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

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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.

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

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1 Introduction

In many parts of the world, salt concentration in groundwater is increasing and soil salinization could be occurred due to the decreasing water table depth and increasing capillary rise, especially in area with unsuitable drainage systems. Therefore, in the irrigated areas, groundwater depth has the utmost importance in controlling soil salinity and waterlogging, and improving plant environment. On the other hand, in arid regions, where the water resources are limited, a gap

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exists between the water supply and the increased water demands. In this situation, controlled groundwater depth is one of the modern techniques that may remediate the problem of water scarcity. In this method, the level of groundwater rises in the soil and gets close to the root zone, therefore, plant can use the groundwater more effectively. The efficiencies of controlled groundwater depth were studied by many researchers (Asseng et al., 2001a, b; Ayars et al., 2006; Steppuhn et al., 2016) and it was concluded that the transition from uncontrolled groundwater depth to controlled system was in response to environmental concerns and the need for improving water management. This is due to the fact that the controlled system provides flexibility in controlling over a wide range of groundwater depth and may be used for managing soil salinity and water use from shallow groundwater.

Khalil et al. (2004) studied the effect of controlled drainage on crop yield, soil salinity and irrigation water. In this research, they compared the rice production and water requirement under two drainage management treatments including conventional drainage and controlled drainage systems. Their results showed that the controlled drainage system and controlled water table depth had no significant positive effect on the rice production or the soil salinity. However, water requirement under the controlled drainage system was 25% less than that in the conventional drainage system. They reported that applying controlled drainage in rice fields have saved about 1×10^9 m^3 of water per year.

In general, irrigation with saline water reduces crop yield and grain quality; however, there are some strategies to lower the yield reduction under saline conditions. Jiang et al. (2012) studied the effects of irrigation water depth, including 375, 300 and 225 mm (W1, W2 and W3, respectively) and water salinity up to 6.1 dS/m on water consumption and water productivity of spring wheat from 2008 to 2010. The highest yield at the same salinity level under saline irrigation water was obtained in W2 (6.9 Mg/hm^2) treatment, also the 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 W2 treatment were higher than those in W1 treatment.

Due to the scarcity of surface water resources, especially during dry season, crops are largely irrigated using the saline groundwater and drainage water. There are several studies indicating that brackish water can be successfully used for irrigation during crop production, however, negative effects on crop production may occur due to the accumulation of salts in the soil (Wang et al., 2015). Liu et al. (2016) found that it was useful by using saline water resources for irrigation during jointing stage of winter wheat in northern China and the yield of winter wheat and summer maize doubled. They mentioned that sufficient fresh water irrigation (i.e., 60–90 mm) during sowing stage of summer maize is necessary to avoid the negative effects of saline irrigation water and guarantee good growth conditions during the early sensitive growing period.

Ma et al. (2008) described crop responses to saline irrigation water based on field experiments. The results showed that the EC_e (saturated paste electrical conductivity) of the top soil (0–100 cm) was 40% higher than that in the subsoil (100–180 cm) under saline irrigation water. Also the salt load rapidly increased, especially in the upper 80 cm. It was concluded that the maximum soil depth that was leached during the wet season was about 150 cm.

Previous researches confirmed that saline irrigation water appears to be economically attractive to farmers in a short term and ecological hazards can be controlled with the proper salt leaching in soil. It seems that the usage of field experiments in a short time would not be appropriate criteria for decision making. Therefore, the usage of modelling is a suitable alternative for field experiments that save time and cost.

In the past decade, the SALTMED model has been used for the integrated field water management (Ragab, 2002a, b). The SALTMED model is a physically based model that includes key processes of evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, nitrogen application rates, water qualities and relationship between crop yield and water use (Ragab, 2002a, b; Ranjbar et al., 2015).

Many researchers have used the SALTMED model to simulate the plant growth and yield for many crops, such as sugar beet, carrots, kale, quinoa and tomatoes (Malash et al., 2011; El-Shafie et al., 2017; Silva et al., 2017). They concluded that the SALTMED model could accurately predict the soil salinity and crop yield under salinity conditions. The SALTMED model was used for simulation of the yield and dry matter of wheat under different depths of irrigation and systems, i.e., sprinkler and basin systems (Razzaghi and Ghannadi, 2016). The wet, medium and dry treatments were considered as irrigation treatments. The results showed that the SALTMED model predicted the wheat yield and dry matter accurately, for both irrigation systems. However, the soil water content was predicted better in sprinkler irrigation system than in basin irrigation method. The SALTMED model was used for simulation of the yield and dry matter of quinoa, as a drought-tolerant crop, under four irrigation levels, i.e., 100% (control treatment), 75%, 50% and 25% of the crop water requirement by Koutar et al. (2017). The SALTMED model was calibrated using the control treatment data and then it was evaluated by the data of the other treatments. The results showed that the SALTMED model simulated the total dry matter and grain yield for the quinoa under different deficit irrigation regimes with a reasonable precision.

The HYDRUS-1D model is another advanced one-dimensional model associated with water, salt and heat movement in the soil (Šimůnek et al., 2008; Luo at al., 2010; Zeng at al., 2014; Noshadi et al., 2017). The HYDRUS-1D software package contains a wide range of approaches that can be selected for simulating variable saturated water flow and solute transport, and considers one-dimensional problems associated with, for example, soil columns, lysimeter, soil profile and plots. In addition to the basic water flow and solute transport processes, HYDRUS-1D can also simulate the transport and production of carbon dioxide and transport of major ions. Furthermore, a wide range of non-equilibrium flow and transport modelling approaches are available in this model (Šimůnek et al., 2008). Jha et al. (2017) and Shahrokhnia and Sepaskhah (2018) simulated the water and nitrogen (N) transport using the HYDRUS-1D model on paddy in a sandy loam soil in India and rapeseed and safflower in a clay loam soil in Iran. The result revealed that this model could simulate the variations of water pressure head and N concentration in soil with the good precision.

As mentioned above, models are effective tools in simulating the effects of different environmental conditions, such as salinity of irrigation water on crop yield. There are many models, such as LEACHC, UNSATCHEM, SWAP (Soil-Water-Plant-Atmosphere), SALTMED and HYDRUS-1D that were developed to simulate these conditions. Although the SALTMED and HYDRUS-1D models are known as powerful tools, comparison of the accuracy of these models in simulating the sol salinity and soil water content in shallow groundwater condition have not been investigated. Therefore, the aim of this study was to evaluate and compare the SALTMED and HYDRUS-1D models in simulating the soil water content and soil salinity, also to evaluate the SALTMED model in simulating the wheat yield under different levels of saline irrigation water and groundwater depth.

2 Materials and methods

2.1 Field experiment

This research was conducted in the College of Agriculture, Shiraz University (36°29′N, 32°52′E; 1810 m a.s.l.), located in a distance of 16 km from the Shiraz City, Iran in 2013. Wheat seeds with a density of 200 kg/hm^2 were planted in 18 soil columns (lysimeters) with the 120 cm height and 40 cm diameter. Soil physical characteristics are shown in Table 1.

Table 1 Soil physical characteristics in different soil depths

Depth (cm)	Soil texture	Clay	Silt	Sand	pH	BD	FC	PWP
		(%)				(g/cm^3)	(cm^3/cm^3)	(cm^3/cm^3)
0–15	Clay loam	30	35	35	8	1.25	0.32	0.11
15–30	Clay loam	30	35	35	8	1.32	0.36	0.12
30–50	Clay loam	39	38	23	8	1.36	0.36	0.14
50–70	Clay	40	39	21	8	1.42	0.39	0.16
70–100	Clay	40	39	21	8	1.42	0.39	0.16

Note: BD, bulk density; FC, volumetric soil water content at field capacity; PWP, volumetric soil water content at permanent wilting point.

Three controlled groundwater depths including 60 (CD60), 80 (CD80) and 100 (CD100) cm and two saline irrigation water treatments, i.e., 4 (EC4) and 8 (EC8) dS/m with three replications were considered as a complete randomized design. Therefore, 18 soil columns were considered for treatments. Four exit pipes were installed at the depths of 30, 60, 90 and 130 cm from top of the soil columns for sampling groundwater and establishing the groundwater depths at desired levels. To establish the groundwater depths at 60, 80 and 100 cm, we entered water with a very low discharge from bottom of soil columns through pipe that was installed at 130 cm depth. The water table depths were controlled by manometer tubes that were installed in the bottom side of the soil column. Groundwater level was measured in the manometer tube. When this level was below the desired groundwater table depth (60, 80 or 100 cm in different treatments), saline water was added using Marriott's bottle to keep the desired water table depth. These volumes of water were measured and considered as groundwater contribution (GC).

The groundwater salinity at the beginning of growing season was equal to fresh water salinity, i.e., 0.76 dS/m. During the growing season, all the soil columns were irrigated at the same time. Before all irrigation events, soil water content at different depths was measured by a portable time-domain reflectometer (TDR) in all soil columns. TDR probes were installed in different depths of soil columns to measure soil water content before each irrigation event. Soil water content was measured at the depth of 30 cm in CD60 treatment, at the depths of 20 and 60 cm in CD80 treatment and at the depths of 15, 45 and 75 cm in CD100 treatment. We determined net irrigation water depth according to the following equation (Brouwer et al., 1989):

$$D = (\mathrm{FC} - \theta_{\mathrm{v}}) \times Z_{\mathrm{r}} , \tag{1}$$

where D is the net irrigation water depth (cm); θ_{v} is the volumetric soil water content within the root depth before irrigation (cm^3/cm^3); FC is the volumetric soil water content at field capacity (cm^3/cm^3); and Z_{r} is the root depth (cm). In Equation 1, Z_{r} is a time variable parameter that obtained from the following equation (Borg and Grimes, 1986):

$$Z_r = (0.5 + 0.5\sin(3.03^{DA_s}/DT_{\mathrm{m}} - 1.47))RD_{\mathrm{m}} , \tag{2}$$

where Z_{r} is the root depth at a given day (cm); DA_{s} is the number of days after planting; DT_{m} is the number of days to reach the maximum root depth, which was considered as 170 d, according to the wheat growth period; and RD_{m} is the maximum depth of roots that was considered as 100, 80 and 60 cm in CD100, CD80 and CD60 treatments.

The irrigation application efficiency (E_{a}) was 80%. Therefore, the gross depth of irrigation water (I_{g}) was calculated as follows (Brouwer et al., 1989):

$$I_{\mathrm{g}} = (D / E_{\mathrm{a}}) \times 100 . \tag{3}$$

We determined the applied irrigation water depth based on the differences between the calculated irrigation water depth and sum of the groundwater contribution and precipitation. The applied irrigation water was measured by a flow meter for each irrigation event. The precipitation was measured in the climatological station near the study area, being about 500 m away.

The saline water was made by adding NaCl and $CaCl_2$ in a ratio of 1:1 into the fresh water and the level of water salinity was measured by electrical conductivity meter. N was applied with a rate of 200 kg/hm^2 urea through irrigation water in two steps, one at the planting time and another at 110 days after planting. At the end of growing season, the harvested wheats (seeds and dry matter) were oven dried and weighed. Also, soil was sampled in 15, 45 and 75 cm of soil depths and the EC_{e} was determined.

2.2 Models

2.2.1 HYDRUS 1-D model

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

Water movement for the experimental situation is described by a modified form of the Richards equation using the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(k(\frac{\partial h}{\partial z} + 1)) - S\,, \tag{4}$$

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

The solution of Equation 4 requires information of the initial distribution of the pressure head within the flow domain:

$$h(x, t) = h_i(x), \quad t = t_0, \tag{5}$$

where h_i (cm) is the water pressure head as a function of x; and t_0 is the time (d) when the simulation begins.

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

$$\left| -k\frac{\partial h}{\partial x} - k \right| \le E, \quad x = L, \tag{6}$$

$$h_A \le h \le h_S, \quad x = L, \tag{7}$$

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

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

In simulation of solute transport, the 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 the concentration at a boundary and Equation 9 used to prescribe the concentration flux at the lower boundary:

$$c = (x, t) = c_0(x, t), \quad x = L, \tag{8}$$

$$-\theta D\frac{\partial c}{\partial x} + qc = q_0 c_0, \quad x = 0, \tag{9}$$

Where q_0 is the upward fluid flux (mg/cm^3); and c_0 is the concentration of the incoming fluid (mg/cm^3).

2.2.2 SALTMED model

The SALTMED model can be used for simulation of soil, water content, soil salinity and crop yield in a variety of irrigation systems, soil types, crops and trees, water application strategies and different water qualities.

In this model, the water flow in soils can be mathematically described by the Richard's equation (Eq. 4). In this equation, the initial and boundary conditions are similar to that described in Section 2.2.1. The movement of solute in the soil system, its rate and direction depends greatly on the path of water movement, but it is also determined by diffusion and hydrodynamic dispersion. By the combination of the diffusion, we can obtain the dispersion and the convection of the overall flux of solute according to Hillel (1977):

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

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

2.3 Model evaluation

Some statistical parameters including normalized root mean square error (NRMSE), index of agreement (d) and error percentage (E) were used for evaluation of simulation accuracy (Loague and Green, 1991). NRMSE provides the total difference between the measured and simulated data proportioned against means of measured data. The lower limit for NRMSE is 0, which occurs when there is no difference between such paired data. Obviously, a smaller value of NRMSE indicates a higher accurate simulation. The value of d was calculated for assessing the accuracy of simulated data. The maximum value for d is 1, which occurs when simulated values are completely identical to the measured values (Willmott et al., 1985). E is defined as a percentage of the difference between the simulated and measured values. A lower value for E means that the simulated result is closer to the measured value.

$$\mathrm{NRMSE} = \left[\sum_{i=1}^{n} \left(P_i - O_i\right)^2 \Big/ n \right]^{1/2} \times 100 \big/ \bar{O}, \tag{11}$$

$$d = 1 - \sum_{i=1}^{n} \left(P_i - O_i\right)^2 \Big/ \sum_{i=1}^{n} \left(\left|P_i - \bar{O}\right| - \left|O_i - \bar{O}\right|\right)^2, \tag{12}$$

$$E = \left(P_i - O_i\right) \big/ Q_i \times 100\%, \tag{13}$$

where P_i is the predicted value; O_i is the observed value; $\bar{O}$ is the mean of observed value; and n is the number of observation.

3 Results and discussion

3.1 Irrigation water depth and soil salinity

The irrigation water depths and the results of statistical analysis are shown in Table 2. Differences between the irrigation water depths in controlled groundwater treatments under the salinities of 4 and 8 dS/m were significant (P<0.01). The irrigation water depths under CD100, CD80 and CD60 treatments with the 8 dS/m salinity level were respectively, 13.0%, 10.9% and 9.6%, less than those obtained with the 4 dS/m salinity level. Decreasing in the water consumption value by increasing the level of water salinity was reported in the study of Jiang et al. (2012). In their research, by increasing the irrigation water salinity from 0.67 to 6.10 dS/m, actual evapotranspiration (ET_a) was reduced from 580 to 560 mm (3.4%).

The reductions of irrigation water depth under CD80 and CD60 treatments with the 4 dS/m salinity level were 18.3% (from 710 to 580 mm) and 36.6% (from 710 to 450 mm), respectively, compared with those obtained under CD100 treatment. And it was 22.4% under CD60 treatment compared with that obtained under CD80 treatment. Also with the 8 dS/m salinity level, the reductions of irrigation water depth under CD80 and CD60 treatments were 16.4% (from 618 to 517 mm) and 34.1% (from 618 to 407 mm), respectively, compared with that obtained under CD100 treatment. And it was 21.3% under CD60 treatment compared with that obtained under CD80 treatment. All of these differences were significant (P<0.01). Therefore, with the salinity levels of 4 and 8 dS/m, the lowest and the highest values of irrigation water were obtained under CD60 and CD100 treatments, respectively (Table 2). The fraction of water requirement could be provided by capillary rise and it was depended on the groundwater depth. Therefore, the capillary rise values were higher under CD60 than under CD100 treatment.

The mean irrigation water depth (over salinity levels) under different water table depths is shown in Table 2. According to the result, the mean reductions in irrigation water depth under CD80 and CD60 treatments were 17.4% (from 664.0 to 548.5 mm) and 35.5% (from 664.0 to 428.5 mm), respectively, compared with that obtained under CD100 treatment, and the reduction in irrigation water depth was 21.9% under CD60 treatment compared with that obtained under CD80 treatment, therefore, the water table depth had a significant effect on the reduction in mean irrigation water depth (P<0.01).

Table 2 Statistical analysis of irrigation water depth, I_g and saturated paste electrical conductivity (EC_e)

Irrigation water salinity (dS/m)	Controlled groundwater depth							
	CD100		CD80		CD60		Mean	
	I_g (mm)	EC_e (dS/m)	I_g (mm)	EC_e (dS/m)	I_g (mm)	EC_e (dS/m)	I_g (mm)	EC_e (dS/m)
4 (EC4)	710^a	4.83^l	580^c	9.87^i	450^e	8.18^j	580^A	7.63^B
8 (EC8)	618^b	7.50^k	517^d	16.63^g	407^f	14.65^h	514^B	12.93^A
Mean	664^A	6.17^C	549^B	13.25^A	429^C	11.42^B		

Note: CD100–CD60 means the 100–60 cm groundwater depths, respectively. I_g, gross depth of irrigation water. Means followed by the same lowercase and uppercase letters in each column or row are not significantly different at P<0.01 level (Duncan multiple range test).

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

The effect of water table depth on EC_e was significant (P<0.01). In other words, in all levels of irrigation water salinity, the values of EC_e under CD80 and CD60 treatments were higher than that obtained under CD100 treatment. The irrigation water depth under CD100 treatment was higher than those obtained under CD80 and CD60 treatments (Table 2). Therefore, the higher leaching fraction was occurred under CD100 treatment compared with those under CD80 and CD60 treatments. The effect of salinity on the mean irrigation water depth was significant (P<0.01). The mean irrigation water depth with the salinity level of 8 dS/m was 11.37% less than that with the salinity level of 4 dS/m. In general, at each level of salinity, the irrigation water depth decreased by decreasing groundwater depth, and at each level of groundwater depth, the irrigation water depth decreased by increasing water salinity level. Decreasing irrigation water depth by increasing in water salinity level occurred as a result of the less crop transpiration due to less water uptake in salinity conditions, the less soil evaporation and therefore, the higher soil water content during the growing season. Also, decreases in irrigation water depth by decreasing the groundwater depth could be due to the higher capillary rise and GC to crop water use (Table 3).

Table 3 Groundwater contribution (GC) to sub-irrigation in different treatments

Irrigation water salinity (dS/m)	CD100		CD80		CD60	
	GC (mm)	GC (%)	GC (mm)	GC (%)	GC (mm)	GC (%)
4 (EC4)	0^a	0.0	130^c	18.3	260^e	36.3
8 (EC8)	92^b	13.0	193^d	27.2	303^f	42.7

Note: CD100–CD60 means the 100–60 cm groundwater depths, respectively. Means followed by the same lowercase letters in each column are not significantly different at P<0.01 level (Duncan multiple range test).

3.2 Calibrations of the SALTMED and HYDRUS-1D models

The SALTMED and HYDRUS-1D models were calibrated using EC4-CD100 treatment. According to the soil physical properties (Table 1), we divided soil profile into three layers and entered the properties of each soil layer including soil texture, initial soil water content, saturated hydraulic conductivity and required parameters of van Genuchten equation (Table 4) in the models. The initial value of these parameters was determined by the RETC software (van Genuchten et al., 1992), and then they were optimized during the calibration process. The calibrated parameters of the SALTMED and HYDRUS-1D models are shown in Table 5.

Table 4 Parameters of the van Genuchten (1980) equation

Soil layer thickness (cm)	*n*	*α* (1/cm)	Lambda pore size distribution index*	Bubbling pressure* (cm)	*K*sat (cm/d)	*θ*sat (cm^3/cm^3)	*θ*res (cm^3/cm^3)
0–30	1.478	0.011	0.478	90.9	188.6	0.462	0.082
30–50	1.413	0.012	0.413	83.3	121.6	0.465	0.090
50–100	1.399	0.012	0.399	83.3	85.8	0.450	0.090

Note: *n* and *α* are shape parameters, respectively; *K*sat is the saturated hydraulic conductivity; *θ*sat and *θ*res are the saturated and residual soil water contents, respectively. * means that these parameters are required for the SALTMED model.

Table 5 Calibrated values of parameters in the HYDRUS-1D and SALTMED models

HYDRUS-1D				
Soil layer thickness (cm)	Disp (cm)	Diff-W (cm^2/d)	Diff-G (cm^2/d)	Sink water[a] (1/d)
0–30	20	2	0	0.096
30–50	20	2	0	0.076
50–100	20	2	0	0.067

SALTMED			
Crop factor	Calibrated value	Crop growth factor	Calibrated value
*K*c Initial	0.38	Photosynthesis efficiency (g/MJ)	1.60
*K*c Mid	1.25	Extinction coefficient	0.45
*K*c End	0.25	PAR ratio	0.50
*K*cb Initial	0.20	*T*max (ºC)	40.00
*K*cb Mid	1.00	Top*T*2[b] (ºC)	28.00
*K*cb End	0.15	Top*T*1[c] (ºC)	25.00
π50 (dS/m)	10.50	*T*min (ºC)	4.00

Note: Disp, longitudinal dispersity; Diff-W, molecular diffusion coefficient in free water; Diff-G, molecular diffusion coefficient in soil air; [a], first-order rate constant for dissolved phase; *K*c, crop coefficient; *K*cb, crop transpiration coefficient; π50, osmotic pressure at which the root water uptake is reduced by 50%; PAR, photosynthetically active radiation; *T*max, maximum air temperature; [b], upper optimum temperature for development; [c], lower optimum temperature for development; Top is the optimum temperature for crop growth; *T*min, minimum air temperature.

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

3.2.1 Soil water content

Predicted values of the soil water content under EC4-CD100 treatment using the two models at different days after planting are shown in Figure 1. There was a good agreement between the predicted and measured soil water content in surface layer (0–30 cm) at different days after planting. In the second layer (30–60 cm), the predicted values of both models were higher than the measured values, whereas, in the third layer (60–90 cm), the SALTMED and HYDRUS-1D models predicted the soil water content, respectively, higher and lower than the measured values. *E*, NRMSE and *d* of simulated soil water content in the whole soil profile were 4.4%, 9.4% and 0.88 for the SALTMED model and 0.5%, 7.6% and 0.89 for the HYDRUS-1D models, respectively. Although, the two models have predicted soil water content very well; however, the prediction of the HYDRUS-1D model for soil water content was more accurate than that of the SALTMED model.

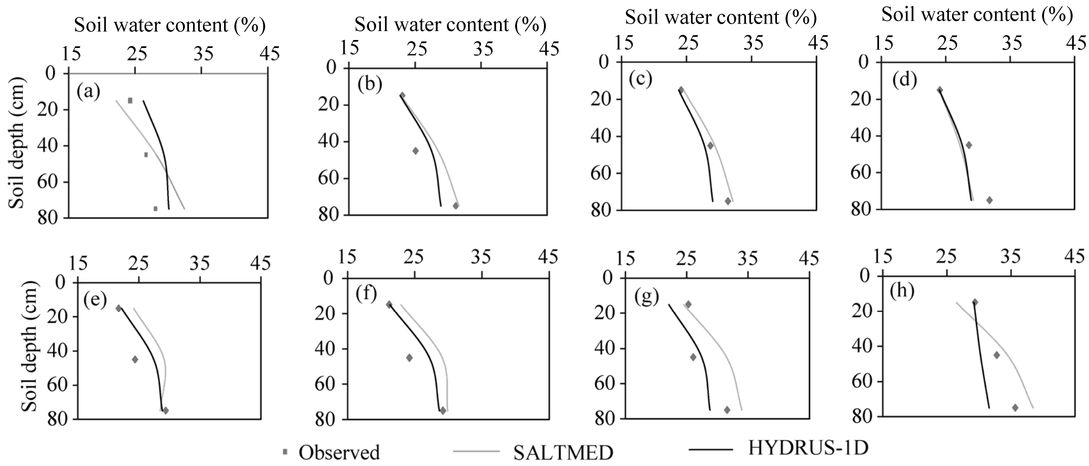

Fig. 1 Observed and simulated soil water contents using the SALTMED and HYDRUS-1D models in EC4-CD100 treatment (calibration step) at different days after planting. (a), 114 d; (b), 126 d; (c), 148 d; (d), 163 d; (e), 177 d; (f), 189 d; (g), 200 d; (h), 212 d.

3.2.2 EC_e

The models simulated EC_e and the associated soil water content at different depths and times. At the same time, the actual EC_e in the experiment is measured. Therefore, by using a correction factor based on the ratio of field soil water content to the saturated soil water content, we adjusted the predicted EC_e to the measured EC_e. Mean values of *E* were 1.0% and 0.8%; NRMSE values were 9.0% and 8.0% and *d* indices were 0.88 and 0.89 for the SALTMED and HYDRUS-1D models, respectively. Despite the fact that these values show the high accuracy of both models in simulation of EC_e, the prediction of the HYDRUS-1D model was more accurate than that of the SALTMED model.

3.3 Validations of the SALTMED and HYDRUS-1D models

The SALTMED and HYDRUS-1D models were validated using all treatments except that used for calibration, i.e., EC4-CD100. Values of NRMSE and *d* indices of the predicted soil water content and soil salinity in the validation step are shown in Table 6.

Table 6 NRMSE and *d* indices during validation process of the SALTMED and HYDRUS-1D models

Parameter	Statistical parameter	EC4-CD80		EC4-CD60		EC8-CD100		EC8-CD80		EC8-CD60	
		H	S	H	S	H	S	H	S	H	S
Soil water content	NRMSE (%)	-	-	0.07	0.12	0.12	0.10	0.10	0.10	-	-
	d	-	-	0.56	0.82	0.73	0.82	0.65	0.81	-	-
Soil salinity	NRMSE (%)	0.06	0.13	0.08	0.10	0.03	0.05	0.06	0.12	0.08	0.15
	d	0.99	0.98	0.99	0.99	0.98	0.91	0.99	0.98	0.99	0.98

Note: NRMSE, normalized root mean square error; *d*, degree of agreement; H, HYDRUS-1D; S, SALTMED. - means no value.

3.3.1 Soil water content

The observed and simulated values of soil water content in soil profile at different days after planting under EC8-CD100 and EC8-CD80 treatments are shown in Figures 2 and 3. Because the soil water content was measured only at the depth of 30 cm in EC4-CD60 treatment, plotting the soil water content profile is not possible for this treatment. Comparison of the predicted soil water content under the EC8-CD100 and EC4-CD100 treatments showed that by increasing the level of water salinity to higher than the wheat threshold salinity level (6.5 dS/m), root water uptake decreased and, therefore, soil profile was wetter. Therefore, the mean predicted soil water content using the both models was higher under EC8-CD100 treatment than under EC4-CD100 treatment.

By raising the obtained water table depth and reaching the saturated zone to the depth of 60 cm below the soil surface, soil water content increased in two consecutive irrigation intervals. Soil water content was increased in top layers of soil profile under EC4-CD60 treatment due to the lower water table depth and higher capillary rises. The simulated soil water content by the both models of this treatment was less than the observed values; whereas, the errors of simulation by the SALTMED and HYDRUS-1D models were –10.7% and –0.4%, respectively. The precision of the HYDRUS-1D model was higher than the SALTMED model, because in this model the effects of waterlogging stress is well considered and when the soil water content is high and root water uptake decreases or stops. The simulated soil water content under EC8-CD80 treatment in surface layer (0–30 cm) was more accurate than that obtained in the deeper layers. It is notable that in this treatment, due to the higher capillary rise, soil salinity in the deeper layers was the highest. This result is in agreement with Kaya et al. (2015), who predicted the soil water contents in 0–30, 30–60 and 60–90 cm soil depths using the SALTMED model. According to their results, simulated water content was more accurate in surface layer than in the third soil layer (R^2 values were 0.86 and 0.80, respectively). They described that the lower R^2 in the deeper layer might be attributed to the neglecting soil drainage properties because of missing data. In another similar research of the HYDRUS-1D model, it was obtained that simulation of soil water content in the 0–40 cm soil depth was more accurate than that obtained in the 40–100 cm soil depth (Zeng et al., 2014).

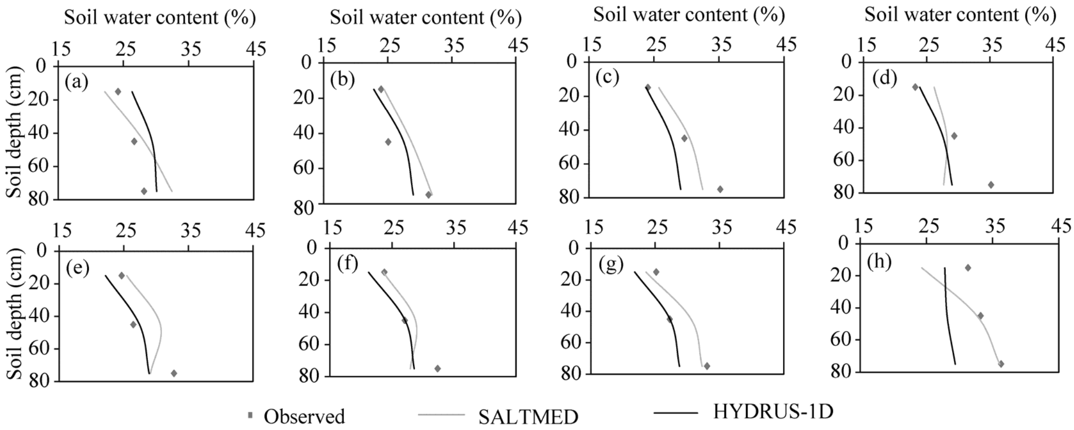

Fig. 2 Observed and simulated soil water contents using the SALTMED and HYDRUS-1D models under EC8-CD100 treatment (validation step) at different days after planting. (a), 114 d; (b), 126 d; (c), 148 d; (d), 163 d; (e), 177 d; (f), 189 d; (g), 200 d; (h), 212 d.

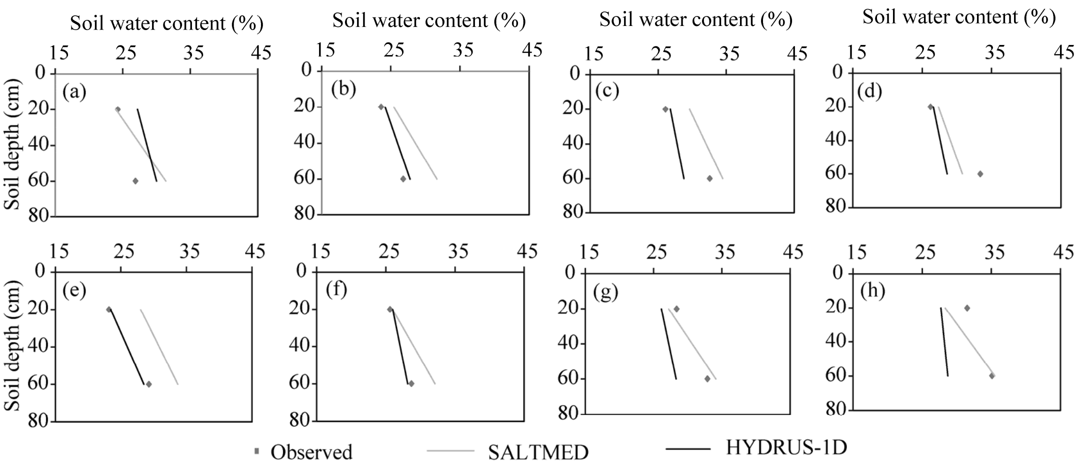

Fig. 3 Observed and simulated soil water contents using the SALTMED and HYDRUS-1D models under EC8-CD80 treatment (validation step) at different days after planting. (a), 114 d; (b), 126 d; (c), 148 d; (d), 163 d; (e), 177 d; (f), 189 d; (g), 200 d; (h), 212 d.

The predicted soil water content in the depth of 30 cm by the HYDRUS-1D model in all treatments was closer to the observed values. In the first layer (0–30 cm), the NRMSE values of EC4-CD100, EC4-CD60, EC8-CD100 and EC8-CD80 treatments in the HYDRUS-1D model were 5.6%, 3.1%, 9.7% and 7.3%, respectively with the average value of 7.3%, and the errors of simulation were –0.7%, –0.4%, –5.0% and 0.2%, respectively, and –1.5% as an average. In the SALTMED model, the NRMSE values of EC4-CD100, EC4-CD60, EC8-CD100 and EC8-CD80 treatments were 0.0%, 12.7%, 11.7% and 8.9%, respectively with the average value of 9.9%, and the errors of simulation were –0.2%, –10.7%, –1.7% and 4.0%, respectively and –2.1% as an average. Therefore, the result of the HYDRUS-1D model was closer to the measured values. In the second layer (30–60 cm), the simulation accuracy of both models under EC4-CD100 and EC8-CD80 treatments was decreased and under EC8-CD100 treatment it was increased. In the second layer, the NRMSE values of EC4-CD100, EC8-CD100 and EC8-CD80 treatments in the HYDRUS-1D model were 8.4%, 8.7% and 12.1%, respectively with the average value of 9.7%, and the errors of simulation were 4.3%, –0.6% and –5.9%, respectively with the average value of –0.5%. In the SALTMED model, the NRMSE values of EC4-CD100, EC8-CD100, and EC8-CD80 treatments were 12.7%, 8.8% and 10.7%, respectively with the average value of 10.7% and the errors of simulation in these treatments were 10.2%, 6.4% and 8.1% with the average value of 8.2%. Therefore, the result of the HYDRUS-1D model with the average NRMSE of 9.7% and the average error of –0.5% is closer to the measured values.

In the third layer (60–90 cm), unlike the two other layers, the NRMSE in the SALTMED model was less than that obtained in the HYDRUS-1D model. The NRMSE in the third layer of EC4-CD100 and EC8-CD100 treatments were 7.9% and 14.4%, respectively with the average of 11.15%, and the errors of simulation were –5.1% and –11.4%, respectively with the average value of –8.3%. In the SALTMED model, the NRMSE of EC4-CD100 and EC8-CD100 treatments were 7.3% and 11.5%, respectively, and the errors of simulation were 3.3% and –5.0%, respectively. Therefore, in the third layer, the result of SALTMED model with the average NRMSE of 9.4% and the average error of –0.9% was closer to the measured values.

The results of calibrated and validated soil water contents are shown in Figure 4. In general, the NRMSE values of EC4-CD100, EC4-CD60, EC8-CD100 and EC8-CD80 treatments in all soil profile were 4.5%, 7.9%, 11.9% and 8.1%, respectively, in the HYDRUS-1D model, they were 9.5%, 7.9%, 9.7% and 11.4%, respectively, in the SALTMED model. Therefore, for all predicted soil water content in different treatments and layers, the HYDRUS-1D model provided a better estimation of soil water content (Fig. 4).

3.3.2 EC_e

Values of EC_e in soil profile using both models at the end of growing season are shown in Figure 5. The HYDRUS-1D model provided more accurate simulation of EC_e at the end of growing season. Of course, the prediction of the SALTMED model in the third layer was very good; however, the order of goodness was decreased to the second and the first layers, due to unsuitable prediction of the capillary rise by this model. In the first layer, the means of E of the predicted soil salinity using the SALTMED and HYDRUS-1D models in all treatments were –9.9% and –1.4%, respectively. The values of this index in the second layer were 7.6% and –3.7%, and in the third layer they were 1.0% and 7.5%, respectively. When all the predicted values under all treatments were plotted and compared against the 1:1 line, it revealed that the NRMSE and d for the HYDRUS-1D model were 6.7% and 0.997, respectively, and for the SALTMED model, they were 12.9% and 0.988, respectively. Therefore, the HYDRUS-1D model provided more accurate simulation for EC_e in soil profile (Fig. 5).

According to the result of Zeng et al. (2014), the simulation of EC_e in surface layer was more accurate than that of the deeper layer and in general, the HYDRUS-1D model showed a good agreement between the simulated and measured EC_e. Najib et al. (2017) simulated the soil salinity profile from different irrigation methods including furrow, basin, sprinkler and drip irrigations and found that the SALTMED model was able to successfully simulate salinity in all irrigation methods. Golabi et al. (2012) found that the predicted soil salinity by the SALTMED model was lower than the measured value because of some uncontrolled factors that existed in the field, but are not considered in the model.

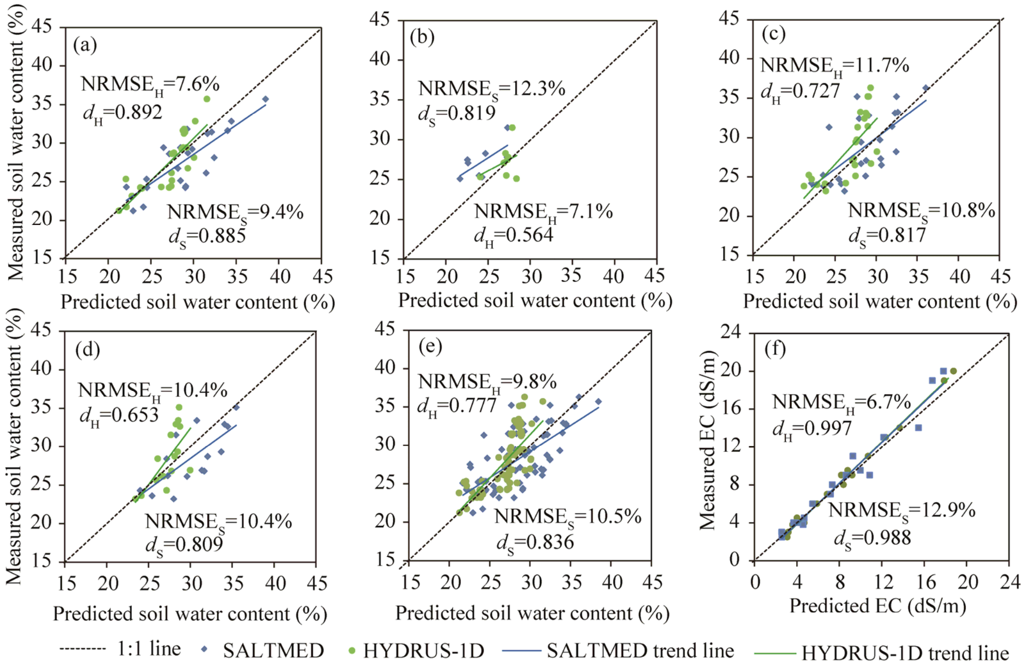

Fig. 4 Comparison of the measured and predicted soil water contents under (a) EC4-CD100, (b) EC4-CD60, (c) EC8-CD100, (d) EC8-CD80 and (e) all treatments. Comparison of the measured and predicted soil salinity under all treatments (f). NRMSE, normalized root mean square error; *d*, degree of agreement. Subscripted S and H represent the SALTMED and HYDRUS-1D models, respectively.

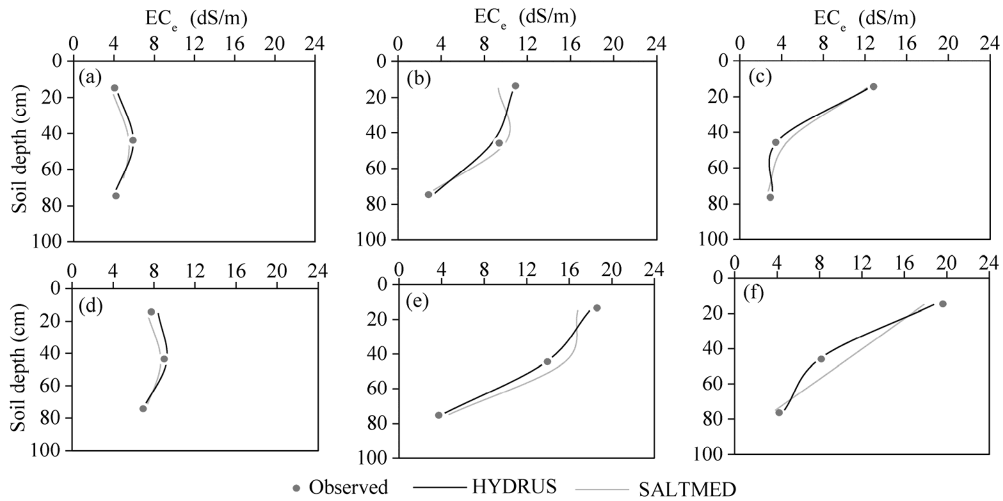

Fig. 5 Observed and simulated saturated paste soil salinities (EC_e) using the SALTMED and HYDRUS-1D models under (a) EC4-CD100 (calibration step), (b) EC4-CD80, (c) EC4-CD60, (d) EC8-CD100, (e) EC8-CD80, and (f) EC8-CD60 treatments.

3.4 Simulations of wheat yield and dry matter using the SALTMED model

The predicted values of wheat yield and dry matter are shown in Table 7 and Figure 6, and the NRMSE and *d* indices were determined. In the water table depth of 80 cm, the groundwater contributed to the plant water uptake through the capillary rise, but when the water table depth reached up to 60 cm, the root zone is saturated and the plant is exposed to waterlogging stress. Therefore, the wheat yield and dry matter in the water table depth of 80 cm were higher than those obtained in the 60 cm depth. This trend was also observed in the model predictions regarding to the NRMSE and d (2.9% and 0.985 for dry matter, and 9.8% and 0.908 for wheat yield, respectively). It is concluded that the SALTMED model provides an accurate simulation for wheat yield and dry matter. The model accuracy in simulation of dry matter was higher than that obtained of crop yield, because the model predicts the dry matter firstly and then determines the crop yield by multiplying dry matter by the harvest index (0.4) that may not be very accurate. This result are similar to the study that was carried out by Aziz Hirich et al. (2012), Akbari Fazli (2013) and other researches that obtained a very good agreement between the measured and predicted crop yield using the SATMED model.

Table 7 Measured and predicted wheat yield and dry matter by the SALTMED model

Treatment		Dry matter (Mg/hm^2)		Error percentage (%)	Wheat yield (Mg/hm^2)		Error percentage (%)
		Predicted	Measured		Predicted	Measured	
EC4	CD100	11.52	11.35	1.5	4.60	4.88	–5.7
	CD80	12.19	11.72	4.0	4.87	5.80	–16.0
	CD60	10.56	10.46	1.0	4.22	4.06	3.9
EC8	CD100	9.40	9.43	–0.3	3.78	3.62	4.4
	CD80	9.68	9.76	–0.8	4.12	4.12	–6.1
	CD60	8.11	8.63	–6.0	3.17	3.17	2.2

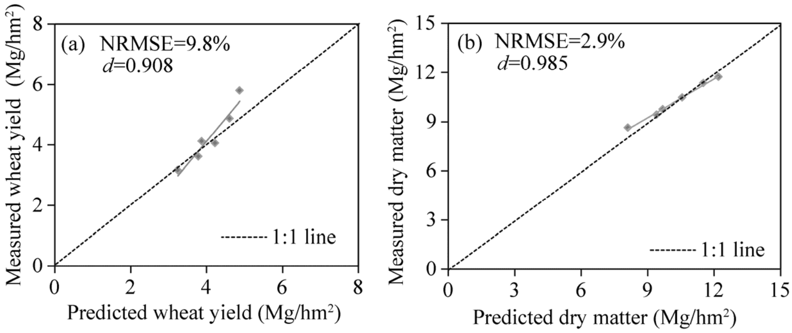

Fig. 6 Relationships between the measured and predicted (a) wheat yield and (b) dry matter

4 Conclusions

The mean soil water content during the growing season showed that in the most cases, soil water content predicted by the HYDRUS-1D model was higher than the measured values and the values predicted by the SALTMED model were higher in the soil surface layer and lower in the deep soil layers than the measured values. The predicted soil water content in different salinity levels and controlled groundwater treatments by the HYDRUS-1D model was generally more accurate than that of the SALTMED model. The accuracy of the predicted soil water content by both two models with the salinity level of 8 dS/m decreased, but the SALTMED model provided more accurate simulation with higher levels of salinity (Table 7). Therefore, it is concluded that the HYDRUS-1D and SALTMED models are appropriate in lower and higher levels of salinity, respectively. In general, simulation of soil salinity by the HYDRUS-1D is more accurate than that of the SALTMED model.

The wheat yield was only predicted by the SALTMED model because the HYDRUS-1D model is not designed to simulate crop yield. Wheat yield and dry matter decreased by increasing the salinity level. By decreasing the water table depth to 80 cm, the wheat yield and dry matter increased; however, by reaching the water table depth to 60 cm, they decreased. When the water table was in the depth of 80 cm, the groundwater contributed to the plant water uptake through the capillary rise; whereas, in the water table depth of 60 cm, a great part of the root was placed in the saturated zone and; therefore, the plant root exposed to waterlogging stress that resulted in wheat yield losses. This trend was also observed in the model predictions. However, the model accuracy in simulation of wheat dry matter was higher than that of wheat yield. In general, the SALTMED model provides an accurate simulation for dry matter and yield of wheat.

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