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Soil salinity and water simulation in corn field irrigated with saline and non-saline water

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Abstract: Simulation models can be important tools for analysing and managing irrigation, soil salinization or crop production problems. In this study, the suitability of SALTMED model to describe soil water movement and overall soil salinity was examined against field data. Measurements on soil water content and salinity, irrigation water quality, plant growth and meteorological data were collected in plots of corn, during one growing season, and used for the calibration and validation of the model. The effectiveness of SALTMED model was evaluated with regard to soil water content and salinity simulations, under full and deficit irrigation with saline and non-saline water. Furthermore, the effects of water and osmotic stress on corn yield were examined under field conditions. The results showed that the model describes adequately soil water content and salt accumulation. According to the measured and computed values, salt built up is mainly restricted in the top 30 cm of the soil profile. Measured corn yield indicated that the effects of water stress are more detrimental than the effects of osmotic stress.

Keywords: Soil water; Salts; Simulation; Deficit irrigation; Saline water; SALTMED model

1. INTRODUCTION

Soil salinity and drought are the most severe abiotic stresses that contribute significantly to decreased productivity of agricultural crops. The salinization of irrigated lands has become a major concern for global food production. The extent of water dedicated to irrigated agriculture is likely to be challenged, as pressure is mounting to meet increased demands for human consumption and industrial uses (Ghassemi et al., 1995; Pitman and Läuchli, 2002; Lekakis and Antonopoulos, 2015). In order to fill the gap between demand and supply of freshwater, agriculture in semi-arid areas will increasingly resort to using marginal-quality waters, such as urban wastewater, drainage water generated by irrigated agriculture and moderately saline surface and groundwater (Qadir et al., 2007; Oster et al., 2012).

Irrigation practices contribute largely to soil salinization, through salt built up and deposition in the soil profile, due to evapo-concentration. To overcome problems associated with soil salinity, management tools such as leaching of excess soluble salts, blending saline with better quality waters, cyclic use of saline and non-saline waters, selecting tolerant varieties of suitable crops and using appropriate agronomic practices are increasingly employed (Qadir and Oster, 2004; Grattan et al., 2012).

There is a growing interest in regulated deficit irrigation and use of saline water resources to improve efficiency of water usage and farm productivity in arid and semi-arid areas (Bourgault et al., 2010). Deficit irrigation amounts and irrigation water salinity influence plant growth affecting several plant physiological mechanisms and morphological characteristics. Salinity stress reduces plant water uptake (Alvarez and Sanchez-Blanco, 2015) and sometimes ion toxicities and nutritional deficiencies may be observed. Water and salinity stress often occur simultaneously, as the soils dry and the salts accumulate in the soil solution (Chaves et al., 2009).

Salinity control requires the examination of salt and water movement processes through the soil profile and prediction of crop response to soil water and soil salinity, under various climatic, soil and agronomic factors (Rasouli et al., 2013). To this aim, mathematical models are considered useful tools for assessing the best management practices under saline conditions (Gonçalves et al., 2006; Poulovassilis et al., 2007; Ramos et al., 2011).

Many models have been developed to describe soil salinity, either through the electrical conductivity of the soil solution (EC_{sw}), or from individual cations (such as Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) of the soil solution. Models ENVIRO-GRO (Pang and Letey, 1998), SWAP (Kroes et al., 1999) and SALTMED (Ragab, 2002) use the solute transport equation to describe EC_{sw} as an individual solute, while models UNSATCHEM (Šimůnek et al., 1996) and HYDRUS (Šimůnek et al., 2008) are more complex, incorporating modules of major ions chemistry in soil, considering also the processes of adsorption and cation exchange. The latest version of model WANISIM (Lekakis and Antonopoulos, 2015) describes the one-dimensional water movement and major cations transport in the soil. The model estimates EC_{sw} with moderate complexity, as the sum of the cations in the soil solution, which is considered as a more accurate approach, than in the form of an independent solute.

SALTMED model (Ragab 2002; 2015) was developed to enhance productivity and sustainability of irrigated cropping on salt-prone lands in the Mediterranean region. The model was successfully calibrated and validated against field data from experiments in many parts of the world (Flowers et al. 2005; Ragab, 2005; Silva et al. 2013). SALTMED has mainly been used to estimate soil water content, crop yield and total crop dry matter under field conditions (Montenegro et al., 2010; Hirich et al., 2012; Pulvento et al., 2013; Ragab et al., 2015), however, rarely has been employed for the description of soil salinity distribution (Ragab et al., 2005).

The calibration and validation of a model under multiple variables such as climatic conditions, irrigation regimes, irrigation water quality and different plants with varying sensitivity to salinity, require a significant amount of field data. SALTMED model requires data of soil water monitoring and salinity, either as the EC_{sw}, or the concentration of different cations. However, soil solution salinity monitoring and measuring is a difficult task under field conditions. Various relationships have been proposed for the determination of the EC of the in situ soil water (EC_{sw}) from the EC of the saturation extract (EC_{e}) (Ayers and Westcot, 1985; Skaggs et al., 2006; Letey, 2007; Lekakis and Antonopoulos, 2015).

The objectives of this paper were as follows: (i) to calibrate and validate SALTMED model results in order to describe soil water content, and overall salinity given by the EC_{sw}, under field conditions, (ii) to examine the simulation results of soil water and salinity considering different treatments of irrigation water amount and quality and (iii) to compare the simulated results with field measurements under deficit irrigation with saline water. In order to achieve the objectives measured data of soil water content and EC_{sw} were collected from experimental corn plots, treated with full and deficit amounts of saline and non-saline irrigation water under the semi-arid climatic conditions of Thessaloniki area in Northern Greece.

2. MATERIALS AND METHODS

2.1 Model description

SALTMED was developed as a physically based model, including a number of physical processes taking place simultaneously in the soil profile (Ragab, 2002). The main features and equations of SALTMED model are described in details by Ragab (2002; 2005). The SALTMED model includes the main processes of evapotranspiration, plant water uptake, soil water movement and solute transport under different irrigation systems, drainage, and the relationship between crop yield and water uptake.

The water flow in soils is described by the well-known Richard's differential equation.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta) \frac{\partial (h+z)}{\partial z} \right) - S_w \tag{1}$$

where θ is the volumetric water content (cm^3cm^{-3}), h is the soil water pressure head (cm), K(θ) is the hydraulic conductivity ($cm\ d^{-1}$), S_w is the sink term for water extraction rate by plant roots ($cm^3\ cm^{-3}d^{-1}$), z is the vertical coordinate positive in the downward direction (cm), and t is the time (d). The soil water retention curve, θ(h), is described by the van Genuchten (1980) model and unsaturated hydraulic conductivity, K(h), is evaluated by the van Genuchten – Mualem model (van Genuchten, 1980). Preferential water flow and hysteresis of soil hydraulic properties are not considered in the model.

The actual water uptake rate is described by Cardon and Letey (1992) approach, which determines the water uptake S_w (d^{-1}) as follows:

$$S_w(z,t) = \frac{S_{max}(t)}{1+((\alpha h + h_o)/h_{o50})^3}\lambda(z,t) \tag{2}$$

where $S_{max}(t)$ is the maximum potential root water uptake ($cm^3cm^{-3}d^{-1}$), λ(z, t) is the depth-and time-dependent fraction of total root mass (-), h_o is the osmotic pressure head (cm), $h_{o50}(t)$ is the time-dependent value of the osmotic pressure (cm) where $S_{max}(t)$ is reduced by 50%, and α is a weighing coefficient that accounts for the differential response of a crop to matric and solute pressure. The $S_{max}(t)$ is calculated as follows:

$$S_{max}(t) = K_c(t)ET_o(t) \tag{3}$$

where $K_c(t)$ is the crop coefficient (-), $ET_o(t)$ is the reference evapotranspiration ($cm\ d^{-1}$). The reference evapotranspiration rate is calculated using the Penman-Monteith equation according to Allen et al. (1998). The rooting depth was assumed to follow the same course as the crop coefficient K_c.

The transient mass transport of a non-reacting solute under variably saturated soil conditions is described through the convection–dispersion differential equation (Bresler et al., 1982; Antonopoulos, 2001):

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z}\right) - \frac{\partial (qC)}{\partial z} - S_s \tag{4}$$

where C is the solute concentration in the soil water ($mg\ cm^{-3}$) or electrical conductivity ($dS\ m^{-1}$), q is the volumetric flux density ($cm\ d^{-1}$), D is the hydrodynamic dispersion coefficient (cm^2d^{-1}), and S_s represents source or sink of solute ($dS\ m^{-1}d^{-1}$). Absorption and exchange of cations between the solid phase and the soil solution are not considered in the model. The water flow and solute transport equations are solved numerically using a finite difference explicit scheme (Ragab, 2002).

The relative crop yield, RY, due to the unique and strong relationship between water uptake and biomass production is estimated as the sum of the actual water uptake over the season divided by the sum of the maximum water uptake (under no water and salinity stress conditions) as:

$$RY = \sum S(z,t) / \sum S_{max}(z,t) \tag{5}$$

The actual yield AY is simply obtainable by:

$$AY = Y_{max} RY \tag{6}$$

whereY_{max} is the maximum yield under optimum and stress free conditions.

Input data are provided in the model through a user-friendly built-in interface regarding four main databases; (1) crop coefficients, rooting depth parameters, and growth length stages, (2) soil hydraulic characteristics and solute transport parameters, (3) irrigation system and frequency of application, (4) meteorological data to estimate water requirements according to FAO-56 (Allen et al. 1998).

2.2 Experimental design and treatments

The field data used for the calibration and validation of the model were collected at the experimental farm of the Aristotle University of Thessaloniki (40^o32 N, 23^o00 E, 16 m above sea level) in Northern Greece, during the year of 2011 and the growing season of corn (April to October). The climate at the experimental area is considered typical of a semi-arid Mediterranean environment, with annual average rainfall and temperature of 458.4 mm and 14.8 ^oC, respectively.

The experiment was a split-plot design. Four different treatments with two levels of electrical conductivity of water (EC_{iw}) equal to 0.8 and 6.4 *dS* m^{-1} and two irrigation amounts of 40 *mm* (full) and 24 *mm* (deficit) per irrigation, in two replicates, were established. Treatments were AFI (EC_{iw} = 0.8 *dS* m^{-1}, 40 *mm*), ADI (EC_{iw} = 0.8 *dS* m^{-1}, 24 *mm*), DFI (EC_{iw} = 6.4 *d* Sm^{-1}, 40 *mm*) and DDI (EC_{iw} = 6.4 *dS* m^{-1}, 24 *mm*). The first letters A and D represent the level of electrical conductivity and the second letter F stands for full and D for deficit irrigation treatments. Maize hybrid PR31G98 (FAO 700, Pioneer Hi-Breed Hellas) was sown in five rows in each plot, with row spacing of 0.80 *m* and spacing between plants along the row of 0.16 *m*. Fertilizer rates were similar to farming practice in the region. Nitrogen was applied at preplanting stage at the rate of 110 *kg* N ha^{-1}, as ammonium phosphate sulphate (22-11-0-13S). More details concerning the experimental design are provided by Lekakis and Antonopoulos (2015).

The physical and initial chemical properties of the soil are given in Table 1. The soil profile was divided into four layers based on different physical soil properties. The soil layers were 0-20, 20-40, 40-90 and 90-110 *cm*.The soil bulk density (ρ_b) and saturated volumetric water content (θ_s) were determined in undisturbed soil samples, collected at the beginning of the experiment from the representative soil layers. The parameters α and n of the van Genuchten (1980) water retention model and saturated hydraulic conductivity (K_{sat}), were then estimated (Table 1).

Table 1. Physical and chemical properties of soil layers

Parameter	**Soil layer cm**							
	AFI - ADI				**DFI - DDI**			
	0-20	**20-40**	**40-90**	**90-110**	**0-20**	**20-40**	**40-90**	**90-110**
Texture	SiCL	SiL	SiL	SL	SiCL	SiL	SiL	SL
ρ_b ($g\ cm^{-3}$)	1.45	1.31	1.14	1.63	1.38	1.47	1.12	1.63
EC ($dS\ m^{-1}$)	0.54	1.02	3.74	3.74	0.60	1.49	3.14	3.57
θ_s (cm^3cm^{-3})	0.52	0.57	0.59	0.50	0.51	0.51	0.59	0.50
θ_r(cm^3cm^{-3})	0.09	0.09	0.07	0.07	0.09	0.09	0.07	0.07
α (cm^{-1})	0.030	0.004	0.015	0.002	0.054	0.019	0.008	0.001
n	1.35	1.23	1.22	2.38	1.37	1.26	1.21	1.83
K_s ($cm\ h^{-1}$)	3.03	1.41	3.72	0.03	3.85	15.48	2.01	0.04

Daily meteorological data were collected from a station nearby the experimental field. Total annual rainfall was 425 *mm* during the year of the experiment. The reference evapotranspiration rate (ET_o) was calculated using the ASCE-standardized Penman-Monteith method (Allen et al., 2005). Crop coefficients (K_c) for every treatment were adjusted for corn growth stages 30/40/50/30 days (Papazafiriou, 1996) and ranged between $K_{ci} = 0.37\pm0.02$, $K_{cm} = 1.36\pm0.07$ and $K_{ce} = 0.21\pm0.06$. The crop evapotranspiration rate (ET_c) was calculated as the product of ET_o and K_c.

Leaf area index (LAI) was measured on a biweekly basis in each treatment during different stages of the corn growing period using the destructive-planimetric method, by measuring the area of all the leaves within a delimited area (Aschonitis et al., 2014). The maximum values of LAI ranged between 5.85±0.49 for AFI, and 5.89±0.84 for DFI. Root depth was also determined on a bi-weekly basis by observations of extracted root system until the middle of the cropping period. Measured root depth data were fit to obtain the parameters of the logistic function, using a maximum root depth of 75 cm (Lekakis et al., 2011).

Irrigation water was applied uniformly on the soil surface using siphons. Irrigation water composition was obtained by adding different amounts of $CaCl_2$, NaCl and $MgCl_2$ to the water available in the region (EC ≤ 1 *dS m*$^{-1}$), maintaining a ratio of 3:3:2 for Ca^{2+}:Mg^{2+}:Na^{+}, initially found in the fresh water. Concentrations were increased to obtain the desirable EC_{iw} of 6.4 *dS m*$^{-1}$. Water composition was monitored in every irrigation for concentrations of Ca^{2+}, Mg^{2+}, Na^{+} and levels of EC_{iw}. According to Ayers and Westcot (1985) classification, irrigation water quality does not affect water infiltration, posing slight to moderate water availability effects for AFI and ADI and severe water availability effects for DFI and DDI treatments.

Six to eight irrigations at 7-10 days intervals were applied during the growing season. Irrigation was resumed when plant-available water was depleted to more than 50% of that achieved in last irrigation. Total irrigation amount during the growing season was 320 *mm*, and 192 *mm*, for full and deficit treatments, respectively. The rainfall during the same period was 95.4 *mm.*

Soil moisture was measured with a dielectric profile probe PR2 (Delta-T Device Ltd). A site specific calibration of PR2 was performed in accordance to the instructions of the manufacturers (Profile Probe User Manual 2.0, Delta-T Device Ltd, 2004). The water content was measured at the depths of 10, 20, 30, 40, 60 and 100 *cm*, corresponding to average soil moisture readings of 5-15, 15-25, 25-35, 35-45, 55-65 and 95-105 cm soil layers.

Electrical conductivity (EC_e) was monitored in the saturation extracts of the soil layers 0-35 and 35-75 *cm* during the growing period. Soil EC_e was measured according to Rhoades (1996). SALTMED model calculates EC_{sw} in the soil solution. In order to compare simulated results and measured values, electrical conductivity should be converted from saturation extract to actual soil moisture. According to the US Salinity Laboratory Staff (1954), the soluble-salt concentration in the saturation extract, tends to be about one-half of the concentration of the soil solution at the upper end of the field-moisture range and about one fourth the concentration that the soil solution would have at the lower, dry end of the field-moisture range. Therefore, EC_{sw} was estimated from EC_e using the following approximations:

$$EC_{sw} = 2 \cdot EC_e \qquad \theta_{sat} \geq \theta \geq \theta_{FC} \tag{7}$$

$$EC_{sw} = 3 \cdot EC_e \qquad \theta_{FC} > \theta \geq \theta_{pwp} \tag{8}$$

$$EC_{sw} = 4 \cdot EC_e \qquad \theta < \theta_{pwp} \tag{9}$$

where θ is the soil moisture and θ_s, θ_{FC} and θ_{pwp} are the water contents at saturation, field capacity and permanent wilting point, respectively.

2.3 Model evaluation

The quantitative procedure of model evaluation was assessed using statistical analysis to calculate the average error (AE), the root mean square error (RMSE) and the coefficient of residual mass (CRM) between the measured and computed values (Antonopoulos, 2001). The statistical criteria are given by:

$$AE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \tag{10}$$

$$RMSE = \left(\frac{1}{n-1} \sum_{i=1}^{n} \left(P_i - O_i\right)^2 \right)^{1/2} \tag{11}$$

$$CRM = \left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i \right) / \sum_{i=1}^{n} O_i \tag{12}$$

where O_i are the observed (measured) values, P_i are model predictions and n is the number of observations. RMSE and AE are given in the units of a particular variable, while CRM is dimensionless. Values of AE, RMSE and CRM close to zero indicate optimum model predictions. The CRM is a measure of the tendency of the model to overestimate or underestimate the measurements. A negative CRM shows a tendency to overestimate.

3. RESULTS AND DISCUSSION

3.1 Soil water simulation results

The simulated and measured values of water content at 10, 30 and 60 *cm* soil depths during the simulation period from 11/5/2011 to 30/11/2011, are presented in Figures 1 and 2. Each figure represents the different irrigation treatments of AFI, ADI, DFI and DDI. Computed values and measured soil water content show similar variation during the simulation period. Soil moisture fluctuation followed the wetting and drying cycles in the 5-15 *cm* soil layer, reaching values close to field capacity, for the AFI and DFI treatments, immediately after an irrigation event and decreasing rapidly due to the effects of high evapotranspiration rates, during the growing period.

Soil water distributions at the 25–35 and 55–65 *cm* layers, show smaller water content variations caused by the applied irrigation water. Soil moisture was reduced dramatically as soon as roots reached the depth of 30 and 60 *cm* in all four treatments. A small amount of water was infiltrated to the soil layers of 25–35 and 55–65 *cm* but it was soon depleted and remained low due to excess water uptake by plant roots.

The statistical criteria AE, RMSE and CRM between computed and measured soil water content, during calibration and validation, are summarized in Table 2.

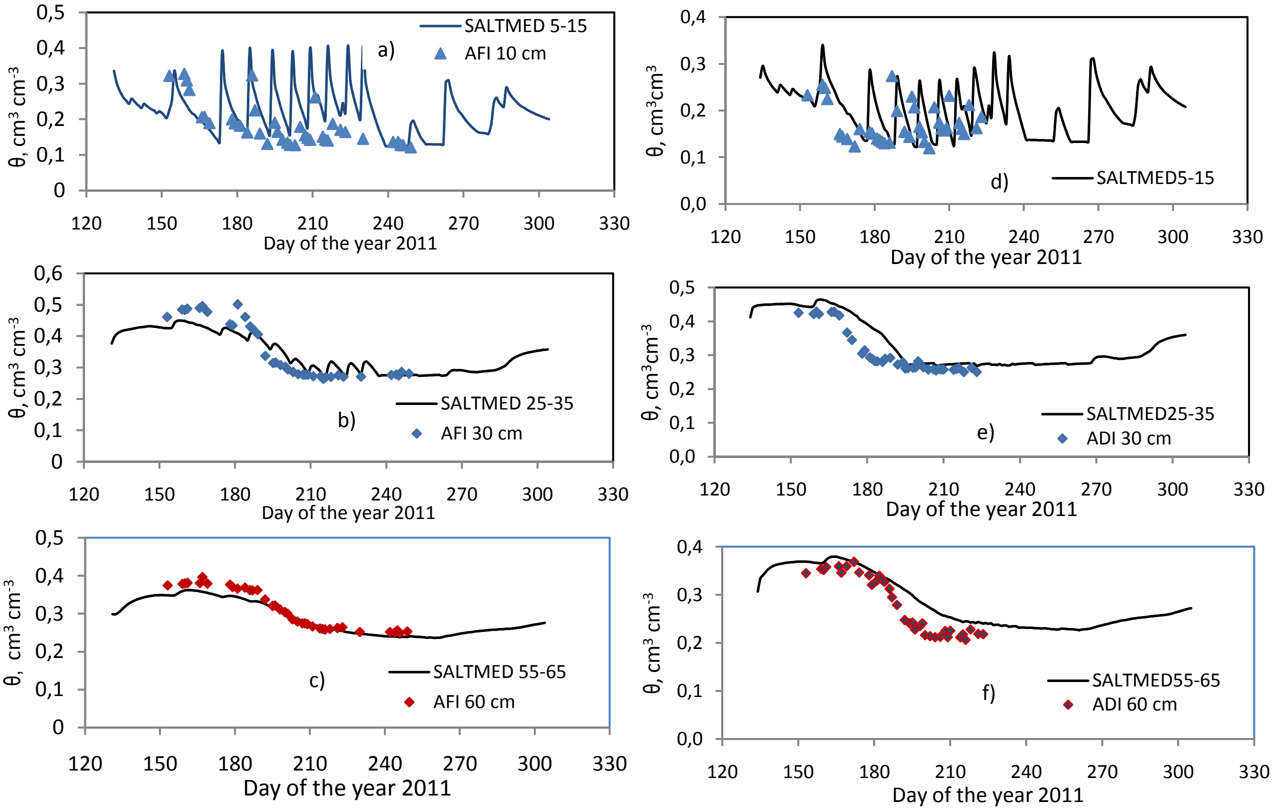

Figure 1. Measured and computed water contents at 5-15, 25-35, and 55-65 cm layers in treatment AFI (a, b, c) and ADI (d,e,f) during the simulation period (1/5/2011 to 30/11/2011).

The discrepancy between measured and simulated water content is generally small. Values of AE ranged from -0.052 to 0.033 cm^3cm^{-3} and values of RMSE ranged from 0.058 to 0.082 cm^3cm^{-3} for both irrigation water treatments. The CRM values indicate that the model overestimates in general the soil moisture (values of -0.771 to -0.011). It underestimates the soil moisture in three out of six depths in AFI treatment and in five out of six depths in DFI, overestimates the soil moisture in five out of six depths in ADI, and mostly overestimates the soil moisture in DDI treatment.

Table 2. Statistical criteria of soil water content simulation results

		10 cm	**20 cm**	**30 cm**	**40 cm**	**60 cm**	**100 cm**	**All depths**
AFI	RMSE (cm^3cm^{-3})	0.091	0.087	0.038	0.092	0.017	0.034	0.067
	AE (cm^3cm^{-3})	0.042	-0.077	0.001	0.086	-0.011	-0.021	0.003
	CRM (-)	-0.232	0.234	-0.002	-0.358	0.035	0.072	-0.011
ADI	RMSE (cm^3cm^{-3})	0.069	0.075	0.044	0.069	0.034	0.041	0.057
	AE (cm^3cm^{-3})	0.036	-0.068	0.032	0.060	0.029	0.029	0.019
	CRM (-)	-0.216	0.237	-0.109	-0.242	-0.107	-0.105	-0.076
DFI	RMSE (cm^3cm^{-3})	0.089	0.146	0.022	0.059	0.050	0.066	0.082
	AE (cm^3cm^{-3})	-0.032	-0.135	0.015	-0.058	-0.044	-0.057	-0.052
	CRM (-)	0.145	0.382	-0.047	0.159	0.132	0.159	-0.307
DDI	RMSE (cm^3cm^{-3})	0.055	0.048	0.103	0.081	0.029	0.033	0.064
	AE (cm^3cm^{-3})	0.015	0.029	0.083	0.056	0.003	0.009	0.033
	CRM (-)	0.002	-0.034	-0.312	-0.227	-0.009	-0.049	-0.771

Lekakis and Antonopoulos (2015), using WANISIM model, obtained AE values ranging from -0.017 to 0.028 cm^3cm^{-3} and RMSE values ranging from 0.04 to 0.06 cm^3cm^{-3}, for the simulation of soil water for the data sets of AFI and DFI treatments. Model WANISIM underestimates soil water content of AFI and overestimates that of DFI treatment. Jarvis et al. (2000) using MACRO model, considered acceptable the simulations of soil water content with average values of RMSE less than 0.06 cm^3cm^{-3} and absolute values of CRM less than 0.07. Bonfante et al. (2010) compared the performance of SWAP, CropSyst and MACRO models and obtained RMSE values ranging from 0.01 to 0.08 cm^3cm^{-3} for different soils and models.

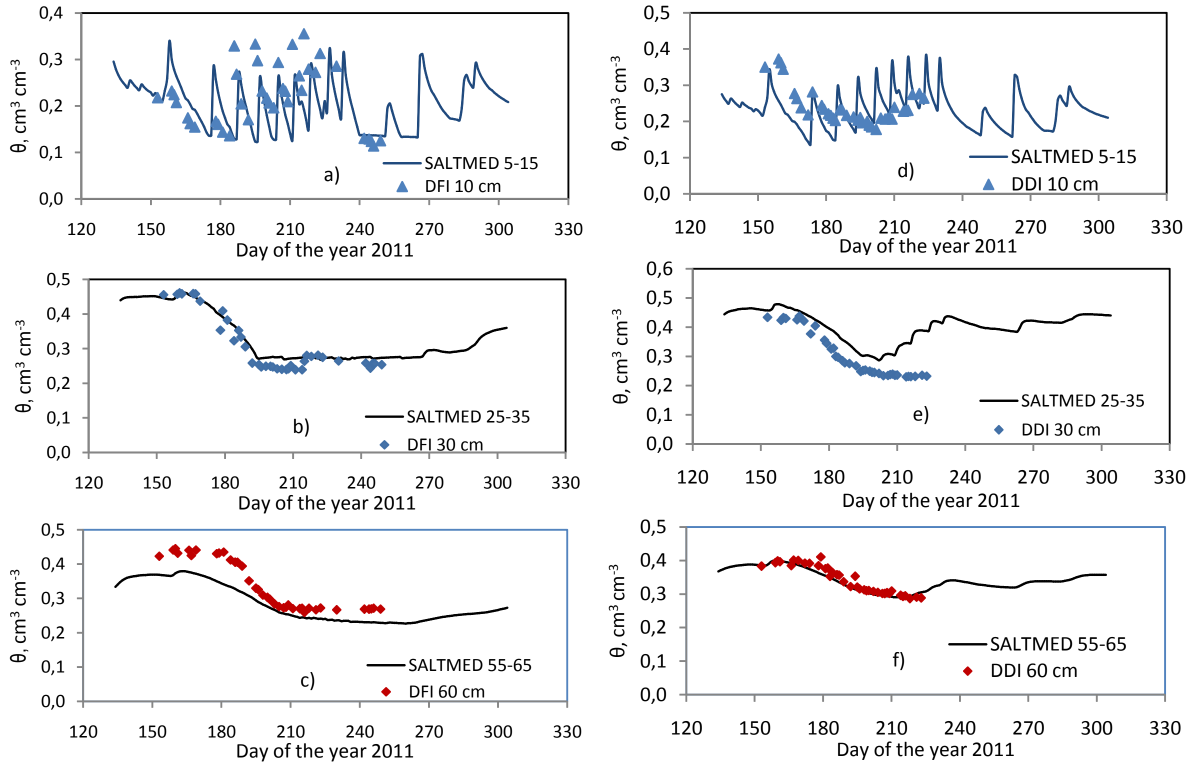

Figure 2. Measured and computed water contents at 5-15, 25-35, and 55-65 cm layers in treatment DFI (a, b, c) and DDI (d,e,f)during the simulation period (1/5/2011 to 30/11/2011).

3.2 Soil salinity simulation results

Figures 3 and 4 show the simulated versus measured data for EC_{sw} for two different soil layers (0-35 and 35-75 *cm*) under full and deficit irrigation with saline and non-saline water. Taking into account the uncertainty connected to the estimation of EC_{sw} from EC_e (Eq. 7-9) it appears that computed values describe satisfactorily the measured values. The measured values of salinity at the deeper layer of ADI and DFI treatments present high dispersion around the simulated values. The simulated results overestimate the measurements in the DFI treatment.

The statistical criteria of AE and RMSE concerning measured and predicted EC_{sw}, are summarized in Table 3. The AE for both layers ranged from -0.347 to 3.156 $dS\ m^{-1}$, while the RMSE from 0.174 to 4.171 $dS\ m^{-1}$. The simulation results of 35-75 *cm* layer of AFI treatment present the better statistical criteria, while the layer of 0-35 *cm* of DFI treatment, the worst. SALTMED model simulations of the total soil salinity resulted in a generally good agreement with the observed distributions in all of the four treatments throughout the simulation period.

In AFI treatment, computed and measured soil salinity reached maximum values of 6 $dS\ m^{-1}$ after the last irrigation in both layers (Fig. 3a). The soil salinity in ADI treatment increased to 4 $dS\ m^{-1}$ in the upper layers and to 2.5 $dS\ m^{-1}$ in the deeper layer, due to deficit irrigation amounts and lower salt loading. The use of the locally available water did not lead to soil salinization, although salt leaching from the surface soil layer caused an increase in the EC_{sw} of the 35-75 *cm* layer to almost saline levels of 4$dS\ m^{-1}$. Soil salinity increased considerably in treatments irrigated with saline waters (DFI and DDI), as it is shown in Figure 4. The use of saline irrigation water with $EC_{iw} = 6.4\ dS\ m^{-1}$ had the higher effect on the soil solution salinity within the irrigation period. The increase in the salinity of the 35-75 *cm* soil layer is mainly attributed to the limited percolation and leaching of salts below the root zone.

Table 3. Statistical results between measured and computed EC_{sw} (obtained for the studied layers of 0-35 and 35-75 cm) during the simulation period

		0-35	35-75	All layers
AFI	AE (dSm^{-1})	-0.757	0.064	-0.347
	RMSE (dSm^{-1})	1.084	0.386	0.814
ADI	AE (dSm^{-1})	0.067	0.523	0.295
	RMSE (dSm^{-1})	0.819	1.308	0.174
DFI	AE (dSm^{-1})	4.718	1.593	3.156
	RMSE (dSm^{-1})	0.768	0.446	4.171
DDI	AE (dSm^{-1})	-0.438	-0.399	-0.419
	RMSE (dSm^{-1})	1.151	1.616	1.968

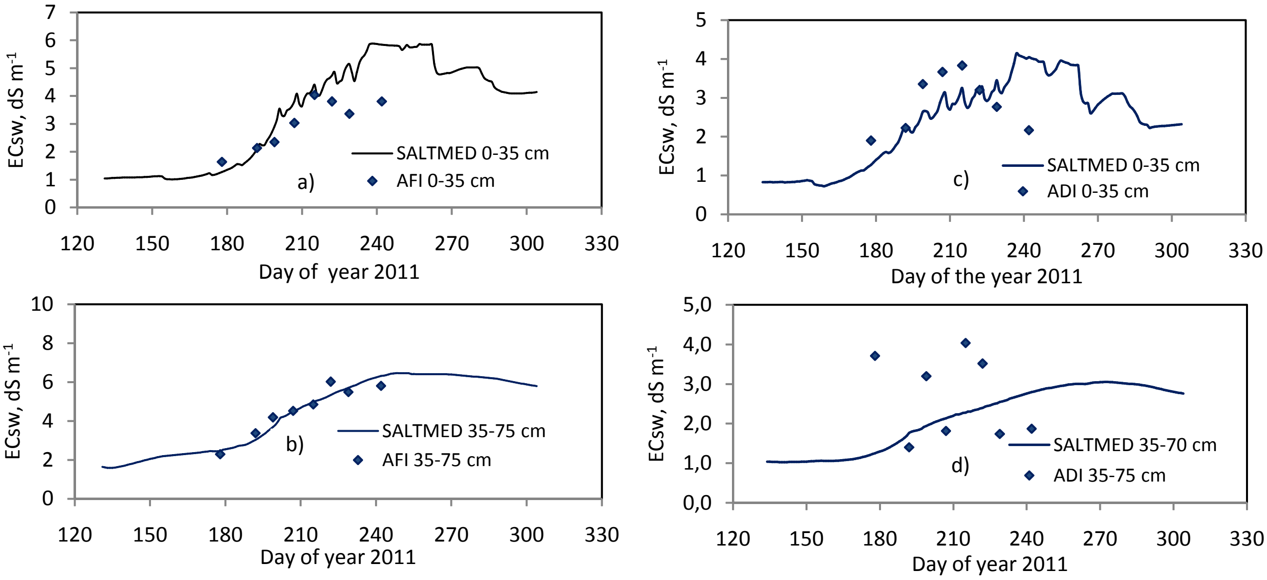

Figure 3. Measured and computed salinity at 0-35, and 35-75 cm layers in treatment AFI (a, b) and ADI (c,d) during the simulation period (1/5/2011 to 30/11/2011).

3.3 Water and salts balance

The computed cumulative water balance components (irrigation and rainfall, water uptake, deep percolation), for the four treatments are listed in Table 4. The cumulative amount of water applied during the simulation period was 415.4 and 287.4 *mm* for full and deficit irrigation, respectively. The rainfall during the same period was 95.4 *mm*. The actual plant uptake was 501.5, 418.45, 432.4 and 364.9 *mm*, respectively, in AFI, ADI, DFI and DDI treatments. Simulation results show that plant uptake was higher than the applied water in all four treatments. Deep percolation appeared only in AFI and DFI treatments. The higher deep percolation in DFI treatment of full irrigation with saline irrigation water is justified by the lower plant uptake due to osmotic stress and greater amount of water available for leaching. The difference between initial and final water storage at the end of the simulation period shows that depletion ranged from 51.6 to 133.7 *mm*, with the maximum depletion in ADI treatment.

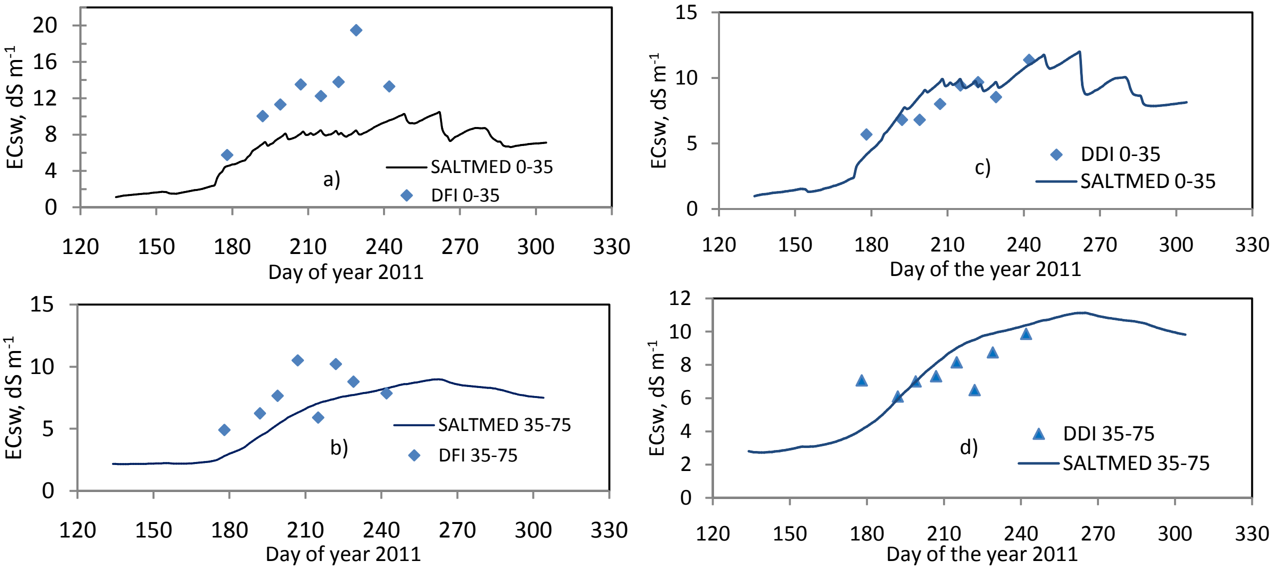

Figure 4. Measured and computed salinity at 0-35, and 35-75 cm layers in treatment DFI (a, b) and DDI (c,d) during the simulation period (1/5/2011 to 30/11/2011).

Table 4. Components of water balance at the end of the simulation period.

	AFI	ADI	DFI	DDI
Cumulative Irrigation and rainfall (*mm*)	415.40	287.40	415.40	287.40
Deep percolation (*mm*)	18.85	0.00	31.53	0.00
Cumulative water uptake (*mm*)	501.50	418.45	432.40	364.88
Initial water storage (*mm*)	360.15	385.16	404.18	424.16
Final water storage (*mm*)	252.14	251.43	352.55	343.96
Water balance (*mm*)	**- 108.10**	**- 133.73**	**- 51.63**	**- 80.20**

The mass balance components for total dissolved solids during the simulation period are presented in Table 5. According to the results, significant amounts of salts were added in the soil through the irrigation water, in treatment DFI. Computed leaching losses were limited, as was deep percolation, in treatments ADI and DDI. Results indicate considerable salt loading in all four treatments during the simulation period. However, treatments receiving saline irrigation water (DFI and DDI) presented significantly higher salt accumulation in the soil profile, than the ones treated with non-saline water (AFI and ADI).

3.4 Plant yield

SALTMED model was successfully able to simulate dry matter and final yield. It has been applied in the past to simulate yield for different crops and environments, like sweet corn, chickpea and quinoa in Marocco (Hirich et al., 2014), chickpea in Portugal (Silva et al., 2013), quinoa in Southern Italy (Pulvento et al., 2013) and tomatoes in Syria and Egypt (Flowers et al., 2005).

Figure 5 presents the computed and measured values of corn yield. The maximum corn yield for the cultivated hybrid in the region is 16.9 $Mg\ ha^{-1}$ (Lekakis et al., 2011). Using that yield as the maximum yield the model estimates the yield for each treatment. The measured yield for DFI treatment is almost equal to that of AFI treatment. Significant differences were detected among the treatments of water stress (ADI, DDI) and fully irrigated treatments (AFI, DFI). According to this observation the water stress (deficit irrigation) causes higher decrease in corn yield than osmotic stress.

Table 5. Components of salts balance at the end of the simulation period.

	AFI	ADI	DFI	DDI
Cumulative salts applied (*kg ha*$^{-1}$)	371.1	232.3	2783.3	1742.2
Leaching (*kg ha*$^{-1}$)	28.4	0	468.7	0
Initial salts mass (*kg ha*$^{-1}$)	1630.7	707.5	1386.4	3110.7
Final salts mass (*kg ha*$^{-1}$)	1974.1	936.7	3706.9	4850.8
Salt balance (*kg ha*$^{-1}$)	+343.3	+229.1	+2320.5	+1739.1

Letey et al. (1985) and Russo and Bakker (1987) noted that higher amounts of water counter balance part of the salinity effects. Consequently, when there is no available irrigation water, then lower quality irrigation water can be used without the risk of further decreasing crop yield (Shani and Dudley, 2001), Oster et al. (2012) compared the simulated yields of forage corn under common soil and water conditions using ENVIRO-GRO, HYDRUS, SALTMED, SWAP and UNSATCHEM models. The salinity of applied irrigation water ranged from 0.5 to 6 $dS\ m^{-1}$. SALTMED simulated lower relative yield, HYDRUS, SWAP and UNSATCHEM higher values and ENVIRO-GRO the highest values. The latter includes a plant based compensation mechanism, which allows water uptake from any portion of the root zone to satisfy plant water requirements.

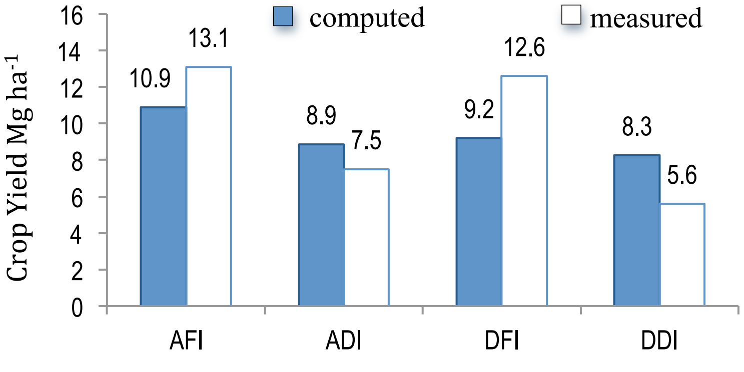

Figure 5. Computed and measured values of corn yield.

4. CONCLUSIONS

SALTMED model was calibrated and validated using measurements from corn plots at an experimental field at Thessaloniki, in Northern Greece. The target variables used for calibration and validation of the model were soil water content and total salinity (expressed by the EC_{sw}) measured at different depths in the soil and during the growing period. Different amounts of irrigation water and of varying quality concerning salinity were used for irrigation on experimental plots.

SALTMED model simulated successfully the soil water content under the different treatments of irrigation water. The accuracy of water content of SALTMED results, at different depths and time, were close to that of other simulation models, as WANISIM model.

The simulation results of total soil salinity were less accurate, probably due to the model approached regarding salinity as an individual solute and not as the results of mass transport of major cations. The results of overall salinity presented in this article consist some of the few existed references in the literature of SALTMED model.

Irrigation with saline water of EC_{iw} = 6.4 *dS* m^{-1}, led to soil salinization in both the deficit and full irrigation treatments and in both soil layers (0-35 and 35-75 *cm*), as was predicted by the model and shown by the measured values. In the case of the locally available water (non-saline), soil salinity after the irrigation period was lower than 4 *dS* m^{-1}.

High-quality data are essential for satisfactory model predictions, especially in computing soil salinity, either as overall salinity (EC_{sw}), or as individual cations. Measurements of soil water and soil salinity in a more frequent and continuous recording are needed for attributing a better model calibration and prediction as well.

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