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Effects of shallow water table, salinity and frequency of irrigation water on the date palm water use

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SUMMARY

In southern Tunisia oases, waterlogging, salinity, and water shortage represent serious threats to the sustainability of irrigated agriculture. Understanding the interaction between these problems and their effects on root water uptake is fundamental for suggesting possible options of improving land and water productivity. In this study, HYDRUS-1D model was used in a plot of farmland located in the *Fatnassa* oasis to investigate the effects of waterlogging, salinity, and water shortage on the date palm water use. The model was calibrated and validated using experimental data of sap flow density of a date palm, soil hydraulic properties, water table depth, and amount of irrigation water. The comparison between predicted and observed data for date palm transpiration rates was acceptable indicating that the model could well estimate water consumption of this tree crop. Scenario simulations were performed with different water table depths, and salinities and frequencies of irrigation water. The results show that the impacts of water table depth and irrigation frequency vary according to the season. In summer, high irrigation frequency and shallow groundwater are needed to maintain high water content and low salinity of the root-zone and therefore to increase the date palm transpiration rates. However, these factors have no significant effect in winter. The results also reveal that irrigation water salinity has no significant effect under shallow saline groundwater.

1. Introduction

Date palm (*Phoenix dactylifera,* Deglet Nour) is the main fruit tree cultivated in Tunisian oases and is naturally adapted to drought conditions in the southern part of the country, where evapotranspiration exceeds 1500 mm year^{-1} and rainfall is less than 100 mm year^{-1} (SANYU Consultants INC., 1996). These systems are intensively cultivated and are particularly known for their important biodiversity. Typically, several crops such date palms, fruit trees, and market gardening are cultivated on the same field (Askri et al., 2010). The irrigation water is mainly supplied by the Northwest Sahara Aquifer System (NWSAS) which consists of the complex terminal and the continental intercalary aquifers. Water management in the oases faces several technical and environmental constraints. There are relevant water losses that occur along the water distribution system, starting from the pumping station until the parcel entrance. These losses decrease the water discharge. Furthermore, illegal planting of private palm trees on parcels of land on the periphery of oases has required more water allocation and the irrigation network capacity became unable to satisfy the water demand (Omrani and Dieter, 2012). These factors induced water shortage in the summer season and consequently the interval between two irrigation applications extended to more than 45 days. Under these conditions, farmers increased the irrigation time and applied excessive amounts of irrigation water to ensure that crop needs are fulfilled. As soils are predominantly sandy, such over-irrigation makes the groundwater table rise up to few centimetres below land surface, leading to positive salt balance in the root-zone and chronic waterlogging (Askri et al., 2010). In Southern Tunisia, the areas affected by soil salinisation (soil salinity >4 dS/m) and groundwater rise (average depth <1.5 m) are estimated to be about 20,000 and 5000 ha, respectively (FAO, 2011). To overcome these problems, a massive effort has been implemented since the 1990s with the execution of the APIOS project (Improvement of Irrigated Areas in Southern Oases) for improving the irrigation and drainage schemes and increasing farmers' incomes (SANYU

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Consultants INC., 1996). The rehabilitation works undertaken allowed 25 to 30% saving of water losses, and adding to that the irrigation interval was shortened by 3 to 2 weeks within the rehabilitated oases (SAPI, 2005). Despite these works, the amounts of irrigation water still exceed the crops water requirement, whereas other parcels suffer from the problem of water shortage in the summer season. Sustainable irrigation management in oases requires the correct determination of water requirement for crops.

Date palm transpiration in Tunisian oases has been documented since the 1970s. El Amami and Laberche (1973) estimated the real water requirements of this tree crop using the soil method (neutron probe and tensiometers). Sellami and Sifaoui (2003) carried out of sap flow measurements on date palms in the oasis of *Tozeur* showing that the variation of sap flow is governed by environmental variables such as soil moisture deficit and vapour pressure deficit. Recently, Ben Aïssa et al. (2009) used a similar approach to quantify date palm transpiration in the *Fatnassa* oasis. They showed that this process considerably affects the short term groundwater regime. However, these studies were based on simplifications where the water consumption of date palm was considered independently of the water table depth, root-zone salinity, fertilizers, and irrigation management. Ghazouani (2009) indicated that the water tale depth has a significant effect ($p < 0.05$) on date palm quantity and a highly significant effect ($p < 0.001$) on its quality.

Understanding the interaction between climatic conditions, irrigation practices, water salinity, groundwater regime, and their effects on root water uptake is fundamental to maintain the existing oases, and thus to ensure the sustainability of date production in Southern Tunisia. Such effects can be conveniently described using HYDRUS-1D package that simulates water and solute transfers across the root-zone (Šimůnek and Suarez, 1997). This model software can evaluate the reduction of transpiration and evaporation from their potential to their actual values based on the conditions prevailing in the soil profile and the specific properties of the vegetation. The objectives of this study are: (i) to validate the HYDRUS-1D model for simulating the date palm transpiration under shallow saline groundwater, and (ii) to analyse the individual and combined effects of water table depth, and salinity and frequency of irrigation water on root water uptake.

2. Materials and methods

2.1. HYDRUS-1D package software

HYDRUS-1D model (Šimůnek et al., 2008) was used to simulate the one dimensional water flow and salt transport in a variably saturated medium. Water flow was simulated with Richards' equation as follows:

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

where θ is the soil water content ($L^3\,L^{-3}$), h is the soil pressure head (L), t is the time (T), z is the vertical coordinate (positive upward), K is the unsaturated hydraulic conductivity ($L\,T^{-1}$), and S is a root extraction term ($L^3\,L^{-3}\,T^{-1}$). The unsaturated soil hydraulic properties were described using the van Genuchten–Mualem functional relationships (Mualem, 1976; van Genuchten, 1980) as follows:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+|\gamma h|^n)^m} & \text{for } h < 0 \\ \theta_s & \text{for } h \geqslant 0 \end{cases} \tag{2}$$

$$K(\theta) = K_s S_e^{1}\left[1 - \left(1 - S_e^{1/m}\right)^{m}\right]^{z} \tag{3}$$

$$m = 1 - 1/n \tag{4}$$

where S_e is the effective saturation:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{5}$$

and where θ_r and θ_s are the residual and saturated soil water contents ($L^3\,L^{-3}$), respectively; K_s is the saturated hydraulic conductivity ($L\,T^{-1}$); γ is the air entry parameter; n is the pore size distribution parameter (–); and l is the pore connectivity parameter, which is always taken as 0.5 (Mualem, 1976).

Salt transport in a homogeneous one-dimensional porous medium was computed using the convection–diffusion equation (CDE) as follow:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial z} - qc\right) - \phi \tag{6}$$

where c is the solute concentration of the liquid phase ($M\,L^{-3}$), D is a combined diffusion and dispersion coefficient ($L^2\,T^{-1}$), and q is the volumetric flux density given by Darcy law ($L\,T^{-1}$), and ϕ is sink or source for solutes ($M\,L^{-3}\,T^{-1}$). In this paper, S and ϕ are associated exclusively with root uptake process. The molecular diffusion under irrigated field conditions is insignificant relative to dispersion, and was neglected in this study (Mandare et al., 2008).

2.2. Root water uptake

Modelling water uptake with sink terms in Eqs. (1) and (6) is a typical macroscopic approach that averages uptake over a large number of roots. It was assumed that the potential root water uptake of the crop can be reduced due to water stress as a result of the adopted irrigation schedule. It was also assumed that the potential root water uptake can be further reduced by osmotic stress, resulting from the use of saline irrigation water. The effects of water and salinity stresses were considered to be multiplicative as described by van Genuchten (1987):

$$S(h, h_0, z) = \alpha_1(h)\alpha_2(h_0)\beta(z)T_p \tag{7}$$

where T_p is the potential transpiration rate ($L\,T^{-1}$), α_1 is the root water uptake stress reduction function ($0 \leqslant \alpha_1 \leqslant 1$) depending on soil water pressure, h (L), α_2 is the root water uptake stress reduction function ($0 \leqslant \alpha_2 \leqslant 1$) depending on osmotic head, h_0 (L), β is the root spatial distribution (L^{-1}). For the $\alpha_1(h)$-function, we used the following water stress reduction function proposed by Feddes et al. (1978):

$$\alpha_1(h) = \begin{cases} 0, & h \leqslant h_4 \text{ or } h > h_1 \\ \frac{h-h_4}{h_3-h_4} & h_4 < h \leqslant h_3 \\ 1, & h_3 < h < h_2 \\ \frac{h-h_1}{h_2-h_1} & h_2 < h \leqslant h_1 \end{cases} \tag{8}$$

where h_1, h_2, h_3, and h_4 are threshold parameters such that water uptake of date palm is at the potential 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. The HYDRUS-1D model includes a database of suggested crop-specific parameters for water uptake. However, the values of h_1, h_2, h_3 and h_4 for the date palm are not available.

For the $\alpha_2(h_0)$-function, we used the piecewise linear (threshold-slope) function proposed by Mass and Hoffman (1977) as follows:

$$\alpha_2(h_0) = 1 - \frac{b}{360}\left(h_0^* - h_0\right) \tag{9}$$

where b is the yield reduction as percent per unit increase salinity of soil water as $dS\,m^{-1}$, and h_0^* is the threshold soil water osmotic head corresponding to the threshold soil water salinity (L). This equation is valid for $h_0 \leqslant h_0^*$. The threshold salinity level for the date palm was assumed to be 4 dS m^{-1}; above this value, the root water uptake declines at a rate of 3.6% per 1 dS m^{-1} increase in soil salinity (Ayers and Westcot, 1985).

The actual transpiration rate, T_a (L T^{-1}), was obtained by integrating Eq. (7) over the root domain as follows:

$$T_a = \int_{L_R} S(h, h_0, z)dz = T_p \int_{L_R} \alpha_1(h)\alpha_2(h_0)\beta(z)dz \qquad (10)$$

where L_R is the root depth (L), which can be either constant or variable during the simulation.

2.3. Boundary conditions

Implementing the atmospheric boundary condition requires specifying irrigation and precipitation rates, as well as the potential evaporation and potential transpiration rates. Potential evapotranspiration rate (ET_0), was computed by the Penman–Monteith FAO-56 approach (Allen et al., 1998). Then, it was partitioned into two components, potential transpiration and potential evaporation rates. Potential transpiration rate was computed as follows:

$$T_p = K_{cb}ET_0 \qquad (11)$$

where K_{cb} is the basal crop coefficient for transpiration (–) given by Allen et al. (1998).

The potential evaporation rate E_p (L T^{-1}) from the land surface was calculated as follows:

$$E_p = K_e ET_0 \qquad (12)$$

where K_e is evaporation coefficient (–), which can be modelled as follows (Allen et al., 1998):

$$K_e = min(K_{cmax} - K_{cb}, fK_{cmax}) \qquad (13)$$

where K_{cmax} is the maximum value of the crop coefficient following rain or irrigation (–), and f is the fraction of soil not covered by plants and exposed to evaporation (–).

The hourly variations of potential transpiration and potential evaporation rates were estimated using an approximated diurnal cycle. The hourly rates were assumed to be zero before sunrise and after sunset (Sellami and Sifaoui, 2003). Beginning at sunrise, they were assumed to follow a sinusoidal form that peaks at 02:00 PM. The integration on truncated sinusoidal expressions gives the daily potential transpiration and potential evaporation rates. The diurnal pattern of potential transpiration rate was calculated as follows (modified Liu et al., 2005):

$$\begin{cases} T_p(t) = 0 & t < 0.208d; t > 0.75d \\ T_p(t) = \frac{\pi}{2DL}\sin(\pi \frac{t}{DL})\overline{T}_p & t \in (0.208d, 0.75d) \end{cases} \qquad (14)$$

where $T_p(t)$ is the hourly potential transpiration rate, $\overline{T}_p$ is the daily potential transpiration rate, DL is the number of daylight hours, and t is the number of hours since sunrise. The hourly potential evaporation rate from land surface was calculated using similar approach.

2.4. Model calibration and validation

2.4.1. Study site

Fatnassa is an ancient oasis located in the governorate of *Kebili* in southern Tunisia (latitude 33°8′N and longitude 8°7′E) (Fig. 1). The bioclimatic classification is *Saharian*. The soils are *gypsiferous* and saline with sandy texture (Boukhsila, 2011). The electrical conductivity of the 0–1.0 m topsoil layer varies between 2.9 and 54.0 dS m^{-1}, with an average of 13.1 dS m^{-1} (Ghazouani, 2009). The most saline areas are located in low zones close to *Chott El Jerid*. The water table depth ranges between 0.8 ± 0.24 m in winter and 1.06 ± 0.40 m in summer (Ben Aïssa et al., 2006). The salinity of the shallow groundwater aquifer varies between 3.78 and 11.84 g l^{-1}, with an average of 7.23 g l^{-1} (Bouarfa et al., 2009).

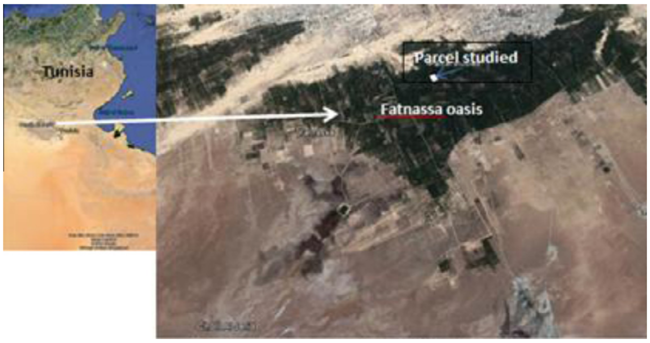

Fig. 1. Map of the *Fatnassa* oasis.

The oasis covers about 214 ha and is divided into individual plots of farmland of different sizes. The cropping system is composed of three distinct crop layers from top to bottom: date palms, fruit trees such as apricot and fig, and fodder crops such as alfalfa. The date palms are all of nearly the same age, the height of their trunks is about 8 m, their density is 200 palms ha^{-1} and the spacing between them is 7 m × 7 m. Surface irrigation by flooding is still the main irrigation system in the oasis. The irrigation water has a pH of 7.7 and electrical conductivity of about 4.0 dS m^{-1} (Table 1). Sodium Adsorption Ratio (SAR) value is 4.9. The irrigation water is managed by the Water Users‘ Association of *Fatnassa* farmers. The irrigation management system, based on rotation delivery schedule, induces water shortage in summer when the distribution capacity of the network reaches its limits. Three treatments of irrigation periods were adopted in the oasis (Table 2): T_1 consists of applying about 10 cm of irrigation water every 44 and 36 days in summer and winter seasons, respectively; T_2 consists of applying about 10 cm of irrigation water every 52 and 43 days in summer and winter seasons, respectively; T_3 consists on applying about 10 cm of irrigation water 45 and 41 days in summer and winter seasons, respectively. The water shortage in summer was considered to be the main cause of the low productivity of the date palm (Ghazouani, 2009). At the oasis scale, the water shortage and the irregularity of irrigation frequency are explained by several reasons such as the leakage of water due to inadequate maintenance and repair of the terminal channels, the continuous increase of irrigated area within the same plot, and the uncontrolled extension of date palm plantations.

2.4.2. Data collection and measurement

The studied period was from July 20 to October 01, 2007. Various input parameters needed to calibrate and validate the HYDRUS-1D model were collected and measured in a 2.0 ha plot of farmland located in the northern part of the *Fatnassa* oasis. Daily values of rainfall, maximum and minimum temperatures, mean humidity, and mean wind velocity were obtained from a weather station located 9 km east of the oasis. Data of diurnal sap flow density of a mature date palm located in the same plot studied were taken from Ben Aïssa and Bouarfa (2009). Canopy transpiration was estimated by multiplying the sap flow density and the

Table 1
Composition of irrigation water in the *Fatnassa* oasis (Bouarfa et al., 2009).

EC	Ca	Mg	Na	K	Cl	SO_4	HCO_3
(dS m^{-1})	(mmol l^{-1})						
3.97	15.07	9.91	17.43	1.02	22.51	16.57	1.33

Table 2
Mean indicators of irrigation performance in the *Fatnassa* oasis.

Irrigation treatment	Actual irrigation intervals (day)		Number of irrigation events		Annual irrigation water depth (cm)
	Summer	Winter	Summer	Winter	
T_1	44	36	4	6	100
T_2	52	43	4	4	80
T_3	45	41	4	5	90

cross-sectional area of the stand per unit area of ground. Hourly water table depths were measured using a water level sensor (Diver DI240, Van Essen Instrument) in a 2.5 m hand-augured well. Soil physical properties and hydraulic parameters were assessed in the plot. Soil samples were collected at three depths below the land surface: 10, 50 and 90 cm. They were air-dried and analysed for particle size distribution first by mechanically sieving to 2, 1 and, 0.5 mm. The <0.5 mm fraction was then analysed using the pipette method in a sedimentation cylinder (Day, 1965). Soil bulk density samples were collected from the same soil pit using a 100 cm^3 cylinder at 20 cm intervals down to 100 cm depth below the land surface. The gravimetric water content at the matric potentials 0, 3.16, 10.0 and 158.50 m was measured in a laboratory following Richards procedure (Richards, 1947). The permeability of the upper soil layer was measured *in situ* using a double-ring infiltrometer. Infiltration under ponded conditions was conducted by manual ponding to 3.0 cm depth. The infiltration rate was found by regressing the recorded cumulative infiltration and time data (Justin et al., 2005).

The depth and distribution of the roots of the monitored date palm were not measured because the water table was shallow. Toumi (1995) investigated date palm root distribution patterns through intensive sampling around a mature date palm (*P. dactylifera, L.*) in the modern oasis of *Draa*, which is located 20 km away from the *Fatnassa* oasis, and found that date palm root depth reached 2.0 m below the land surface, with 50% of the roots are concentrated within the 0–1 m layer, and more that 80% within the 0–1.5 m layer. Therefore, the modelled rooting depth was set at 2.0 m (Fig. 2). We assumed that the date palm had no need of expanding their roots below this depth since the groundwater was shallow with a consolidated gypsum layer at the bottom of the soil profile (Boukhsila, 2011). The modelled rooting depth was divided into three zones of different thickness (Oihabi, 1991; Zaid and Jiménez, 2002):

Zone I, called respiratory zone: It is localised at the palm base surrounding area with a 0.2 m depth. The roots in this zone play only a respiratory role and are ignored in the simulation process.

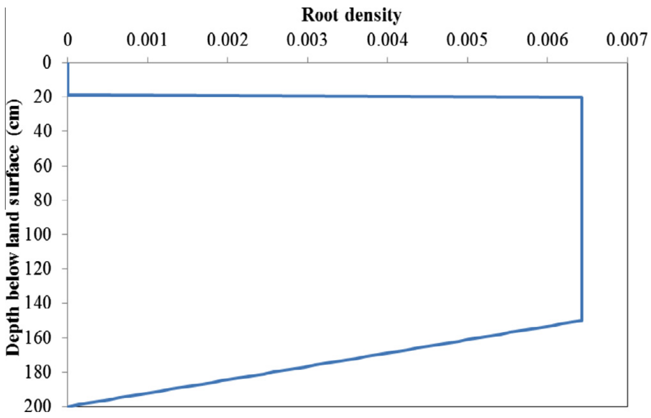

Fig. 2. Spatial distribution of root density of date palm tree.

Zone II, called nutritional zone: This is a deep zone between 0.2 and 1.5 m depth which contains the highest proportion of primary and secondary roots. This zone could contain 1000 roots/m^2 and more than 1.60 g of roots/100 g soil. These roots are quite uniform.

Zone III, called absorbing zone: The root density is lower than in zone II, with only about 200 roots/m^2. The root density decreases linearly from a maximum value at 1.5 m depth to zero at 2.0 m depth.

2.5. Calibration and validation of HYDRUS-1D model

Water flow and salt transport modelling was carried out for the plot studied considering a uniform and isotropic sandy soil profile 200 cm deep. The numerical grid was discretised in 200 nodes of 1.0 cm each to form a regular grid 200 cm long. The values of K_{cmax} and K_{cb} for the date palm are 1.20 and 0.85, respectively (Allen et al., 1998). The shaded area of this tree-crop was estimated to be 40%. From Eq. (13): $K_e = \min(1.2–0.85,\ 0.6 \times 1.2) = 0.35$. The parameters for root water uptake are not available in the literature for date palm. In all simulations, h_3^{high} and h_3^{low} were set to be 5.0 and 7.0 m, respectively, and h_4 to be -150 m, as suggested by Feddes et al. (1976) for various vegetable crops (Table 3). The values of h_1 and h_2 parameters were fixed using a trial-and-error procedure based on available data from a sap flow study which took place from July 20 to August 19, 2007 (DOY 202 to DOY 232). The validity of these parameters was then tested using independent measurements of sap flow density from August 20 to October 01 (DOY 233 to DOY 275), 2007. The time step of the simulations is one hour. For the initial conditions, we choose a pressure head distribution starting with 300 cm at soil surface and increasing linearly to the pressure head of 0 cm at the water table. The estimated hourly potential transpiration and potential evaporation rates were used for the atmospheric boundary condition. The hourly values of the bottom pressure head were deduced from the water table depth. For salt transport, the salt concentration at the soil surface corresponds to the one of the irrigation water. Given that the groundwater salinity was not measured, a constant salt concentration of 7.23 g l^{-1} was used as the bottom boundary conditions; it corresponds to the average salt concentration of the groundwater calculated at the oasis scale.

The accuracy of the simulation results was evaluated by the root mean square error (RMSE) between the measured and simulated sap flow density of the monitored date palm. The RMSE was calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum (O_i - P_i)^2} \qquad (15)$$

where n is the number of observations, O_i is the ith measured sap flow density (l s^{-1}), and P_i is the ith predicted sap flow density (l s^{-1}). In addition, regression analyses between the simulated and measured daily transpiration rate were performed.

2.6. Numerical experiments

After validating the HYDRUS-1D model, three different schedules of irrigation water were designed on the basis of the local irrigation management. The aim was to identify a water table depth and an irrigation water salinity that were sufficient to maintain the soil water availability and soil salinity at safe levels, while meeting the water requirements of date palm. Root water uptake was simulated by HYDRUS-1D model with a daily time step during the period from May 1, 2003 to April 30, 2007. Simulations were performed using different water table depths (WTD), from 0.5 to 2.0 m, and irrigation water salinities, from 0 to 4 g l^{-1}. The scenario with no water table was also considered. The water table was as-

Table 3
Soil water and crop parameter values used in the HYDRUS model for estimating date palm transpiration and soil evaporation in the *Fatnassa* oasis.

Parameter	Value	Source
Van Genuchten model parameters		
Volumetric water content at saturation θ_s (cm^3 cm^{-3})	0.3	Measured
Residual volumetric water content θ_r (cm^3 cm^{-3})	0.038	Adjusted using the RETC software
γ (cm^{-1})	0.114	Adjsuted using the RETC software
n	1.573	Adjsuted using the RETC software
Ks (cm day^{-1})	11.0	Measured
ℓ	0.5	Mualem (1976)
Root water uptake reduction parameters		
h_1	0.0	Model calibration
h_2	0.0	Model calibration
h_3^{high} (cm)	−500	Feddes et al. (1976)
h_3^{low} (cm)	−700	Feddes et al. (1976)
h_4 (cm)	−15,000	Feddes et al. (1976)
Crop parameters		
K_{cb}	0.85	Allen et al. (1998)
K_{cmax}	1.20	Allen et al. (1998)
f	0.4	Ghazouani (2009)
Soil dispersion length (cm)	1.0	Flury et al. (1998), van den Bosch et al. (1999)

sumed to be in hydrostatic equilibrium with the soil profile at the start of the simulations (initial condition). The initial salt concentrations were assumed to be 8.38 and 7.23 g l^{-1}, respectively, above and below the water table. For the lower boundary condition, a constant salt concentration of 7.23 g l^{-1} was assumed.

The irrigation treatments T_1, T_2 and T_3 were simulated using the HYDRUS-1D model to assess the influence of different irrigation schedules on date palm water use.

3. Results and discussion

3.1. Climatic conditions in the Kebili region

The prevailing weather conditions in the *Kebili* city from January 2003 to December, 2007 are shown in Table 4. The data reveal that the mean maximum monthly temperature was 33.3 °C during the summer months from June to September, while the mean minimum monthly temperature was 11.3 °C during the winter months from December to February. The average relative humidity varied from about 29% in July to 66% in December. The annual potential evapotranspiration (ET_0) varied from 2344 to 2670 mm year^{-1} with an average of 2482 mm year^{-1}. Rainfall was generally insignificant.

Fig. 3 shows the daily potential transpiration of date palm within the agricultural year 2006–2007 (May through April). It can be seen that T_p increased from 1.8 mm day^{-1} in February, before the pollination stage, to 19.1 mm day^{-1} in June at the *kalal* stage; then it decreased to 4.1 mm day^{-1} in September at end of the *Tamer* stage. After the date palm harvest, T_p declined to reach the minimum value of 0.6 mm day^{-1} in December and January, when date palm was pruned. The maximum values of T_p were 19.1 and 16.5 mm day^{-1} in June and July, respectively, at the fruits formation stage, when air temperature and wind speed were high, and relative humidity was low.

3.2. Soil physical properties

Soil main physical properties are presented in Table 5. Sand content varies from 97.6% to 98.2% and silt from 1.4% to 2.1%. Clay content also varies from 0.4% to 1.1%. According to the USDA textural classification system, the soil texture is classified as sand (Soil Conservation Service, 1972). The hydraulic conductivity of the upper layer is 11 cm h^{-1}. The saturated soil water content (θ_s) varies from 0.28 to 0.32 cm^3 cm^{-3}. The vertical distribution of soil texture is quite homogeneous. Thus, the soil hydraulic properties were assumed uniform across the soil profile. The unknown parameters (θ_r, γ and n) were predicted using the nonlinear least-squares optimisation program RETC. vanGenuchten et al., 1991) from average soil water retention data, bulk density, and percentages of sand, silt, and clay. The saturated soil water content was fixed at 0.30 cm^3 cm^{-3}, which is the mean value of θ_s across the soil profile. The estimated values of θ_r, γ and n are 0.038, 0.114, and 1.573, respectively. The soil dispersion length was set to 1.0 cm for sandy soil (Flury et al., 1998; van den Bosch et al., 1999).

3.3. Groundwater dynamics

Three irrigation events were recorded in the plot studied during the monitored period. The total amount of irrigation water was 45 cm (about 15 cm per irrigation event). The water table responded quickly to these recharge events (Fig. 4), but remained below the respiratory zone of the date palm. This dynamic response of the shallow water table was observed in many Tunisian oases and was explained by the high amounts of irrigation water and the high infiltration capacity of the sandy soil (Goussi, 1996; Askri et al., 2010).

3.4. Model calibration

Different simulations were carried out to test the role of the $\alpha_1(h)$-function (Eq. (8)) and to estimate the values of the specific crop parameters h_1 and h_2. The model is very sensitive to these parameters as they define the pattern of root water uptake close to saturation. The best fitting between the measured and predicted sap flow densities is for $h_1 = h_2 = 0$ cm with $\alpha_1(h)$ close to one in the saturated zone. To illustrate the performance of HYDRUS-1D model, the time course of simulated sap flow density was compared to the measured data during 31 days (Fig. 5). The model provides very good estimates of hourly sap flow compared to the thermal dissipation measurements with a relatively small RMSE value of 1.31 l h^{-1}. The beginning and the stopping of the sap flow corresponded with sunrise at 08:00 AM and sunset at 08:00 PM,

Table 4
The average monthly values of daily air temperature, relative humidity (RH), wind speed (U), Potential evapotranspiration (ET_0), and accumulated rainfall at *Kebili* region from January 01, 2003 to December 31, 2007.

Parameter	January	February	March	April	May	June	July	August	September	October	November	December
Air temperature (°C)	11.3	13.1	17.1	21.3	26.0	30.6	33.3	33.2	28.3	24.8	17.0	12.0
RH (%)	58.5	51.5	44.2	42.9	34.3	29.6	29.2	32.9	42.9	47.8	55.9	66.2
U (m/s)	3.9	4.2	4.8	5.4	5.7	5.6	5.4	5.3	4.8	4.3	3.8	3.8
ET_0 (mm/day)	2.6	3.6	5.3	7.1	9.6	11.4	11.8	11.0	7.8	5.8	3.4	2.2
Rainfall (mm)	13.9	7.1	8.6	59	4.4	1.7	0.3	0.9	9.3	8.6	9.8	16.9

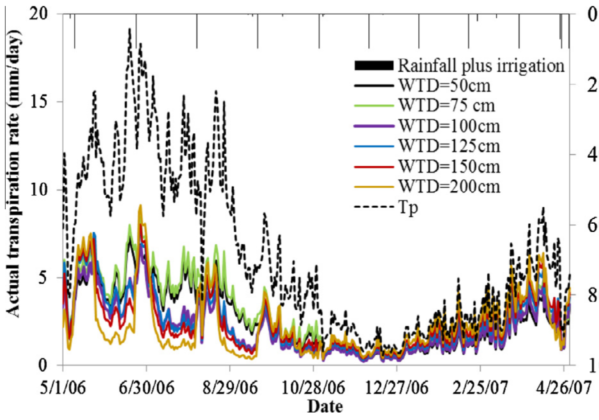

Fig. 3. Potential and actual transpiration rate of date palm under different water table depths (WTD) during the agricultural year 2006–2007.

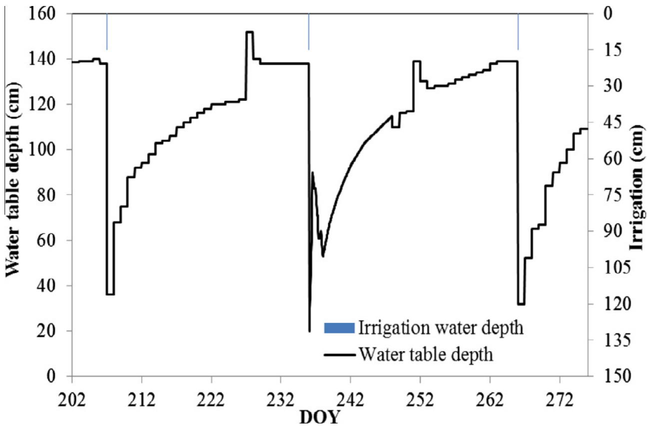

Fig. 4. Water table depth and amount of irrigation water measurement from Day 202 (July 20, 2007) to Day 275 (October 01, 2007) in the parcel studied.

respectively. The sap flow began to rise from 08:00 AM and reached its maximum at 02:00 PM. The model overestimates some values of maximum hourly sap flow density. These discrepancies may be related to uncertainties in the estimation of potential evapotranspiration, which was calculated using weather data measured out of the *Fatnassa* oasis. The multi-layer cropping system inside the oasis can greatly change the temperatures underneath the canopy and influence transpiration and evaporation rates (Sellami and Sifaoui, 1999).

No sap flow reduction was observed even during the two days when the water table level was at 40 cm below the land surface or less. Date palm absorbed water without being affected by shallow saline groundwater. These results show that the root water uptake of this variety of date palm is not affected by the presence of a water-table in its root profile, provided the water table is below its respiratory zone.

During the period from July 20 to August 19, 2007, the measured transpiration rate varied between 7.08 and 9.95 mm day^{-1} with an average of about 8.46 mm day^{-1} and standard deviation of 1.0 mm day^{-1}, while the simulated transpiration rate varied between 6.34 and 10.38 mm day^{-1} with an average of 8.23 mm day^{-1} and a standard deviation of 1.03 mm day^{-1}. The simulated transpiration rate tended to follow the 1:1 line (R^2 = 0.75) when compared with measured values (Fig. 6).

3.5. Model validation

From August 20 to October 01, 2007 there is a good agreement between measured and simulated hourly sap flow densities with a relatively small RMSE value of 1.32 l h^{-1} (Fig. 7). Measured and

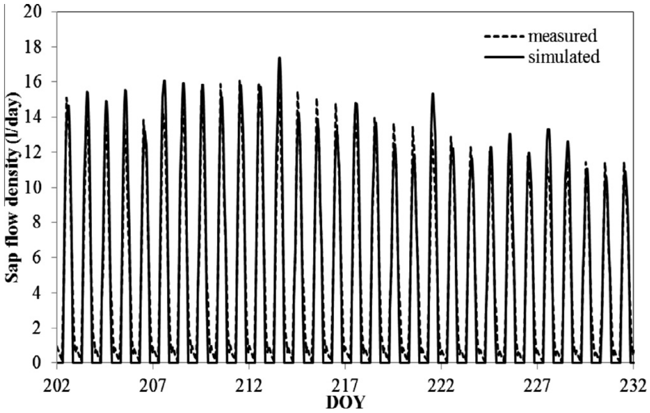

Fig. 5. Time courses of measured (discontinuous line) and simulated (continuous line) values of date palm transpiration rates from Day 202 (July 20, 2007) to Day 232 (August 19, 2007), hourly basis.

simulated sap flow densities were close to zero after sunset and before sunrise, increased at 08:00 AM, reached a maximum at 02:00 PM, and decreased after that. The observed peak magnitudes of the hourly sap flow density were over-predicted by the model during the first ten days of the simulation and under-predicted during the rest of the simulation period. This can be explained partly by the experimental errors that may influence the water and solute transfer across the soil profile. Indeed, the measured transpiration rate was given with an error of about 10% in optimal condition; may be more if the hourly values were considered (Cabibel and

Table 5
Soil physical and hydraulic properties for soil profile in the plot studied.

Depth (cm)	Particle size distribution			Bulk density (g/cm^3)	Volumetric water content (cm^3 cm^{-3}) at			
	Sand (%)	Loam (%)	Clay (%)		Saturation	Field capacity (−316 cm)	−1000 cm	Wilting point (−15,850 cm)
0–15	98.2	1.4	0.4	1.52	0.31	0.08	0.06	0.05
15–25				1.55	0.28	0.05	0.04	0.03
25–35				1.48	0.29	0.06	0.05	0.04
35–45				1.46	0.30	0.07	0.05	0.04
45–55	97.4	1.5	1.1	1.51	0.30	0.07	0.05	0.04
55–65				1.49	0.32	0.09	0.07	0.06
65–75				1.54	0.30	0.07	0.06	0.04
75–85				1.55	0.29	0.06	0.05	0.04
85–95	97.2	2.1	0.7	1.53	0.30	0.07	0.06	0.04
95–105				1.55	0.30	0.07	0.06	0.04
Average	97.6	1.7	0.7	1.52	0.30	0.07	0.06	0.04

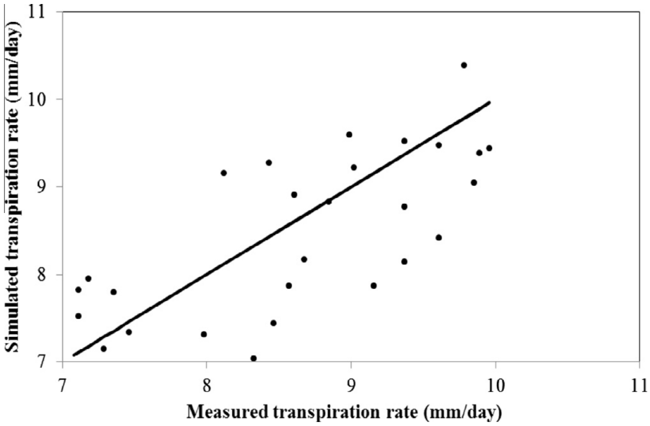

Fig. 6. Overall comparison of daily actual transpiration rate of date palm between measurement and simulation in the calibration experiment; regression coefficient $R^2 = 0.75$.

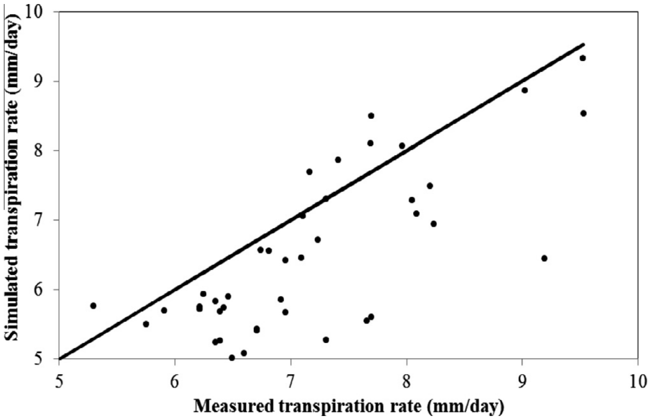

Fig. 8. Overall comparison of daily actual transpiration rate of date palm between measurement and simulation in the validation experiment; regression coefficient $R^2 = 0.65$.

Do, 1991). Furthermore, the amounts of irrigation water were estimated with an error of about 10%.

The measured transpiration rate of the date palm varied between 4.8 and 9.5 mm day^{-1} with an average of 7.1 mm day^{-1}, while the simulated rates ranged between 3.9 and 9.3 mm day^{-1} with an average of 6.4 mm day^{-1}. The coefficient of correlation ($R^2 = 0.66$) shows an acceptable correlation between measured and simulated daily transpiration rates (Fig. 8).

3.6. Numerical experiments

3.6.1. Effect of water table depth on the date palm water use

The effect of change in water table depth on the date palm water use (transpiration) was analysed for the irrigation water treatment T_1 with a salt concentration of irrigation water close to 2.56 g l^{-1}. A constant pressure head (corresponding to the position of the water table) was used as bottom boundary condition.

Daily variation in actual transpiration rate during the agricultural year 2006–2007 (May 2006 through April 2007) is shown in Fig. 3 for different water table depths. This rate ranged from 0.3 to 6.8 mm day^{-1}, with an average of 2.2 mm day^{-1}, and from 0.4 to 9.1 mm day^{-1}, with an average of 2.4 mm day^{-1} for WTD = 100 cm and WTD = 200 cm, respectively. Increasing the water table depth from 100 to 200 cm decreases the actual evaporation rate at the soil surface and consequently decreases the root-zone salinity. In fact, the evaporation rate depends upon water table depth and decreases as this depth increases (data are not shown). For comparison, daily measured transpiration rate of date palm ranged from 1.9 to 9.9 mm day^{-1} in the semi-arid environment of Jordan Valley (Mazahrih et al., 2012), and from 1.9 to 7.3 mm day^{-1} in the arid region of the middles Kingdom of Saudi Arabia (Kassem, 2007).

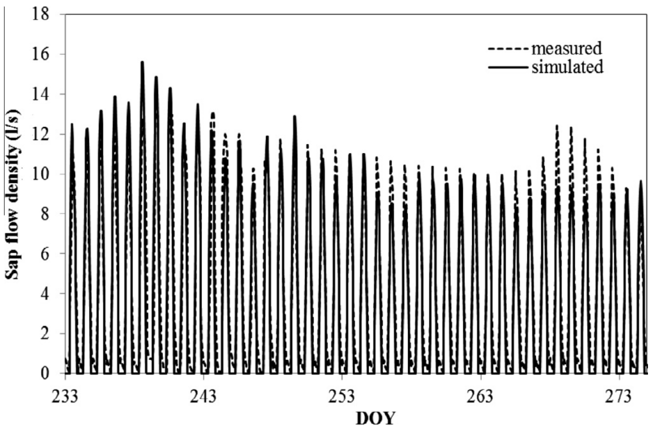

Fig. 7. Time courses of measured (discontinuous line) and simulated (continuous line) values of date palm transpiration rates from Day 233 (August 20, 2007) to Day 275 (October 01, 2007), hourly basis.

Simulation scenarios reveal that in summer season, the actual transpiration was significantly less than the potential one because the water content in the root-zone was too low and its salinity was too high to sustain the potential uptake rate. For WTD = 200 cm, the mean water content of the root-zone was between 0.04 and 0.18 cm^3 cm^{-3}, with an average of 0.07 cm^3 cm^{-3}; and the mean root zone-salinity was between 13.5 and 22.2 g l^{-1}, with an average of 19.2 g l^{-1} (data are not shown). These values of salinity are higher than the Mass and Hoffman (1977) threshold values for date palm salt tolerance. This means that an irrigation interval of 44 days in summer may induce a sever water and salinity stress. A deep water table considerably decreases the actual transpiration during periods when no rainfall and no irrigation occur. This reinforces the point that this tree crop is able to meet its water needs with shallow groundwater despite its high salinity.

In winter, the actual transpiration rate has little variations from 0.3 to 1.2 mm day^{-1} and from 0.4 to 1.9 mm day^{-1} for WTD = 100 cm and WTD = 200 cm, respectively. These results show that during this cold and wet season, the effect of water table depth on the date palm water use is not significant. For all scenarios, the actual transpiration rate was very close to the potential one because the mean water content of the root-zone was high and the mean root-zone salinity was relatively low. In winter, the date palm transpiration seems to be not affected by the low irrigation frequency even when the water table is deep.

Relative transpiration of a crop was defined as the ratio of the cumulative annual actual transpiration to the cumulative annual potential transpiration under no-drought and no-salinity stress conditions. The influences of water table depth on mean root-zone salinity and relative transpiration are shown in Fig. 9 for the agricultural year 2006–2007. The scenario with WTD = 75 cm has the highest relative transpiration (48%), and the scenario with WTD = 100 cm the lowest one (34%). The date palm transpiration was likely hampered by salt stress. When the water table depth increased from 50 to 75 cm, the mean annual root-zone salinity decreased by about 2 g l^{-1} and the relative transpiration increased by about 6%. In this case, soil desalinisation occurred due to the mixing of the bottom upflow solution with the root zone solution. Increasing the water table depth from 50 to 75 cm decreases the

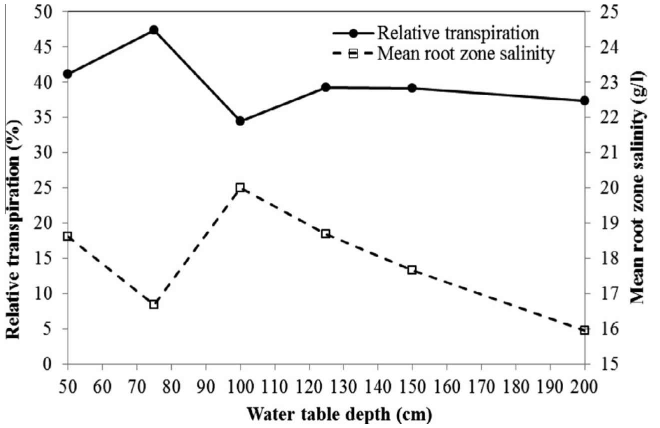

Fig. 9. Effects of water table depth on relative transpiration of date palm and mean root zone salinity.

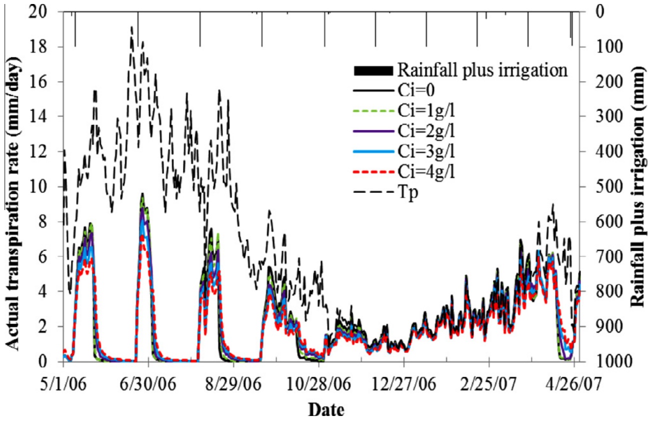

Fig. 10. Daily actual transpiration rate of date palm under different concentrations of irrigation water during the agricultural year 2006–2007.

root-zone water storage and consequently increases the bottom upflow rate to maintain this depth constant. The mixing of 7.23 g l^{-1} upflow solution with higher than 13 g l^{-1} root-zone solution leads to its dilution. The mean root-zone salinity increased by about 3 g l^{-1} and consequently the relative transpiration decreased by about 13% when the water table depth increased from 75 to 100 cm. For the last depth, the capillary action does not carry water to the unsaturated zone as fast as evaporation takes it away. Due to the drying of the unsaturated zone, evaporation from the soil surface induced soil salinisation. Finally, the increase in water table depth from 100 to 200 cm induced a linearly decrease of the mean annual root-zone salinity from 20 to 16 g l^{-1}. In this case, the soil desalinisation is explained by the decrease in actual evaporation at the soil surface. For comparison, the average annual root-zone salinity for WTD = 75 cm was higher than that for WTD = 200 cm, while the highest relative transpiration corresponded to the first water table depth. This result shows that the environmental stress on the date palm water use was not effectively alleviated with the decline of salt storage because of concurrent decrease in water content of the root-zone.

3.6.2. Effect of irrigation water salinity on date palm water use

The effect of change in irrigation water salinity on actual transpiration of the date palm was simulated without water table to avoid the influence of groundwater on this process. The bottom boundary conditions were defined as free drainage for water and zero concentration gradient for salt transport.

Fig. 10 shows the daily variation in actual transpiration rate during the agricultural year 2006–2007 for different irrigation water salinities. In summer, the actual transpiration rate was significantly low during periods without irrigation or rainfall. After irrigation and rainfall events, the date palm responded quickly to water input for all salinities of irrigation water. In winter, the actual transpiration rate has an increasing trend which is independent of water input, but closely related to meteorological factors such as temperature and humidity.

Fig. 11 shows the average root-zone salinity and relative transpiration under different irrigation water salinities. Average root-zone salinity increased and relative transpiration decreased with increased irrigation water salinity. The relative transpiration decreases from 34% to 30% if this salinity increases from 0 to 4 g l^{-1}. The low values of relative transpiration are explained mainly by the low irrigation frequency. Date palm is considered as one of the most tolerant crops to salinity; it is slightly affected by salinity stress. A previous study conducted in an Egyptian oasis showed that date palm can produce full yield if it was irrigated with saline water up to 2 g l^{-1} but the date palm yield was reduced by about 10%, 25%, and 50% if the irrigation water salinity rises to 3, 5, and 8 g l^{-1}, respectively (El-Bana and Ibrahim, 2008). In *Wergla* basin (north-eastern Sahara in Algeria), the impact of soil salinity on date palm yield was not significant when the groundwater was shallow (Bouhoun et al., 2011).

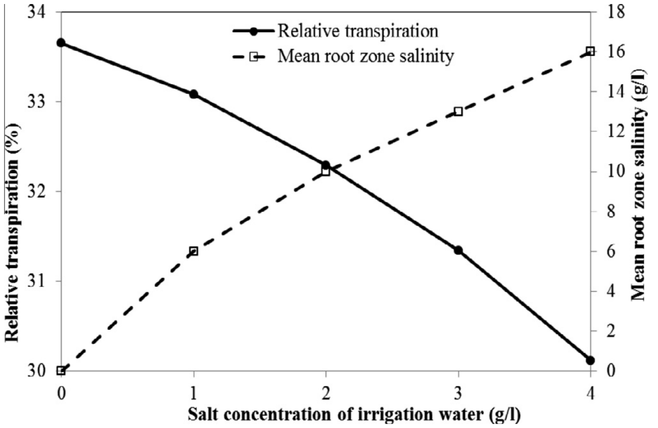

Fig. 11. Relative transpiration of date palm and mean root zone salinity for different concentrations of irrigation water.

3.6.3. Combined effects of water table depth and irrigation water salinity on date palm water use

Simulation results indicate that relative transpiration is low in all scenarios (Fig. 12). Relative transpiration ranges from 33% for 100 cm water table depth and an irrigation water salinity close to 4.0 g l^{-1} to 50% for 75 cm water table depth and irrigation water free of salt.

The analysis of the interaction between water table depth and irrigation water salinity shows that there is no significant effect of water salinity on relative transpiration when the water table is shallow. For WTD = 50 cm, the increase in salinity from 0 to 4 g l^{-1} decreases the relative transpiration by only 4%. In contrast, the effect is more significant if the water table is deep. For WTD = 200 cm, the increase in salinity from 0 to 4 g l^{-1} decreases the relative transpiration by 9%. The effect of water table depth on relative transpiration is significant for all irrigation water salinities. For irrigation water salinity close to zero, the relative transpiration decreases by 12% when the water table depth increases from 75 to 100 cm.

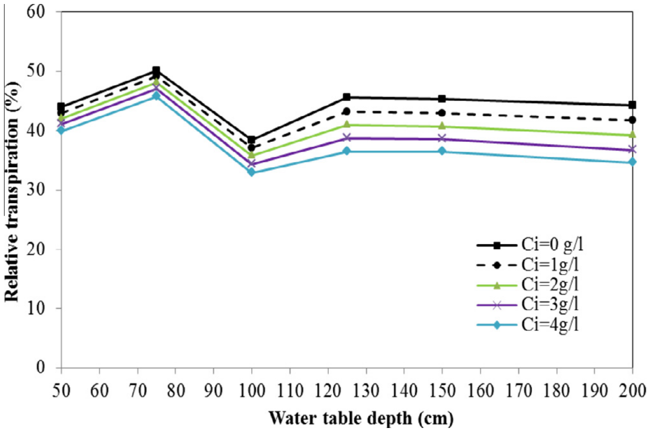

Fig. 12. Relative transpiration of date palm under different water table depths and concentrations of irrigation water.

3.6.4. Effect of irrigation frequency on date palm water use

The effect of irrigation frequency on date palm water use was simulated using a free drainage boundary condition at the bottom of the soil profile. The salt concentration of the irrigation water salinity was taken as 2.56 g l^{-1}.

During the agricultural year 2006–2007, the cumulative annual rainfall recorded in *Kebili* city was 25.6 cm and the cumulative annual irrigation depths recorded in the *Fatnassa* oasis were 100, 90, and 80 cm for the irrigation treatments T_1, T_3, and T_2 respectively (Table 2). Despite different irrigation management practices, relative transpiration decreases from 32% to only 27% when the number of irrigation application decreases from 6 to 4 in winter (Fig. 13). Generally, the sustainability criterion is not satisfied under the above three irrigation treatments. They are not recommended in the *Fatnassa* oasis, where the evaporative demand is very high in summer. The date palm water use might be improved by increasing the number of irrigation applications in this season. The predicted average root-zone pressure head under the different irrigation treatments is shown in Fig. 14. The irrigation treatments T_1, T_2 and T_3 exhibit low pressure heads mainly in summer season due to the absence of rainfall, the low irrigation frequency, and the high evaporative demand. During this season, values of matric potentials lower than 12,000 cm were reached. As the winter season started, the root-zone pressure heads increased drastically.

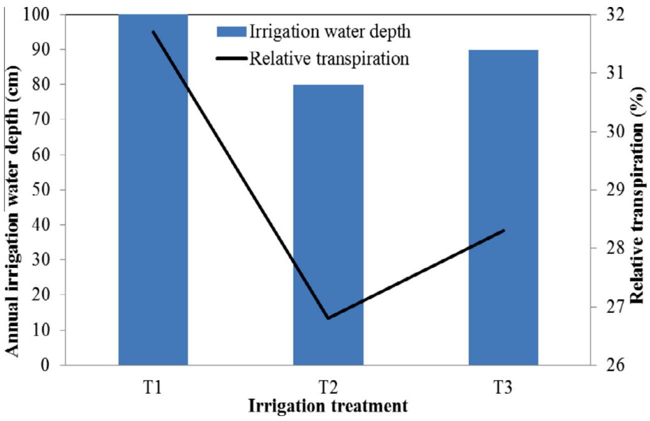

Fig. 13. Annual irrigation water depths and relative transpiration of date palm for different irrigation treatments (T_1, T_2, and T_3).

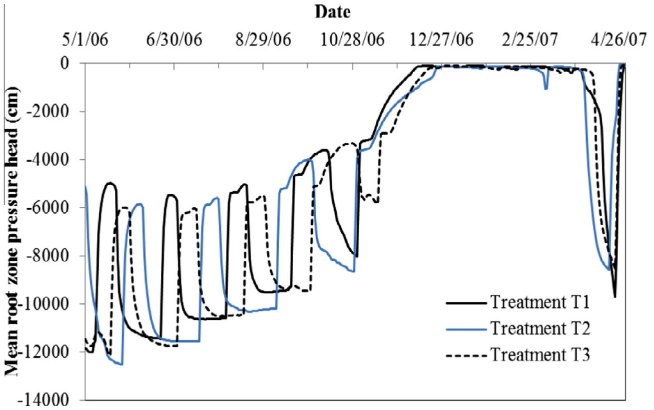

Fig. 14. Simulated average root zone soil pressure heads for T_1, T_2, and T_3 during the agricultural year 2006–2007, expressed in centimetres.

4. Conclusion

HYDRUS-1D model provided accurate simulations of date palm transpiration under shallow saline groundwater. Using data on climate, sap flow density, soil hydraulic properties, water table depth, and amount of irrigation water, acceptable agreement between simulated and measured date palm transpiration was achieved during a 74 days period.

Simulation results show that the effects of water table depth and irrigation frequency on the date palm transpiration vary according to the season. In summer, this process is negatively affected by the low irrigation frequency and the deep water table. These factors decrease the water content and increase the salinity of the root-zone. The presence of shallow groundwater during this dry and hot season increases the extractable water capacity of soil and enhances root water uptake. Therefore, increasing the date palm transpiration in summer requires reducing the irrigation intervals and maintaining the water table at a shallow depth (about 75 cm below land surface). In winter, the insignificant effect of the irrigation frequency suggests that the number of irrigation events can be reduced to save water. The results also reveal that, under shallow saline groundwater, the irrigation water salinity has no significant effect on date palm transpiration. Therefore, in southern Tunisia oases where saline waters can be viewed as an important source of irrigation during hot and dry periods, the use of marginal water can be an alternative for irrigating salt tolerant date palm. It is worthwhile noting that the date palm water use may be affected by agronomic and environmental factors that were not taken into account in this study. In future research, including these factors in the model simulations would be useful for a better understanding of the date palm transpiration.

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