Application of SALTMED and HYDRUS-1D models for simulations of soil water content and soil salinity in controlled groundwater depth postprint

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Abstract

Salinization is a gradual process that should be monitored. Modelling is a suitable alternative technique that saves time and cost for the field monitoring. But the performance of the models should be evaluated using the measured data. Therefore, the aim of this study was to evaluate and compare the SALTMED and HYDRUS-1D models using the measured soil water content, soil salinity and wheat yield data under different levels of saline irrigation water and groundwater depth. The field experiment was conducted in 2013 and in this research three controlled groundwater depths, i.e., 60 (CD60), 80 (CD80) and 100 (CD100) cm and two salinity levels of irrigation water, i.e., 4 (EC4) and 8 (EC8) dS/m were used in a complete randomized design with three replications. Soil water content and soil salinity were measured in soil profile and compared with the predicted values by the SALTMED and HYDRUS-1D models. Calibrations of the SALTMED and HYDRUS-1D models were carried out using the measured data under EC4-CD100 treatment and the data of the other treatments were used for validation. The statistical parameters including normalized root mean square error (NRMSE) and degree of agreement (d) showed that the values for predicting soil water content and soil salinity were more accurate in the HYDRUS-1D model than in the SALTMED model. The NRMSE and d values of the HYDRUS-1D model were 9.6% and 0.64 for the predicted soil water content and 6.2% and 0.98 for the predicted soil salinity, respectively. These indices of the SALTMED model were 10.6% and 0.81 for the predicted soil water content and 11.0% and 0.97 for the predicted soil salinity, respectively. According to the NRMSE and d values for the predicted wheat yield (9.8% and 0.91, respectively) and dry matter (2.9% and 0.99, respectively), we concluded that the SALTMED model predicted the wheat yield and dry matter accurately.

Full Text

Preamble

Application of SALTMED and HYDRUS-1D Models for Simulating Soil Water Content and Soil Salinity Under Controlled Groundwater Depth

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Abstract: Salinization is a gradual process that requires continuous monitoring. Modeling offers a suitable alternative technique that saves time and costs associated with field monitoring, though model performance must be evaluated using measured data. Therefore, this study aimed to evaluate and compare the SALTMED and HYDRUS-1D models using measured soil water content, soil salinity, and wheat yield data under different levels of saline irrigation water and groundwater depth. The field experiment was conducted in 2013, employing three controlled groundwater depths—60 cm (CD60), 80 cm (CD80), and 100 cm (CD100)—and two salinity levels of irrigation water, 4 dS/m (EC4) and 8 dS/m (EC8), arranged in a completely randomized design with three replications. Soil water content and soil salinity were measured throughout the soil profile and compared with values predicted by the SALTMED and HYDRUS-1D models. Model calibration was performed using data from the EC4-CD100 treatment, while data from the remaining treatments were used for validation. Statistical parameters including normalized root mean square error (NRMSE) and degree of agreement (d) indicated that the HYDRUS-1D model predicted soil water content and soil salinity more accurately than the SALTMED model. The HYDRUS-1D model achieved NRMSE and d values of 9.6% and 0.64 for predicted soil water content, and 6.2% and 0.98 for predicted soil salinity, respectively. Corresponding indices for the SALTMED model were 10.6% and 0.81 for soil water content, and 11.0% and 0.97 for soil salinity. Based on NRMSE and d values for predicted wheat yield (9.8% and 0.91, respectively) and dry matter (2.9% and 0.99, respectively), we concluded that the SALTMED model accurately predicted wheat yield and dry matter.

Keywords: wheat; yield; dry matter; simulation; normalized root mean square error

1 Introduction

In many parts of the world, salt concentration in groundwater is increasing, and soil salinization can occur due to decreasing water table depth and increasing capillary rise, particularly in areas with inadequate drainage systems. In irrigated regions, groundwater depth is of utmost importance for controlling soil salinity and waterlogging while improving the plant environment. Conversely, in arid regions where water resources are limited, a gap exists between water supply and increasing demand. In this context, controlled groundwater depth represents a modern technique that may remediate water scarcity problems. In this method, the groundwater level rises in the soil and approaches the root zone, enabling plants to utilize groundwater more effectively. The efficiency of controlled groundwater depth has been studied by numerous researchers (Asseng et al., 2001a, b; Ayars et al., 2006; Steppuhn et al., 2016), who concluded that transitioning from uncontrolled to controlled groundwater systems addresses environmental concerns and improves water management. This is because controlled systems provide flexibility in managing a wide range of groundwater depths and can be used to manage soil salinity and water use from shallow groundwater.

Khalil et al. (2004) investigated the effects of controlled drainage on crop yield, soil salinity, and irrigation water requirement, comparing rice production and water needs under conventional and controlled drainage systems. Their results showed that while the controlled drainage system and controlled water table depth had no significant positive effect on rice production or soil salinity, water requirement under controlled drainage was 25% lower than under conventional drainage. They reported that implementing controlled drainage in rice fields could save approximately 1\$×10^{9}\$ m^3 of water annually.

In general, irrigation with saline water reduces crop yield and grain quality; however, several strategies can mitigate yield reduction under saline conditions. Jiang et al. (2012) studied the effects of irrigation water depth (375, 300, and 225 mm, designated W1, W2, and W3, respectively) and water salinity up to 6.1 dS/m on water consumption and productivity of spring wheat from 2008 to 2010. The highest yield at a given salinity level was obtained in the W2 treatment (6.9 Mg/ha), and water use efficiency (WUE, 1.25-1.63 kg/m^3) and irrigation water use efficiency (IWUE, 2.11-2.36 kg/m^3) in the W2 treatment exceeded those in the W1 treatment.

Due to scarcity of surface water resources, especially during dry seasons, crops are largely irrigated using saline groundwater and drainage water. Several studies indicate that brackish water can be successfully used for crop production; however, negative effects on crop production may occur due to salt accumulation in the soil (Wang et al., 2015). Liu et al. (2016) found that using saline water resources for irrigation during the jointing stage of winter wheat in northern China was beneficial, doubling the yield of winter wheat and summer maize. They noted that sufficient fresh water irrigation (60–90 mm) during the sowing stage of summer maize is necessary to avoid negative effects of saline irrigation water and ensure good growth conditions during the early sensitive period.

Ma et al. (2008) described crop responses to saline irrigation water based on field experiments, showing that the electrical conductivity of the saturated paste extract (ECe) in the topsoil (0–100 cm) was 40% higher than in the subsoil (100-180 cm) under saline irrigation. The salt load increased rapidly, particularly in the upper 80 cm, and the maximum soil depth leached during the wet season was approximately 150 cm.

Previous research confirms that saline irrigation water appears economically attractive to farmers in the short term, and ecological hazards can be controlled through proper salt leaching. However, short-term field experiments may not provide appropriate criteria for decision-making. Therefore, modeling offers a suitable alternative to field experiments, saving both time and cost.

Over the past decade, the SALTMED model has been used for integrated field water management (Ragab, 2002a, b). SALTMED is a physically based model that includes key processes such as evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, nitrogen application rates, water qualities, and relationships between crop yield and water use (Ragab, 2002a, b; Ranjbar et al., 2015). Many researchers have applied SALTMED to simulate plant growth and yield for various crops including sugar beet, carrots, kale, quinoa, and tomatoes (Malash et al., 2011; El-Shafie et al., 2017; Silva et al., 2017), concluding that it accurately predicts soil salinity and crop yield under saline conditions. Razzaghi and Ghannadi (2016) used SALTMED to simulate wheat yield and dry matter under different irrigation depths and systems (sprinkler and basin), finding accurate predictions for both systems, though soil water content was predicted better under sprinkler irrigation. Koutar et al. (2017) applied SALTMED to simulate quinoa yield and dry matter under four irrigation levels (100%, 75%, 50%, and 25% of crop water requirement), calibrating the model with control treatment data and evaluating it with other treatments. Results showed reasonable precision in simulating total dry matter and grain yield under deficit irrigation regimes.

The HYDRUS-1D model is another advanced one-dimensional model for water, salt, and heat movement in soil (Šimůnek et al., 2008; Luo et al., 2010; Zeng et al., 2014; Noshadi et al., 2017). The HYDRUS-1D software package offers numerous approaches for simulating variably saturated water flow and solute transport, addressing one-dimensional problems in soil columns, lysimeters, soil profiles, and plots. Beyond basic water flow and solute transport, HYDRUS-1D can simulate carbon dioxide transport and production and major ion transport, with a wide range of non-equilibrium flow and transport modeling approaches available (Šimůnek et al., 2008). Jha et al. (2017) and Shahrokhnia and Sepaskhah (2018) simulated water and nitrogen transport using HYDRUS-1D for paddy in sandy loam soil in India and rapeseed and safflower in clay loam soil in Iran, revealing good precision in simulating water pressure head and nitrogen concentration.

As noted above, models are effective tools for simulating effects of environmental conditions such as irrigation water salinity on crop yield. Numerous models including LEACHC, UNSATCHEM, SWAP (Soil-Water-Plant-Atmosphere), SALTMED, and HYDRUS-1D have been developed for this purpose. Although SALTMED and HYDRUS-1D are recognized as powerful tools, comparison of their accuracy in simulating soil salinity and water content under shallow groundwater conditions has not been investigated. Therefore, this study aimed to evaluate and compare SALTMED and HYDRUS-1D in simulating soil water content and salinity, and to evaluate SALTMED in simulating wheat yield under different saline irrigation water levels and groundwater depths.

2.1 Field Experiment

This research was conducted at the College of Agriculture, Shiraz University (36°29 N, 32°52 E; 1810 m a.s.l.), located 16 km from Shiraz City, Iran, in 2013. Wheat seeds were planted at a density of 200 kg/ha in 18 soil columns (lysimeters) measuring 120 cm in height and 40 cm in diameter. Soil physical characteristics are presented in Table 1 .

Three controlled groundwater depths—60 cm (CD60), 80 cm (CD80), and 100 cm (CD100)—and two saline irrigation water treatments, 4 dS/m (EC4) and 8 dS/m (EC8), with three replications were arranged in a completely randomized design, totaling 18 soil columns. Four exit pipes were installed at depths of 30, 60, 90, and 130 cm from the soil column top for groundwater sampling and establishing desired groundwater depths. To maintain groundwater depths at 60, 80, and 100 cm, water was introduced at very low discharge from the column bottom through a pipe installed at 130 cm depth. Water table depths were monitored using manometer tubes installed at the column bottom. When the level fell below the desired depth (60, 80, or 100 cm depending on treatment), saline water was added using a Mariotte bottle to maintain the target water table depth. These water volumes were measured and recorded as groundwater contribution (GC).

Groundwater salinity at the beginning of the growing season equaled fresh water salinity (0.76 dS/m). All soil columns were irrigated simultaneously throughout the season. Before each irrigation event, soil water content at various depths was measured using a portable time-domain reflectometer (TDR). TDR probes were installed at different depths: 30 cm in CD60 treatment, 20 and 60 cm in CD80 treatment, and 15, 45, and 75 cm in CD100 treatment. Net irrigation water depth was determined using the following equation (Brouwer et al., 1989):

$$D = 0.5 \times (\theta_{FC} - \theta_v) \times Z_r \qquad (1)$$

where D is net irrigation water depth (cm), θ_v is volumetric soil water content within the root zone before irrigation (cm^3/cm^3), θ_{FC} is volumetric soil water content at field capacity (cm^3/cm^3), and Z_r is root depth (cm). In Equation 1, Z_r is a time-dependent parameter obtained from (Borg and Grimes, 1986):

$$Z_r = RD_m \times \left(0.5 + 0.5 \times \sin\left(3.03 \times \frac{D_{As}}{D_{Tm}} - 1.47\right)\right) \qquad (2)$$

where Z_r is root depth on a given day (cm), D_{As} is days after planting, D_{Tm} is days to reach maximum root depth (considered 170 days based on the wheat growth period), and RD_m is maximum root depth (100, 80, and 60 cm for CD100, CD80, and CD60 treatments, respectively).

Irrigation application efficiency (E_a) was 80%. Gross irrigation water depth (I_g) was calculated as (Brouwer et al., 1989):

$$I_g = \frac{D}{E_a} \qquad (3)$$

Applied irrigation water depth was determined as the difference between calculated irrigation water depth and the sum of groundwater contribution and precipitation. Applied irrigation water was measured by a flow meter for each event. Precipitation was measured at a climatological station approximately 500 m from the study area.

Saline water was prepared by adding NaCl and $CaCl_2$ in a 1:1 ratio to fresh water, with salinity level measured by an electrical conductivity meter. Nitrogen was applied at 200 kg/ha as urea through irrigation water in two stages: at planting and 110 days after planting. At season end, wheat (seeds and dry matter) was harvested, oven-dried, and weighed. Soil samples were collected at 15, 45, and 75 cm depths to determine ECe.

2.2.1 HYDRUS-1D Model

Input parameters for the HYDRUS-1D model included soil profile data, soil hydraulic characteristics, water flow boundary conditions, solute transport parameters and related boundary conditions, root water and solute uptake models, and evapotranspiration data.

Water movement for the experimental conditions is described by a modified Richards equation based on assumptions that the air phase plays an insignificant role in liquid flow and that water flow due to thermal gradients is negligible:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial h}{\partial x}\right) - S \qquad (4)$$

where ∂ denotes partial derivative, h is water pressure head (cm), θ is volumetric water content (cm^3/cm^3), t is time (d), S is root water uptake rate ($cm^3/(cm^3 \cdot d)$), and k is unsaturated hydraulic conductivity (cm/d).

Solving Equation 4 requires information on initial pressure head distribution within the flow domain:

$$h(x, t_0) = h_i(x) \qquad (5)$$

where h_i (cm) is water pressure head as a function of x, and t_0 (d) is simulation start time.

For the upper boundary condition given by Equation 5, h is considered at the soil surface-air interface (exposed to atmospheric conditions). The atmospheric boundary condition with surface layer permits water accumulation on the surface. Surface water height increases due to precipitation and decreases through infiltration and evaporation. The numerical solution of Equation 4 is obtained by limiting the absolute value of surface flux through two conditions (Neuman et al., 1974):

$$|E| \leq k(h_A) \quad \text{and} \quad |E| \leq k(h_S) \qquad (6)$$

where E is the maximum potential infiltration or evaporation rate under current atmospheric conditions (cm/d), and h_A and h_S are the minimum and maximum pressure heads allowed at the soil surface under prevailing soil conditions (cm), respectively.

The lower boundary condition applied in this study was a seepage face at the bottom of the soil profile through which water can exit the saturated portion of the flow domain. This boundary condition is commonly applied to laboratory soil columns when the local pressure head at the profile bottom ($x = 0$) is negative.

For solute transport simulation, upper and lower boundary conditions were concentration flux boundary condition (determining liquid-phase concentration of infiltration water) and concentration boundary condition (determining liquid-phase concentration at the boundary), respectively.

Equation 8 prescribes concentration at a boundary, while Equation 9 prescribes concentration flux at the lower boundary:

$$c(x,t) = c_0(t) \qquad (8)$$

$$-q_0 c + \theta D \frac{\partial c}{\partial x} = q_0 c_0 \qquad (9)$$

where q_0 is upward fluid flux (mg/cm^3) and c_0 is incoming fluid concentration (mg/cm^3).

2.2.2 SALTMED Model

The SALTMED model simulates soil water content, soil salinity, and crop yield across various irrigation systems, soil types, crops, water application strategies, and water qualities.

In this model, water flow in soils is mathematically described by Richards' equation (Eq. 4) with initial and boundary conditions similar to those described in Section 2.2.1. Solute movement in the soil system, including its rate and direction, depends heavily on water movement paths but is also determined by diffusion and hydrodynamic dispersion. Combining diffusion with convection yields the overall solute flux according to Hillel (1977):

$$J = -\theta D_h \frac{\partial c}{\partial x} - \theta D_s \frac{\partial c}{\partial x} + v\theta c \qquad (10)$$

where c is solute concentration (mmol/L) in flowing water, v is average flow velocity (L/t), D_h is hydrodynamic dispersion in soil (L^2/t), and D_s is solute diffusion in soil (L^2/t), which decreases because the liquid phase occupies only a fraction of soil volume and due to the tortuous flow path.

2.3 Model Evaluation

Statistical parameters including normalized root mean square error (NRMSE), index of agreement (d), and error percentage (E) were used to evaluate simulation accuracy (Loague and Green, 1991). NRMSE represents the total difference between measured and simulated data normalized against the mean of measured data. The lower limit for NRMSE is 0, occurring when no difference exists between paired data; smaller NRMSE values indicate higher simulation accuracy. The d index assesses simulation accuracy, with a maximum value of 1 when simulated values are identical to measured values (Willmott et al., 1985). E is defined as the percentage difference between simulated and measured values, with lower values indicating closer agreement.

$$\mathrm{NRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}}{\bar{O}} \times 100 \qquad (12)$$

where P_i is predicted value, O_i is observed value, $\bar{O}$ is mean observed value, and n is number of observations.

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \qquad (13)$$

3 Results and Discussion

3.1 Irrigation Water Depth and Soil Salinity

Irrigation water depths and statistical analysis results are shown in Table 2 . Differences in irrigation water depths among controlled groundwater treatments under 4 and 8 dS/m salinities were significant ($P<0.01$). Under CD100, CD80, and CD60 treatments with 8 dS/m salinity, irrigation water depths were 13.0%, 10.9%, and 9.6% lower, respectively, than those with 4 dS/m salinity. Reduced water consumption with increasing water salinity was reported by Jiang et al. (2012), who found that actual evapotranspiration (ETa) decreased from

580 to 560 mm (3.4%) when irrigation water salinity increased from 0.67 to 6.10 dS/m.

Compared with CD100 treatment, irrigation water depth reductions under CD80 and CD60 treatments with 4 dS/m salinity were 18.3% (from 710 to 580 mm) and 36.6% (from 710 to 450 mm), respectively. The reduction was 22.4% under CD60 compared with CD80 treatment. With 8 dS/m salinity, reductions under CD80 and CD60 treatments were 16.4% (from 618 to 517 mm) and 34.1% (from 618 to 407 mm), respectively, compared with CD100, and 21.3% under CD60 compared with CD80. All differences were significant ($P<0.01$). Consequently, the lowest and highest irrigation water depths were obtained under CD60 and CD100 treatments, respectively, at both salinity levels (Table 2). The fraction of water requirement supplied by capillary rise depended on groundwater depth, with higher capillary rise values under CD60 than CD100 treatment.

Mean irrigation water depth (averaged across salinity levels) under different water table depths is shown in Table 2. Results indicate mean reductions of 17.4% (from 664.0 to 548.5 mm) and 35.5% (from 664.0 to 428.5 mm) under CD80 and CD60 treatments, respectively, compared with CD100 treatment. The reduction was 21.9% under CD60 compared with CD80 treatment. Thus, water table depth significantly affected mean irrigation water depth reduction ($P<0.01$).

Mean ECe at the end of the growing season and statistical analysis for all water table depths and irrigation water salinities are shown in Table 2. Under CD80 and CD60 treatments, ECe at the soil surface increased due to enhanced root water uptake in the surface layer. Under CD100 treatment, ECe increased at the soil surface due to decreasing capillary rise values with increasing unsaturated soil depth, then decreased near the water table due to saturation conditions. Mean ECe under CD100, CD80, and CD60 treatments showed significant differences between 4 and 8 dS/m salinity levels ($P<0.01$; Table 2). In controlled groundwater treatments, ECe increases with 8 dS/m salinity were 35.6%, 68.5%, and 79.1% compared with 4 dS/m salinity for CD100, CD80, and CD60, respectively (Table 2).

Water table depth significantly affected ECe ($P<0.01$). At all irrigation water salinity levels, ECe values under CD80 and CD60 treatments exceeded those under CD100 treatment. Irrigation water depth under CD100 treatment was higher than under CD80 and CD60 treatments (Table 2), resulting in higher leaching fractions under CD100 compared with CD80 and CD60 treatments. Salinity significantly affected mean irrigation water depth ($P<0.01$), with mean depth 11.37% lower at 8 dS/m than at 4 dS/m salinity. In general, irrigation water depth decreased with decreasing groundwater depth at each salinity level, and decreased with increasing water salinity at each groundwater depth. Decreased irrigation water depth with increasing salinity resulted from reduced crop transpiration due to lower water uptake under saline conditions, reduced soil evaporation, and consequently higher soil water content during the growing season. Decreased irrigation water depth with decreasing groundwater depth was attributed to higher capillary rise and groundwater contribution to crop water use (Table 3).

3.2 Model Calibrations

The SALTMED and HYDRUS-1D models were calibrated using the EC4-CD100 treatment. Based on soil physical properties (Table 1), the soil profile was divided into three layers, with properties for each layer—including soil texture, initial soil water content, saturated hydraulic conductivity, and van Genuchten equation parameters (Table 4)—entered into the models. Initial parameter values were determined using RETC software (van Genuchten et al., 1992) and optimized during calibration. Calibrated parameters for both models are shown in Table 5 .

The water uptake reduction model proposed by Feddes et al. (1974) was used in both models to simulate root water uptake under saline conditions. In this approach, maximum root depth, salinity threshold, and slope of the yield function decreased with increasing salinity, with values of 100 cm, 6.5 dS/m, and 7.8%/(dS/m), respectively (Allen et al., 1998).

3.2.1 Soil Water Content Predicted soil water content values under EC4-CD100 treatment from both models at different days after planting are shown in Figure 1 [Figure 1: see original paper]. Good agreement existed between predicted and measured soil water content in the surface layer (0–30 cm) at various days after planting. In the second layer (30–60 cm), both models overpredicted values compared with measurements, while in the third layer (60–90 cm), SALTMED overpredicted and HYDRUS-1D underpredicted soil water content.

Error (E), NRMSE, and d indices for simulated soil water content across the entire profile were 4.4%, 9.4%, and 0.88 for SALTMED, and 0.5%, 7.6%, and 0.89 for HYDRUS-1D, respectively. Although both models predicted soil water content well, HYDRUS-1D provided more accurate predictions than SALTMED.

3.2.2 ECe Both models simulated ECe and associated soil water content at different depths and times, while actual ECe was measured experimentally. Using a correction factor based on the ratio of field soil water content to saturated soil water content, predicted ECe was adjusted to match measured ECe. Mean E values were 1.0% and 0.8%, NRMSE values were 9.0% and 8.0%, and d indices were 0.88 and 0.89 for SALTMED and HYDRUS-1D, respectively. Despite high accuracy for both models, HYDRUS-1D predicted ECe more accurately than SALTMED.

3.3 Model Validations

The SALTMED and HYDRUS-1D models were validated using all treatments except the calibration treatment (EC4-CD100). NRMSE and d indices for predicted soil water content and soil salinity during validation are shown in Table 6 .

3.3.1 Soil Water Content Observed and simulated soil water content profiles at different days after planting under EC8-CD100 and EC8-CD80 treatments are shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper]. Since soil water content was measured only at 30 cm depth in EC4-CD60 treatment, profile plotting was not possible for this treatment. Comparison of predicted soil water content between EC8-CD100 and EC4-CD100 treatments showed that increasing water salinity above the wheat threshold salinity level (6.5 dS/m) decreased root water uptake, resulting in a wetter soil profile. Consequently, mean predicted soil water content from both models was higher under EC8-CD100 than under EC4-CD100 treatment.

Raising the water table depth and bringing the saturated zone to 60 cm below the soil surface increased soil water content between two consecutive irrigation intervals. Soil water content increased in top profile layers under EC4-CD60 treatment due to lower water table depth and higher capillary rise. Both models underpredicted soil water content for this treatment, with simulation errors of -10.7% for SALTMED and -0.4% for HYDRUS-1D. HYDRUS-1D demonstrated higher precision because it better accounts for waterlogging stress effects, reducing or stopping root water uptake when soil water content is high.

Simulated soil water content under EC8-CD80 treatment in the surface layer (0-30 cm) was more accurate than in deeper layers. Notably, due to higher capillary rise, soil salinity in deeper layers was highest in this treatment. This finding aligns with Kaya et al. (2015), who predicted soil water content at 0–30, 30–60, and 60–90 cm depths using SALTMED. Their results showed better accuracy in the surface layer than in the third layer (R^2 values of 0.86 and 0.80, respectively), attributing lower R^2 in deeper layers to neglected soil drainage properties from missing data. Similar HYDRUS-1D research found more accurate simulation in 0–40 cm depth than in 40–100 cm depth (Zeng et al., 2014).

HYDRUS-1D predictions of soil water content at 30 cm depth in all treatments were closer to observed values. In the first layer (0–30 cm), NRMSE values for EC4-CD100, EC4-CD60, EC8-CD100, and EC8-CD80 treatments were 5.6%, 3.1%, 9.7%, and 7.3%, respectively (average 7.3%), with simulation errors of -0.7%, -0.4%, -5.0%, and 0.2% (average -1.5%). In SALTMED, NRMSE values were 0.0%, 12.7%, 11.7%, and 8.9% (average 9.9%), with errors of -0.2%, -10.7%, -1.7%, and 4.0% (average -2.1%). Thus, HYDRUS-1D results were closer to measured values.

In the second layer (30–60 cm), simulation accuracy for both models decreased under EC4-CD100 and EC8-CD80 treatments but increased under EC8-CD100 treatment. HYDRUS-1D NRMSE values for EC4-CD100, EC8-CD100, and EC8-CD80 treatments were 8.4%, 8.7%, and 12.1% (average 9.7%), with simulation errors of 4.3%, -0.6%, and -5.9% (average -0.5%). SALTMED NRMSE values were 12.7%, 8.8%, and 10.7% (average 10.7%), with errors of 10.2%, 6.4%, and 8.1% (average 8.2%). Therefore, HYDRUS-1D results (average NRMSE 9.7%, average error -0.5%) were closer to measured values.

In the third layer (60-90 cm), SALTMED NRMSE was lower than HYDRUS-1D NRMSE. For EC4-CD100 and EC8-CD100 treatments, HYDRUS-1D NRMSE values were 7.9% and 14.4% (average 11.15%), with simulation errors of -5.1% and -11.4% (average -8.3%). SALTMED NRMSE values were 7.3% and 11.5%, with errors of 3.3% and -5.0%. Thus, in the third layer, SALTMED results (average NRMSE 9.4%, average error -0.9%) were closer to measured values.

Overall calibration and validation results are shown in Figure 4 [Figure 4: see original paper]. Across all treatments and layers, HYDRUS-1D NRMSE values were 4.5%, 7.9%, 11.9%, and 8.1% for EC4-CD100, EC4-CD60, EC8-CD100, and EC8-CD80 treatments, respectively, while SALTMED values were 9.5%, 7.9%, 9.7%, and 11.4%. Therefore, HYDRUS-1D provided better soil water content estimation across all treatments and layers (Fig. 4).

3.3.2 ECe ECe values in the soil profile from both models at the end of the growing season are shown in Figure 5 [Figure 5: see original paper]. HYDRUS-1D provided more accurate ECe simulation at season end. While SALTMED prediction was very good in the third layer, accuracy decreased in the second and first layers due to inadequate capillary rise prediction. In the first layer, mean E values for predicted soil salinity were -9.9% for SALTMED and -1.4% for HYDRUS-1D. In the second layer, values were 7.6% and -3.7%, and in the third layer, 1.0% and 7.5%, respectively. When all predicted values across treatments were plotted against the 1:1 line, HYDRUS-1D achieved NRMSE and d values of 6.7% and 0.997, respectively, while SALTMED values were 12.9% and 0.988. Thus, HYDRUS-1D provided more accurate ECe simulation in the soil profile (Fig. 5 [Figure 5: see original paper]).

According to Zeng et al. (2014), ECe simulation in the surface layer was more accurate than in deeper layers, and HYDRUS-1D generally showed good agreement between simulated and measured ECe. Najib et al. (2017) simulated soil salinity profiles from different irrigation methods (furrow, basin, sprinkler, and drip) and found SALTMED successfully simulated salinity across all methods. Golabi et al. (2012) found SALTMED-predicted soil salinity was lower than measured values due to uncontrolled field factors not considered in the model.

3.4 Simulations of Wheat Yield and Dry Matter Using the SALTMED Model

Predicted wheat yield and dry matter values are shown in Table 7 and Figure 6 [Figure 6: see original paper], with NRMSE and d indices determined. At 80 cm water table depth, groundwater contributed to plant water uptake through capillary rise, but at 60 cm depth, the root zone became saturated and plants experienced waterlogging stress. Consequently, wheat yield and dry matter at 80 cm water table depth exceeded those at 60 cm depth. This trend was reflected in model predictions, with NRMSE and d values of 2.9% and 0.985 for dry matter, and 9.8% and 0.908 for wheat yield, respectively. Thus, SALTMED accurately simulated wheat yield and dry matter. Model accuracy for dry matter simulation exceeded that for yield because the model first predicts dry matter then determines yield by multiplying by harvest index (0.4), which may introduce additional error.

These results align with studies by Aziz Hirich et al. (2012), Akbari Fazli (2013), and others that found excellent agreement between measured and predicted crop yield using the SALTMED model.

4 Conclusions

Mean soil water content during the growing season showed that in most cases, HYDRUS-1D predictions were higher than measured values, while SALTMED predictions were higher in surface layers and lower in deep layers than measured values. HYDRUS-1D generally provided more accurate soil water content predictions across different salinity levels and controlled groundwater treatments than SALTMED. Prediction accuracy for both models decreased at 8 dS/m salinity, though SALTMED performed better at higher salinity levels (Table 7). Therefore, HYDRUS-1D and SALTMED are appropriate for lower and higher salinity levels, respectively. Overall, HYDRUS-1D simulated soil salinity more accurately than SALTMED.

Wheat yield was predicted only by SALTMED, as HYDRUS-1D is not designed for crop yield simulation. Wheat yield and dry matter decreased with increasing salinity level. Decreasing water table depth to 80 cm increased wheat yield and dry matter, but further decrease to 60 cm reduced them. At 80 cm water table depth, groundwater contributed to plant water uptake through capillary rise, whereas at 60 cm depth, a large portion of roots was in the saturated zone, exposing plants to waterlogging stress and causing yield losses. This trend was captured in model predictions. However, model accuracy for dry matter simulation exceeded that for yield simulation. Overall, SALTMED provides accurate simulation of wheat dry matter and yield.

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