areas.

Conclusion

The results of our field investigation of soil salinisation in a representative area of the Saharan oases of Tunisia showed that the current irrigation practises contribute greatly to salt accumulation within the soil profile. The effects of different irrigation management strategies on soil electrical conductivity, using numerical simulations with HYDRUS-1D, showed that saline irrigation water can be used to maintain safe levels of both electrical conductivity (soil salinisation <4 dS m^{-1}) and soil water content (>0.04 cm^3 cm^{-3}) if frequent irrigations with small amounts of water (90 % of evapotranspiration requirements) are applied throughout the year. Root zone salinisation and the soil water content also may be affected by some agronomic and environmental factors that were not taken into account in this study, and future research that includes these factors in the model simulations would be useful for understanding irrigation management of date palms in arid lands.

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