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Research Paper

Modelling soil water dynamics of full and deficit drip irrigated maize cultivated under a rain shelter

María G. González [a], Tiago B. Ramos [b], Reimar Carlesso [a], Paula Paredes [b], Mirta T. Petry [a], Juliano D. Martins [a], Núbia P. Aires [a], Luis S. Pereira [b,c,*]

[a] Rural Sciences Center, Federal University of Santa Maria, Santa Maria, Brazil
[b] CEER, Biosystems Engineering, Institute of Agronomy, University of Lisbon, Portugal
[c] CAPES, Federal University of Santa Maria, Santa Maria, Brazil

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The model HYDRUS-1D was used to simulate soil water dynamics of full and deficit irrigated maize grown under a rainout shelter during two crop seasons. Four irrigation treatments were established based on the amount of water applied to fulfil crop water requirements. Treatment D1 was irrigated to fully satisfy crop water requirements, while treatments D2 (mild deficit), D3 (moderate deficit), and D4 (severe deficit) were for increased controlled water stress conditions. The computation and partitioning of evapotranspiration data into soil evaporation and crop transpiration was carried out with the SIMDualKc model, and then used with HYDRUS-1D. The soil hydraulic properties were determined from numerical inversion of field water content data. The compensated root water uptake mechanism was used to describe water removal by plants. The HYDRUS-1D model successfully simulated the temporal variability of soil water dynamics in treatments irrigated with full and deficit irrigation, producing RMSE values that varied between 0.014 and 0.025 $cm^3\ cm^{-3}$ when comparing model simulations with field measurements. Actual transpiration varied between 224 and 483 mm. Potential transpiration reductions varied from 0.4 to 48.8% due to water stress, but plants were able to compensate for the water deficits in the surface layers by removing more water from the deeper, less stressed layers. HYDRUS-1D water balance estimates were also comparable with the corresponding ones determined with the SIMDualKc water balance model. Both modelling approaches should contribute to improve the web-based IRRIGA system, used to support farm irrigation scheduling in Brazil.

1. Introduction

Improving irrigation water management for increased productivity is a major objective of irrigated agriculture. This is also true for Brazil, which has a large share of the world's fresh water resources in the Amazon River basin, but also a large climate diversity offering a variety of challenges. Brazil has various climatic zones consisting of the humid equatorial

* *Corresponding author*. CEER-Biosystems Engineering, Institute of Agronomy, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal.
E-mail address: lspereira@isa.ulisboa.pt (L.S. Pereira).
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Nomenclature

a_D	empirical parameter of the deep percolation parametric function
b_D	empirical parameter of the deep percolation parametric function
CN	curve number
E	potential soil evaporation, mm
E_a	actual soil evaporation, mm
ET_c	crop evapotranspiration, mm
ET_o	reference evapotranspiration, mm
f_c	fraction of soil covered by the crop
$f_{eff\ mulch}$	effective fraction of soil covered by mulch
$f_{r\ mulch}$	fraction of soil covered by mulch
f_w	fraction of soil cover wetted by irrigation
h	pressure head, cm
H	crop height, cm
K_{cb}	basal crop coefficient
K_e	soil evaporation coefficient
K_s	saturated hydraulic conductivity, cm d^{-1}
L	length season stages, d
L_R	root domain, cm
n	number of observations
p	depletion fraction for no stress
P	predicted values
$\overline{P}$	mean model predictions
RAW	readily available water, mm
REW	readily evaporable water, mm
S	actual volume of water removed from unit volume of soil per unit of time, $cm^3\ cm^{-3}\ d^{-1}$
S_e	effective saturation, cm
S_p	potential volume of water removed from unit volume of soil per unit of time, $cm^3\ cm^{-3}\ d^{-1}$
t	time, d
T_a	actual non-compensated transpiration rate, cm d^{-1}
T_{ac}	actual compensated transpiration rate, cm d^{-1}
T_p	potential transpiration rate, cm d^{-1}
TAW	total available water, mm
TEW	total evaporable water, mm
O	observations
$\overline{O}$	mean observations
z	vertical space coordinate, cm
Z_e	evaporable layer depth, m
α	empirical shape parameters, cm^{-1}
$\alpha(h)$	soil water stress function
β	normalised root density distribution function, cm^{-1}
η	empirical shape parameters
ℓ	pore connectivity/tortuosity
θ	volumetric soil water content, $cm^3\ cm^{-3}$
θ_r	residual water content, cm
θ_s	saturated water contents, cm
$\omega(t)$	root adaptability factor

Subscripts

RAW	readily available water
m	measured FDR values, $cm^3\ cm^{-3}$
h	measured volumetric soil water retention values, $cm^3\ cm^{-3}$
i	time, d

zone in the north; the semi-arid northeast, the tropical and dry central Brazil, the highlands tropical zone in the southeastern region, and the subtropical zone in the south. Despite almost 70% of water being used in agriculture, irrigation is only carried out on 15% (5.5 million ha) of the land while the country's irrigation potential is estimated at 29.3 million ha. As Brazil plans to expand its irrigated areas in the next decades (IICA, 2008), there is a need to improve irrigation water management and optimise water use and water productivity (Pereira, Cordery, & Iacovides, 2012), particularly in areas where water scarcity is likely to increase.

The Federal University of Santa Maria (Rio Grande do Sul State, Brazil) has been developing the IRRIGA System (Carlesso, Petry, & Trois, 2009), which is a web-based decision support system (www.irrigasystem.com) aimed at improving crop water and irrigation requirement estimates and supporting irrigation scheduling, i.e. defining the appropriate irrigation dates and volumes to be applied. The system presently monitors more than 120,000 ha every year in different climatic regions of Brazil, including high-rainfall areas in the south and low-rainfall areas in central Brazil. Deficit irrigation has been considered as a valuable strategy to be implemented with the IRRIGA system in order to maximise water productivity in water scarce regions (Rodrigues, Martins, Silva, Carlesso, & Pereira, 2013). Irrigation is optimised when water deficits are avoided during drought-sensitive growth stages of a crop; outside these periods, irrigation may be limited or even unnecessary. Thus, the adoption of deficit irrigation implies appropriate knowledge of crop water requirements, effects of water deficits at the various crop growth stages on crop physiology and yield, and the economic impacts of yield reduction strategies (English & Raja, 1996; Paredes, Rodrigues, Alves, & Pereira, 2014; Pereira, Oweis, & Zairi, 2002; Rodrigues et al., 2013).

Recently, Martins et al. (2013) used the SIMDualKc model to analyse the water balance in irrigated maize while considering full and deficit irrigation strategies in order to improve the background support of the IRRIGA software for different climatic zones. Maize, one of the most important crops in Brazil currently grown in more than 14 million ha (FAO, 2014), has been reported to be sensitive to drought stress during most of its growth season, particularly during the reproductive stage (e.g., Çakir, 2004; Bergamaschi et al., 2006; Igbadun, Salim, Tarimo, & Mahoo, 2008; Farré & Faci, 2009; Grassini et al., 2011). Therefore, following controlled water deficits in maize irrigation requires precise irrigation scheduling, which is usually carried out using advanced simulation model predictions like those provided by SIMDualKc, which has the advantage of adopting the FAO dual crop coefficient approach for partitioning evapotranspiration into soil evaporation and crop transpiration (Martins et al., 2013; Rosa et al., 2012).

Martins et al. (2013) defined the irrigation scheduling by modelling the water balance for the entire root domain using the SIMDualKc water balance model (Rosa et al., 2012). Water balance models are simple to use as they require very few parameters related to the soil, plant and climatic conditions but provide quite accurate model predictions (e.g., Liu, Teixeira, Zhang, & Pereira, 1998; Chopart et al., 2007; Khaledian, Mailhol, Ruelle, & Rosique, 2009), in particular when using the dual Kc approach (Paredes et al., 2014; Zhao et al., 2013). On the other hand, the HYDRUS software package (Šimůnek, van Genuchten, & Šejna, 2008) used in this study is a state-of-the art model for simulating water, heat, and solute transport in one-, two-, and three-dimensional variably-saturated porous media that can become a valuable tool for improving irrigation management under deficit irrigation. The model numerically solves water flow in homogeneous and heterogeneous soils, and water uptake by plants relative to the various soil layers of the root domain. Thus, the model requires more detailed characterisation of the soil hydraulic properties, which may not be easily obtained in many regions of the world. Nonetheless, among other capabilities, the model has been widely used for simulating soil water dynamics in varied range of soils, irrigation systems, and crop conditions (e.g., Ajdary, Singh, Singh, & Khanna, 2007; Bof Bufon, Lascano, Bednarz, Booker, Gitz, 2012; Lazarovitch, Šimůnek, & Shani, 2005; Phogat, Skewes, Mahadevan, & Cox, 2013; Ramos et al., 2012; Skaggs, Trout, Šimůnek, & Shouse, 2004). However, only a few of those studies have been substantiated with field validation. Dabach, Lazarovitch, Šimůnek, and Shani (2013) have also recently implemented in HYDRUS a system-dependent boundary condition that triggers irrigation when a certain soil pressure head is reached at a specific location, something that seems particularly interesting for implementing better irrigation practices while considering deficit irrigation strategies.

The main objectives of this study were: (a) to calibrate and validate the HYDRUS-1D software package to model soil water dynamics in maize grown under a shelter, while considering various treatments of full and deficit irrigation; (b) to compare water balance results of HYDRUS-1D and SIMDualKc, taking into account that the former computes results soil layer by soil layer, while the latter calculates for the entire soil profile without distinguishing between soil layers; and (c) to contribute for improving the background information of the web-based IRRIGA system used to support Brazilian farmers irrigation scheduling decisions.

2. Material and methods

2.1. Location

The field experiment was conducted at the experimental field site of the Agricultural Engineering Department, Federal University of Santa Maria (UFSM), Rio Grande do Sul State, Brazil (29°41′24″S; 53°48′42″W; 100 m). The climate in the region is subtropical humid, with no dry season and with hot summer, classified as “cfa” in the Köppen classification. Annual reference evapotranspiration averages 857 mm, while mean annual precipitation is 1711 mm (period 1969–2005).

The soil was classified as Ultisol (Soil Survey Staff, 2006) with a loam texture in the top soil layers and a clay texture in the bottom layer. Disturbed and undisturbed soil samples (71 cm^3) were collected at the beginning of the experiment from different soil layers of a representative soil profile. The average values of the main soil physical properties are presented in Table 1. The particle size distribution was obtained using an ASTM 151H soil hydrometer (Chase Instruments Co., USA). The dry bulk density was obtained by drying volumetric soil samples (71 cm^3) at 105 °C for 48 h. Soil water retention at matric potentials between −10 and −5000 cm were determined with a pressure plate apparatus (Soil Moisture Equipment Corp., USA) and between −5000 and −15000 cm were measured with a WP4 dewpoint potentiometer (Decagon Devices, USA). The total porosity was determined from the particle and bulk densities.

2.2. Irrigation treatments

The field experiment consisted of irrigating maize (*Zea Mays* L.) with a drip irrigation system under controlled stress conditions during the growing seasons of 2010/2011 and 2011/2012, here denoted as Crop Seasons 1 and 2, respectively. The drip irrigation system was equipped with pressure-compensating in-line drippers placed along the crop lines spaced 0.5 m apart, and operating at 100 kPa with a discharge of 1.2 l h^{-1}. Further information on the irrigation system is provided by Martins et al. (2013).

Four irrigation treatments (D1–D4), with four replicates each (in plots of 3 × 6 m^2), were established in both growing seasons based on the amount of water applied to fulfil crop water demand. Irrigation treatments were established by combining the daily values of reference evapotranspiration (ET_o), determined using the FAO Penman-Monteith method, and the dual crop coefficient approach (Allen, Pereira, Raes, & Smith, 1998; Allen, Pereira, Smith, Raes, & Wright, 2005), as follows:

$$ET_c = (K_{cb} + K_e)ET_o \quad (1)$$

where ET_c is the crop evapotranspiration (mm d^{-1}), K_{cb} is the basal crop coefficient, which represents the plant transpiration component (–), and K_e is the soil evaporation coefficient (–). The present study followed that described by Martins et al. (2013) using the dual crop coefficient approach with the model SIMDualKc (Rosa et al., 2012).

Irrigation strategies were:

- Treatment D1, intended to fulfil 100% of ET_c.
- Treatment D2 (mild deficit) aimed at fulfilling 84% of ET_c in Crop Season 1, and 70% of ET_c in Crop Season 2.
- Treatment D3 (moderate deficit) aimed at fulfilling 64% of ET_c in Crop Season 1, and 51% of ET_c during Crop Season 2.
- Treatment D4 (severe deficit) was irrigated to satisfy 43% of ET_c in Crop Season 1, and 45% of ET_c during Crop Season 2.

During Crop Season 1, irrigation amounts were triggered when the cumulative ET_c reached an average of 25 mm (D1), 30 mm (D2), 36 mm (D3), and 43 mm (D4) in the respective plots. During Crop Season 2, irrigation amounts were triggered

Table 1 – Main physical characteristics of the soil profile.

Soil depth (cm)	Particle size distribution			Bulk density ($g\ cm^{-3}$)	Total porosity ($cm^3\ cm^{-3}$)	Volumetric water contents ($cm^3\ cm^{-3}$)					
	Sand (%)	Silt (%)	Clay (%)			Matric potential: −10 cm	−60 cm	−330 cm	−1000 cm	−5000 cm	−15000 cm
0–10	36.0 (2.5)	44.6 (0.7)	19.4 (0.1)	1.37 (0.07)	0.519 (0.05)	0.484 (0.02)	0.402 (0.02)	0.337 (0.01)	0.288 (0.02)	0.194 (0.06)	0.119 (0.06)
10–25	35.5 (1.4)	40.3 (2.6)	24.2 (3.0)	1.37 (0.03)	0.491 (0.04)	0.462 (0.02)	0.371 (0.01)	0.312 (0.01)	0.265 (0.03)	0.159 (0.01)	0.112 (0.04)
25–55	32.1 (4.8)	35.4 (2.2)	32.5 (2.8)	1.37 (0.05)	0.477 (0.12)	0.408 (0.11)	0.341 (0.10)	0.269 (0.13)	0.224 (0.07)	0.152 (0.02)	0.117 (0.02)
55–90	24.2 (5.8)	31.7 (8.1)	44.1 (3.0)	1.30 (0.06)	0.476 (0.09)	0.439 (0.04)	0.380 (0.01)	0.329 (0.02)	0.281 (0.02)	0.236 (0.04)	0.191 (0.08)

Values in brackets correspond to the standard deviation of the values measured in the different plots.

when the cumulative ET_c reached an average of 25 mm (D1), 34 mm (D2), 40 mm (D3), and 43 mm (D4).

Irrigation requirements were complemented with rainfall amounts of 73 mm (Crop Season 1) and 95 mm (Crop Season 2) during the initial crop growth stage, i.e., during the first 18 and 20 days, respectively, to ensure an adequate and uniform initial crop growth. During the remaining crop growth stages, the irrigated area was protected by a rainout shelter, consisting of two metallic structures of $16 \times 10\ m^2$, covering an area of $320\ m^2$. The rainout shelter was moved to cover the experimental site moments before any rainfall occurred, thus making it possible to accurately apply deficit irrigation treatments throughout the growing season without influence of rainfall.

In Crop Season 1, maize was sown on January 6, 2011, and was harvested on May 14, 2011. Direct seeding was used, with $3\ t\ ha^{-1}$ of dry mulch of beans on the soil surface. In Crop Season 2, maize was sown on October 15, 2011 and harvested on February 14, 2012. Direct seeding with $3\ t\ ha^{-1}$ of dry mulch of oats was also practiced. A row spacing of 0.50 m, oriented North–South, and a plant density of 6.5 plants m^2 were adopted in both crop seasons. Further details of the experiment conducted during Crop Season 1 are given by Martins et al. (2013). Crop and irrigation practices in Crop Season 2 were similar.

Soil water content was measured with an FDR (Frequency Domain Reflectometer) composed of CS616 sensors, multiplexers AM16/32 and a data logger CR1000 (Campbell Scientific, Inc., USA). Measurements were taken daily, from sowing to harvest. Measurements taken during the first day were used to define the initial soil water conditions in the model simulation. The sensors were installed at depths of 0–10, 10–25, 25–55, and 55–90 cm, with a total of 4 sensors per plot.

2.3. *Modelling approach*

The HYDRUS-1D software package (Šimůnek, Šejna, Saito, Sakai, & van Genuchten, 2013) was used to numerically simulate one dimensional (1D) water flow in the experimental plots. The 1D version of HYDRUS was selected due to the small spacing between emitters (0.5 m) and the relatively large application depths per irrigation event (25–43 mm).

The variable-saturated water flow was described using the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S(z,t) \tag{2}$$

where θ is the volumetric soil water content ($cm^3\ cm^{-3}$), t is time (d), z is the vertical space coordinate (cm), h is the pressure head (cm), K is the hydraulic conductivity ($cm\ d^{-1}$), and S is the sink term accounting for water uptake by plant roots ($cm^3\ cm^{-3}\ d^{-1}$). The unsaturated soil hydraulic properties were described using the van Genuchten–Mualem functional relationships (van Genuchten, 1980), as follows:

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left(1 + |\alpha h|^{\eta}\right)^m} \tag{3}$$

$$K(h) = K_s S_e^{\ell}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{4}$$

in which S_e is the effective saturation, θ_r and θ_s denote the residual and saturated water contents ($cm^3\,cm^{-3}$), respectively, K_s is the saturated hydraulic conductivity ($cm\ d^{-1}$), α (cm^{-1}) and η (–) are empirical shape parameters, $m = 1 - 1/\eta$, and ℓ is a pore connectivity/tortuosity parameter (–).

The soil hydraulic parameters (θ_r, θ_s, α, η, ℓ, and K_s) were first derived from particle size distribution and bulk density information presented in Table 1 with the ROSETTA pedotransfer function (Schaap, Leij, & van Genuchten, 2001). The parameter θ_r was not further modified, following Šimůnek, Angulo-Jaramillo, Schaap, Vandervaere, and van Genuchten (1998) and Jacques, Šimůnek, Timmerman, and Feyen (2002), who found that this parameter did not influence the simulated time series of θ and h significantly. The inverse modelling approach proposed by Šimůnek and van Genuchten (1996) was then used to calibrate θ_s, α, η, ℓ, and K_s in the different soil layers of each treatment. The soil hydraulic parameters (θ_s, α, η, ℓ, and K_s) were calibrated using field data from Crop Season 1 (Jan–May 2011) and were validated during Crop Season 2 (Oct 2011–Feb 2012).

The unknown soil hydraulic parameters were first obtained through minimisation of the difference between observed and simulated soil water contents defined in an objective function using the Levenberg–Marquardt nonlinear minimisation method (Marquardt, 1963). Details of the optimisation procedure have been extensively described by Šimůnek and van Genuchten (1996), Šimůnek, Angulo-Jaramillo, et al. (1998), Šimůnek, Wang, Shouse, and van Genuchten (1998), and Ramos, Gonçalves, Martins, Van Genuchten, and Pires (2006) and will not be given here. In this study, the objective function Φ (θ_m, θ_h) was defined in terms of the daily average volumetric water contents measured with the FDR sensors (θ_m) in the plots of each treatment, and the measured volumetric soil water retention values at −10, −60, −330, −1000, −5000, and −15000 cm matric potentials (θ_h) determined in different layers of a representative soil profile (Table 1). θ_m are the average values of 4 plots per treatment and θ_h are also average values relative to various plots. The weighting coefficients were set to 1, thus assuming that variances of the errors inside a particular measurement set were similar (Šimůnek & van Genuchten, 1996).

Fitting a large number of parameters simultaneously may enhance the likelihood of non-uniqueness and instability in the inverse solution. Thus, parameter fitting was carried out using a sequential approach to minimise those problems. The optimisation process was performed from the top to the bottom layer, one layer per turn as described by Jacques et al. (2002). When the hydraulic parameters of all layers were estimated, some further tuning was done by re-estimating the parameters of each layer until no further improvement was achieved.

The fitted soil hydraulic parameters were then validated by simulating soil water dynamics in Crop Season 2 using a direct approach. Soil hydraulic parameters were only considered calibrated when $RMSE_{validation} = RMSE_{calibration} + 0.01\ cm^3\ cm^{-3}$ (tolerance interval). Due to the fact that the objective function $\Phi(\theta_m, \theta_h)$ contained no information on K(h), the optimisation process often produced similar fits to Crop Season 1 data using different combinations of the soil hydraulic parameters (especially, ℓ and K_s). Thus, a series of restrictions were implemented in the objective function, with ℓ being often fitted to −1 (Schaap & Leij, 2000) and $Ks \leq 100\ cm\ d^{-1}$.

The sensitivity of the hydraulic parameters was performed before model calibration based on the standard deviation obtained during the estimation of a parameter. This was given by the T-value, calculated as the ratio of the estimated value parameter to its standard error. A higher T-value indicates a lower absolute deviation parameter and increased sensitivity of the parameter model's predictions (Arbat, Puig, Barragán, Bonany, & Cartagena, 2005). Similarly to Abbasi, Jacques, Šimůnek, Feyen, and van Genuchten (2003), the most sensitive parameters were θ_s, η, and K_s.

The sink term, S in Eq. (2), was calculated as the distribution of the potential transpiration rate, T_p ($mm\ d^{-1}$), over the root zone using the normalised root density distribution function, β (cm^{-1}), multiplied by the dimensionless stress response function, α(h), accounting for water stress (Feddes, Kowalik, & Zaradny, 1978; Skaggs, van Genuchten, Shouse, & Poss, 2006; Šimůnek & Hopmans, 2009):

$$S(h,z,t) = \alpha(h,z,t)S_p(t) = \alpha(h,z,t)\beta(z,t)T_p(t) \tag{5}$$

where S(h, z, t) and S_p(h, z, t) are the potential and actual volumes of water removed from unit volume of soil per unit of time ($cm^3\ cm^{-3}\ d^{-1}$), respectively, and α(h, z, t) is a prescribed dimensionless function of the soil water pressure head ($0 \leq \alpha \leq 1$). The local actual compensated transpiration rate, T_{ac} ($mm\ d^{-1}$), was defined over the root domain, L_R, as follows (Jarvis, 1989; Šimůnek & Hopmans, 2009):

$$\frac{T_{ac}}{T_p} = \begin{cases} \dfrac{T_a}{T_p} = \dfrac{\int_{L_R} \alpha(h,z,t)\beta(z,t)dz}{\omega(t)} = 1 & \omega_c < \omega \leq 1 \\ \dfrac{T_a}{T_p} = \dfrac{\int_{L_R} \alpha(h,z,t)\beta(z,t)dz}{\omega_c} = \dfrac{\omega(t)}{\omega_c} < 1 & \omega < \omega_c \end{cases} \tag{6}$$

where T_a is the actual non-compensated transpiration rate ($mm\ d^{-1}$), $\omega(t)$ is the dimensionless water stress index, also defined as the root adaptability factor (Jarvis, 1989), which represents a threshold value above which root water uptake reduced in stressed parts of the root zone is fully compensated by increased uptake from other parts, and ω_c is a critical value of the water stress index ($0 < \omega_c \leq 1$). Thus, when $\omega_c \leq \omega$ there is non-compensated root water uptake, otherwise compensated root water uptake is obtained (Skaggs et al., 2006; Šimůnek & Hopmans, 2009). The critical stress index ω_c was set here at 0.8 since Šimůnek and Hopmans (2009) hypothesised that agricultural plants may have a relatively high ω_c and thus their ability to compensate natural stresses is limited. Root water uptake reduction due to water stress, α(h), was described using the model developed by Feddes et al. (1978), where h_1, h_2, h_3, and h_4 are the threshold pressure head parameters. Water uptake is at the potential rate when the pressure head is between h_2 and h_3, drops off linearly when $h > h_2$ or $h < h_3$, and becomes zero when $h < h_4$ or $h > h_1$. Soil water pressure head parameters were taken from Wesseling, Elbers, Kabat, and van den Broek (1991), and were: $h_1 = -15$ cm;

$h_2 = -30$ cm; h_3 shifted from −325 to −600 cm depending on T_p, and $h_4 = -8000$ cm.

In this study, potential evaporation (E_p) and T_p rates in each irrigation treatment were obtained from Eq. (1). All calculations relative to the dual Kc approach (Allen et al., 1998, 2005) were carried out with the SIMDualKc model (Rosa et al., 2012) and then used with HYDRUS-1D. In a review by Kool et al. (2014), the dual Kc approach compared well with a variety of ET partitioning approaches. Previous applications to maize, wheat and soybeans (Wei, Paredes, Liu, Chi, & Pereira, 2015; Zhao et al., 2013) also proved the appropriateness of model estimation of soil evaporation through comparison of simulated values with those observed with microlysimeters. In addition, studies with tree crops have also demonstrated the appropriateness of ET partitioning after comparing estimates of soil evaporation with measurements taken in microlysimeters, and plant transpiration with sap-flow measurements (Paço, 2012, 2014).

The SIMDualKc calibration procedure sought to obtain the crop parameters K_{cb} and p (depletion fraction for no stress) relative to all crop growth stages, the soil evaporation parameters TEW (total evaporable water, mm), REW (readily evaporable water, mm) and Z_e (evaporable layer depth, m), and the empirical parameters a_D and b_D of the deep percolation parametric function. The calibration was performed by minimising the differences between observed and simulated daily available soil water (ASW) relative to the entire root depth (60 cm) using the irrigation schedules as they were actually applied in the field. Calibration was performed using the experimental values observed during Crop Season 1. Based on soil water observations, the initial depletion for the root zone was set at 8% of TAW and the initial depletion of the evaporable layer was set at 0% of TEW.

Martins et al. (2013) described the calibration procedure used with the 2010/2011 dataset (Crop Season 1) where the search of parameters was performed in various steps: (1) a set of initial soil and crop parameters was selected to start the calibration; (2) a trial and error procedure was developed for selecting the crop parameters K_{cb} and p that minimised the deviations between simulated and observed soil water contents; (3) when K_{cb} and p values were in an acceptable range and estimation errors were small and showing little variation from one iteration to the next, trial and error was applied to the soil parameters and the CN value; (3) a final adjustment was applied again to the crop parameters until the referred deviations were minimised. The calibrated parameters used are summarised in Table 2. The validation consisted of using the parameters previously calibrated (K_{cb}, p, TEW, REW, Z_e, CN, a_D and b_D) with data obtained in Crop Season 2. A discussion on the procedures used and related limitations is provided by Martins et al. (2013).

2.4. Goodness-of-fit indicators

Model validation was carried out by comparing field measured water content values with HYDRUS-1D simulations using visual analysis and several goodness-of-fit statistical indicators, including the regression coefficient (b), the determination coefficient (R^2), the mean error (ME), the root mean square error (RMSE), and the modelling efficiency (EF) according to Nash and Sutcliffe (1970). These were defined as:

$$b = \frac{\sum_{i=1}^{n} O_i P_i}{\sum_{i=1}^{n} O_i^2} \tag{7}$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\left[\sum_{i=1}^{n} (O_i - \overline{O})^2\right]^{0.5} \left[\sum_{i=1}^{n} (P_i - \overline{P})^2\right]^{0.5}} \right\}^2 \tag{8}$$

$$ME = \frac{1}{n} \sum_{i=1}^{n} (O_i - P_i) \tag{9}$$

$$RMSE = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} \tag{10}$$

$$EF = 1.0 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{11}$$

where O_i and P_i are the observed and predicted values at time i (i = 1, 2, …, n), respectively, $\overline{O}$ and $\overline{P}$ are the mean observations and model predictions, respectively, and n is the number of observations. b values close to 1, and ME and RMSE values close to zero indicate good model predictions. Values of R^2 close to 1.0 indicate that the model explains well the variance of observations. Values of EF range from $-\infty$ and 1.0, with values close to 1.0 indicating that the residuals variance is much smaller than the observed data variance, hence that model predictions are good (Legates & McCabe, 1999).

3. Results and discussion

3.1. Soil water content simulations

Figure 1 presents the soil water contents measured with an FDR system during both crop seasons in treatment D1 (full irrigation), and compares these values with the results of the HYDRUS-1D simulations from sowing to harvest (121 days in Crop Season 1; 122 days in Crop Season 2). Figures 2 and 3, and 4 present the same comparisons for treatments D2 (mild stress), D3 (moderate stress), and D4 (severe stress), respectively. The amounts of precipitation and net irrigation water applied and the respective irrigation schedules are also shown. As referred earlier, irrigation water depths averaged from 25 to 43 mm in the different treatments. However, in Crop Season 2, due to an accident while managing the irrigation system, treatments D1 (Fig. 1) and D3 (Fig. 3) received 82 and 102 mm, respectively, applied in a single event 83 days after sowing (DAS).

Water content measurements increased rapidly with irrigation and then gradually decreased until the next irrigation event as a result of water uptake and redistribution. Water content variations were obviously larger near the soil surface because root water uptake was higher there than in deeper layers and, also, due to soil evaporation despite this being quite small due to mulch effects. The bottom layer (55–90 cm)

Table 2 – Crop and soil parameters used for estimating plant transpiration and soil evaporation for the FAO dual crop coefficient approach used by models HYDRUS-1D and SIMDualKc (source for Crop Season 1: Martins et al., 2013).

Parameter	Season 1 (2010/2011)	Season 2 (2011/2012)
Observed		
Planting date	January 6, 2011	October 15, 2011
Harvest date	May 14, 2011	February 14, 2012
Length stages (d):		
L_{ini}	18	20
L_{dev}	20	36
L_{mid}	62(D1); 62(D2); 51(D3); 45(D4)	46(D1); 46(D2); 41(D3); 36(D4)
L_{late}	21(D1); 21(D2); 32(D3); 38(D4)	20(D1); 20(D2); 25(D3); 30(D4)
H (cm):		
H_{ini}	10	15
H_{dev}	38	34
H_{mid}	230(D1); 220(D2); 210(D3); 200(D4)	240(D1); 229(D2); 218(D3); 171(D4)
H_{late}	230(D1); 220(D2); 210(D3); 200(D4)	240(D1); 229(D2); 218(D3); 171(D4)
f_c (–):		
$f_{c\ ini}$	0.01	0.01
$f_{c\ dev}$	0.20	0.20
$f_{c\ mid}$	0.90(D1); 0.90(D2); 0.85(D3); 0.80(D4)	0.90(D1); 0.90(D2); 0.85(D3); 0.80(D4)
$f_{c\ late}$	0.70(D1); 0.70(D2); 0.65(D3); 0.60(D4)	0.85(D1); 0.85(D2); 0.75(D3); 0.70(D4)
f_w (–)	0.6	0.6
$f_{r\ mulch}$ (–)	1.0	1.0
$f_{eff\ mulch}$ (–)	0.9	0.9
TAW (mm)	173.0	173.0
RAW (mm)	86.5	86.5
Calibrated		
Depletion fraction (–):		
p_{ini}	0.5	0.5
p_{dev}	0.5	0.5
p_{mid}	0.5	0.5
p_{end}	0.5	0.5
TEW (mm)	49	49
REW (mm)	12	12
Z_e (mm)	15	15
$K_{cb\ ini}$ (–)	0.20	0.20
$K_{cb\ mid}$ (–)	1.12	1.12
$K_{cb\ end}$ (–)	0.20	0.20
CN (–)	75	75
a_D (–)	353	353
b_D (–)	−0.022	−0.022

L, length season stages; H, crop height; f_c, fraction of soil covered by the crop; f_w, fraction of soil cover wetted by irrigation; $f_{r\ mulch}$, fraction of soil covered by mulch; $f_{eff\ mulch}$, effective fraction of soil covered by mulch; TAW, total available water; RAW, readily available water; p, depletion fraction; TEW, total evaporable water; REW, readily evaporable water; Z_e, depth of the soil surface layer that is subjected to drying by way of evaporation; K_{cb}, basal crop coefficient; CN, curve number; a_D and b_D, empirical parameters of the deep percolation equation (Liu et al., 2006); ini, dev, mid, and late, crop initial, development, mid-season, and end season stages, respectively.

also showed smaller water content variations due to its hydraulic characteristics, resulting from the higher clay content (Table 1). Model simulations were able to closely reproduce the FDR measured values during most of the crop growth seasons. Table 3 presents the goodness-of-fit indicators comparing measured and simulated soil water content values for each treatment and crop season. The goodness-of-fit tests confirmed the generally accurate model performance, resulting in b values that varied between 0.951 and 1.024 and $R^2 \geq 0.92$, thus not showing bias of estimation. Moreover, an EF > 0.89 indicated that the variance of residuals was much smaller than the variance of the observations. The ME values varied between −0.008 and 0.008 $cm^3\ cm^{-3}$, while the RMSE values varied between 0.014 and 0.025 $cm^3\ cm^{-3}$. The goodness-of-fit indicators are within the range of values reported for water content simulations using different versions of the HYDRUS model (e.g., Skaggs et al., 2004; Ajdary et al., 2007; Bof Bufon et al., 2012; Kandelous, Šimůnek, van Genuchten, & Malek, 2011; Ramos et al., 2011, 2012; Phogat, Skewes, Mahadevan, et al., 2013; Phogat, Skewes, Cox, et al., 2013; Phogat, Skewes, Mahadevan, et al., 2013).

Despite the general good agreement between measured data and model simulations, all experimental treatments registered a small difference between 20 and 40 DAS during Crop Season 1 (2010/2011). Model simulations produced larger soil water contents than field measured values during this short period which corresponded to the crop development stage (Table 2). Thus, crop water use seems to have been here slightly underestimated. These values were taken directly from Martins et al. (2013), who estimated E and T_p after

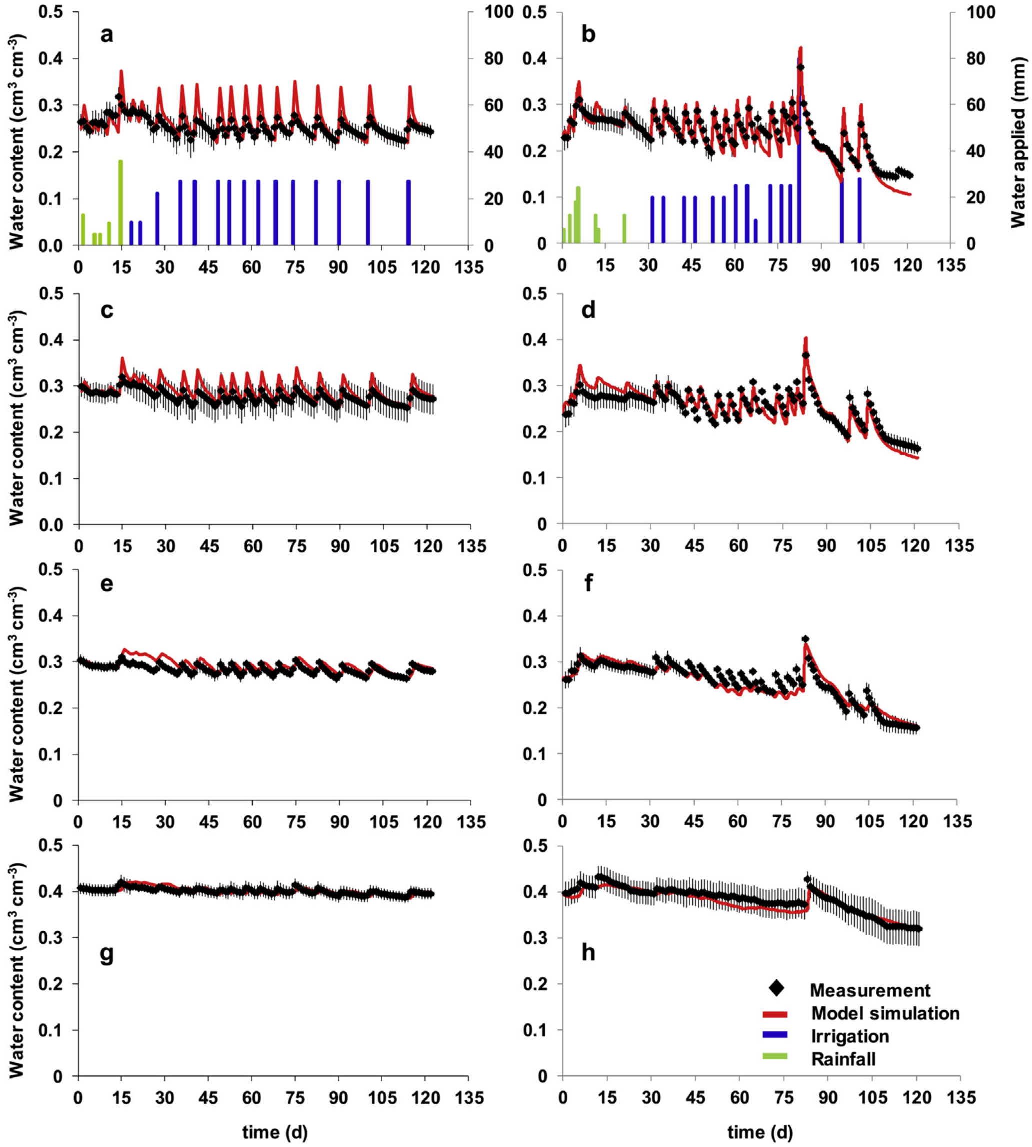

Fig. 1 – Measured and Hydrus-1D simulated soil water contents at different depths in treatment D1 (full irrigation) relative to Season 1 on left (a, 0–10 cm; c, 10–25 cm; e, 25–55 cm; and g, 55–90 cm) and to Season 2 on right; (b, 0–10 cm . d, 10–25 cm; f, 25–55 cm; and h, 55–90 cm). Vertical bars correspond to the standard deviation of observations.

integrating field water contents measurements and performing the water balance for the entire root zone with the SIMDualKc model (Rosa et al., 2012). Decreasing the initial and the crop development length periods shown in Table 2 slightly would probably improve HYDRUS-1D predictions during this period. Ramos et al. (2012) provided an extensive review of the causes related to field measurement, model input, and model structure errors which explained the deviations between measured and simulated water contents in their experiment, and this could also be assumed for the current experiment. However, the problems that relate to the representativeness of the FDR measurements to describe the distribution of water under a highly non-uniform irrigation system were here minimised as soil hydraulic properties were calibrated in each treatment by numerical inversion of field water content data.

Table 4 lists the calibrated parameters of the van Genuchten–Mualem model for the different layers of each treatment. These parameters were first calibrated by fitting model simulations to field water retention data measured in Crop Season 1, and then validated by testing the calibrated parameters in soil water content simulations during Crop Season 2. The parameters K_s and α showed the largest variability, with a coefficient of variation of 137 and 67%, respectively, when considering all layers in the different experimental plots simultaneously, and between 70–112% and 30–72%, respectively, when considering the soil hydraulic parameters by soil layer. The large variation of K_s values with depth was related to the increase of clay and decrease of sand content in the bottom soil layer and, mainly, due to the effect of no tillage and mulch, applied every crop season during the last five years on a soil previously under natural pasture, on soil structure. A review by Strudley, Green and Ascough (2008) showed that K_s tends to be higher under no-tillage but actual responses vary with soil characteristics and water regimes.

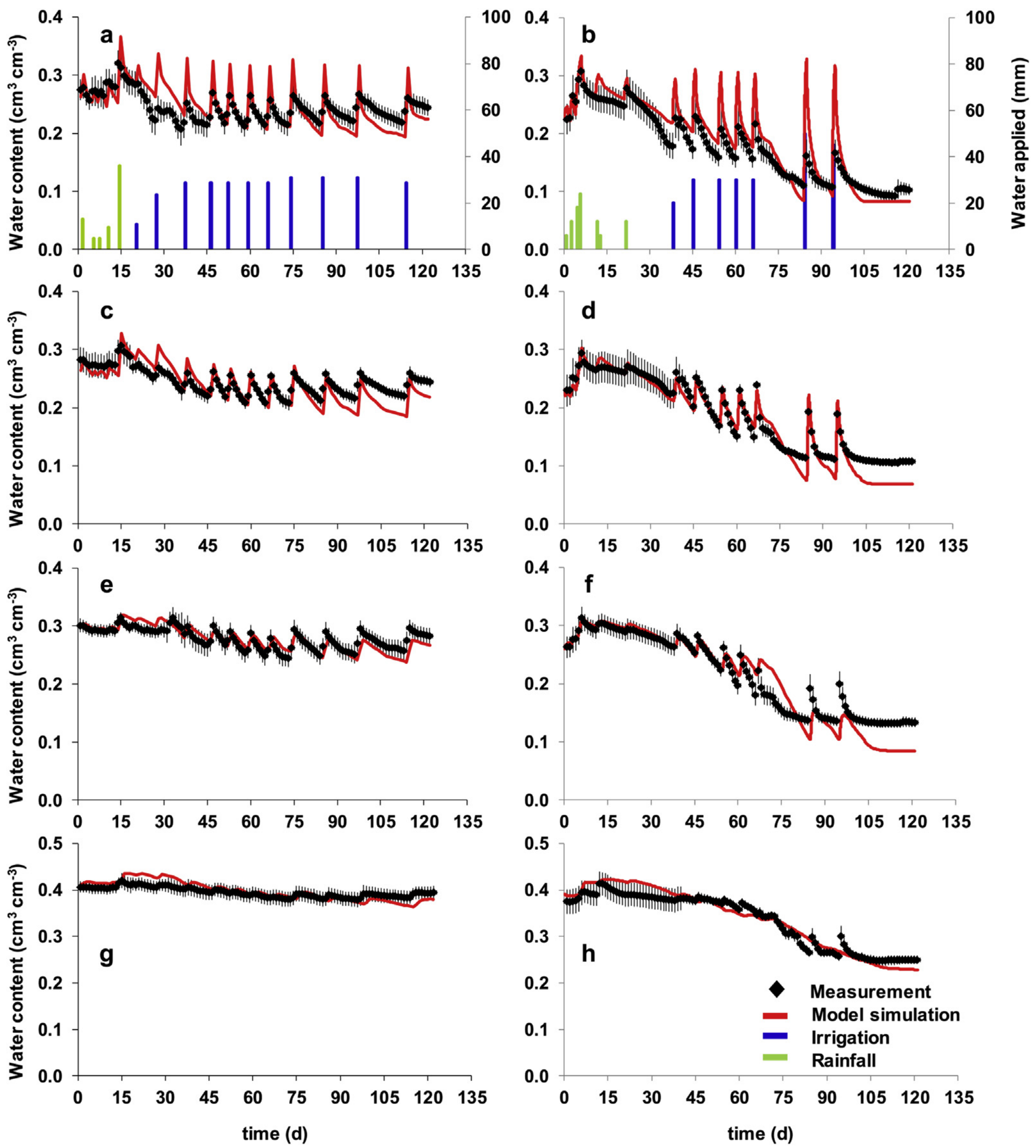

Fig. 2 – Measured and Hydrus-1D simulated soil water contents at different depths in treatment D2 (mild deficit irrigation) relative to Season 1 on left (a, 0–10 cm; c, 10–25 cm; e, 25–55 cm; and g, 55–90 cm) and to Season 2 on right; (b, 0–10 cm . d, 10–25 cm; f, 25–55 cm; and h, 55–90 cm). Vertical bars correspond to the standard deviation of observations.

Similar results were reported by Cavalieri et al. (2009) for Brazilian soils. Reichert, Suzuki, Reinert, Horn, and Häkansson (2009) reported a high decrease of K_s with depth, varying with compaction, for Brazilian soils similar to those used in this study. Blanco-Canqui and Lal (2007) reported that mulched treatments had a K_s 123 times greater than the non-mulched soil, which results from the increase of micro- and macroporosity due to reduced soil disturbance and straw mulch. If these results explain the observed high vertical variability of K_s, they still do not prove that the great difference between the upper and lower soil layers in this study is definitely correct. Table 4 shows that the standard error of K_s was quite large particularly for the bottom layer. A study aimed at understanding the variability of the soil hydraulic properties including K_s is now beginning.

The coefficients of variation obtained for θ_r and η were always lower than 11% whether grouping the soil hydraulic parameters by layer or by considering the entire set. Similar behaviour was reported by Abbasi et al. (2003). Thus, by calibrating the soil hydraulic properties in each layer of the various treatments, the numerical inversion technique allowed the effect of soil variability on model simulations to be included. One other advantage of this approach was that it also broadly considered the effect of different characteristics of the soil matrix and macropore channels on soil water dynamics. These soil characteristics cannot be assessed with conventional methods for measuring soil hydraulic properties (Cameira, Ahuja, Fernando, & Pereira, 2000), but were probable important in our experiment since soil structure has probably been benefiting from no tillage practices for quite some years.

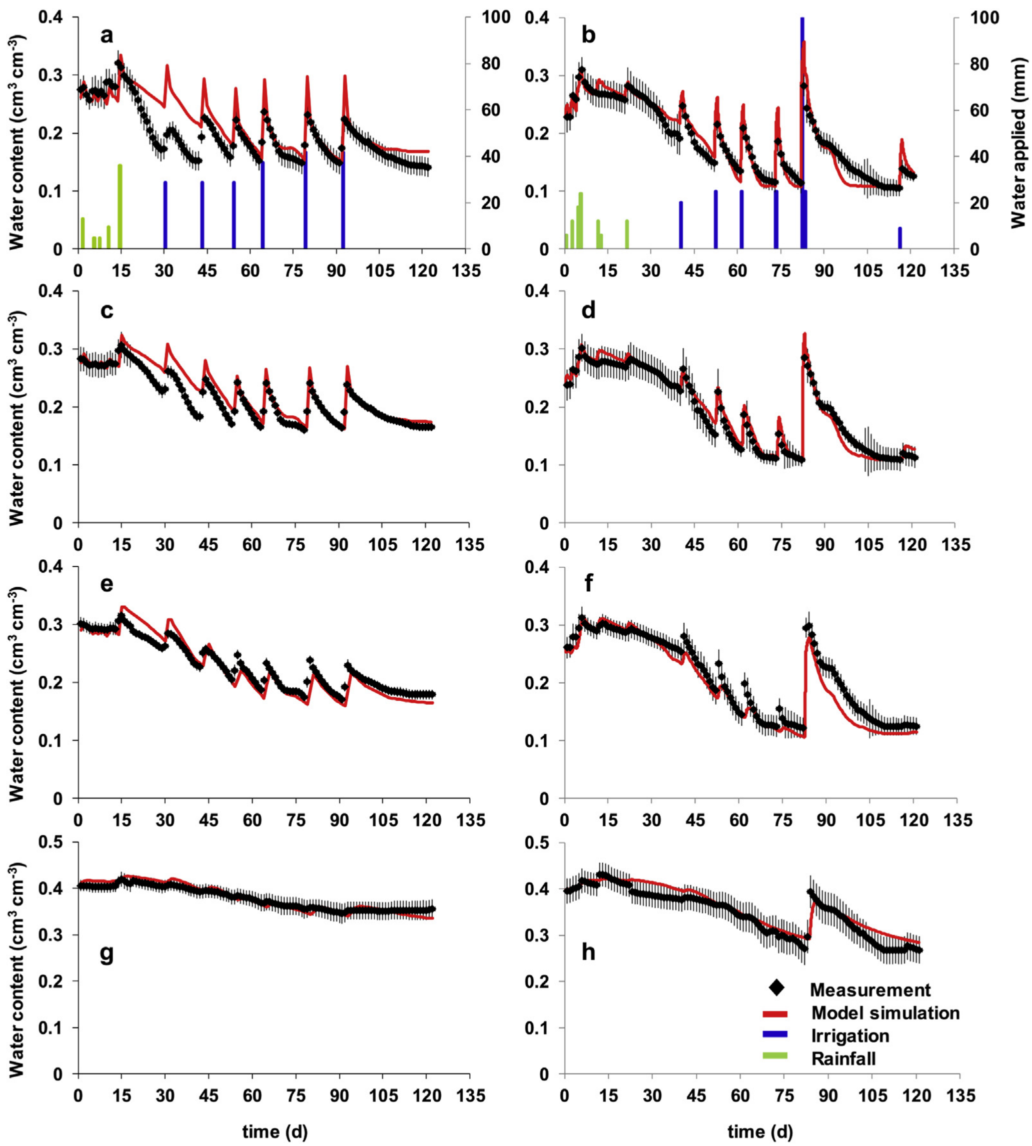

Fig. 3 – Measured and Hydrus-1D simulated soil water contents at different depths in treatment D3 (moderate deficit irrigation) relative to Season 1 on left (a, 0–10 cm; c, 10–25 cm; e, 25–55 cm; and g, 55–90 cm) and to Season 2 on right; (b, 0–10 cm . d, 10–25 cm; f, 25–55 cm; and h, 55–90 cm). Vertical bars correspond to the standard deviation of observations.

3.2. *Water balance and water deficits*

Figure 5 shows the evolution of soil pressure heads for the different treatments. These are the corresponding soil pressure heads of the HYDRUS-1D simulated water content values presented in Figs. 1–4. During Crop Season 1, soil pressure heads in treatments D1 and D2 were maintained perfectly within the interval in which water uptake was at the potential rate, i.e., between h_2 and h_3. With SIMDualKc, it was also observed that the soil water content was always kept above the water stress threshold (Martins et al., 2013). Thus, applying less water in D2 was not enough to reduce the potential transpiration during Crop Season 1. Soil pressure head values in treatment D3 were also maintained between h_2 and h_3 during the first 50 days. They then dropped to be between h_3 and h_4 during drier periods, increasing again with irrigation to soil pressure heads above h_3. However, Fig. 6 shows that root water uptake was not affected in treatment D3 ($T_p = T_{ac}$) during the entire Crop Season 1 as maize was able to compensate for reduced root water uptake from more stressed regions of the root zone by removing more water from less-stressed soil regions where water was held with smaller capillary forces, thus more easily available to the plants. In this case, maize was able to remove more water from the soil layer between 55 and 90 cm depth which remained unstressed during most of Crop Season 1 (soil pressure heads close to h_3). A similar condition was observed with SIMDualKc, which has shown that soil water contents were kept above the water stress threshold. As explained by Šimůnek and Hopmans (2009) relative to HYDRUS behaviour, water uptake increase (compensation) is maximum in parts of the root zone where the root water uptake is optimal, equal to zero in parts of the root zone where the pressure head is below the wilting point or above the anaerobiosis point, and

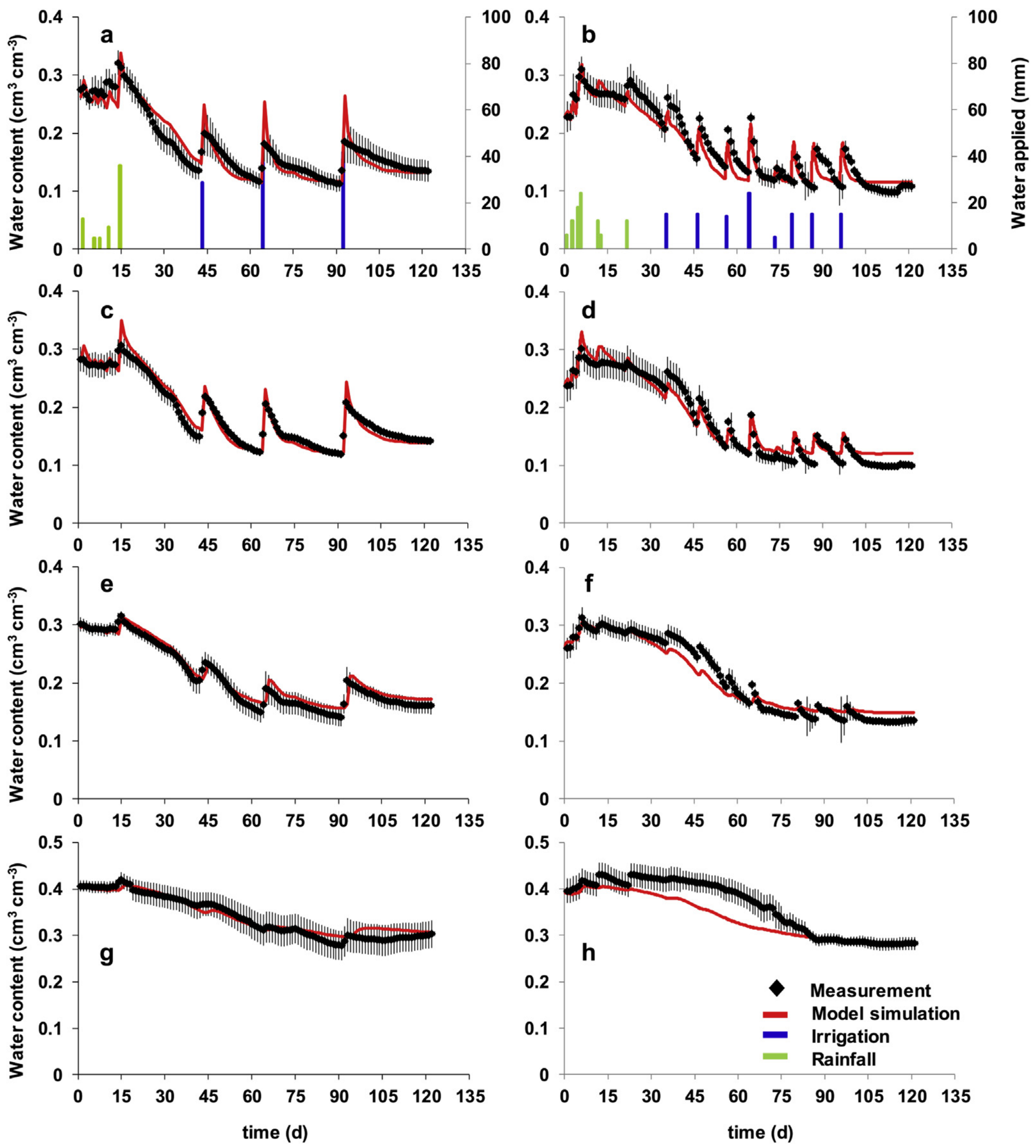

Fig. 4 – Measured and Hydrus-1D simulated soil water contents at different depths in treatment D4 (severe deficit irrigation) relative to Season 1 on left (a, 0–10 cm; c, 10–25 cm; e, 25–55 cm; and g, 55–90 cm) and to Season 2 on right; (b, 0–10 cm . d, 10–25 cm; f, 25–55 cm; and h, 55–90 cm). Vertical bars correspond to the standard deviation of observations.

Table 3 – Goodness-of-fit indicators resulting from comparing measured and simulated soil water contents.

Treatments	b (–)	R^2 (–)	ME ($cm^3\ cm^{-3}$)	RMSE ($cm^3\ cm^{-3}$)	EF (–)
Season 1 (2010/2011)					
D1	1.024	0.920	−0.008	0.019	0.899
D2	1.001	0.921	0.000	0.020	0.905
D3	1.022	0.937	−0.007	0.022	0.929
D4	1.009	0.973	−0.002	0.014	0.972
Season 2 (2011/2012)					
D1	0.989	0.947	0.003	0.017	0.941
D2	1.013	0.938	−0.001	0.025	0.918
D3	1.010	0.970	−0.001	0.017	0.962
D4	0.951	0.963	0.008	0.023	0.947

D1, full irrigation; D2, mild deficit; D3, moderate deficit; and D4, severe deficit.
b, regression coefficient; R2, coefficient of determination; ME, mean error; RMSE, root mean square error; EF, model efficiency.

Table 4 – Soil hydraulic parameters estimated by numerical inversion with HYDRUS-1D.

Treatments	Soil depth (cm)	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	α (cm^{-1})	η (–)	K_s[a] ($cm\ d^{-1}$)	ℓ (–)
D1	0–10	0.052	0.435 (0.012)	0.018 (0.003)	1.438 (0.044)	50.0 (28.3)	–1.00
	10–25	0.052	0.423 (0.012)	0.013 (0.002)	1.400 (0.042)	10.0 (4.0)	–1.00
	25–55	0.064	0.376 (0.013)	0.007 (0.002)	1.500 (0.093)	20.0 (2.0)	–1.00
	55–90	0.103	0.454 (0.008)	0.006 (0.001)	1.300 (0.039)	3.0 (0.9)	0.00 (0.1)
D2	0–10	0.052	0.425 (0.015)	0.011 (0.002)	1.560 (0.057)	10.0 (3.5)	–1.00
	10–25	0.052	0.366 (0.013)	0.006 (0.001)	1.750 (0.082)	5.0 (1.8)	–1.00
	25–55	0.064	0.330 (0.009)	0.003 (0.001)	1.819 (0.193)	5.0 (3.6)	–1.00
	55–90	0.103	0.456 (0.009)	0.003 (0.001)	1.600 (0.120)	0.4 (0.2)	1.00 (3.0)
D3	0–10	0.052	0.386 (0.015)	0.011 (0.002)	1.400 (0.034)	50.0 (15.2)	0.18 (2.04)
	10–25	0.052	0.354 (0.010)	0.006 (0.001)	1.450 (0.033)	10.0 (1.7)	–1.00
	25–55	0.064	0.359 (0.012)	0.005 (0.001)	1.614 (0.058)	10.0 (7.0)	–1.00
	55–90	0.103	0.432 (0.006)	0.002 (0.000)	1.500 (0.127)	0.2 (0.1)	–0.45 (1.84)
D4	0–10	0.052	0.448 (0.017)	0.010 (0.002)	1.418 (0.022)	100.0 (117.3)	–1.00
	10–25	0.052	0.434 (0.016)	0.007 (0.001)	1.430 (0.022)	50.0 (31.7)	–1.00
	25–55	0.064	0.334 (0.008)	0.002 (0.000)	1.430 (0.037)	1.7 (1.1)	–1.00
	55–90	0.103	0.420 (0.007)	0.001 (0.000)	1.300 (0.047)	1.6 (1.2)	0.65 (3.31)

θ_r, residual soil water content; θ_s, saturated soil water content; α and n, empirical shape parameters; Ks, saturated hydraulic conductivity; ℓ, pore connectivity/tortuosity parameter; D1, full irrigation; D2, mild deficit; D3, moderate deficit; D4, severe deficit.
[a] Values in brackets correspond to the standard error of the estimated values.

proportional to the water stress response for other pressure head values. Treatment D4 showed a contrasting behaviour. Here, maize was not able to fully compensate the water deficits shown in Fig. 5 by extracting more water from the deeper layer. Thus, HYDRUS-1D results showed that potential transpiration decreased due to water stress in Treatment D4 after day 50 (Fig. 6). Both HYDRUS-1D and SIMDualKc models behaved similarly but the interpretation relative to compensation of water uptake is more clear with HYDRUS-1D, though it is not evident that the gain in information justifies the more detailed soil parameterisation of this model.

Figures 5 and 6 show that the water deficits imposed during Crop Season 2 were more pronounced than in Crop Season 1. During season 2, treatment D1 showed soil pressure heads usually varying between h_2 and h_3. However, soil pressure heads also increased above h_1 for a short period (day 83) in the surface layer due to the irrigation incident reported earlier, and decreased below h_3 during the late ripening period. This later water deficit caused a small decrease of potential transpiration between days 116–121 (Fig. 6). Treatments D2 to D4 showed long periods in which soil pressure heads were maintained between h_3 and h_4. Thus, Fig. 6 shows that potential root water uptake reductions ($T_p > T_{ac}$) due to water stress increased in those treatments. D4 registered the longest stress period (from day 50 to harvest). While the compensation mechanism was able to remove more water from deeper layers, this was never sufficient to reach T_p in any of the treatments, as was observed during Crop Season 1.

Table 5 shows the components of the water balance estimated with the HYDRUS-1D model in the different experimental treatments. During Crop Season 1, potential root water uptake reduction due to water stress [$(T_P - T_{ac})/T_P \times 100$] was only observed in treatment D4 (26.8%). During Crop Season 2, potential root water uptake reductions due to water stress were 0.4, 11.8, 18.5, and 48.8% in treatments D1, D2, D3, and D4, respectively. Table 5 also shows that, if the compensation mechanism had not been considered, T_p reductions due to water stress would have been more pronounced. During Crop Season 1, treatments D3 and D4 would have resulted in T_p reductions of 3.2 and 30.1%, respectively, due to water stress. During Crop Season 2, T_p reductions would have been 0.8–1.7% greater than those observed when considering the compensation mechanism. Thus, the value of $\omega_c = 0.8$ adopted in this study seems reasonable since, as referred earlier, maize has a limited ability to compensate for natural stresses (Šimůnek & Hopmans, 2009).

Despite the fact that SIMDualKc does not specifically consider root water uptake with compensation, results closely resemble the ones obtained with HYDRUS-1D (Table 6) for the components of the water balance estimated with the SIMDualKc model for both crop seasons. During Crop Season 1, only treatments D3 and D4 registered root water uptake reductions of 0.3 and 19.6% due to water stress. During Crop Season 2, Tp reductions due to water stress reached 1.0, 14.6, 15.7, and 36.6% in treatments D1, D2, D3, and D4, respectively. The main difference was thus registered in treatment D3 during Crop Season 1 where HYDRUS-1D showed that maize was able to compensate the water stress deficit while SIMDualKc did not (although T_p reduction was only 0.3%). Although, ω_c may need to be better calibrated for maize (or any other crop) in future applications, the compensation mechanism seems to be a more realistic approach when simulating the root zone than non-compensation. Šimůnek and Hopmans (2009) showed how neglecting root water uptake compensation by plant roots in water stress conditions could result in significant errors when estimating plant transpiration and the soil water balance. Differences between the models result therefore from the fact that a mechanistic approach is used in HYDRUS-1D with discrimination of the various soil layers, while a soil water balance is applied to the entire root zone in SIMDualKc. However, in a model like the one incorporated in the IRRIGA software it is not possible to

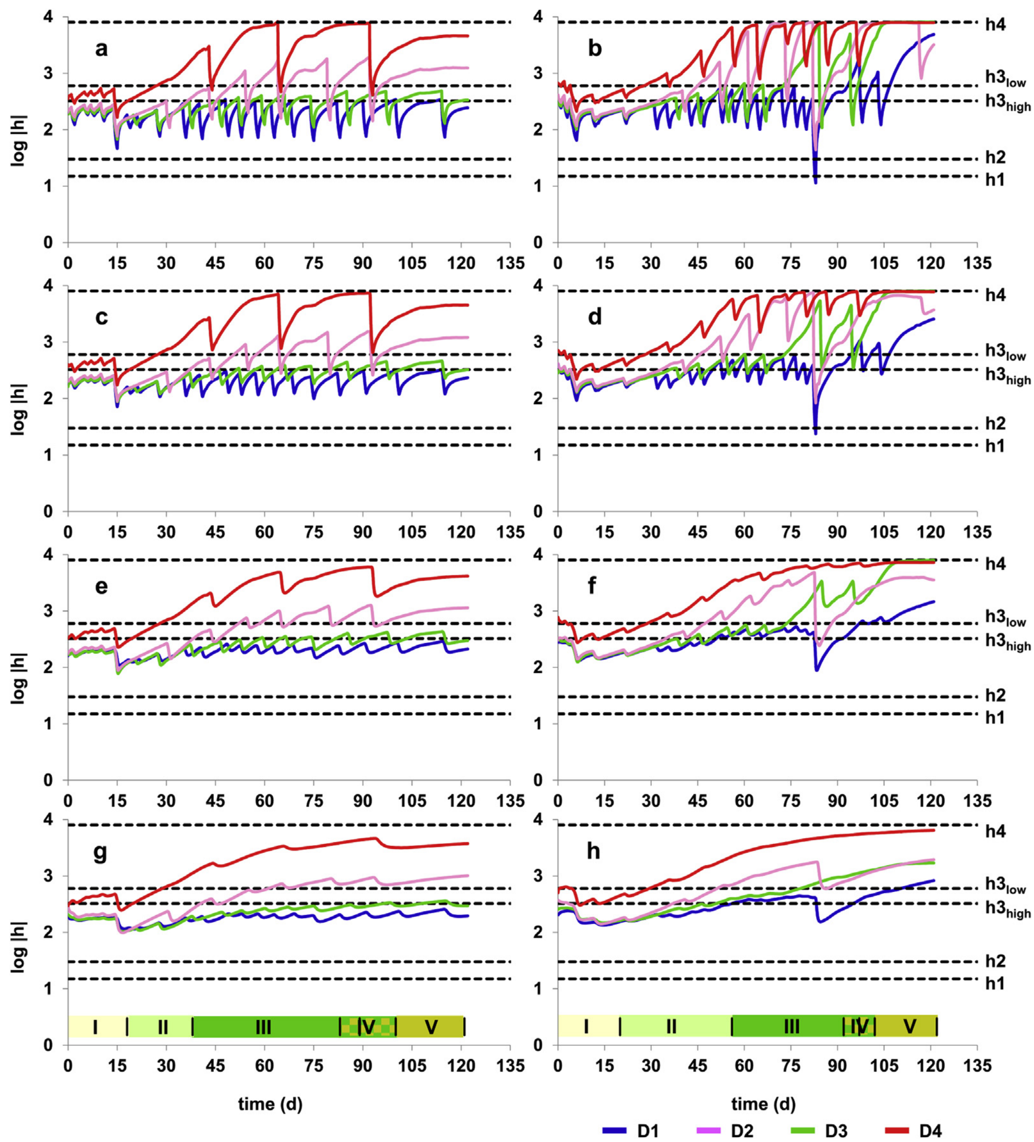

Fig. 5 – Hydrus-1D simulated soil pressure heads, for Crop Season 1, on left (a: 0–10 cm; c: 10–25 cm; e: 25–55 cm; g: 55–90 cm), and for Crop Season 2, on right (b: 0–10 cm; d: 10–25 cm; f: 25–55 cm; h: 55–90 cm). The crop stages are: I: initial; II: crop development; III: first part of mid-season; IV: second part of mid-season; V: late season. The threshold hydraulic heads used with the soil water stress model are: h_1, h_2, $h_{3\ low}$, $h_{3\ high}$ and h_4. Water uptake is at the potential rate when the pressure head is between h_2 and h_3, drops off linearly when $h > h_2$ or $h < h_3$, and becomes null when $h < h_4$ or $h > h_1$. (The length of the mid-season stage decreased from D1 to D4).

adopt a layered approach because parameterisation has to be simple.

Tables 5 and 6 further show that actual evaporation (E_a) values, calculated based on the availability of water in the soil profile, were relatively low due to the soil mulch, varying between 24 mm in treatment D4 and 33 mm in treatment D1 during Crop Season 1, and between 29 mm in treatment D4 and 42 mm in treatment D1 during Crop Season 2. HYDRUS-1D estimates for percolation varied between 33 and 83% of the water applied during Crop Season 1, and between 22 and 47% during Crop Season 2. Figure 7 shows the daily percolation of water through the bottom of the soil profile computed with HYDRUS-1D. Percolation values were higher during the initial crop season stage when the crop was not yet sheltered from rainfall. During Crop Season 1, 22% of the total amount of percolation in treatment D1 occurred during this stage, while in treatment D4 that value reached 67%. During Crop Season 2, the corresponding values were relatively similar, with 36 and 62% of the water percolating during the initial crop stages due to rainfall in treatments D1 and D4, respectively. The influence of rainfall on percolation values was thus obviously greater in treatments under stress conditions (D3 and D4) than under no-stress conditions (D1 and D2). Figure 7 also shows that despite the large depth of water applied in D1 and D3 during Crop Season 2 at day 83, percolation values did not increase dramatically as the soil was relatively dry and was able to store most of the irrigation water applied. The percolation values estimated with SIMDualKc (Table 6) were

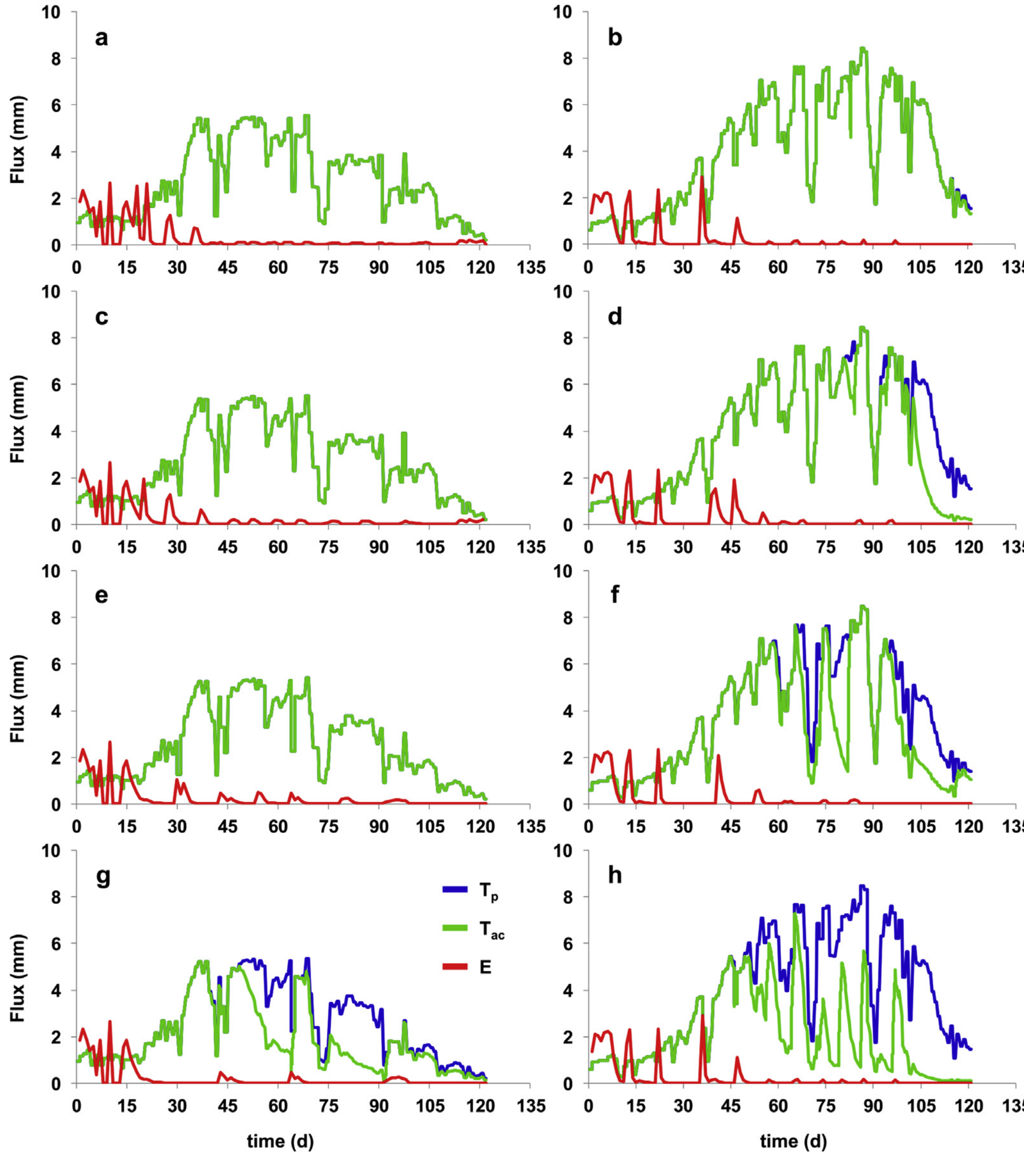

Fig. 6 – Potential (T_p) and actual transpiration (T_{ac}) and soil evaporation (E) in Crop Season 1, on left (a: D1, full irrigation; c: D2, mild deficit; e: D3, moderate deficit; and g: D4, severe deficit), and in Crop Season 2, on right (b: D1, full irrigation; d: D2, mild deficit; f: D3, moderate deficit; and h: D4, severe deficit).

relatively similar despite the percolation function included in this model is empirically based (Liu, Pereira, & Fernando, 2006), but which parameters were calibrated together with other crop and soil parameters as described in Section 2.3. Nevertheless, actual evaporation and actual transpiration were very similar when comparing both models.

The usability of input data for the IRRIGA software is worth discussion. Weather data used in the system is collected from a network of automatic weather stations (Carlesso et al., 2009). Basic soil hydraulic parameters are obtained from local sampling and analysed in the laboratory. Crop data is provided by users with the help of technical staff visiting the areas. Therefore, it is possible to use a model like SIMDualKc when crop parameters such as those listed in Table 2, mainly crop height and the fraction of soil covered by the crop, are routinely observed in the field, or when collected field data becomes part of specific databases that can create sets of default values that can be associated with crops and regions. The length of crop stages, which are given in Table 2 in days, are often used in IRRIGA as cumulative growth degree days. These aspects are progressively being implemented in IRRIGA, where data on crop coefficients are also being upgraded. The usability of HYDRUS-1D is more difficult because the requirements of layered soil information on soil hydraulic properties, even when pedotransfer functions are available, is quite demanding.

4. Conclusions

The HYDRUS-1D model successfully simulated the temporal variability of soil water dynamics in treatments irrigated with full and deficit irrigation Based on model simulations, actual transpiration varied between 224 and 331 mm during Crop

Table 5 – Water balance estimated with HYDRUS-1D for each treatment.

Treatments	Net rainfall (mm)	Net irrigation (mm)	Δ Soil storage (mm)	Percolation (mm)	R + I + S−P	Actual evaporation (mm)	Potential transpiration (mm)	Compensated actual transpiration (mm)	Non-compensated actual transpiration (mm)	E + T_{ac}	Water balance error (%)
	R	I	S	P		E	T_p	T_{ac}	T_a		
Crop season 1											
D1	68	369	−11	83	365	33	331	331	331	364	0.22%
D2	68	300	−34	42	360	31	330	330	330	361	−0.25%
D3	68	207	−93	33	335	29	313	313	303	342	−1.90%
D4	68	108	−110	44	242	24	306	224	214	248	−2.10%
Crop season 2											
D1	90	391	−84	47	518	42	485	483	475	525	−1.24%
D2	90	235	−149	22	452	32	485	428	422	460	−1.69%
D3	90	231	−109	26	404	28	464	378	372	406	−0.47%
D4	90	108	−103	43	258	29	475	243	241	272	−4.65%

D1, full irrigation; D2, mild deficit; D3, moderate deficit; and D4, severe deficit.
Δ Soil Storage = $\theta_{final} - \theta_{initial}$.
Water balance error = (inputs − outputs)/inputs × 100.

Table 6 – Water balance estimated with SIMDualKc for each treatment.

Treatments	Total rainfall (mm)	Total irrigation (mm)	Δ Soil storage (mm)	Percolation (mm)	R + I + S − P	Mulch storage (mm)	Actual evaporation (mm)	Potential transpiration (mm)	Actual transpiration (mm)	E + T (mm)	Water balance error (%)
	R	I	S	P			E		T		
Crop season 1											
D1	73	389	−3	86	379	25	33	331	331	364	−2.15
D2	73	316	−19	33	375	21	31	330	330	361	−1.72
D3	73	218	−89	24	356	16	29	313	312	341	−0.26
D4	73	113	−122	23	285	10	24	306	246	270	1.62
Crop season 2											
D1	95	412	−98	83	522	26	42	485	480	522	−4.30
D2	95	248	−129	23	449	18	32	485	414	446	−3.18
D3	95	243	−122	39	421	17	28	464	391	419	−3.26
D4	95	113	−140	17	331	10	29	475	301	330	−2.59

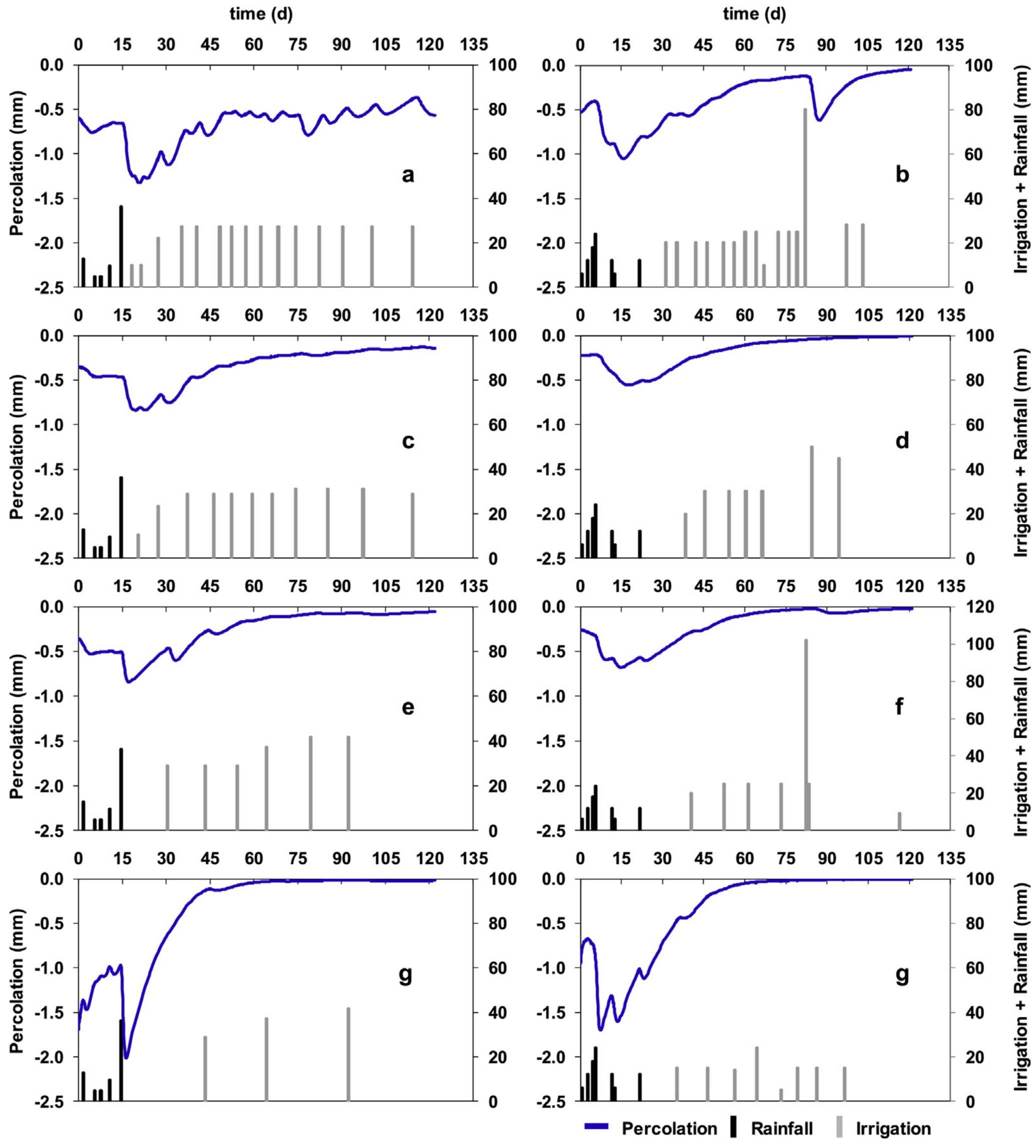

Fig. 7 – Daily percolation in Crop Season 1, on left (a: D1, full irrigation; c: D2, mild deficit; e: D3, moderate deficit; and g: D4, severe deficit), and in Crop Season 2, on right (b: D1, full irrigation; d: D2, mild deficit; f: D3, moderate deficit; and h: D4, severe deficit).

Season 1, but only treatment D4 registered root water uptake reductions due to water stress (26.8%). Soil pressure heads in treatments D1 and D2 were always kept between the interval which maximises root water uptake, while the compensation mechanism in HYDRUS-1D allowed more water to be removed from the deeper, less stressed layers in treatment D3, thus compensating for the water deficits in the surface layers. During Crop Season 2, actual transpiration varied between 243 and 483 mm. The stress conditions imposed during this season were more pronounced and root water uptake reductions varied 0.4–48.8%, depending on the stress conditions. Results from the SIMDualKc water balance model were similar.

The HYDRUS-1D model proved to be an effective tool for understanding water dynamics processes through the various soil layers, thus allowing root water uptake in the different layers to be observed and therefore to have some evidence of the mechanisms that led to or compensated water stress for the crop. This was the main advantage over the SIMDualKc model since ET was partitioned between soil evaporation and crop transpiration with this model. By contrast, the larger requirements for soil hydraulics parameterisation in HYDRUS-1D give an advantage to SIMDualKc, whose parameterisation is much easier. Nevertheless, using the information provided by both models was helpful to improve the capabilities of the irrigation scheduling model used with the IRRIGA System. However, this system still requires a purposeful setting up of a focused database and the revision of the technical procedures and configurations based on frequently collected field data. Meanwhile, for future studies the rainout shelter facilities need to be better explored to allow an improved perception of water stress impacts at different crop growth stages.

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REFERENCES

Abbasi, F., Jacques, D., Šimůnek, J., Feyen, J., & van Genuchten, M. T. (2003). Inverse estimation of soil hydraulic and solute transport parameters from transient field experiments: heterogeneous soil. *Transactions of ASAE, 46*, 1097–1111.

Ajdary, K., Singh, D. K., Singh, A. K., & Khanna, M. (2007). Modelling of nitrogen leaching from experimental onion field under drip irrigation. *Agricultural Water Management, 89*, 15–28.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration – Guidelines for computing crop water requirements. In *Irrigation and Drainage Paper* (Vol. 56). Rome, Italy: FAO.

Allen, R. G., Pereira, L. S., Smith, M., Raes, D., & Wright, J. L. (2005). FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. *Journal of Irrigation and Drainage Engineering, 131*, 2–13.

Arbat, G., Puig, J., Barragán, J., Bonany, J., & Cartagena, F. R. (2005). Modelación directa e inversa de la dinámica del agua en una plantación de manzanos regada por microaspersión. In F. J. S. Calvete, & A. P. González (Eds.), *VII Jornadas de Investigación en la Zona no Saturada del Suelo* (pp. 243–248). A Coruña.

Bergamaschi, H., Dalmago, G. A., Comiran, F., Bergonci, J. I., Müller, A. G., França, S., et al. (2006). Deficit hídrico e produtividade na cultura do milho. *Pesquisa Agropecuária Brasileira, 41*, 243–249.

Blanco-Canqui, H., & Lal, R. (2007). Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. *Soil Science Society of America Journal, 71*, 1166–1173.

Bof Bufon, V., Lascano, R. J., Bednarz, C., Booker, J. D., & Gitz, D. C. (2012). Soil water content on drip irrigated cotton: comparison of measured and simulated values obtained with the HYDRUS-2D model. *Irrigation Science, 30*, 259–273.

Çakir, R. (2004). Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research, 89*, 1–16.

Cameira, M. R., Ahuja, L., Fernando, R. M., & Pereira, L. S. (2000). Evaluating field measured soil hydraulic properties in water transport simulations using the RZWQM. *Journal of Hydrology, 236*, 78–90.

Carlesso, R., Petry, M. T., & Trois, C. (2009). The use of a meteorological station network to provide crop water requirement information for irrigation management. In D. Li, & C. Zhao (Eds.), *IFIP Advances in Information and Communication Technology 293: Vol. 1. Computer and computing technologies in agriculture II* (pp. 19–27). Springer.

Cavalieri, K. M. V., Silva, A. P., Tormena, C. A., Leão, T. P., Dexter, A. R., & Håkansson, I. (2009). Long-term effects of no-tillage on dynamic soil properties in a Rhodic Ferrasol. *Soil & Tillage Research, 103*, 158–164.

Chopart, J. L., Mézino, M., Aure, F., Le Mézo, L., Mété, M., & Vauclin, M. (2007). OSIRI: a simple decision-making tool for monitoring irrigation of small farms in heterogeneous environments. *Agricultural Water Management, 87*, 128–138.

Dabach, S., Lazarovitch, N., Šimůnek, J., & Shani, U. (2013). Numerical investigation of irrigation scheduling based on soil water status. *Irrigation Science, 31*, 27–36.

English, M., & Raja, S. N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management, 32*, 1–14.

FAO. (2014). *FAOSTAT*. Rome, Italy: Food and Agriculture Organization of the United Nations. URL http://faostat3.fao.org/faostat-gateway/go/to/home/E. Last accessed on 27.05.14.

Farré, I., & Faci, J.-M. (2009). Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. *Agricultural Water Management, 96*, 383–394.

Feddes, R. A., Kowalik, P. J., & Zaradny, H. (1978). *Simulation of field water use and crop yield*. Wageningen, The Netherlands: Simulation Monographs Pudoc.

van Genuchten, M. T. (1980). A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal, 44*, 892–898.

Grassini, P., Yang, H., Irmak, S., Thorburn, J., Burr, C., & Cassman, K. G. (2011). High-yield irrigated maize in the Western U.S. Corn Belt: II. Irrigation management and crop water productivity. *Field Crops Research, 130*, 133–141.

Igbadun, H. E., Salim, B. A., Tarimo, A. K. P. R., & Mahoo, H. F. (2008). Effects of deficit irrigation scheduling on yields and soil water balance of irrigated maize. *Irrigation Science, 27*, 11–23.

IICA. (2008). *A irrigação no Brasil. Situação e Directrizes*. Brasília, Brazil: Instituto Interamericano de Cooperação para a Agricultura, Ministério da Integração Nacional.

Jacques, D., Šimůnek, J., Timmerman, A., & Feyen, J. (2002). Calibration of Richards' and convection–dispersion equations to field–scale water flow and solute transport under rainfall conditions. *Journal of Hydrology, 259*, 15–31.

Jarvis, N. J. (1989). A simple empirical model of root water uptake. *Journal of Hydrology, 107*, 57–72.

Kandelous, M. M., Šimůnek, J., van Genuchten, M. Th, & Malek, K. (2011). Soil water content distributions between two emitters of a subsurface drip irrigation system. *Soil Science Society of America Journal, 75*, 488–497.

Khaledian, M. R., Mailhol, J. C., Ruelle, P., & Rosique, P. (2009). Adapting PILOTE model for water and yield management under direct seeding system: the case of corn and durum wheat in a Mediterranean context. *Agricultural Water Management, 96*, 757–770.

Kool, D., Agam, N., Lazarovitch, N., Heitman, J. L., Sauer, T. J., & Ben-Gal, A. (2014). A review of approaches for evapotranspiration partitioning. *Agriculture and Forest Meteorology, 184*, 56–70.

Lazarovitch, N., Šimůnek, J., & Shani, U. (2005). System-dependent boundary condition for water flow from subsurface source. *Soil Science Society of America Journal, 69*, 46–50.

Legates, D. R., & McCabe, G. J., Jr. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research, 35*, 233–241.

Liu, Y., Pereira, L. S., & Fernando, R. M. (2006). Fluxes through the bottom boundary of the root zone in silty soils: parametric approaches to estimate groundwater contribution and percolation. *Agriculture Water Management, 84*, 27–40.

Liu, Y., Teixeira, J. L., Zhang, H. J., & Pereira, L. S. (1998). Model validation and crop coefficients for irrigation scheduling in the North China Plain. *Agricultural Water Management, 36*, 233–246.

Marquardt, D. W. (1963). An algorithm for least-squares estimation of non-linear parameters. *SIAM Journal on Applied Mathematics, 11*, 431–441.

Martins, J. D., Rodrigues, G. C., Paredes, P., Carlesso, R., Oliveira, Z. B., Knies, A. E., et al. (2013). Dual crop coefficients for maize in southern Brazil: model testing for sprinklers and drip irrigation and mulched systems. *Biosystems Engineering, 115*, 291–310.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models, part I - A discussion of principles. *Journal of Hydrology, 10*, 282–290.

Paredes, P., Rodrigues, G. C., Alves, I., & Pereira, L. S. (2014). Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies. *Agricultural Water Management, 135*, 27–39. and Corrigendum in Agricultural Water Management, 141, 84.

Paço, T. A., Ferreira, M. I., Rosa, R. D., Paredes, P., Rodrigues, G. C., Conceição, N., et al. (2012). The dual crop coefficient approach using a density factor to simulate the evapotranspiration of a peach orchard: SIMDualKc model vs. eddy covariance measurements. *Irrigation Science, 30*(2), 115–126.

Paço, T. A., Pôças, I., Cunha, M., Silvestre, J. C., Santos, F. L., Paredes, P., et al. (2014). Evapotranspiration and crop coefficients for a super intensive olive orchard. An application of SIMDualKc and METRIC models using ground and satellite observations. *Journal of Hydrolology, 519*, 2067–2080.

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management, 108*, 39–51.

Pereira, L. S., Oweis, T., & Zairi, A. (2002). Irrigation management under water scarcity. *Agricultural Water Management, 57*, 175–206.

Phogat, V., Skewes, M. A., Cox, J. W., Alam, J., Gigson, G., & Šimůnek, J. (2013). Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. *Agricultural Water Management, 127*, 74–84.

Phogat, V., Skewes, M. A., Mahadevan, M., & Cox, J. W. (2013). Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. *Agricultural Water Management, 118*, 1–11.

Ramos, T. B., Gonçalves, M. C., Martins, J. C., Van Genuchten, M. Th, & Pires, F. P. (2006). Estimation of soil hydraulic properties from numerical inversion of tension disk infiltrometer data. *Vadose Zone Journal, 5*, 684–696.

Ramos, T. B., Šimůnek, J., Gonçalves, M. C., Martins, J. C., Prazeres, A., Castanheira, N. L., et al. (2011). Field evaluation of a multicomponent solute transport model in soils irrigated with saline waters. *Journal of Hydrology, 407*, 129–144.

Ramos, T. B., Šimůnek, J., Gonçalves, M. C., Martins, J. C., Prazeres, A., & Pereira, L. S. (2012). Two-dimensional modeling of water and nitrogen fate from sweet sorghum irrigated with fresh and blended saline waters. *Agricultural Water Management, 111*, 87–104.

Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., & Häkansson, I. (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil & Tillage Research, 102*, 242–254.

Rodrigues, G. C., Martins, J. D., Silva, F. G., Carlesso, R., & Pereira, L. S. (2013). Modelling economic impacts of deficit irrigated maize in Brazil with consideration of different rainfall regimes. *Biosystems Engineering, 116*, 97–110.

Rosa, R. D., Paredes, P., Rodrigues, G. C., Alves, I., Fernando, R. M., Pereira, L. S., et al. (2012). Implementing the dual crop coefficient approach in interactive software: 1. Background and computational strategy. *Agricultural Water Management, 103*, 62–77.

Schaap, M. G., & Leij, F. J. (2000). Improved prediction of unsaturated hydraulic conductivity with the Mualem–van Genuchten model. *Soil Science Society of America Journal, 64*, 843–851.

Schaap, M. G., Leij, F. J., & van Genuchten, M. T. (2001). ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology, 251*, 163–176.

Šimůnek, J., Angulo-Jaramillo, R., Schaap, M. G., Vandervaere, J. P., & van Genuchten, M. T. (1998). Using an inverse method to estimate the hydraulic properties of crusted soils from tension disc infiltrometer data. *Geoderma, 86*, 61–81.

Šimůnek, J., & van Genuchten, M. T. (1996). Estimating unsaturated soil hydraulic properties from tension disc infiltrometer data by numerical inversion. *Water Resources Research, 32*, 2683–2696.

Šimůnek, J., van Genuchten, M. T., & Šejna, M. (2008). Development and applications of the HYDRUS and STANMOD software packages, and related codes. *Vadose Zone Journal, 7*, 587–600.

Šimůnek, J., & Hopmans, J. W. (2009). Modeling compensated root water and nutrient uptake. *Ecological Modeling, 220*, 505–521.

Šimůnek, J., Šejna, M., Saito, H., Sakai, M., & van Genuchten, M. T (2013). *The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media: Version 4.16*. Riverside: Department of Environmental Sciences, University of California.

Šimůnek, J., Wang, D., Shouse, P. J., & van Genuchten, M. T. (1998). Analysis of a field tension disc infiltrometer data by parameter estimation. *International Agrophysics, 12*, 167–180.

Skaggs, T. H., van Genuchten, M. T., Shouse, P. J., & Poss, J. A. (2006). Macroscopic approaches to root water uptake as a function of water and salinity stress. *Agricultural Water Management, 86*, 140–149.

Skaggs, T. H., Trout, T. J., Šimůnek, J., & Shouse, P. J. (2004). Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *Journal of Irrigation and Drainage Engineering, 130*, 304–310.

Soil Survey Staff. (2006). *Keys to soil taxonomy* (10th ed.). Washington, DC: Natural Resources Conservation Service, United States Department of Agriculture.

Strudley, M. W., Green, T. R., & Ascough, J. C., II (2008). Tillage effects on soil hydraulic properties in space and time: state of the science. *Soil & Tillage Research, 99*, 4–48.

Wei, Z., Paredes, P., Liu, Y., Chi, W.-W., & Pereira, L. S. (2015). Modelling transpiration, soil evaporation and yield prediction of soybean in North China Plain. *Agriculture Water Management, 147*, 43–53.

Wesseling, J. G., Elbers, J. A., Kabat, P., & van den Broek, B. J. (1991). *SWATRE: Instructions for input*. Report. Wageningen, Netherlands: Winand Staring Cent..

Zhao, N., Liu, Y., Cai, J., Paredes, P., Rosa, R. D., & Pereira, L. S. (2013). Dual crop coefficient modelling applied to the winter wheat - summer maize crop sequence in North China Plain: basal crop coefficients and soil evaporation component. *Agricultural Water Management, 117*, 93–105.