

Field-evaluation of DRAINMOD-S for predicting soil and drainage water salinity under semi-arid conditions in Turkey

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Abstract

The aim of this study was to determine the reliability of DRAINMOD-S for simulating water management in irrigated land and to simulate drainage system design criteria to ensure high crop yields for the western part of the Central Kızılırmak Basin in Turkey. The model was tested under arid conditions using field data for winter wheat and corn. Daily water-table depth, drain outflows and drainage water salinity were monitored throughout the growing season. Soil salinities were measured to a depth of 1.00 m from the soil surface. The reliability of the model was evaluated by comparing measured and predicted values of the daily ground water table depth, drain outflows, drainage water and soil salinity during each season, and relative crop yield. Good agreement was found between the measured and predicted values. Absolute deviation was 5.68 cm for water table depth, 10.13 mm for drain outflows, 0.66 dS m⁻¹ for drainage water salinity, and ranged from 0.51 to 0.96 dS m⁻¹ for soil salinity. The corresponding coefficients of efficiency (*E*) were between 0.48 and 0.95. The results also showed that DRAINMOD-S can be recommended as a useful tool for design and evaluation of irrigation and drainage systems in salt-affected soils under arid and semi-arid climates.

Additional key words: corn; drainage system; water table management modeling; wheat.

Resumen

Evaluación de terreno de DRAINMOD-S para prever la salinidad de la tierra y del agua de drenaje bajo condiciones áridas en Turquía

El objeto de este estudio fue determinar la fiabilidad de DRAINMOD-S para simular la gestión del agua en suelos regados y el criterio de diseño del sistema de drenaje a fin de asegurar el rendimiento de las cosechas en la parte oeste de la Cuenca Central de Kızılırmak, Turquía. El modelo fue comprobado bajo condiciones áridas, utilizando datos de campo relativos al trigo de invierno y maíz. Se observaron diariamente, a lo largo de la temporada de crecimiento, la profundidad del nivel freático, el flujo y la salinidad del agua de drenaje. La salinidad del suelo se midió a la profundidad de 1,00 m. Se evaluó la fiabilidad del modelo comparando los valores diarios medidos y simulados y se encontró un buen ajuste entre ambos valores. La desviación absoluta fue de 5,68 cm para la profundidad del nivel freático; 10,13 cm para el flujo de drenaje; 0,66 dS m⁻¹ para la salinidad del agua de drenaje; y entre 0,51 y 0,96 dS m⁻¹ para la salinidad del suelo. Los correspondientes coeficientes de eficiencia (*E*) estuvieron entre 0,48 y 0,95. Según los resultados de la simulación, son necesarios un espaciamiento entre drenajes de 125 m y una profundidad de drenaje de 160 cm para asegurar una buena cosecha e impedir la degradación del suelo y del agua en esta zona. Los resultados demuestran que DRAINMOD-S puede ser una herramienta útil para el diseño y la evaluación de los sistemas del riego y de drenaje en suelos salinos bajo climas áridos y semiáridos.

Palabras clave adicionales: gestión del nivel freático; maíz; sistema de drenaje; trigo.

Introduction

Water logging problems in arid and semiarid regions are usually associated with issues of high soil salinity. Salinity build-up in the soil can have an adverse effect

on crop yield due to a large number of factors. Previous studies showed that 2.8 million hectares within Turkey have both salinity and water logging problems (Sonmez *et al.*, 2003). Climatic, geochemical and hydrological conditions often promote salt accumulation in the soil

profile, particularly in semi-arid areas such as the Central Anatolian region. Traditionally, irrigation and drainage systems were designed, constructed and managed separately. More often, irrigation systems were introduced without considering the drainage needs. Therefore, poor water management and agronomic practices without sufficient drainage systems are the major causes of salinity.

The design and operation of combined irrigation–drainage systems require simulation of the water regime in the soil profile. Due to system complexity and the excessive time and cost of field experiments, simulation models can provide a method to significantly reduce the required time and effort and could be used to describe the performance of water management systems. In recent years, computer simulation models have been developed that describe that performance. Field-testing of the model over a wide range of climatic conditions, soil and agricultural conditions is, therefore, an essential part of model evaluation and calibration. Once the model has been calibrated, the model constitutes an excellent tool for long-term planning of water management systems.

Several models are available and have been used for this purpose (Skaggs, 1999). Currently, some computer simulation models can simulate surface and subsurface flows as well as chemical transport through soil [ANSWERS (Bouraoui *et al.*, 2002), CREAMS (Knisel, 1980), GLEAMS (Knisel, 1993), SALTMOD (Bahceci *et al.*, 2006; Bahceci and Nacar, 2007), SWAT (Arnold *et al.*, 1998), ADAPT (Alexander, 1988), and DRAINMOD (Skaggs, 1980)]. One of the most widely used models is DRAINMOD, developed by Skaggs (1976, 1978). This model employs the concept of macroscopic water balance in a vertical soil column at the midpoint between parallel drains. The model is relatively simple and has been used by experts throughout the USA as well as in other parts of the world (Skaggs, 1999). However, only a modified version of this model, termed DRAINMOD-S, can reliably simulate the combined effect of drainage design and irrigation management on soil salinity, and also crop yields in irrigated arid and semi-arid lands.

The DRAINMOD-S simulation model is a simplified water balance approach, simulating water flow in irrigated land with shallow ground water tables. DRAINMOD-S provides daily average flux as a function of depth in the unsaturated zone above the groundwater table (Kandil, 1992; Kandil *et al.*, 1992). The average flux over time step Δt at any distance Z below the soil

surface is determined by breaking the profile into depth increments, Δz and calculating the volume of water removed or added to each increment. In the saturated zone, the vertical fluxes are linearly decreased from the net recharge at the water table level, to zero at the impermeable layer depth. In addition, a profile of soil moisture content is also generated using soil moisture characteristic data based on the drained-to-equilibrium assumption. This method has proved to give reliable results for flux computation (Skaggs *et al.*, 1991) and solute transport (Kandil *et al.*, 1992) when compared to fluxes predicted with a finite element solution of the Richards equation. The advective-dispersive-reactive equation (mass balance approach) has been used to simulate total dissolved salt concentrations in the soil profile at each time step (Kandil, 1992).

The objectives of this study was to determine the reliability of DRAINMOD-S for simulating water management in irrigated land and to simulate drainage system design criteria to ensure high crop yields for the western part of the Central Kızılırmak Basin in Turkey.

Material and methods

Site description

Experimental sites are located in western part of the Central Kızılırmak Basin (39°25'N, 33°23'E) of the Central Anatolia region in Turkey. A continental climate is seen in regions distant from the sea and surrounded by mountains; Central Kızılırmak Basin is in this category. Temperature differences between night and day and summer and winter are sharp, and rain is relatively infrequent. Winters are long and cold with heavy snowfall, while summers are short but hot. The rainiest months are November and May. Almost no effective rain falls during the summer. Average annual rainfall for the region is approximately 350 mm and annual evaporation is 1255 mm. Small areas with microclimate effects experience somewhat higher annual rainfall but, as a whole, the area has a very uniform, semi-arid type climate. Near freezing or freezing temperatures prevail from about mid-November to mid-March. Average annual wind speed is 1.2 m s⁻¹. Overall basin area was 2,527 ha and the field experiment was conducted on 7.3 ha in the Bala Agricultural Research Station (Figure 1).

The dominant soils in the Basin are the Reddish Brown and Brown soil groups. Soils at the experimen-

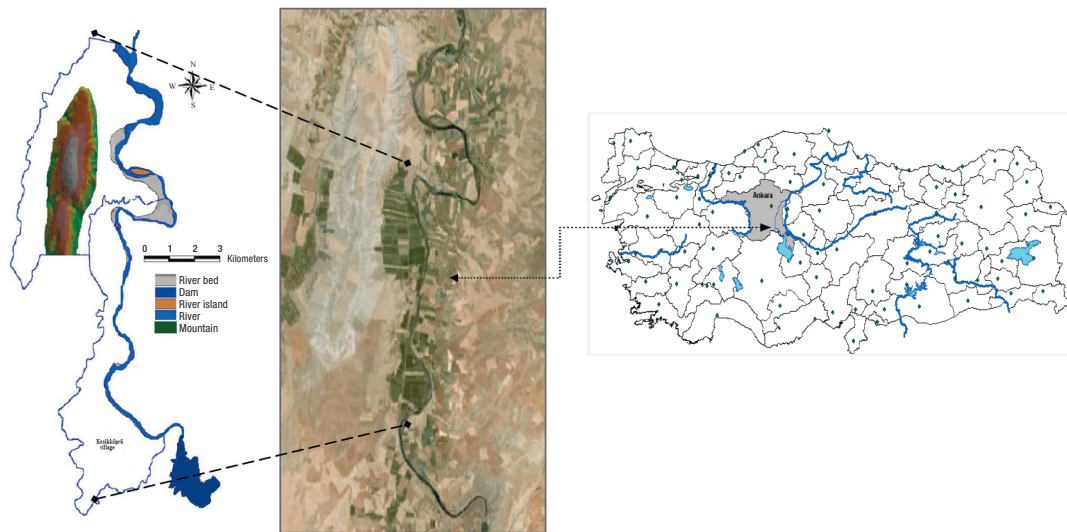


Figure 1. Experimental field site.

tal site are generally heavy textured. Soil textures are medium and fine near the riverbed. Soil textures were 60% clay (C), 25% clay loam (CL), 7% sandy loam (SL) and 7% loam (L) in the experimental site. Bulk density, available moisture capacities and infiltration rates varied between 1.17 and 1.56 g cm⁻³, 20 and 58 mm/30 cm, and 1.5 and 27.6 mm h⁻¹, respectively, depending on soil textures.

Wheat (*Triticum durum*) is the most important crop in the region, but yields are irregular, and crops fail in years of drought. Most of the wheat is planted in the late fall, as soon as there is significant moisture for seeding. Within the experimental site, corn (*Zea mays*) and dry bean (*Phaseolus vulgaris*) are largely grown under irrigation.

Irrigation waters are diverted from Kesikkopru Dam Lake; the reservoir volume at normal water surfaces elevation 95.00 hm³. During the growing period, irrigation water quality was moderate saline (Ayers and Westcot, 1994) and total dissolved solids were between 1.57 and 1.86 dS m⁻¹ (1,005-1,190 mg L⁻¹).

Model description

The DRAINMOD water management simulation model (Skaggs, 1978; Skaggs *et al.*, 1991) was developed for the comprehensive analysis of soil water movement on a field scale where most water management facilities are designed and installed as a single unit. The DRAINMOD model predicts the response of the ground water table and the soil water above the

ground water table to other hydrologic components, such as infiltration and evapotranspiration (ET), as well as to surface and subsurface drainage, and the use of ground water table control or subirrigation. The new version of the model, DRAINMOD-S (Kandil, 1992), includes an explicit solution of the advective-dispersive equation to predict solute transport. The model is used to evaluate the effect of the water management system on crop yield in the form of drought stress, excess stress, salinity stress and planting delay for the simulated crop rotation. In general, the main input data are soil properties, water management variables, climate conditions and crop data.

The basic advective-dispersive differential equation to predict solute transport [1] reads:

$$\frac{\partial \theta C'}{\partial t} = \nabla \cdot (\theta D_h \nabla C' - qC) + R(C'') + \Gamma_c \quad [1]$$

where C' is the volume-average solute concentration (mg L⁻¹); θ is the volumetric soil moisture content (cm³ cm⁻³); t is the time (day); D_h is the second-rank hydrodynamic dispersion coefficient (cm² day⁻¹); q is a flux vector (cm day⁻¹); $R(C'')$ is a general solute reaction term (mg L⁻¹ day⁻¹); and Γ_c represents the solute sources (mg L⁻¹ day⁻¹). The equation [2] can be approximated for downward flow as:

$$C_{i,yeni} = \frac{C_{i,o} \theta_{i,o}}{\theta_{i,ini}} + \frac{(M_o - M_i)}{\Delta Z \theta_{i,ini}} + \frac{\Gamma \Delta t}{\theta_{i,ini}} \quad [2]$$

where $C_{i,o}$ and $C_{i,ini}$ are the salt concentrations at the end of the previous and the new time steps (mg L⁻¹); $\theta_{i,o}$ and $\theta_{i,ini}$ are the soil moisture contents of layer i at the

end of the previous and the new time steps; M_i and M_o are the mass of salt (mg) entering and leaving the soil layer i in time Δt ; Γ is a source/sink term ($\text{mg L}^{-1} \text{day}^{-1}$); Z is the vertical distance increment (cm); and t is the time increment (day).

The model calculates daily total dissolved salt concentrations in the soil profile (mg L^{-1}) and drainage water salinity level (mg L^{-1}). Salinity results were divided by 640 to convert from mg L^{-1} to dS m^{-1} . Evaluation of salinity results were made as dS m^{-1} .

Input data for the DRAINMOD-S model

Input data for DRAINMOD-S included climatological, soil property, crop variables, irrigation, and drainage system data.

Climatological data: Using DRAINMOD-S to simulate the on-farm water management system requires daily ET and hourly precipitation weather data. Hourly precipitation, maximum-minimum daily temperature, class-A pan evaporation (pan coefficient 0.70), wind speed, and sunshine hours were continuously obtained from Bala auto-meteorological station, located 2 km from the experimental site. Daily potential evapotranspiration (PET) was computed for the years 2000 and 2003 using the FAO Penman Monteith (FAO, 1998) methods.

Soil data: The lateral saturated hydraulic conductivity (K_{sat}) was measured in the field with the auger hole method. Table 1 shows the soil physical properties and saturated hydraulic conductivity values of the experimental field.

Soil water characteristics of the soil profile down to the drain depth were obtained in the laboratory using undisturbed soil cores using pressure plate tests, which

allowed calculation of the volumetric water content at suction pressures of 10, 20, 33, 63, 346, and 1500 kPa (Table 2).

The drainage volume, upward flux and infiltration parameters were calculated by an internal DRAINMOD-S subroutine, which uses the soil water characteristic of each layer of the soil to produce values of volume drained for water table positions ranging from the surface to the bottom of the soil profile (Skaggs, 1980). The soil water available to the plant is limited by the upward flux from the water table to the plant roots. The soil preparation program includes a routine that calculates the maximum water table depths that will support a given upward flux value (Skaggs, 1980). Coefficients of the Green-Ampt infiltration equation and maximum rate of upward water movement as a function of the ground water table depth were determined from the lateral saturated hydraulic conductivity and soil water characteristic relationships using the *soilprep* program of the model.

Salinity data: Four different sampling points were chosen for measuring soil salinity. Soil samples were collected at 20 cm increments within the soil profile, down to 100 cm below the soil surface, at the beginning (as initial soil salinity) and end of every growing period. Irrigation water samples were taken before irrigation events for salinity analysis. Irrigation water salinities were within the range 1.574 – 1.867 dS m^{-1} . Dispersivity coefficient was derived using the Neuman (1990) equation [3]:

$$\alpha_L = 0.0175L^{1.46} \quad [3]$$

where α_L is dispersivity and L is the field scale. Dispersivity was calculated as 4.13 cm.

Sensitivity analysis of the model was performed on the dispersivity parameter of salinity input. Dispersivities were tested between 3 cm and 20 cm. The

Table 1. Soil hydraulic conductivity and texture of the field site

Soil depths (cm)	Hydraulic conductivity (cm h^{-1})	Texture
0-12	1.24	Silty clay loam
12-23	0.69	Clay loam
23-54	0.33	Clay
54-102	0.54	Clay
102-140	0.20	Clay
140-180	0.45	Clay
180-220	0.12	Silty clay
220-300	0.68	Clay
300-400	0.25	Clay
400-450	0.07	Clay

Table 2. Soil water characteristics (volumetric water content $\text{cm}^3 \text{cm}^{-3}$)

Depth (cm)	Soil water pressure head (cm of water)						
	0	-10	-20	-33	-63	-346	-15000
0-12	0.410	0.390	0.350	0.330	0.280	0.223	0.165
12-23	0.398	0.378	0.338	0.302	0.262	0.213	0.151
23-54	0.437	0.413	0.404	0.395	0.391	0.358	0.216
54-102	0.456	0.432	0.420	0.415	0.400	0.356	0.231
102-140	0.469	0.439	0.432	0.421	0.408	0.365	0.248
140-180	0.450	0.437	0.425	0.413	0.399	0.361	0.231

results of the sensitivity analysis on dispersivity showed that it had very little effect on the model outputs.

Crop data: Relative crop yield in DRAINMOD is predicted as a product of relative crop yields resulting from planting delay (YR_p), wet stress (YR_w), drought stress (YR_d) and salinity effect (YR_s). Model defined the relative yield as a function of four components in Eq. [4]:

$$YR = Y / Y_o = YR_w * YR_d * YR_s * YR_p \quad [4]$$

where YR (% of maximum potential yield), is the relative yield; Y is the yield for a given year; Y_o is the optimum long term average yield; YR_w is the relative yield if only reductions due to excessive soil water conditions are considered; YR_d is the relative crop yield if only reductions due to deficient soil water conditions are considered; YR_s is the relative crop yield if the only reductions are due to soil salinity; and YR_p is the relative yield that would be obtained if only a reduction due to planting date delay is considered (for experimental field, planting delay effect on crop yield is negligible).

DRAINMOD estimates relative yield by the use of the stress day index (SDI) approach which is described by Hiler and Clarck (1971). YR_w is computed by using the SDI method, which considers the crop susceptibility to excessive soil-water conditions for different growth stages during the growing season.

The model used for predicting corn yield response can be summarized as [Eq. 5, 6, 7]:

$$YR_w = YR_{wmax} \text{ for } SDI_w < 8 \quad [5]$$

$$YR_w = YR_{wmax} - D_{slope} * SDI_w \quad [6]$$

for $8 < SDI_w < (Y_{rwmax}/D_{slope})$

$$YR_w = 0.00 \text{ for } SDI_w > (YR_{wmax}/D_{slope}) \quad [7]$$

where YR_{wmax} is the maximum yield (%) in the absence of excessive soil-water, D_{slope} is the slope of the predicting equation, and SDI_w is the SDI for wet conditions.

The SDI_w is expressed as [Eq. 8]:

$$SDI_w = \sum_{i=1}^N [CS_{wi} * SD_{wi}] \quad [8]$$

where N is the number of days in the growing season, CS_{wi} is the crop susceptibility factor for excessive wet conditions for day i (as affected by genotype, soil type, fertility, temperature, etc.) and SD_{wi} is the stress day factor for day i and is taken as the daily value of SEW_{30} (sum of excess water). The SEW_{30} was defined by Sieben (1964) and has been used by many researchers including Kanwar *et al.* (1988).

Relative crop yields resulting from drought stress is expressed as [Eq. 9]:

$$YR_d = YR_{dmax} - YR_{dslope} * SDI_d \quad [9]$$

where YR_{dmax} is the maximum relative yield (%) in the absence of deficient soil-water stresses, YR_{dslope} is the slope of the predicting equation, and SDI_d is the SDI for drought conditions [Eq. 10].

$$SDI_d = \sum_{i=1}^N [CS_{di} * SD_{di}] \quad [10]$$

where CS_{di} and SD_{di} are, respectively, crop susceptibility factors and the stress day for growth period i , and N is the number of periods in the growing season. The SD_{di} is defined as [Eq. 11]:

$$SD_{di} = \sum_{j=1}^{N_i} 1 - \frac{AET_j}{PET_j} \quad [11]$$

where AET and PET are, respectively, the actual and potential daily evapotranspiration (ET), and N_i is the number of days in the i^{th} growing period.

An excessive accumulation of salts in the soil profile causes a decline in productivity. Soil salinity affects plants directly by reducing the osmotic potential of the soil solution and by the toxicity of specific ions such as boron, chloride and sodium. Some plants can survive in salt affected soil but many are affected to varying extents, depending on their tolerance to salinity. The same crop may even have different levels of salinity tolerance during its different growing stages. Mass and Hoffman (1977) indicate that each increase in soil salinity (salinity was expressed in terms of the electrical conductivity of the saturated extract) in excess of the concentrations that initially begin to affect yield will cause a proportional decrease in yield.

They proposed the following equation [12] to express this effect:

$$YR_s = 100 - b * (EC_e - a) \quad [12]$$

where YR_s is the relative crop yield (%) if the only reductions are due to soil salinity; EC_e is the salinity of the soil saturated extract (dS m^{-1}); a is the salinity threshold value for the crop, representing the maximum EC_e at which a 100% yield can be obtained (dS m^{-1}); and b is the yield decrement per unit of salinity, or % yield loss per unit of salinity (EC_e) between the threshold value (a) and the EC_e value representing the 100% yield decrement. The threshold value depends on the crop tolerance to salinity. The coefficients a and b for

corn and wheat were 1.7 dS m⁻¹ and 12% per dS m⁻¹, and 6.0 dS m⁻¹ & 7.1% per dS m⁻¹ respectively (Maas and Hoffman, 1977).

Drainage system parameters: Subsurface drainage systems at the field site were installed in 1998. Drainage system input parameters required for simulation include the depth from the soil surface to the drain, drain spacing, drainage coefficient, the effective radius of the drains used and the depth of the impermeable layer. Drainage design variables inputs for experimental site was drain depths 1.80 m, drain spacing 50 m, drainage coefficient (m day⁻¹) effective drain radius 0.030 m and actual distance from surface to impermeable layer 4.50 m.

Evaluation procedure

A statistical evaluation of model reliability was performed by comparing measured and predicted daily water table elevations, drainage flow, and soil salinity at the end of the each season, drainage water salinity and relative crop yields.

The agreement between predicted and measured values was quantified by calculating the standard errors (*SE*), average absolute deviations (α) and coefficient of efficiency (*E*). The average absolute deviation was calculated for each test period as given in equation [13] (Janssen and Heuberger, 1995):

$$\alpha = \frac{\sum_{i=1}^n |Y_m - Y_p|}{n} \quad [13]$$

where Y_m is the i^{th} measured value; Y_p is the i^{th} predicted value for a total number of events n , which is the total number of days in the case of ground water table depth, drain outflow, soil salinity and relative crop yield. The standard error (*SE*) was calculated as in Equation [14] (Lyman, 1993):

$$SE = \sqrt{\frac{\sum_{i=1}^n (Y_m - Y_p)^2}{n}} \quad [14]$$

The coefficient of efficiency *E* has been widely used to evaluate the performance of solute transfer models (James and Burges, 1982; Janssen and Heuberger, 1995; El-Sadek *et al.*, 2001, 2003; Singh *et al.*, 2001; Fernandez *et al.*, 2006; Dayyani *et al.*, 2009). Nash and Sutcliffe (1970) defined the coefficient of efficiency, or modeling efficiency (*E*) as in Equation [15]:

cient of efficiency, or modeling efficiency (*E*) as in Equation [15]:

$$E = 1 - \frac{\sum_{i=1}^n (Y_m - Y_p)^2}{\sum_{i=1}^n (Y_m - Y_{avg})^2} \quad [15]$$

where n is the total number of observations; Y_m is the observed value of the i^{th} observation; Y_p the predicted value of the i^{th} observation; and Y_{avg} the mean of the observed values ($i = 1$ to n). *E* values ranges from minus infinity to 1.0, with a value of 1.0 representing a perfect prediction, a value of 0 (zero) representing a prediction no better than using the mean of measured values, and lower values representing a progressively worse prediction. Values of *E* between 0.50 and 1.00 are considered acceptable.

Model calibration

Calibration is the process where the model's input parameters are changed to obtain the optimal agreement between the predicted and observed system variables (Singh *et al.*, 2006). The model was calibrated using the monthly drain flow data for seven months from March to September in 2001. Calibration proceeded by manually adjusting lateral saturated hydraulic conductivity K_{sat} (cm h⁻¹) of soil layers, which is the most uncertain and sensitive soil parameter used in DRAINMOD. Hydraulic conductivity K_{sat} (cm h⁻¹) was adjusted manually in the model and simulation results compared to statistically with observed data. This process was repeated until calibration parameters were in a certain range to minimize the differences between the predicted and observed drain flow during the March to September in 2001.

However, Skaggs (1982) suggested that changing various input parameters to obtain the optimal agreement between the predicted and observed system variables would not provide a meaningful test of the model's reliability. Therefore, both measured and adjusted K_{sat} values were in the range reported by Smedema and Rycraft (1983) for soil texture.

Experimental studies and model validation

The water table elevation midway between drains was measured in 5 cm diameter observation wells,

drilled to the depth of the restrictive layer, and fitted with automatic water level recorders to record the depth of the water table every 10 minutes. Drainage volumes were collected to determine quantity bucket, and fill up time was recorded using a chronometer. Soil moisture was measured with a Neutron Probe for 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm soil depths twice per week. Irrigation water was applied based on soil moisture depletion, using a linear move sprinkler irrigation system. To measure soil salinity, 20 different sampling points were chosen and samples were collected at 20 cm increments within the soil profile, down to 100 cm below the soil surface, before and after the growing season.

The crop rotation for the experiment was winter wheat followed by corn. The simulations were performed for 3 years (2001-2002-2003). Winter wheat and corn were planted on the 1st of October 2001 and 1st of May 2003, respectively.

Results and discussion

Simulation of water table depths

The observed and simulated water table depths for winter wheat in 2001-2002 and corn in 2003 are presented in Figures 2 and 3, respectively.

The computed standard errors (SE) and average absolute deviation (α) for the water table managements during the simulation period (from 18th of October 2001 to 31st December 2002 for wheat; 1st of May to 15th of October 2003) are given in Table 3. Generally, DRAINMOD-S simulated the pattern of water table fluctuations with a good degree of accuracy for all years. Observed and simulated water tables often rise rapidly in response to rainfall and irrigation events, causing rapid fluctuations and time lags, which result in a lower E value. In this situation, E values were 0.66 and 0.56 for 2001-2002 and 2003, respectively. The E values for water table predictions were considered good, considering that the water table fluctuated rapidly in response to rainfall or irrigation events. The results showed good agreement between measured and predicted water table depth midway between drains. The average absolute deviations were 5.7 cm for 2001-2002 and 5.0 cm for 2003, while the standard errors obtained were 7.5 cm and 5.7 cm, respectively.

Simulation of drain outflows

The relationship between observed and predicted monthly drain flow during the calibration period is given Figure 4. The predicted and observed drain out-

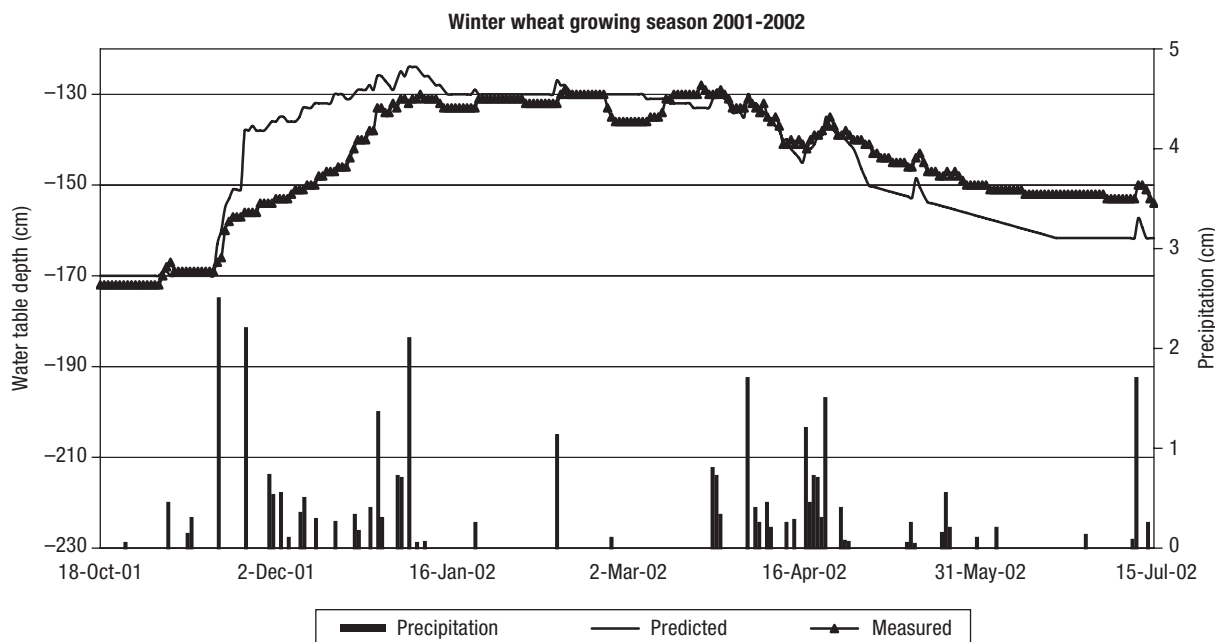


Figure 2. Observed and simulated water table depths (WTD) for 2001-2002.

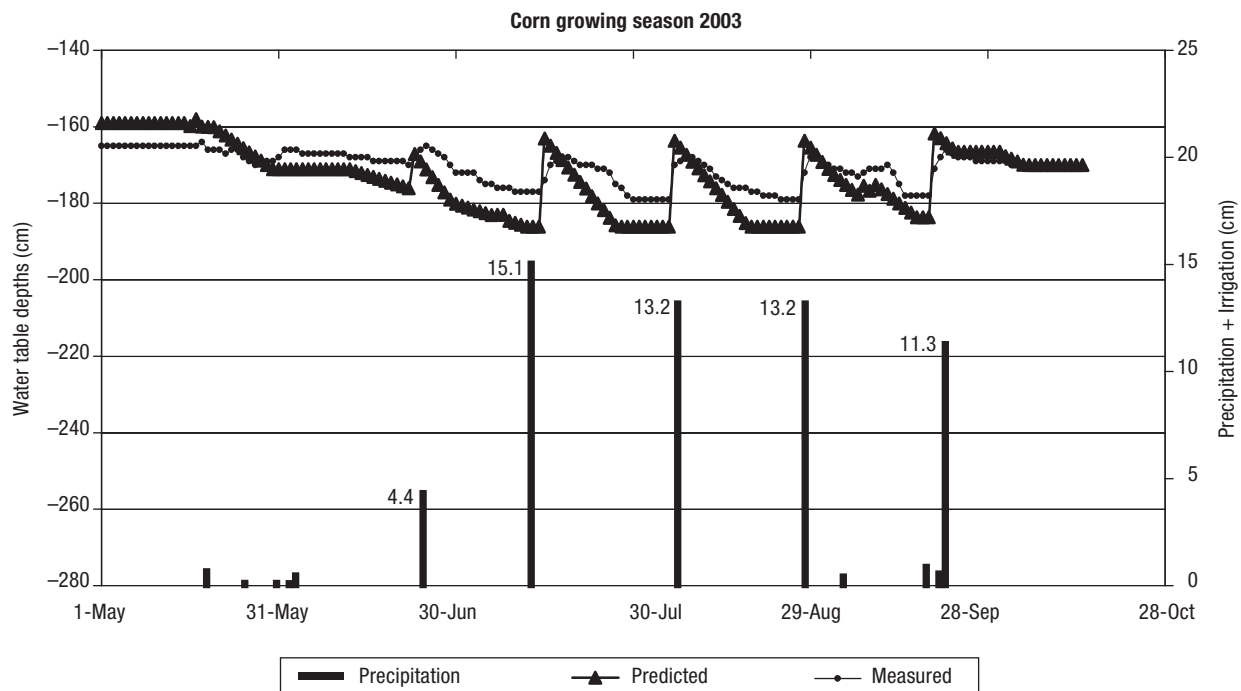


Figure 3. Observed and simulated water table depths (WTD) for 2003.

flows for winter wheat in 2001-2002 are plotted in Figure 5 and for corn in 2003 in Figure 6.

Although in many instances, simulated drain flows were slightly underestimated, the timing of simulated and observed peaks matched reasonably well. DRAINMOD-S accurately simulated the pattern of drain outflows over the simulated period (2001-2003). The model predictions closely follow the trend of the ob-

served values (Table 3). The peak drainage flows were also simulated relatively accurately.

It can be seen that drain outflows (after heavy rainfall and irrigation events) were predicted well ($E = 0.56$ and 0.63) and the simulated values were in good agreement with the observed values. This indicates that the model is capable of simulating drain flow accurately in semi-arid regions.

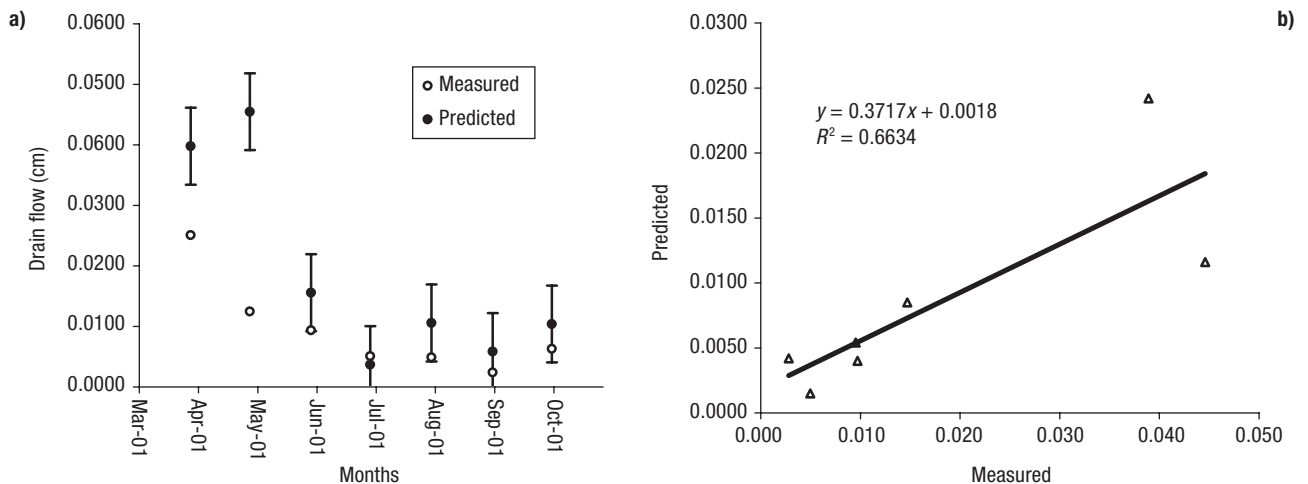


Figure 4. Measured and predicted monthly drain flow (a), the relationship between measured and predicted drain flow during the calibration period (b). Bar shows standard deviation.

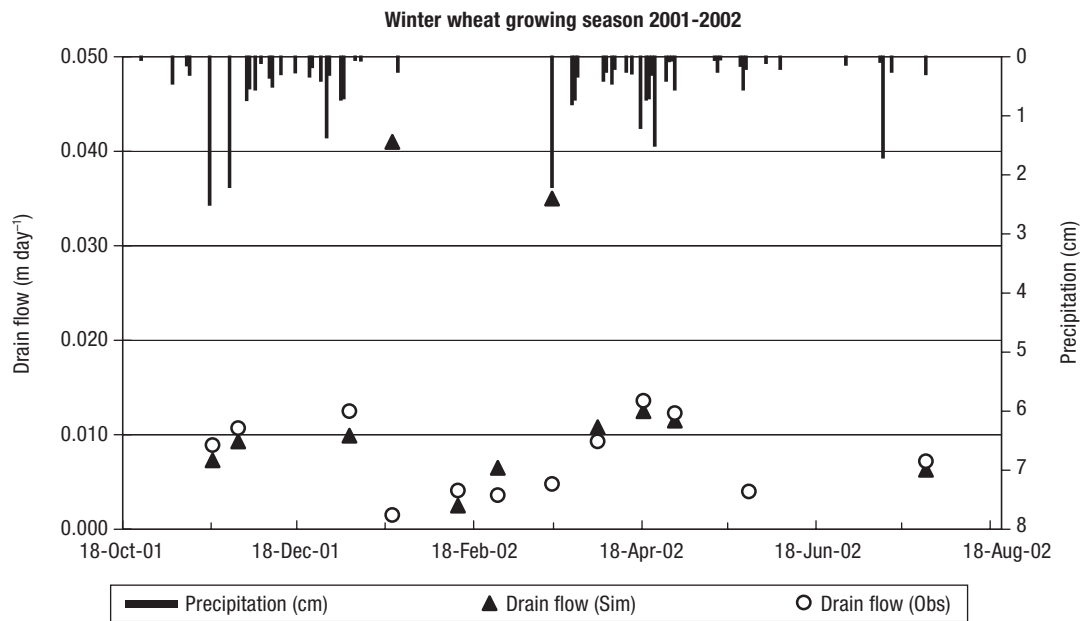


Figure 5. Observed and simulated drain flow for winter wheat.

Simulation of soil and drainage water salinity level

A series of 20 representative soil sampling points were chosen near observation wells to obtain salinity data. Soil samples were collected for 20 cm increments of soil profile down to 100 cm below the soil surface

before planting of winter wheat (as initial soil salinity) and after the wheat and corn growing period. Variations in soil salinity according to soil depths are presented in Figures 7 (a-winter wheat, b-corn).

The agreement was quantified by conducting statistical analysis between the observed and simulated soil salinities. Average absolute deviations (α) and standard

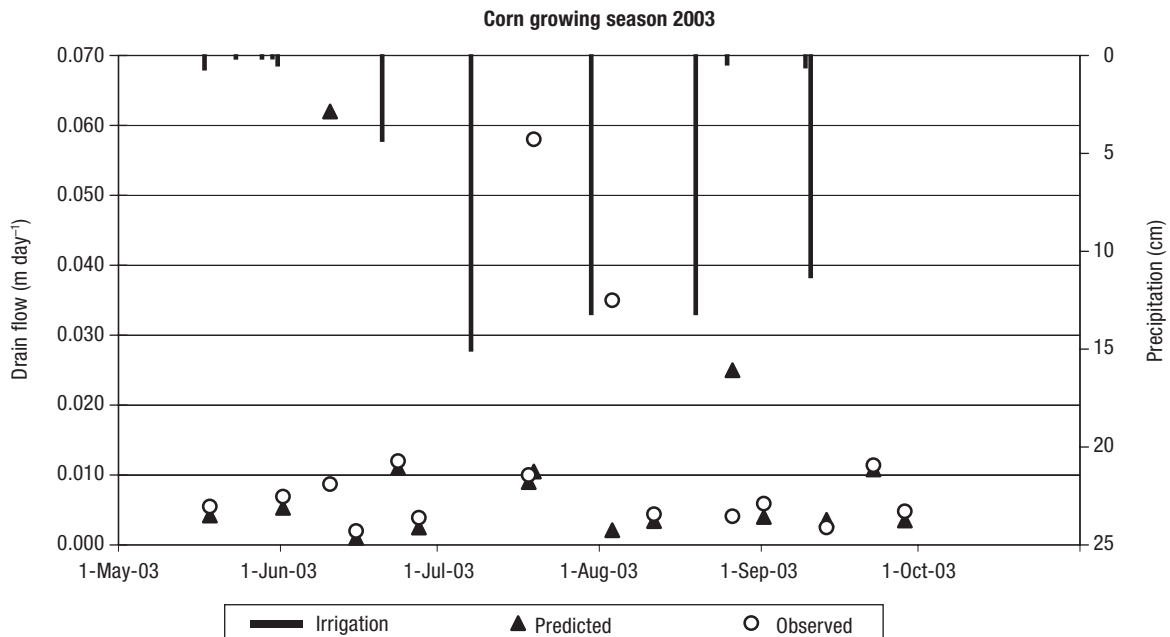


Figure 6. Observed and simulated drain flow for corn.

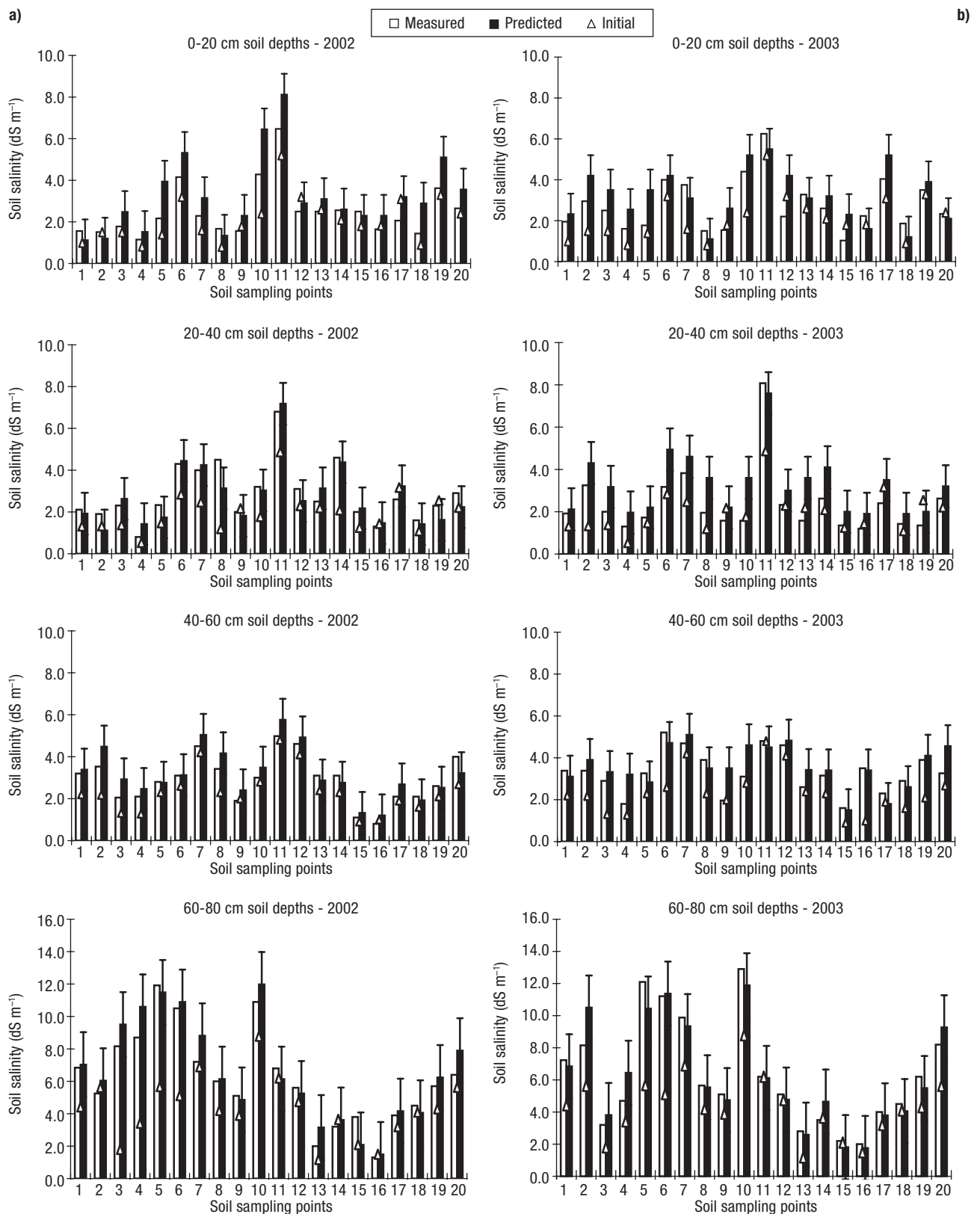


Figure 7. Comparison of initial, measured and predicted soil salinity at the end of the simulation period for winter wheat (a) and corn (b).

Table 3. Comparison of predicted and measured water table depths and drain flow

Statistical parameter	Water table depths		Drain flow	
	Wheat 2001-2002	Corn 2003	Wheat 2001-2002	Corn 2003
n	271	167	12	15
α (mm)	56.89	49.96	10.13	11.19
SE (mm)	74.64	57.09	18.21	21.03
E	0.66	0.56	0.56	0.63

Table 4. Average absolute deviations (α) standard errors of estimate (SE) and modeling coefficient (E) for measured and predicted soil salinity

Season	Depths (cm)	n	α (dS m ⁻¹)	SE (dS m ⁻¹)	E
2002	0-20	20	0.87	1.04	0.61
	20-40	20	0.51	0.67	0.81
	40-60	20	0.53	0.79	0.63
	60-80	20	0.77	0.95	0.94
2003	0-20	20	0.81	0.95	0.60
	20-40	20	0.96	1.10	0.68
	40-60	20	0.57	0.74	0.48
	60-80	20	0.69	0.92	0.95

Table 5. Irrigation date and irrigation water amount

Irrigation date	Irrigation water amount, mm
23 June	43.4
15 July	171.6
6 August	132.0
28 August	132.0
19 September	113.1

Table 6. Predicted relative yield components of winter wheat and corn

Crop	Excess (RY _w)	Deficit (RY _d)	Salinity (RY _s)	Overall (RY)
Winter wheat	100	94.1	97.4	91.4
Corn	100	100	86.6	86.6

errors of estimate (SE) and coefficient of efficiency or modeling efficiency (E) for measured and predicted soil salinity were given in Table 4.

Wheat was grown without irrigation. Total applied irrigation water for corn was 592.1 mm, and was set to just satisfy ET requirements with no additional water for leaching salt. Irrigation time and applied irrigation water are presented in Table 5. Four different sampling

points are given in Figure 8 to illustrate soil salinity changes within the soil profile.

The results indicated that the effect of irrigation salt content on the soil salinity was more pronounced in the deep layers than in the surface layer. The only unacceptable prediction ($E \leq 0.50$) was for 40-60 cm soil depth in 2003. Other results presented a very good prediction for soil salinity, with E values between 0.60 and 0.95.

The agreement was quantified by conducting statistical analysis between the observed and simulated drainage water salinities. The salinity of the drain water samples ranged between 2.11 and 8.49 dS m⁻¹ throughout the observation period. Predicted drainage water salinities were within approximately the same range. A slight improvement in drainage water quality was observed towards the end of the corn growing season. In general, good agreement was observed between the simulated and measured drain water salinity, with $E = 0.85$. Measured and predicted drainage water salinity is presented Figure 9.

Crop yield predictions

Winter wheat and corn were harvested on the 30th of July in 2002 and the 15th of October 2003, respectively. Crop yield was 4.92 t ha⁻¹ for winter wheat and 9.44 t ha⁻¹ for corn in the experimental field. According to data from the General Directorate for Agricultural Production Development (Turkish Ministry of Agriculture), standard actual crop yields for winter wheat and corn are 5.50 t ha⁻¹ and 11.60 t ha⁻¹, respectively for the project basin.

Model run and crop yield were predicted for the simulation period. Predicted relative yields components (RY_w · RY_d · RY_s · RY_p) are given in Table 6. The simulated and observed relative yields are plotted in Figure 10.

The observed and simulated relative yields were 89-91% for winter wheat and 81-86% for corn, respectively. Wheat was grown under dry (without irrigation) conditions, so both soil salinity and stress caused by deficit water conditions were slightly reduced to wheat crop yield. Predicted yields for corn suggest that crop yield was negatively affected by high soil salinity.

Effect of drain depth and drain spacing on crop yield

Simulations were conducted for crop rotation (the experiment used winter wheat followed by corn) to

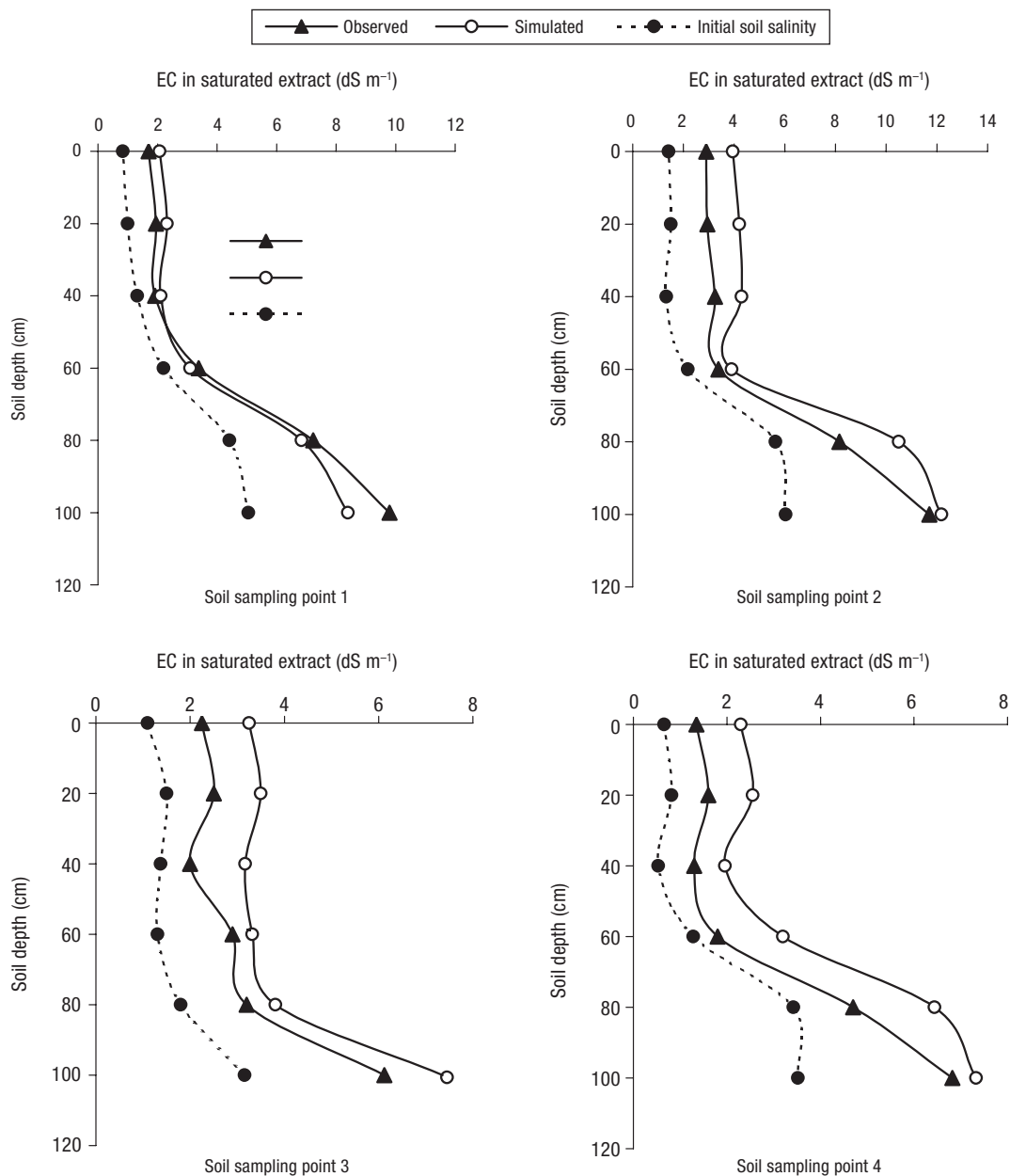


Figure 8. Observed and simulated salinity in soil profile.

determine the effect of drain depth and spacing on crop yields for the western part of the Central Kızılırmak Basin. Predicted overall crop yields are presented Table 7 and Figure 11. It was assumed that crop yield did not decrease greatly with deep drain depths because of the heavy soil texture of the experimental field. According to the yield simulation results for different drain depth and drain spacing scenarios, the highest yields were obtained with 125 m drain spacing and 160 cm drain depth, which can be

recommended for the western part of the Central Kızılırmak Basin in Turkey.

Conclusions

The water management model DRAINMOD-S was tested using data from field experiments at Bala Agricultural Station in the western part of the Central Kızılırmak Basin in Turkey for two cropping seasons;

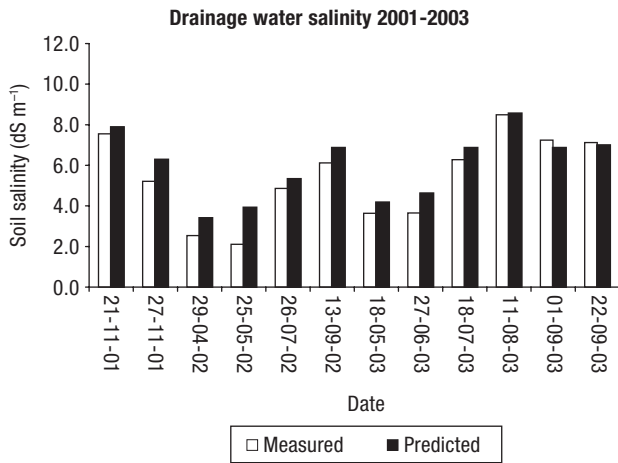


Figure 9. Observed and simulated drainage water salinity.

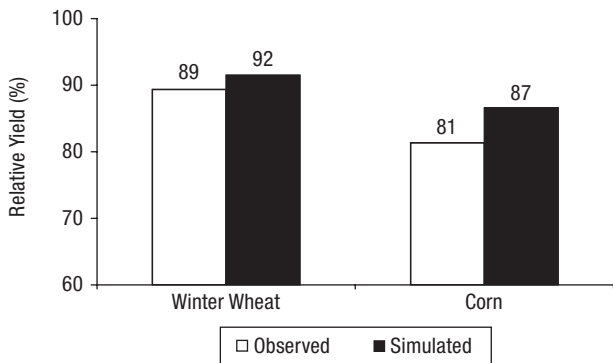


Figure 10. Observed and simulated relative yields.

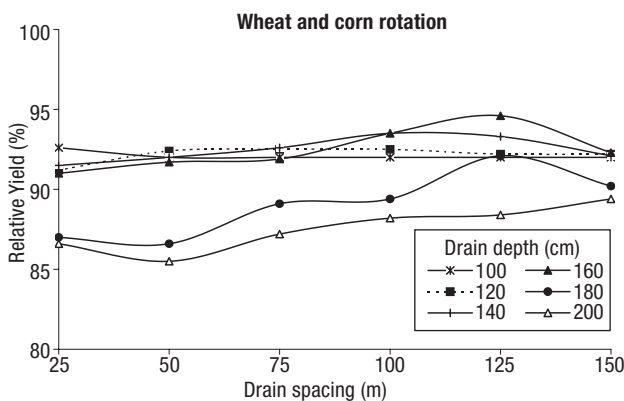


Figure 11. Simulated relative yields for wheat and corn rotation.

winter wheat 2001-2002 and corn 2003. The reliability of the model was evaluated by comparing measured and predicted values of daily ground water table depth, drainage flows, soil salinity during each season, and relative crop yield.

Table 7. Predicted overall crop yields for winter wheat and corn rotation at different drain spacing

Drain depth (cm)	Drain spacing (m)					
	25	50	75	100	125	150
	Relative yields (%)					
100	92.6	92.0	92.0	92.0	92.0	92.0
120	91.2	92.4	92.5	92.5	92.2	92.2
140	91.5	92.0	92.6	93.5	93.3	92.1
160	91.0	91.7	91.9	93.5	94.6	92.3
180	87.0	86.6	89.1	89.4	92.1	90.2
200	86.6	85.5	87.2	88.2	88.4	89.4

Satisfactory agreement was found between the measured and predicted water table depth within absolute average deviations range from 49.9 to 56.9, drain flows from 10.1 to 11.2, soil salinity from 0.51 to 0.96 dS m⁻¹, drainage water salinity 0.66 dS m⁻¹.

Based on the results of the study it is concluded that DRAINMOD-S can be used to predict the effect of drainage system design on water table elevations and soil salinity level. Also the results indicated that the model enabled the description of relative yields of corn and wheat crops. The model showed the potential for long-term simulation and planning of water table management under the semi-arid conditions of the Central Kızılırmak Basin of Turkey.

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