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A comparison of the HYDRUS (2D/3D) and SALTMED models to investigate the influence of various water-saving irrigation strategies on the maize water footprint

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ABSTRACT

In this comparative research, we applied the HYDRUS (2D/3D) and SALTMED models to investigate the influence of various water-saving irrigation strategies on maize water footprints (*WFs*). The models were first calibrated and validated based on data collected in a two-year field investigation under five water-saving irrigation treatments: full irrigation (FI), partial root-zone drying at water deficit levels of 55% (PRD_{55}) and 75% (PRD_{75}), and deficit irrigation at the same levels (DI_{55} and DI_{75}). While the SALTMED model performed well when simulating crop growth parameters, with absolute relative error (|*RE*|) of 3.5–12%, the HYDRUS (2D/3D) model was more accurate when simulating soil water and solute transport, with the normalized values of the root mean square error (*nRMSEs*, 6.7–31.8%) and the mean bias error (*nMBEs*, 7.7–34.3%) lower than by SALTMED. This better performance of HYDRUS (2D/3D) resulted in 0.6–3.0% and 5.3–30.2% lower values of estimated consumptive and degradative *WFs*, respectively, compared to values estimated by SALTMED. While no considerable differences were observed among various irrigation treatments regarding their consumptive WFs for the maize production, PRD_{75} may represent a safer option under the water crisis, since its grey *WF* was 17.1–77.2% lower than those estimated for the other water-saving irrigation treatments. This WF reduction was accompanied by an insignificant reduction in crop yield and improved N uptake. Based on our results, while HYDRUS (2D/3D) provides more reliable results, both the HYDRUS (2D/3D) and SALTMED models may be applied for the evaluation of new targets implemented for achieving sustainable agriculture in water-scarce regions.

1. Introduction

Water and agricultural authorities indicate that the scarcity of fresh water is a major worldwide concern (Karandish and Šimůnek, 2017) which threatens food security. Irrigated agriculture increased rapidly throughout the world to satisfy the increasing demand for food (Yao et al., 2017). In many countries, agriculture is the biggest fresh water user, accounting for over 90% of diverted water. According to the Food and Agriculture Organization (FAO) of the United Nations (AQUASTAT, 2016), in Iran in 2004, nearly 68% of total renewable water resources were used, of which 92.2% was allocated to the agricultural sector, while the municipal and industrial sectors consumed only 6.6% and 1.2%, respectively (AQUASTAT, 2016). Therefore, efficient water management in the agricultural sector may represent the main source of fresh water across the country.

Adapting water-saving irrigation strategies such as deficit irrigation (DI) or partial root zone drying (PRD), in which crops receive less irrigation water during their growing season (Karandish and Šimůnek, 2016a), may be a rational decision to cope with fresh water scarcity. Many researchers have investigated economic and environmental consequences of applying DI (Stone, 2003; Klocke et al., 2004; Payero et al., 2006) or PRD (Dry et al., 2000; Kang and Zhang, 2004; Kirda et al., 2004; Tang et al., 2005; Shao et al., 2008; Karandish and Šimůnek, 2016a,b). They mostly concluded that while significant economic losses may be expected for agricultural crops under DI, PRD may produce water savings without a significant decrease in yields.

Various indicators have been developed over the past decades to address the profitability of new water-saving irrigation strategies. Among these, the water footprint (WF) index is known as the most comprehensive indicator. The WF is a multi-dimensional index of human appropriation of freshwater resources, which could facilitate a proper assessment of patterns of consumption, production, and trade as

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a function of water consumption (Hoekstra et al., 2011; Hoekstra, 2013, 2017). One of the most highlighted advantages of the WF index is that it is possible to apply it for evaluating such appropriation at various spatial (i.e., for example, at the field, basin, national, or even global scale) and temporal scales. Such assessment may be carried out for an individual process, or for a number of processes, involved in the production and/or consumption of a product.

Previous researchers have mainly focused on the WF assessment at the national or global scales (e.g., Chukalla et al., 2017, 2018; Karandish and Hoekstra, 2017; Lee et al., 2017; Zhuo et al., 2016a,b; Yoo et al., 2016a, b; Chukalla et al., 2015; Mekonnen and Hoekstra, 2014, 2015, 2016; Hoekstra, 2013), while its field-scale application has received less attention. Additionally, only few researchers have estimated the WF related to the crop production based on data collected during field experiments, although it is expected that such assessment would produce more realistic results.

Since field experiments are very time consuming and expensive, a large number of the mathematical/conceptual models for simulating soil-water-crop relationships have been developed that can, after proper validation, be used in scenario assessment. The modeling approach, although considered to be a useful alternative to field investigations, always involves uncertainties, the range of which depends on many factors, including embedded governing equations and formulas for estimating target parameters. Hence, employing the best available model may produce more reliable results for the policy makers when developing new targets for achieving sustainable agriculture. While there are numerous crop-growth simulation models, only a few of them are suitable to simulate PRD conditions. Among these, the SALTMED model of Ragab et al. (2005) has proven to be highly accurate (Ragab et al., 2005; Pulvento et al., 2013; Ragab et al., 2015; Ragab, 2015; Pulvento et al., 2015a; Hassanli et al., 2016; Afzal et al., 2016; Abdelraouf and Ragab, 2018). Additionally, Karandish and Šimůnek (2016a,b, 2017) demonstrated that soil water and solute dynamics under PRD conditions is very well captured also by the HYDRUS model (Šimůnek et al., 2008, 2016).

Hence, in the current research, we carried out a comparative analysis to address the following objectives: (i) to evaluate the performance of the SALTMED model for simulating soil-water-crop relationships under various water-saving irrigation strategies, (ii) to compare the maize consumptive and degradative water footprints estimated using HYDRUS (2D/3D) and SALTMED, and finally, (iii) to propose the most appropriate water-saving irrigation strategy for the maize production in Iran while both water and environmental issues are taken in consideration.

2. Materials and methods

2.1. Field experiment

Filed data were collected during a two-year experiment (2010 and 2011) in an 825 m^2 (15 × 55 m) maize field at the Sari Agricultural Sciences and Natural Resources University (SANRU: 36.3∘ N, 53.04∘ E; 15 m below sea level). Sandy clay loam and clay loam textures were observed in the 0–20 and 20–100 cm soil depths, respectively. Daily weather data were recorded at the weather station near the experimental field. The field trial was carried out using a complete block design. Irrigation treatments consisted of full irrigation (FI), two partial root-zone drying (PRD) treatments (PRD_{75} and PRD_{55}), and two deficit irrigation (DI) treatments (DI_{75} and DI_{55}) in three replicates. Each treatment occupied a total area of 165 m^2 (15 × 11 m), and each replicate of a specific treatment occupied an area of 55 m^2 (5 × 11 m). Before sowing, soil samples were collected every 20 cm down to the 80 cm soil depth for the analysis of soil chemical and physical properties. The field was then equipped with a surface drip irrigation system. Having emitters 20 cm apart and an emitter discharge rate of 2 L hr^{-1}, drip lines were placed on the soil surface 75 cm apart (Fig. 1).

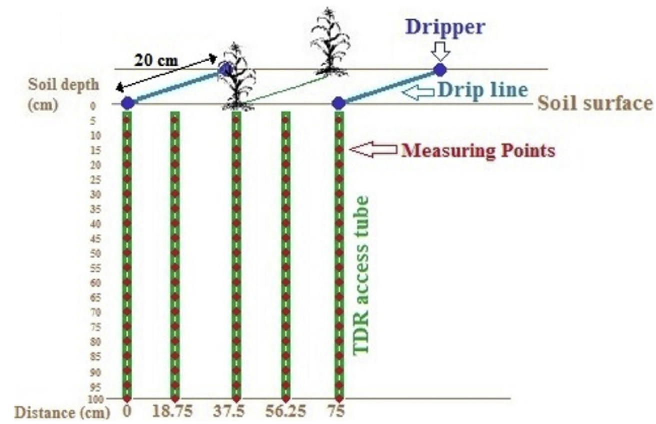

Fig. 1. Horizontal locations of laterals, drippers, and plants in the experimental field, and vertical locations of TDR probes in the maize root zone. A rectangular domain of 75*80 cm was considered in the HYDRUS and SALTMED models since the maximum rooting depth was measured to be 80 cm during both cropping cycles.

Thereafter, five 100 cm long TDR probes (Trime FM; IMKO; Germany) were installed in each treatment (i.e., 25 TDR probes were installed in the study area; 5 probes * 5 treatments) for continuous monitoring of the soil water content (SWC) during both growing seasons.

Fig. 1.

With a 75 × 20 cm crop row and crop spacing, maize single-cross hybrid 704 was sown 5 cm deep, between and parallel to drip lines, on May 26 both in 2010 and 2011. On May 26 in 2010 and 2011, 150 kg ha^{-1} triple superphosphate was applied to the field. On June 12, 2010 and June 5, 2011, 65 kg ha^{-1} urea and 50 kg ha^{-1} potassium sulfate were applied via irrigation water (fertigation). In addition, these fertilizers were also applied on July 19, 2010 and July 9, 2011, at rates of 135 kg ha^{-1} and 100 kg ha^{-1} for urea and potassium sulfate, respectively.

Maize was irrigated using the surface drip irrigation system every other day. The irrigation water quality was measured weekly; the electrical conductivity of irrigation water (EC_{iw}) was in the range of 0.8–1.5 dS m^{-1}, with averages of 1 dS m^{-1} and 1.1 dS m^{-1} during the entire cropping cycles of 2010 and 2011, respectively.

For each irrigation event, the irrigation water depth for the FI treatment was calculated as follows:

$$[I_n]_{FI} = \sum_{i=1}^{m} \{[\theta_{FCi} - (\theta_{BIi})_{FI}] D_i\} \quad (1)$$

where $[I_n]_{FI}$ is the net irrigation depth (mm) of the nth irrigation event for the FI treatment, θ_{FCi} is the volumetric SWC at field capacity (FC, $cm^3\,cm^{-3}$) of the ith soil layer, $(\theta_{BIi})_{FI}$ is the volumetric SWC of the ith soil layer before irrigation ($cm^3\,cm^{-3}$) in the FI treatment, D_i is the soil layer thickness (mm), i is the soil layer, and m refers to the number of soil layers down to a specific soil depth, for which $[I_n]_{FI}$ is calculated.

All treatments received the same amount of irrigation water during the first 55 days after sowing (DAS) in 2010 and during 45 DAS in 2011. Irrigation treatments were implemented during 55–107 DAS in 2010 and during 45–110 DAS in 2011, during which the PRD_{55} and DI_{55} treatments received 55% of the FI treatment's irrigation amount at each irrigation event, while the PRD_{75} and DI_{75} treatments receive 75%. While in the FI and DI treatments, both drip lines were operated simultaneously, in the PRD treatments during the PRD period, to ensure partial root-zone drying, just one of the drip lines was operated while the other one was not during each irrigation event. Only half of the root zone was thus irrigated during the PRD period, while irrigation shifted between the two sides of the plants each week.

Prior to the onset of the irrigation treatments (i.e., on 55 DAS in 2010 and 45 DAS in 2011) and then once a week (i.e., on 60, 66, 72, 78, 84, 90, 96, 102, and 106 DAS in 2010 and 52, 58, 64, 70, 76, 82, 88, 94, 100, 106, and 110 DAS in 2011), soil samples were collected every 20 cm vertically to a depth of 80 cm and at five equal horizontal distances between two drip lines for each treatment. Soil samples were analyzed for their total nitrogen (TN) and NO_3^--N concentrations. At the same dates, three crops per plot (i.e., each plot is considered as one replicate of a treatment) were harvested for determining total crop N uptake, total wet and dry biomass, and the leaf area index (LAI). All considered soil and crop properties, as well as maize grain yield, were also determined at harvest (107 DAS in 2010 and 110 DAS in 2011). A detailed description of various measurements is provided in Karandish and Šimůnek (2018).

Soil physical properties, including soil texture, volumetric soil water contents at field capacity, a permanent wilting point, sand, silt, and clay contents, soil organic matter, and initial soil water and soil salinity contents were measured at soil samples collected during the growing season. Retention curves were measured for two soil horizons. For this purpose, soil samples were taken for each treatment in three replicates every 20 cm to a depth of 80 cm before crop sowing using a 2-in ID augur. SWCs at 11 different pressure heads were measured in the laboratory at each sample using a pressure plate apparatus. The van Genuchten (1980) model parameters were then fitted to observed retention data.

2.2. The SALTMED model

2.2.1. Model description

The SALTMED model (Ragab, 2015) is a physically based holistic model, which includes the following key processes: evapotranspiration, crop water uptake, water and solute transport under different initial and boundary conditions, drainage, and the relationship between crop yield and water uptake (Ragab et al., 2005; Ragab, 2015).

Potential evapotranspiration is estimated using the FAO-Penman-Monteith equation (Allen et al., 1998):

$$ET_O = \frac{0.408(R_n - G) + \gamma(\frac{900}{T+273}) \times U_2 \times (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

where Δ is the slope of the vapor pressure curve (kPa $^{O}C^{-1}$), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa $^{O}C^{-1}$), T is the average air temperature (^{O}C), U_2 is the average wind speed (m s^{-1}) at a 2-m height, G is the soil heat flux density (MJ m^{-2} d^{-1}), e_s is the saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).

Based on calculated ET_O, crop evapotranspiration (ET_c, mm) is then calculated as follows (Allen et al., 1998):

$$ET_c = (K_{cb} + K_e) \times ET_O \quad (3)$$

where K_{cb} is the basal crop coefficient and K_e is the evaporation coefficient (Allen et at., 1998). The product $K_{cb} \times ET_O$ represents crop transpiration and $K_e \times ET_O$ bare soil evaporation. The crop coefficient is then defined as $K_c = K_{cb} + K_e$.

Actual root water uptake is then estimated using the approach developed by Cardon and Letey (1992), who determined root water uptake ($S(z,t)$, mm d^{-1}) as:

$$\begin{cases} S(z, t) = \left[\dfrac{S_{max}(t)}{1 + \left(\frac{a(t)h + \pi}{\pi_{50}(t)}\right)^3}\right]\lambda(z, t) \\ \lambda(z) = \begin{cases} 5/3L \; for \; z \le 0.2L \\ \frac{25}{12L} \times \left(1 - \frac{z}{L}\right) for \; 0.2L < z \le L \\ 0.0 \; for \; z > L \end{cases} \end{cases} \quad (4)$$

where $S_{max}(t)$ is maximum potential root water uptake at time t and depth z, z is the vertical depth, $\lambda(z, t)$ is the depth-time dependent fraction of the total root mass, L is the maximum rooting depth, π is the osmotic pressure head, h is the matric pressure head, $\pi_{50}(t)$ is the osmotic pressure head for which $S_{max}(t)$ is reduced by half, and $a(t)$ is a weighting coefficient, which accounts for differential responses of a crop to matric and osmotic stresses, which may be defined as $\frac{\pi_{50}(t)}{h_{50}(t)}$, where $h_{50}(t)$ is the matric pressure head for which $S_{max}(t)$ is reduced by half.

There are two options in the SALTMED model for simulating crop yield. One can calculate crop yield either using the relative yield index (RY) or more precisely using the crop growth status. In the second approach, which was employed in our study, crop yield is obtained by calculating the daily biomass production (Δq) and the harvest index (HI) (Exkersten and Jansson, 1991). On a daily scale, the Δq is calculated as follows:

$$\begin{cases} \Delta q = NA \\ NA = A - R \\ A = E \times I \times f(Temp) \times f(T) \times f(Leaf - N) \\ I = Rs\,(1 - e^{-l \times LAI}) \end{cases} \quad (5)$$

where Δq is increased crop biomass, NA is the net assimilation rate, A is the assimilation rate, R is the respiration loss, E is the photosynthesis efficiency (g dry matter MJ^{-1}), I is the radiation input, R_s is solar radiation (MJ m^{-2} d^{-1}), k is the extinction coefficient ($k \cong 0.6$), LAI is the leaf area index, and $f(temp)$, $f(T)$, and $f(Leaf\text{-}N)$ are stress factors related to heat stress, transpiration stress, and leaf N content, respectively. Based on daily calculated Δq, the AY at the end of the growing season, subject to existing stresses (i.e., salinity, water, or nutrient stresses), can then be calculated as follows:

$$AY = \sum\nolimits_{whole\ cropping\ cycle} \Delta q \times HI \quad (6)$$

The Richards equation is used in the SALTMED model for simulating two-dimensional water flow in the soil, while the nutrient transport is simulated using the diffusion-dispersion-convection equation (Hillel, 1977):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial k}{\partial z} - S_w \quad (7)$$

$$\frac{\partial \theta c}{\partial t} = \left\{\frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial c}{\partial x} + \theta D_{xz}\frac{\partial c}{\partial z}\right) + \frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial c}{\partial z} + \theta D_{zx}\frac{\partial c}{\partial x}\right)\right\} - \left(\frac{\partial q_x c}{\partial x} + \frac{\partial q_z c}{\partial z}\right) - S_c \quad (8)$$

where θ is the volumetric SWC (L^3L^{-3}), K is the unsaturated hydraulic conductivity function (LT^{-1}), h is the soil water pressure head (L), x is the lateral coordinate, z is the vertical coordinate (positive downwards), t is time (T), S_w denotes root water uptake (T^{-1}), c is the solute concentration in the liquid phase (ML^{-3}), q_x and q_z are the components of the volumetric flux density (LT^{-1}), D_{xx}, D_{zz}, and D_{xz} are the components of the dispersion tensor (L^2T^{-1}), and S_c is the sink term (nutrient uptake, $ML^{-3}T^{-1}$).

The soil hydraulic properties (i.e., the $\theta - h$ and $\theta - K$ relationships) are in the SALTMED model described using the analytical functions of van Genuchten (1980):

$$\begin{cases} \theta(h) = \theta_r + \left[\frac{(\theta_s - \theta_r)}{(1 + |\alpha h|^n)^m}\right] \\ K(h) = K_s K_r(h) = K_s S_e^{1/2}\left[1 - (1 - S_e^{\frac{1}{m}})^m\right]^2 \end{cases} \quad (9)$$

where θ_r is the residual soil water content (L^3L^{-3}), θ_s is the saturated soil water content (L^3L^{-3}), K_s is the saturated hydraulic conductivity (LT^{-1}), K_r is the relative hydraulic conductivity (-), α (L^{-1}) and n (-) are shape factors, $m = 1 - 1/n$, and S_e is the normalized volumetric soil water content.

While the SALTMED model can consider subsurface drainage for both horizontally or vertically installed tile drains, this option is not used in this study. A more detailed description of the model is provided in Ragab et al. (2005, 2015) and Ragab (2015).

2.2.2. Data requirements

The main inputs of the SALTMED model include: (i) meteorological data, (ii) soil and crop properties, (iii) model parameters, (iv) and water and nutrient management data. These input data may be directly measured or may be obtained from the SALTMED database, which provides default values for more than 200 plant species and 40 different soil types.

The soil hydraulic parameters for the SALTMED model were discussed above. Since the SALTMED model requires the pore size distribution index λ, we estimated this parameter as $\lambda = nm$ based on the fitted n and m in the van Genuchten (1980) model. Soil solute transport parameters were taken from Karandish and Šimůnek (2017).

Crop parameters, including the cropping calendar (i.e., sowing and harvesting dates, and duration of different growth stages), crop height, rooting depth, LAI values, crop yield, and *HI* (harvest index) were taken from field-based measurements. Crop coefficients (K_c) were taken from Karandish and Šimůnek (2016a). K_e values were taken from the FAO-Irrigation and Drainage paper no 56 (Allen et al., 1998), and K_{cb} values were then estimated as $K_{cb} = K_c\text{-}K_e$. Crop growth parameters were taken from the model database, except for the harvest index (i.e., the *HI* values), which was directly measured in the field. The initial estimates of water uptake parameters were also taken from FAO-56 (Allen et al., 1998). These parameters were then fine-tuned during the calibration process, which is described in the following section. Water and nutrient management data, including the number and dates of irrigation events, irrigation water depths, irrigation water quality, the number and dates of fertilization events, fertilizers types, and fertilization rates were based on field measurement data.

2.2.3. Calibration and validation process

In the calibration process, the SALTMED model was first run using the initial measured/default values of soil and crop parameters. Thereafter, relevant model parameters (both soil and crop parameters) were adjusted to obtain the best agreement between measured and simulated data for the 2010 growing season, including crop yield, aboveground biomass, LAIs, soil water content, soil electrical conductivity, and soil NO_3^- content. The following parameters were fine-tuned during the calibration process using a trial-and-error approach: (i) crop parameters including K_e, K_{cb}, a crop fraction cover (f_c), π_{50}, and photosynthesis efficiency, and (ii) soil hydraulic parameters including K_s, θ_s, the pore size distribution index λ, and the air-entry value.

Data collected during the 2011 growing season for all treatments were then used to validate the SALTMED model. In the validation process, the SALTMED model was run with calibrated soil and crop parameters, while the accuracy of model predictions was evaluated for crop yield, aboveground biomass, LAIs, soil water content, soil electrical conductivity, and soil NO_3^- content.

2.3. The HYDRUS (2D/3D) model

The HYDRUS (2D/3D) model (Šimůnek et al., 2008, 2016) is a powerful numerical model that can simulate soil water and solute dynamics under various irrigation treatments and for different initial and boundary conditions. Karandish and Šimůnek (2016a, b, 2017, 2018) employed this model to simulate soil water and solute dynamics under different irrigation treatments during the 2010 and 2011 growing seasons. They provided detailed information on the modeling approach including the model description and governing equations, data requirements by the model, and how these data were collected during the current field investigation. Additionally, they provided details about model calibration and validation. Hence, detailed information about the HYDRUS modeling can be found in Karandish and Šimůnek (2016a, b, 2017, 2018).

2.4. Comparison of the two models

While the SALTMED and HYDRUS (2D/3D) models use similar equations for simulating water and solute transport in soils, they use different approaches to calculate the effects of the matric and osmotic stresses on root water uptake. SALTMED uses an additive function while HYDRUS (2D/3D) allows users to choose different options. While crop yield can only be obtained in HYDRUS as the ratio (*RY*) of actual and potential crop evapotranspiration, it is expected to be described more accurately in SALTMED, which uses multiple crop parameters to simulate crop yield during the cropping cycle. As described in Section 2.2, there is an option in SALTMED to obtain actual crop yield based on crop growth parameters rather than based only on *RY*. The HYDRUS (2D/3D) model, on the other hand, cannot simulate the crop growth status and only simulates actual evaporation and transpiration. As a result, differences can be expected in crop yields and crop water consumptions simulated using the two models.

2.5. Criteria indices

The accuracy of both models was evaluated using selected criteria indices, including the normalized root mean square error (*nRMSE*), the normalized mean bias error (*nMBE*), and the relative error (RE), as defined by the following equations:

$$nRMSE = \frac{\sqrt{\frac{(O_i - P_i)^2}{n}}}{\bar{O}_i} \tag{10}$$

$$nMBE = \frac{\frac{(O_i - P_i)}{n}}{\bar{O}_i} \tag{11}$$

$$RE = \frac{(P_i - O_i)}{O_i} \times 100\% \tag{12}$$

where P_i and O_i are predicted and observed data, respectively, $\bar{O}_i$ is the average of the observed data, and n is the number of observations. We use the normalized criteria indices instead of the absolute indices to better evaluate the models performance. While the *nRMSE* reflects the model accuracy, the *nMBE* and RE characterize the bias provided by the SALTMED and/or HYDRUS (2D/3D) models.

2.6. WF accounting

The water footprint (WF) related to the crop production consists of two main components: the consumptive WF, including blue (WF_{blue}) and green (WF_{green}) WFs, and the degradative grey WF (WF_{grey}). The WF_{blue} is estimated by dividing blue evapotranspiration (ET_{blue}, $m^3\,ha^{-1}$) by crop yield (Y, t ha^{-1}), while the WF_{green} is calculated by dividing green evapotranspiration (ETgreen, $m^3\,ha^{-1}$) by Y:

$$\begin{cases} WF_{green}\,(m^3\,t^{-1}) = \frac{ETgreen}{Y} \\ WF_{blue}\,(m^3\,t^{-1}) = \frac{ETblue}{Y} \end{cases} \tag{13}$$

where *ET*blue is a part of total evapotranspiration, which is supplied from blue water (i.e., blue water refers to water supplied to crops from surface and/or groundwater resources during the cropping cycle), and *ET*green is a part of crop evapotranspiration, which is supplied from green water (i.e., green water refers to water supplied due to effective precipitation stored in the rooting zone during the cropping cycle). Crop evapotranspiration (*ET*) is thus equal to *ET*blue + *ET*green. *ET* was estimated by the SALTMED and/or HYDRUS(2D/3D) models.

The following soil water balance was adopted to calculate ET_{blue} and ET_{green}:

$$S_{[t]} = S_{[t-1]} + P_{[t]} + I_{[t]} + CR_{[t]} - RO_{[t]} - ET_{[t]} - DP_{[t]} \tag{14}$$

where $S_{[t]}$ and $S_{[t-1]}$ are soil water storages at the end of days t and t-1, respectively, $P_{[t]}$ is precipitation on day t, $I_{[t]}$ is irrigation on day t, $CR_{[t]}$ is capillary rise from groundwater, $RO_{[t]}$ is surface runoff, $ET_{[t]}$ is evapotranspiration, and $DP_{[t]}$ is deep percolation. All terms are in mm. Following Allen et al. (1998), the capillary rise is set equal to zero since the groundwater table was more than one meter below the rooting zone during the entire cropping cycle of both years. For each day, the relative contributions of P and I to $P+I$ were used to calculate the green and blue fractions of RO. The fractions of green and blue water in the soil water storage over time were calculated following Chukalla et al. (2015); Zhuo et al. (2016a), Karandish and Hoekstra (2017); Karandish et al. (2018). This method is based on the assumption that the storage of green water in the soil increases when rainfall infiltrates into the soil and that the storage of blue water increases when precipitation infiltrates. The fractions of green and blue water in the total soil water storage at the end of the previous day were used to calculate the fractions of green and blue ET and DP on day t.

The degradative grey WF (WF_{Grey}, $m^3\,t^{-1}$) is the volume of freshwater required to assimilate the pollutant loads to freshwater bodies to the ambient water quality standard. The degradative grey WF ($m^3\,t^{-1}$), which is related to surplus N loads to water bodies, was estimated using the procedure introduced by Hoekstra et al. (2011):

$$WF_{Grey}\ (m^3t^{-1}) = \frac{\alpha AR}{(C_{max} - C_{nat})Y} \tag{15}$$

where α is the leaching-runoff fraction, AR is the chemical application rate to the agricultural soils (kg ha^{-1} y^{-1}) (i.e., αAR is the pollutant load to freshwater bodies), C_{max} and C_{nat} are, respectively, the ambient water quality standard (i.e., the maximum allowable concentration in kg m^{-3}) and its natural background concentration in a receiving body (kg m^{-3}), and Y is crop yield (kg ha^{-1}). A maximum acceptable N concentration of 50 mg nitrate l^{-1} (or 11.3 mg N l^{-1}) was adopted in this study based on the EU Nitrates Directive (Monteny, 2001) and C_{nat} was set to 1.5 mg l^{-1} (Mekonnen and Hoekstra, 2015). αAR was estimated using either the HYDRUS (2D/3D) or SALTMED modeling, resulting in the model-simulated WF_{Grey}, or using field data, resulting in the measured WF_{Grey}. To calculate the measured grey WF, αAR for a specific treatment was set to residual N in the rooting zone at the end of the growing cycle (Frank et al., 2013). As described in Section 2.1, residual N at harvest was measured for all treatments and for both cropping cycles.

3. Results and discussion

First, we will discuss the capability of the two models (SALTMED first, followed by HYDRUS (2D/3D) (2D/3D)) to represent the collected experimental data. After the calibration and validation of the two models, we will use them to evaluate WF components for different treatments and to find out the best water-saving irrigation treatment for sustainable maize production in the study area (Table 1).

3.1. The SALTMED model efficiency

3.1.1. Soil water content

Based on the criteria indices presented in Table 2, the SALTMED model was capable of simulating SWCs during the calibration period with relatively high accuracy. Based on the $nMBE$ values reported in Table 2, SWCs were underestimated by 0.9–14.2%. Except for the FI treatment, SWCs were better estimated for three top soil layers (i.e., 0–60 cm) than for the 60–80 cm soil depth. For the FI treatment, large differences between measured and simulated SWCs at the 60–80 cm soil depth may be explained by the fact that during individual irrigation events water infiltrated deeper into the soil than for the other water-saving irrigation treatments. In addition, more accurate results were obtained when simulating SWCs under the DI treatment, likely due to lower SWC variations as a result of limited irrigation and root water uptake

Table 1
The measured soil and crop properties used in the SALTMED model.

Type	Parameter*		Growing season 2010	Growing season 2011
Crop properties	Sowing date		May 26	May 26
	Harvest		September 9	September 12
	Rooting depth	Maximum (cm)	80	80
		Minimum (cm)	15	15
	Potential crop yield (t ha-1)**		7.0	6.6
	Crop coefficient (Kc)***	Kc-ini	Ke = 0.32 Kcb = 0.20	Ke = 0.51 Kcb = 0.15
		Kc-mid	Ke = 0.11 Kcb = 1.15	Ke = 0.11 Kcb = 1.13
		Kc-late	Ke = 0.26 Kcb = 0.19	Ke = 0.31 Kcb = 0.23
	Length of cropping cycle	initial stage	22	22
		developing stage	22	22
		mid-season stage	38	38
		late-season stage	25	28
	The whole cropping cycle		107	110
Soil properties	Bulk density (gr cm3)		1.4	1.4
	Soil texture		Sandy clay loam	Sandy clay loam
	Maximum soil depth (cm)		80	80
	Soil water content at saturation (%)		0.47	0.47
	Water content at field capacity (%)		30	30
	Water content at wilting point (%)		15	15

* All parameters reported in this Table are measured values.
** Potential crop yield was determined for the FI treatment.
*** K_c values are set to those reported by Karandish and Šimunek (2016a).

During the validation period (i.e., the 2011 growing season), $nRMSE$s and $nMBE$s varied in the range of 0.7–5.8% and 1–11.5%, respectively, which is an indication that the SALTMED model can capture well both temporal and spatial variations of SWCs under different treatments. Such results are also supported by other researchers (e.g., Hassanli et al., 2016; Afzal et al., 2016; Ragab et al., 2015; Fghire et al., 2015; Rameshwaran et al., 2015; Pulvento et al., 2013, 2015a,b).

3.1.2. Soil salinity and N content

The results of the quantitative assessment summarized in Table 2 indicate a good agreement between the observed and SALTMED-simulated soil salinities, expressed using the electrical conductivity of the soil solution (EC_{sw}), both for the calibration and validation periods. Simulated EC_{sw} concentrations agreed well with observed values, with $nRMSE$ = 2.4–11.3% and $nMBE$ = 0.8–10.3% for the calibration period and $nRMSE$ = 2.2–11.1% and $nMBE$ = 1.4–7.0% for the validation period. A close match was also obtained between the observed and simulated soil NO_3^- contents for various treatments and different soil layers. Simulated soil NO_3^- contents agreed well with observed values, with $nRMSE$s ranging from 3.5 to 13.2% and 2.5–12.7% in 2010 and 2011, respectively, and $nMBE$s ranging from -9.9–11.5% and -3.8–11.7% in 2010 and 2011, respectively. Hence, the SALTMED model is capable of capturing the spatial and temporal trends in EC_{sw} and soil NO_3^- contents well.

3.1.3. Crop N uptake

A comparison between the observed and model-simulated crop N uptake also indicates that reliable results were provided by the SALTMED model. Simulated crop N uptake was close to measured values, with $nRMSE$s ranging from 5.1 to 6.4% and 2.5–6.7% during the

Table 2
Criteria indices (*nRMSE, nMBE*) comparing the measured and SALTMED-simulated soil data during the calibration (the 2010 growing season) and validation (the 2011 growing season) periods for various irrigation treatments (FI, DI_{55}, DI_{75}, PRD_{55}, and PRD_{75}).

Period	Parameter	Depth	FI		PRD_{75}		PRD_{55}		DI_{75}		DI_{55}	
			nRMSE (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)
Calibration period	Soil water content	0-20 cm	2.0	2.9	2.4	3.0	2.7	2.7	1.2	1.5	2.1	2.3
		20-40 cm	1.9	2.7	2.1	2.6	2.3	2.4	1.1	1.5	1.8	2.3
		40-60 cm	1.5	1.7	1.6	2.2	2.0	1.7	1.1	1.5	1.3	1.5
		60-80 cm	0.5	0.9	5.2	14.2	13.1	12.3	3.7	5.9	4.9	6.9
	Soil salinity*	0-20 cm	8.6	3.4	11.3	10.3	7.2	3.6	8.9	2.7	5.3	1.8
		20-40 cm	4.0	1.5	5.1	4.5	3.0	1.5	3.7	1.2	2.5	0.8
		40-60 cm	9.5	3.6	10.7	9.2	2.9	2.6	7.7	2.6	7.1	2.3
		60-80 cm	7.4	2.7	6.7	6.0	2.4	2.1	7.3	2.4	5.0	1.6
	Soil NO_3 content	0-20 cm	6.4	2.6	4.7	1.5	3.9	1.0	11.5	−9.9	4.9	2.4
		20-40 cm	7.3	4.7	4.6	3.0	3.6	0.6	5.5	3.8	3.5	0.8
		40-60 cm	5.1	−0.3	4.2	−2.4	5.7	5.2	13.2	11.5	8.0	7.2
		60-80 cm	7.1	0.9	10.4	3.0	10.2	3.0	10.2	3.0	10.4	3.0
	Crop N uptake		6.1	−3.6	5.3	−3.4	6.4	−3.8	6.1	−3.2	5.1	−2.0
Validation period	Soil water content	0-20 cm	2.7	2.2	2.5	4.1	1.1	1.4	3.1	6.7	5.8	11.5
		20-40 cm	0.8	2.6	2.1	2.5	2.0	2.3	0.9	1.4	1.2	1.4
		40-60 cm	0.9	1.6	2.0	2.9	1.5	1.8	1.0	1.5	1.0	1.4
		60-80 cm	0.7	1.3	1.9	2.1	1.2	1.5	0.8	1.0	1.3	1.7
	Soil salinity*	0-20 cm	7.1	3.1	6.5	4.3	5.7	4.6	11.1	7.0	7.2	2.8
		20-40 cm	3.4	1.4	2.9	2.0	2.4	1.9	5.4	3.4	3.5	1.4
		40-60 cm	8.2	3.5	5.9	4.0	3.0	2.6	10.9	6.7	9.6	3.8
		60-80 cm	5.7	2.2	3.3	2.2	2.2	1.9	9.0	5.6	6.0	2.5
	Soil NO_3 content	0-20 cm	4.1	1.8	5.3	2.0	2.5	−1.5	3.7	−2.7	3.8	−2.9
		20-40 cm	5.5	−0.3	7.0	4.5	4.6	−1.0	3.5	−0.3	4.5	−1.0
		40-60 cm	9.2	−3.8	4.1	0.9	7.3	5.3	5.3	−2.2	9.7	7.6
		60-80 cm	11.1	10.1	12.7	11.7	12.7	11.7	12.6	11.7	12.7	11.7
	Crop N uptake		2.5	1.2	4.9	1.5	6.5	5.1	5.7	4.3	6.7	2.6

2010 and 2011 cropping cycles, respectively. While crop N uptake was generally overestimated during the calibration period, with *nMBEs* ranging from -3.8% to -2%, it was generally underestimated during the validation period, with *nMBE*s ranging from 1.2% to 5.1%.

3.1.4. Aboveground biomass and LAI

In addition to simulating soil water and solute dynamics, a reliable description of the crop response to applied treatments is also important when applying the SALTMED model. Hence, we assessed the capability of the SALTMED model to capture temporal variations in the aboveground biomass (*DM*) and leaf area index (LAI) for various treatments during the 2010 (the calibration period) and 2011 (the validation period) growing seasons. Although SALTMED in general underestimated *DM* by 3–14% in 2010 and 4–14% in 2011, simulated *DM* was highly correlated with observed values, with R^2 ranging from 0.96 to 0.99 (Fig. 2). With respect to the average bias evaluated over the whole cropping cycle, SALMED simulated *DM* best for the PRD_{55} treatment and worst for the FI treatment during both calibration and validation periods.

An inspection of the time-series of observed and model-simulated LAIs (Fig. 3) shows that LAI is usually underestimated by 3–10% during the 2010 growing season and by 2–18% in 2011. However, a visual inspection of scatter plots in Fig. 3, which compares the observed and SALTMED-simulated LAIs, clearly indicates the high potential of the SALTMED modeling. Notice the high values of R^2 in Fig. 3 (i.e., R^2 = 0.95-0.99). In general, better results were obtained for the PRD treatments when simulating temporal variations of LAIs. Nevertheless, the paired *t*-test analysis for the statistical comparison of the observed and SALTMED-simulated data demonstrated no significant difference between the observed and model-simulated DMs and LAIs, during the 2010 and 2011 cropping cycles.

3.1.5. Yield, total biomass, and maximum LAI

Table 3 shows the measured and SALTMED-simulated crop yield, total biomass, and maximum LAI, and the corresponding relative errors (*RE*) for different treatments in the 2010 and 2011 growing seasons. With *RE*s ranging from 3.5 to 8.3% in 2010 and 3.6–7.9% in 2011, the SALTMED model is well capable of simulating maize crop yield. Hassanli et al. (2016) reported *RE*s in the range of 0.9–24.7% when simulating maize crop yield under various water and saline stress treatments. *RE*s in our study are also within the range of those reported by Ragab et al. (2005) ($|RE| = 0 - 21.5\%$, with an average of 5.7%), by Razzaghi et al. (2011) for quinoa seed yield ($|RE| = 0.8 - 2.2\%$, with an average of 1.5%), by Kaya et al. (2015) for quinoa yield ($|RE| = 1.2 - 12.6\%$, with an average of 6.1%), and by Hirich et al. (2012) for simulating corn yield ($|RE| = 0 - 29.1\%$, with an average of 13.8%).

The SALTMED-simulated values underestimated measured total biomass at harvest by 5.7–12% and 4.3–10% in 2010 and 2011, respectively. The model performed better for the water stress treatments compared to the FI treatment. A close match was also obtained between the observed and model-simulated LAI_{max}, with $|RE|$ ranging from 4.6 to 9.1% and 4–9% in the 2010 and 2011 growing seasons.

3.2. The HYDRUS (2D/3D) model efficiency

3.2.1. Soil water and solute dynamics

Based on the results reported in our previous papers (Karandish and Šimůnek, 2016a, b, 2017, 2018), and the *nRMSE* and *nMBE* values reported in Table 4, the HYDRUS (2D/3D) model capable of simulating soil water and solute dynamics, with *nRMSE* = 0.4–11.5% and *nMBE* = 0.7–12.5% for the soil water content, *nRMSE* = 1.8–10.9% and *nMBE* = -6.8–10% for the soil NO_3^- content, *nRMSE* = 2.2–5.9% and *nMBE* = -3.1–4.5% for crop N uptake, and *nRMSE* = 2.1–9.1% and *nMBE* = 0.7–8.2% for soil EC_{sw}. Most earlier studies demonstrated the high capability of the HYDRUS (2D/3D) model to describe soil water and solute dynamics for various initial and boundary conditions (e.g., Cote et al., 2003; Gärdenäs et al., 2005; Assouline et al., 2006; Hanson et al., 2006; Ajdary et al., 2007; Crevoisier et al., 2008; Siyal and Skaggs, 2009; Mubarak, 2009; Li and Liu, 2011; Ramos et al., 2011, 2012; Tafteh and Sepaskhah, 2012; Phogat et al., 2013, 2014; Zeng et al., 2014; Mguidiche et al., 2015; Karandish and Šimůnek, 2016a,

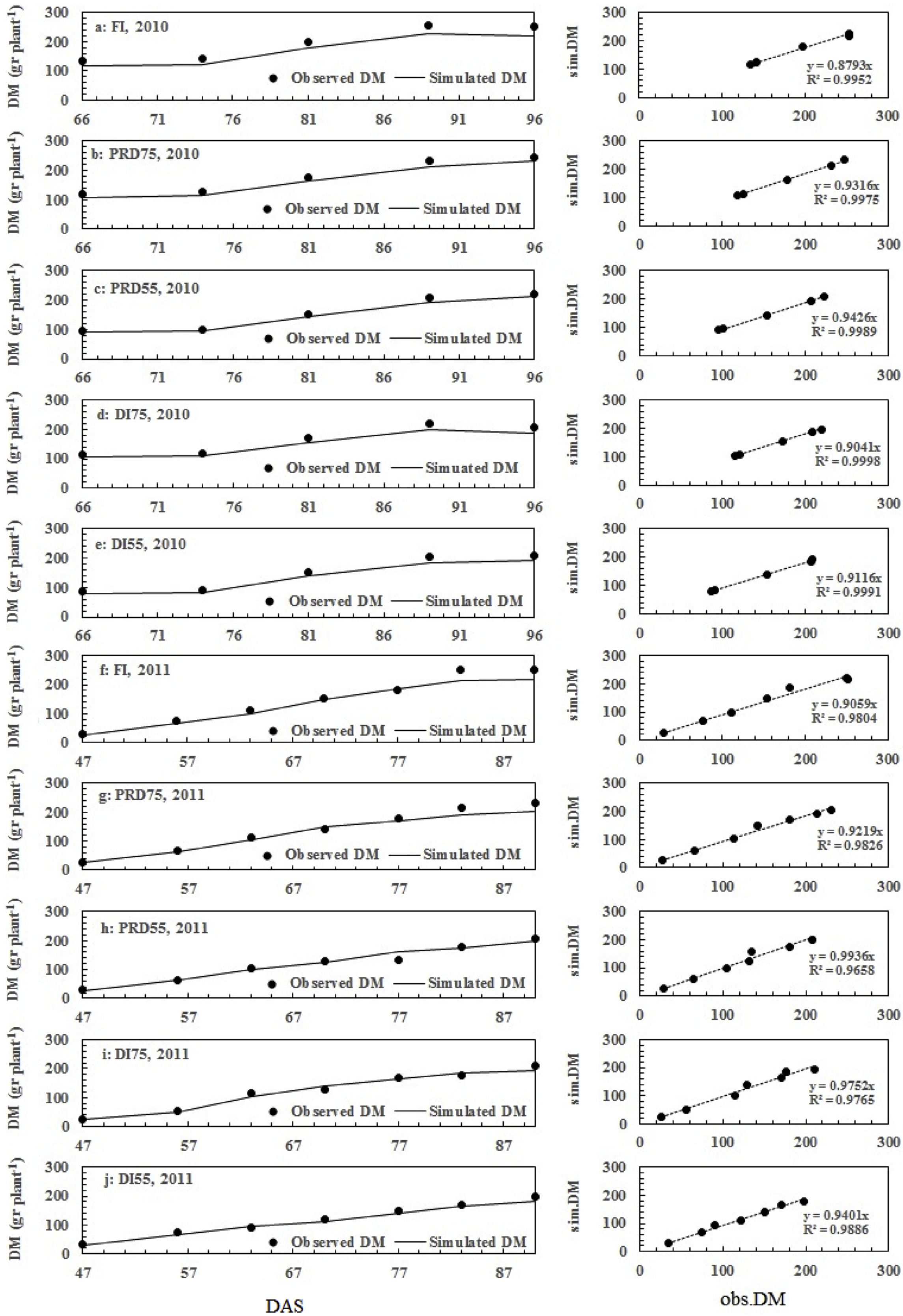

Fig. 2. Temporal variation of the observed and SALTMED-simulated aboveground biomass (DM, gr plant^{-1}) for various treatments (FI, DI_{55}, DI_{75}, PRD_{55}, and PRD_{75}) during the calibration (i.e., the 2010 growing season) and validation (i.e., the 2011 growing season) period. DAP – days after planting.

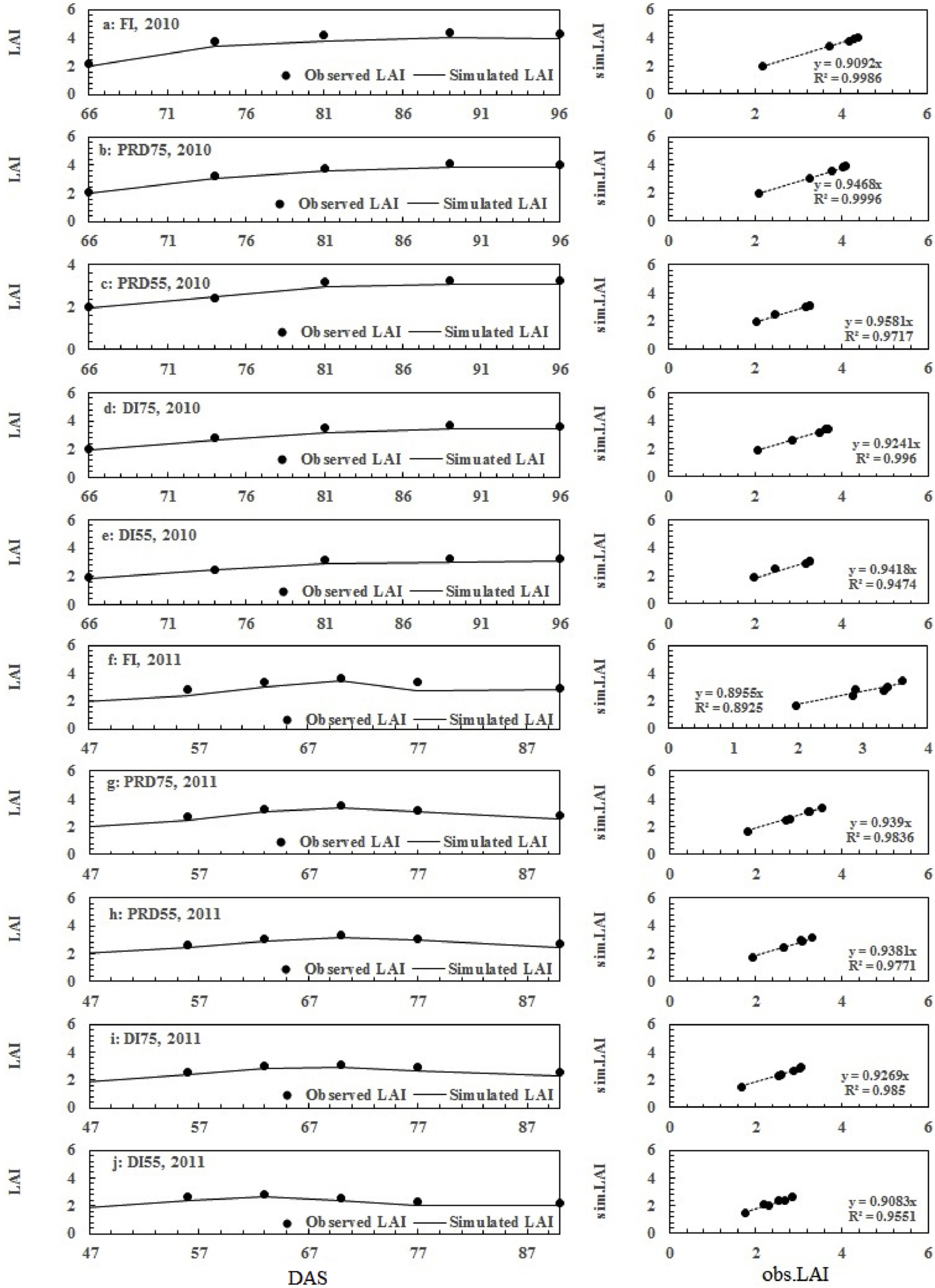

Fig. 3. Temporal variation of the observed and the SALTMED-simulated leaf area index (LAI) for various treatments (FI, DI_{55}, DI_{75}, PRD_{55}, and PRD_{75}) during the calibration (i.e., the 2010 growing season) and validation (i.e., the 2011 growing season) periods. DAP – days after planting.

Table 3
The observed and SALTMED-simulated crop yield, total biomass, and maximum leaf area index (LAI) for various treatments (FI, DI_{55}, DI_{75}, PRD_{55}, and PRD_{75}) in the 2010 and 2011 cropping cycles. *RE* – relative maximum error.

Year	Treatment	Crop yield (t ha^{-1})		*RE* (%)	Total biomass (t ha^{-1})		*RE* (%)	Maximum LAI		*RE* (%)
		Observed	Simulated		Observed	Simulated		Observed	Simulated	
2010	FI	7	6.4	−8.3	25.7	22.6	−12	4.4	4	−9.1
	PRD_{75}	6.9	6.6	−4.2	21.8	20.1	−7.9	4.09	3.85	−6
	PRD_{55}	3.3	3.2	−3.5	14.6	13.8	−5.7	3.27	3.12	−4.6
	DI75	5.8	5.4	−6.3	17.8	16.4	−7.6	3.68	3.42	−7
	DI_{55}	3.2	3.0	−5.1	14	13.1	−6.3	3.26	3.07	−5.7
2011	FI	6.6	6.1	−7.9	19	17.1	−10	3.6	3.28	−9
	PRD_{75}	6.2	6.0	−3.9	18.7	17.4	−6.8	3.54	3.35	−5.4
	PRD_{55}	5.7	5.5	−3.6	16	15.3	−4.3	3.3	3.17	−4
	DI_{75}	5.3	5.0	−5.5	16.5	15	−9.1	3.06	2.84	−7.3
	DI_{55}	4.9	4.7	−4.9	15.2	14	−8.2	2.85	2.66	−6.6

2016b, 2017, 2018).

Crop yield. Since the HYDRUS (2D/3D) model doesn't simulate crop yield directly, we estimated crop yield based on the ratio of actual and potential evapotranspiration, since there is general belief among scientists that crop yield is linearly correlated with crop transpiration (Payero et al., 2006; Klocke et al., 2004; Stone, 2003). Table 5 shows the observed and HYDRUS (2D/3D)-simulated crop yields for different treatments, as well as the corresponding *RE*s. Absolute *RE*s (i.e., |*RE*|) range from 2.2 to 15.6% and 4.9–13.8% in 2010 and 2011, respectively.

3.3. The comparison of the models

The HYDRUS (2D/3D) model performed better than the SALTMED model when simulating soil water and solute dynamics under defined treatments, with 11.6–31.1% lower *nRMSE* and 11.7–31.7% lower *nMBE* when simulating soil water contents, 13.7–31.8% lower *nRMSE* and 14.3–34.3% lower *nMBE* when simulating soil NO_3^- contents,

Table 5
The observed and HYDRUS-simulated crop yield and the corresponding relative errors (*RE*) for various treatments (FI, DI_{55}, DI_{75}, PRD_{55}, and PRD_{75}) in the 2010 and 2011 cropping cycles.

Year	Treatment	Crop yield (t ha^{-1})		*RE* (%)
		Observed	Simulated	
2010	FI	7	7.0	0.0
	PRD_{75}	6.9	6.8	−2.2
	PRD_{55}	3.3	3.8	15.2
	DI_{75}	5.8	6.4	10.1
	DI55	3.2	3.7	15.6
2011	FI	6.6	6.6	0.0
	PRD_{75}	6.2	6.5	5.4
	PRD_{55}	5.7	5.4	−4.9
	DI_{75}	5.3	6.0	13.8
	DI_{55}	4.9	5.4	10.9

Table 4
Criteria indices (*nRMSE*, *nMBE*) comparing the measured and HYDRUS-simulated soil and crop data during the calibration (the 2010 growing season) and validation (the 2011 growing season) periods for various irrigation treatments (FI, DI_{55}, DI_{75}, PRD_{55}, and PRD_{75}).

Period	Parameter	Depth	FI		PRD_{75}		PRD_{55}		DI_{75}		DI_{55}	
			nRMSE (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)	*nRMSE* (%)	*nMBE* (%)
Calibration period	Soil water content	0-20 cm	1.4	2.0	1.7	2.1	1.9	1.9	0.9	1.1	1.4	1.6
		20-40 cm	1.5	2.1	1.6	2.0	1.7	1.9	0.9	1.1	1.4	1.8
		40-60 cm	1.3	1.4	1.3	1.8	1.7	1.5	0.9	1.3	1.1	1.3
		60-80 cm	0.4	0.7	4.6	12.5	11.5	10.9	3.3	5.2	4.3	6.1
	Soil salinity*	0-20 cm	7.0	2.6	9.0	8.2	5.7	2.9	7.1	2.1	4.2	1.4
		20-40 cm	3.5	1.3	4.5	3.9	2.5	1.3	3.2	1.0	2.2	0.7
		40-60 cm	8.2	3.1	9.1	7.9	2.4	2.2	6.6	2.2	6.0	2.0
		60-80 cm	6.5	2.4	5.8	5.2	2.1	1.8	6.3	2.1	4.3	1.4
	Soil NO_3 content	0-20 cm	4.7	1.7	3.3	1.1	2.8	0.7	8.2	−6.8	3.4	1.7
		20-40 cm	5.5	3.4	3.4	2.2	2.7	0.4	4.2	2.8	2.6	0.6
		40-60 cm	4.2	−0.3	3.4	−1.9	4.6	4.2	10.8	9.3	6.5	5.9
		60-80 cm	6.0	0.8	8.6	2.5	8.6	2.5	8.6	2.5	8.6	2.5
	Crop N uptake		5.0	−3.0	4.3	−2.8	5.3	−3.1	5.1	−2.6	4.2	−1.7
Validation period	Soil water content	0-20 cm	2.0	1.5	1.8	3.0	0.8	1.0	2.3	4.8	4.2	8.4
		20-40 cm	0.6	2.0	1.6	2.0	1.6	1.8	0.7	1.1	0.9	1.1
		40-60 cm	0.8	1.3	1.6	2.4	1.3	1.5	0.9	1.2	0.8	1.2
		60-80 cm	0.6	1.1	1.6	1.8	1.0	1.3	0.7	0.9	1.1	1.5
	Soil salinity*	0-20 cm	5.6	2.2	4.9	3.3	4.3	3.4	8.6	5.2	5.3	2.1
		20-40 cm	2.8	1.1	2.3	1.6	1.9	1.5	4.2	2.5	2.7	1.1
		40-60 cm	6.6	2.7	4.6	3.1	2.3	2.1	8.6	5.2	7.5	3.0
		60-80 cm	5.2	2.0	2.9	2.1	2.0	1.7	8.3	5.0	5.5	2.2
	Soil NO_3 content	0-20 cm	3.0	1.2	3.6	1.5	1.8	−1.1	2.7	−1.8	2.6	−2.1
		20-40 cm	4.2	−0.2	5.1	3.4	3.4	−0.7	2.6	−0.2	3.2	−0.7
		40-60 cm	7.1	−2.8	3.1	0.7	5.5	4.0	4.1	−1.6	7.3	5.7
		60-80 cm	9.5	8.6	10.9	10.0	10.8	10.0	10.8	10.0	10.8	10.0
	Crop N uptake		2.2	1.0	4.3	1.3	5.7	4.5	5.1	3.8	5.9	2.3

Table 6
Field-based calculated and model-simulated consumptive *WF* and degradative grey *WF* for various treatments in 2010 and 2011 cropping cycles.

Year	Treatment	HYDRUS (2D/3D)				SALTMED				Field-based
		Crop yield (t ha^{-1})	ET_a (mm)	Consumptive *WF* ($m^3\,t^{-1}$)	Grey *WF* ($m^3\,t^{-1}$)	Crop yield (t ha^{-1})	ET_a (mm)	Consumptive *WF* ($m^3\,t^{-1}$)	Grey *WF* ($m^3\,t^{-1}$)	Grey *WF* ($m^3\,t^{-1}$)
2010	FI	7	650.3	929	398	6.4	604.4	942	453	321
	PRD_{75}	6.8	627.2	926	466	6.6	616.1	932	492	385
	PRD_{55}	3.8	535.9	1411	1339	3.2	462.1	1451	1631	1391
	DI_{75}	6.4	593.2	929	691	5.4	518.1	953	830	686
	DI_{55}	3.7	531.5	1438	1529	3	450.5	1483	1880	1690
2011	FI	6.6	572.5	871	296	6.1	534	879	388	325
	PRD_{75}	6.5	566.7	871	357	6	524.3	880	472	411
	PRD_{55}	5.4	470.3	872	1110	5.5	475.7	866	1339	1164
	DI_{75}	6	523.3	873	950	5	447.8	894	1362	1174
	DI_{55}	5.4	471.2	870	1518	4.7	414.2	889	1883	1728

10.8–17.8% lower *nRMSE* and 11.0–18.0% lower *nMBE* when simulating crop N uptake, and 6.7–25.5% lower *nRMSE* and 7.7–28.1% lower *nMBE* when simulating soil EC_{sw}. Such differences may originate from the fact that the HYDRUS (2D/3D) and SALTMED models use different types of boundary conditions for water flow and solute transport.

However, the SALTMED-simulated yields are more accurate compared to those simulated by HYDRUS. The |*RE*| obtained by the HYDRUS (2D/3D) model were generally 1.3–11.7% higher compared to those obtained by the SALTMED model, except for the PRD_{75} treatment in 2010, for which the |*RE*| by the HYDRUS (2D/3D) model was 2% smaller than that obtained by the SALTMED model. Better performance of the SALTMED model in simulating crop yield is related to the embedded driving equations and formulas for estimating crop yield (Hassanli et al., 2016; Oster et al., 2012). In fact, yield estimations based on the crop growth parameters rather than *RY* provided better results for the SATMED-simulated yields.

3.4. *WF* accounting

Table 6 shows the consumptive and degradative grey *WF*s estimated using the results of the HYDRUS (2D/3D) and SALTMED models for various treatments in 2010 and 2011. The HYDRUS (2D/3D)-estimated consumptive *WF*s are 0.3–3.2% lower than those estimated by the SALTMED model. The consumptive *WF* is influenced by the yield and crop water consumption (Karandish and Hoekstra, 2017; Karandish and Šimůnek, 2018). Any increase in crop yield and/or reduction in crop water consumption may reduce the consumptive *WF* related to crop production. Table 6 indicates that compared to the SALTMED predictions, HYDRUS (2D/3D) simulated a lower crop yield reduction than the reduction in the crop water consumption, which resulted in lower consumptive *WF*s. Crop yield and water consumption estimated by HYDRUS (2D/3D) are 3–23.3% and 1.8–18% lower, respectively, than those estimated by SALTMED.

The HYDRUS (2D/3D)-estimated grey *WF*s were 5.3–30.2% lower than those estimated using SALTMED, which may be associated with the higher HYDRUS (2D/3D)-estimated yield (Table 5). Table 6 also shows that the HYDRUS (2D/3D)-estimated grey *WF*s provided a closer match to those calculated based on field measurements. While for HYDRUS (2D/3D), |*RE*| ranged from 0.7 to 24.2%, for SALTMED it ranged from 8.9 to 41.2%. Such results may be associated with a better estimation of crop N uptake, and consequently, soil N residual at harvest by the HYDRUS (2D/3D) model (Table 4).

Except for the PRD_{55} and DI_{55} in 2010, no considerable differences were observed in estimated consumptive *WF*s for various treatments. In the absence of the water stress, 906.5 ± 35.5 m^3 of water is required to produce a unit (ton) of maize in the study area. Applying water stress may produce a relative change of -0.3%–54.7% in the estimated consumptive *WF*, with a particular increase under PRD_{55} and DI_{55} in 2010. Such an increase is mainly due to a significant reduction in crop yield under the PRD_{55} and DI_{55} treatments in 2010 rather than the associated reduction in the crop water consumption. Nearly similar consumptive *WF*s estimated for the other treatments may be justified by the fact that the negative consequences of reduced yield under the water stress are compensated by the positive consequences of the reduced crop water consumption.

Based on the estimated grey *WF*, which is an indicator of adverse environmental effects of human activities and water quality management, the PRD application may be safer than DI when water resources are limited in the study area. A unit of maize under PRD_{75} and PRD_{55} is produced with 32.6–65.3% and 12.4–32.7% fewer pollutant loads to freshwater bodies than under DI_{75} and DI_{55}, respectively. The smallest grey *WF*s can always be found under FI, followed by PRD_{75}. The grey *WF* under PRD_{75} was slightly higher than under the FI treatment, accounting for 8.6–26.7%, which may be attributed to lower yield and N water uptake under PRD_{75}. Nevertheless, the PRD_{75} treatment seems to be the safest water-saving irrigation strategy in the study area, since the estimated grey *WF* for PRD_{75} was 17.1–77.2% lower than those estimated for the other water-saving irrigation treatments.

4. Conclusions

Using data collected during a two-year field investigation in a surface drip-irrigated maize field, we compared the performance of the SALTMED and HYDRUS (2D/3D) models in simulating water and solute dynamics, maize growth, and maize consumptive and degradative *WF*s under various water-saving irrigation strategies, including full irrigation (FI), partial root-zone drying (PRD), and deficit irrigation (DI). The consumptive and degradative *WF*s estimated by HYDRUS (2D/3D) were 0.6–3% and 5.3–30.2%, respectively, lower than those estimated by the SALTMED model. However, the grey *WF*s simulated by HYDRUS (2D/3D) were in better agreement with those estimated using the field-collected data, particularly due to the more accurate estimation of soil N dynamics. While the gross blue water consumption is 25 or 45% lower for considered water-saving irrigation strategies (DI_{75} and PRD_{75} or DI_{50} and PRD_{50}, respectively), the corresponding reduction in maize grain yield under the water stress resulted in insignificant differences in the estimated maize consumptive *WF*s among various treatments. Regarding the grey *WF*, which is an indicator of the negative environmental impact of human activities and water quality management, PRD_{75} produced better results than the other water-saving irrigation treatments, suggesting that sustainable agriculture may be easier achieved under PRD_{75}. Reliable estimates of both consumptive and degradative grey *WF*s related to the maize production for various treatments by the HYDRUS (2D/3D) and SALTMED models indicate that there is an alternative approach to the labor- and time-consuming field investigations. Nevertheless, more accurate results are expected to be achieved when employing the HYDRUS (2D/3D) model.

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