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Optimizing agricultural water use through simulation of soil water content and water uptake under soil moisture and irrigation water salinity stresses: case study of corn roots using SWAP model

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Abstract

In order to evaluate soil water content and water uptake by corn plant roots (Single cross 260) under different soil moisture and water salinity stresses using the agro-hydrological Soil–Water–Atmosphere–Plant (SWAP) model, an experiment was conducted in 2015 at the green house of the Agriculture Research Center of Shahrood, Iran. The statistical model employed was a split plot based on a randomized complete block design with three replications. The main plots consisted of three levels of irrigation; 50 (I_1) (full irrigation as the control), 75 (I_2) and 100% (I_3) of Total Available Water (TAW) depletion while the sub-plots consisted of three levels of salinity of irrigation water; 2 (S_1), 4 (S_2) and 6 (S_3) ds.m^{-1}. The results showed a good correspondence between the simulated soil moisture, water uptake and measured values. The normalized root mean square error (nRMSE) and the root mean square error (RMSE) values of the predicted soil moisture were 4.58 and 24.96 and for the water uptake by the roots were 23.37 and 35.48, respectively. The R^2 of coefficient of simulation for water uptake by roots in different treatments were 0.38 to 0.8. The dataset of the predicted and measured values were close to the 1:1 scale line for both soil moisture and water uptake. This study indicated that the SWAP model can be used as a powerful tool to simulate field water cycle and evaluate irrigation practices. Accordingly, taking into account the existing conditions of the region such as weather and soil type and preparing scenarios based on possible management options, management strategies can be optimized according to the results achieved for the SWAP model simulation.

Keywords: Total available water depletion, water uptake, Irrigation management, Soil hydraulic parameters, SWAP.

Introduction

Water shortage particularly in arid and semi-arid areas have been threatening food security for millions of people. Considering that Iran is located in the arid and semi-arid zone of the world, crop production is not possible without irrigation management. In areas where crops are irrigated, management and proper planning is necessary for optimal use of water. Irrigation management, reform and careful planning for the optimal use of water in arid and semi-arid areas is possible using simulation models.

In recent decades the use of simulation models has considerably increased throughout the world (Jeleyni et al., 2005). Various researchers have used SWAP model for simulating water and solute transport in soil profiles (Kiyani, 2007), yield forecasting (Khani et al., 2007) irrigation scheduling (Akbari et al., 2009) and the results obtained have mostly been satisfactory.

Bonfante et al. (2011) compared three models; SWAP, MACRO and CropSyst in simulating soil moisture profiles on the corn fields of Northern Italy. Overall, SWAP model indicated a better performance due to the use of different numerical solution techniques considering

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the proper boundary conditions at the top and bottom of soil samples. Kiayni (2007) simulated water transmission, solutes and relative yield of wheat using SWAP model for two years and concluded that the model accurately simulates soil moisture content, soil salinity and relative yield of wheat at field conditions. Vazifedoust et al. (2008) extracted water productivity functions for wheat, sunflower, corn and sugar beet after calibration of the SWAP model by changing the depth and irrigation intervals. They showed irrigation scheduling increases water productivity. In the semi-arid areas of North West India, Singh (2003) used SWAP model to evaluate wheat and cotton yields under different salinity regimes. Ying et al. (2011) simulated water balance for the cultivation of winter wheat under deficit irrigation using SWAP model in China and reported the accuracy of water flux simulation in the root zone with statistical indicators RMSE and MRE to be 2.4 and 8%, respectively.

Utset et al. (2007) simulated water use for sugar beet in the Mediterranean climatic conditions using SWAP model and obtained a correlation coefficient value of 0.75 between the measured and simulation. Marinov et al. (2005) simulated soil water flow and soil nitrogen cycle using two models; SWAP and ANIMO; and evaluated positively the results of soil water flow simulation through SWAP model. Verdinejad et al. (2008) used SWAP to determine the optimal depth for different crops under different salinity conditions. Zare Abyane et al. (2010) estimated the distribution pattern of soil moisture under drip irrigation in an onion field using the SWAP model and obtained values for RMSE, nRMSE and MAE at a 60 cm depth from the emitters as 0.001, 0.03 and 0.07, respectively. While at 10 cm depth from the emitters, the values recorded were 0.08, 0.02 and 0.07 respectively. Statistically, low measurement error in SWAP model represents perfect accuracy of application in simulation of soil moisture distribution in the root zone.

The objective of this study was to evaluate the efficacy of SWAP model in simulating the effects of water and salinity stress on soil water content and water uptake by plant roots in maize fields.

Materials and Methods

This experiment was conducted in summer 2015 at the green house of the Agricultural Research Center of Shahrood, Iran located in longitude 25°36′E, latitude 58°54′N and at an elevation of 1380 m. According to long-term data and measurements from Shahrood synoptic stations, the average annual air temperature, maximum temperature in the warmest month of the year and the minimum temperature in the coldest month of the year are 33.1, 15.2 and - 1.5°C respectively. The average annual rainfall in this region is 156.1 mm.

The experiment was conducted using a split plot based on randomized complete block design with three replications. The main plots consisted of three levels of irrigation; 50 (I_1) (control), 75 (I_2) and 100% (I_3) of Total Available Water (TAW) depletion and the sub-plots included three levels of salinity 2 (S_1), 4 (S_2) and 6 (S_3) $ds.m^{-1}$.

To prepare the planting beds, pots with a diameter of 25 cm and a depth of 27 cm were filled with cultivated soil (after passing 2mm sieve) from the Shahrood Agricultural Research Center. The physical and chemical properties of the soil at the experiment site are presented in Table 1. To measure soil moisture, a tensiometer set was placed at a depth of 15 cm in each pot after calibration. To obtain a precise estimation of soil water content in treatment (I_3) fiber glass blocks in addition to the use of a tensiometer was placed at a depth of 15 cm. The first irrigation was applied equally to all treatments immediately after planting. Saline water was prepared by mixing tap water with sodium chloride and salinity was measured with electrical conductivity meter set (EC meter). Soil moisture content between field capacity (FC) and permanent wilting point (PWP) were determined with the pressure plate and the values obtained were 0.23 and 0.13 cm^3, respectively.

Corn cultivar KSC 260 was cultivated for the experiment. After determination of seed viability (96%) and disinfection with a fungicide (Thiram), the seeds were planted, three seeds per treatment at 5 cm depth on July 15th, 2015. After emergence, plants were thinned to one plant per pot. Upon maturity which is indicated by the formation of a black layer at the base of each grain, the corn was harvested on October 30th, 2015.

SWAP model

The SWAP model is a one-dimensional physically-based, agro-hydrological model. It is designed to simulate water flow, solute transport and plant growth in a soil–water–atmosphere–plant environment (Feddes et al., 1978).

SWAP simulates vertical soil water flow in saturated and unsaturated zones by the well-known Richards' equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S(h)$$

(1)

where t denotes time, dz is the vertical coordinate taken as positive upwards (cm), K(h) is the hydraulic conductivity specified by Van Genuchten–Mualem model (Van Genuchten, 1980) (cm/d) and S(h) represents water extraction by plant roots (1/d), and S(h) is usually defined for a uniform root distribution. SWAP requires various data as input, and the most important state variables are referred to as soil and crop parameters.

The measured soil physical properties were fitted to the Van Genuchten–Mualem equations with the RETC code (Van Genuchten et al., 1991). The fitted values were considered as the initial soil parameters in the model calibration. For crop growth, the detailed crop development model was chosen. The rooting depth, leaf area and plant height were described as functions of the crop development stage according to measurements. The upper boundary condition of SWAP was described by the potential ET, irrigation and daily precipitation. The potential ET was estimated by the Penman–Monteith equation [Allen et al., 1998]. Actual evaporation was derived by the Black et al. (1969) equations which is a function of potential ET. The data needed for the SWAP model is presented in Table 4.

SWAP model was also run with the default values and it was found that the model is remarkably sensitive to crop parameters. The input parameters for the plant in the model are presented in Table 3. SWAP simulations were conducted after calibration and validation. The root mean square error (RMSE) and the normalized root mean square error (nRMSE) were used as criteria to evaluate the model's performance.

Table 1. Soil physical and chemical properties

PWP	FC	K (p.p.m)	P (p.p.m)	Total N %	OC %	pH	EC *10^3	SP	Clay%	Silt%	Sand%
13	23	500	7	0.04	0.4	8.1	0.71	24	25	27	48

Table 2. The calibrated Van Genuchten–Mualem hydraulic parameters

θ_{res} ($Cm^3.Cm^{-3}$)	θ_{sat} ($Cm^3.Cm^{-3}$)	α (1/Cm)	n (-)	K_{SAT} ($Cm.d^{-1}$)
0.06	0.423	0.0456	1.46	25.0

Table 3. Input for detailed crop model

Parameter	Value
Temperature sum from emergence to anthesis (c^0)	1235
Temperature sum from anthesis to maturity (c^0)	1357
specific leaf area ($ha.kg^{-1}$)	0.0035
Maximum relative increase in LAI	0.01
Light use efficiency for real leaf ($kgCO_2J^{-1}$)	0.6
Max CO2 assimilation rate	73.7

Table 4. Data required for the SWAP model

Data	Parameter	Data Resource	Data	Parameter	Data Resource
Meteorological	Solar radiation	*	Irrigation	Date Irrigation	**
	The minimum and maximum daily temperature	*		Irrigation depth	**
	Mean steam pressure	*		salinity of irrigation water	***
	Sunny hours	*		Irrigation method	Surface
	Mean wind speed	*	Plant	Plant height and root depth	**
	Daily rainfall	*		Crop coefficient (Kc)	***
soil	Soil texture	**		LAI	**
	Limits of root penetration	**		Absorption factor	***
	Initial conditions	**		ET_0	***
	Boundary conditions	**		Tolerance threshold in salinity	***
	Soil moisture curve	****		Light use efficiency	***
	Soil moisture content	**		Specific leaf area	***
	Hydraulic conductivity	**		Temperature sum from emergence to anthesis	**
	Hydraulic parameters	RET C		Temperature sum from anthesis to maturity	**

* Meteorological station, **: Measurement of field, ***: Resources survey, ****: Experimental Data

Results and discussion

Simulation of soil moisture

As an example, the comparison between observed and simulated values of soil moisture for the treatment S_1I_1 is presented in Figure 1. Figure 2 shows the comparison of the simulated and measured soil moisture for all treatments. The line in this figure represents the potential 1:1 relationship and the closer the points to the line, the higher the correlation between the measured and simulated dataset. In treatments S_2I_2, S_3I_2 and S_2I_3, simulated soil moisture by the model was higher than the measured values while in treatments S_2I_1, S_3I_1 and S_1I_2 the estimated values were more than actual values at the beginning of growing season. In other cases, the simulated soil moisture was in agreement with the measured values. Model error at the beginning of the growing season may be due to measurement errors, which plays an important role in the difference between measured and simulated values. Part of the differences observed between the measured and simulated soil water content may be due to inherent limitations of the models. For example, the effect of hysteresis and water flow passage through large soil pores had not been dealt with in the model simulation.

The evaluation criteria of soil moisture simulation in all treatments are presented in Table 5. nRMSE values below 10% indicates the accuracy of soil moisture estimation by the model. In treatment S_3I_3, the model showed lower accuracy in simulations than other treatments, because of the error in measuring soil moisture with a tensiometer in high suctions and the impossibility of using fiber glass blocks in high salinity treatments.

Falah (2013) compared the different methods of measuring soil moisture with simulated values by SWAP model in Qazvin, Iran and reported RMSE values at different depths in the range 0.053— 0.029 cm^3/cm^3.

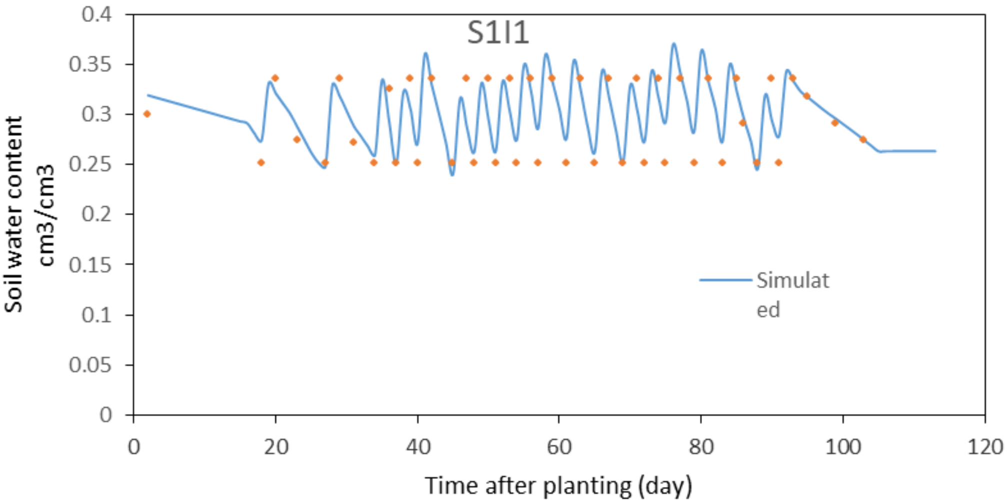

Figure 1. Comparison of the measured and simulated soil water content (treatment S_1I_1)

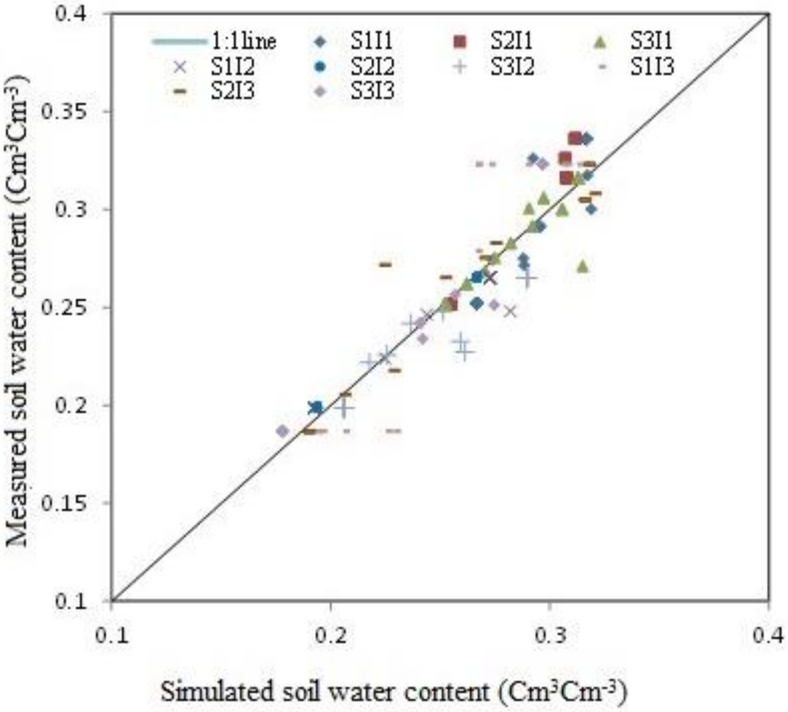

Figure 2. Comparison between the predicted and measured soil water content for all treatments. The line represents the potential 1:1 relationship between the data sets.

Simulation of water uptake by roots

Figure 3 compares simulated and measured water uptake by roots for all treatments. Dispersions of points around the 1:1 scale line indicates that the simulated water uptake by roots are in agreement with the measured values. The evaluation criteria of water uptake simulation by roots in all treatments are presented in Table 6. The nRMSE values of between 20 to 30% represents the normal accuracy of water uptake simulation by the roots. The minimum and maximum nRMSE obtained were 26.28 and 32.72% for treatments S_3I_3 and S_3I_1, respectively. Proper estimation of water uptake by roots in high water stress and salinity treatments suggest that the model is able to simulate the interaction between water stress and salinity on the water uptake by the roots.

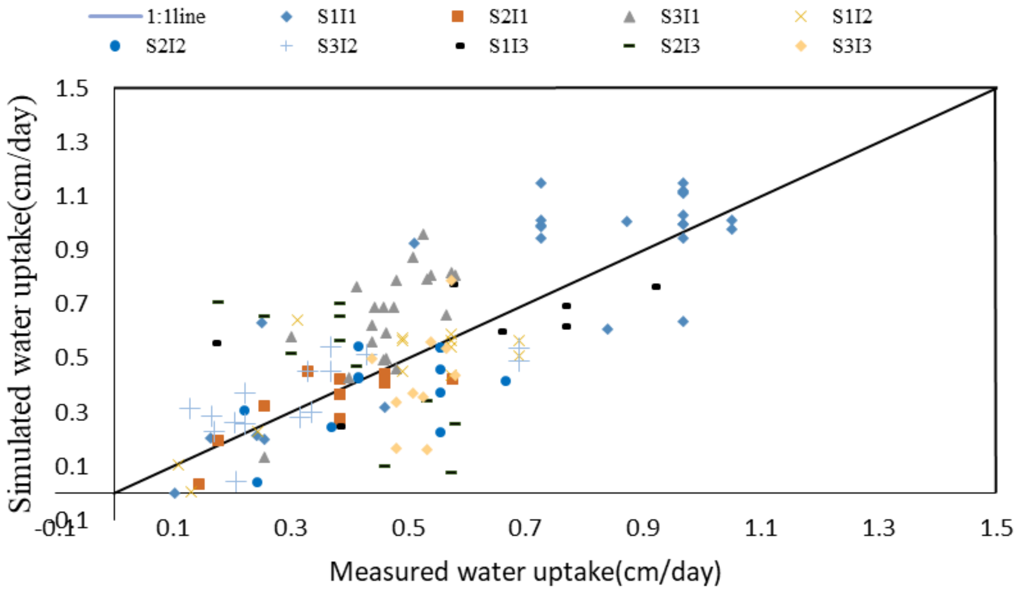

Figure 3. Comparison between the predicted and measured root water uptake for all treatments. The line represents the potential 1:1 relationship between the data sets.

Table 6. The RMSE, nRMSE and R^2 values of simulated root water uptake (model validation).

Irrigation levels	Salinity levels	RMSE (Cm^3Cm^{-3})	nRMSE (%)	R^2
	S_1	0.245	32.40	0.39
I_1	S_2	0.084	23.37	0.40
	S_3	0.227	32.72	0.52
	S_1	0.126	27.48	0.50
I_2	S_2	0.126	26.43	0.52
	S_3	0.123	38.17	0.53
	S_1	0.184	28.48	0.53
I_3	S_2	0.106	26.44	0.80
	S_3	0.111	26.28	0.42

Yield Simulation

Shown in Figure 3 are the yield in salinity treatments 2 (S_1), 4 (S_2) and 6 (S_3) ds m^{-1} and the different scenarios considered by the model (salinity 5 and 7 ds m^{-1}). Simulation results performed by the SWAP model under various scenarios at different salinity levels and water stress indicated no significant effect on the yield response by increasing irrigation water salinity from 4 to 7 ds m^{-1}. In the treatment 75% of Total Available Water (TAW) depletion (I_2), the final yield was more than both full irrigation (I_1) and 100% of Total Available Water (I_3) depletion treatments.

Due to the growing trend in groundwater reduction which leads to increased salinity, planting corn at higher salinity is not logical and operational and the only advisable option is proper irrigation scheduling which means suitable irrigation at right quantity, quality and time.

Conclusions

Considering that Shahrood in the Semnan Province is a city critical in terms of water shortage, providing guidelines for planning and management of irrigation water is necessary. In this circumstance, the results of simulations could save time and budget. However, in this study, the results of the water uptake by roots simulations were sub-optimal, but the comparison of simulated and observed values over the 1:1 scale line indicated the accuracy of the model to simulate the interaction between salinity and water stress affecting soil moisture content and water uptake by roots.

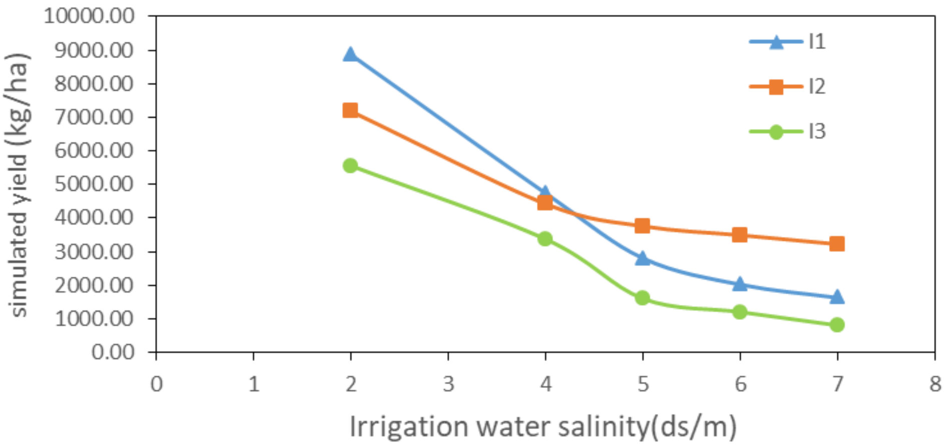

Figure 4. Amount of yield under different scenarios in irrigation treatments

As a result, considering the climatic conditions of the region and soil type with the scenarios based on possible management options, provides a means of offering optimal management strategies. This can be achieved through simulation models, among the available methods. In our study, we showed that the SWAP model simulations can be used successfully towards this goal. In the future research, limitations of the model and available data should be addressed for increasing efficiency of the approach.

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