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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:

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

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

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

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:

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

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