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Full Length Research Paper

Estimating effects of drainage design parameters on crop yields under irrigated lands using DRAINMOD

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The purpose of this study is to predict optimal drainage design parameters for ensuring maximum crop yield under irrigated arid lands. The water management simulation model, DRAINMOD was applied to compute the effects of land drainage on soil moisture conditions in the root zone and their effect on crop yield in Bala-Koprukoy Basin in Central Anatolia Region of Turkey. Soil, crop and site parameters were obtained as inputs from field experiments. Model was run for 5 years to simulate optimum drainage design parameters (drain depth, drain spacing) while controlling soil salinity in root zone. Soil water conditions were simulated for crop rotation of corn and wheat. Yields of individual crops were predicted for each growing season. Results of the simulations were analyzed to identify alternative of subsurface drainage system that would satisfy maximum crop productions. According to the simulation results the optimum drain depth were found to be 1.2 m and drain spacing were 160 m for the multiple cropping *s*ystem in study area.

Key words: DRAINMOD, drainage, drain space, drain depth, wheat, corn.

INTRODUCTION

The main reason for drainage on agricultural land has been to enhance crop production. Drainage removes excess water from the soil and helps to create a well-aerated root environment that enhances plant uptake of nutrients. Drainage on wet agricultural soils allows timely field operations, and helps plant growth to begin early, continue vigorously, and achieve improved levels of productivity. In states that depend heavily on irrigation from surface water supplies, subsurface drainage is often used to prevent harmful buildup of salt in the soil. Drainage benefits crop production by minimizing risks, improving efficiency, and increasing net income.

The main cause for waterlogging and soil salinization is usually water seepage from the irrigation canals that lose a lot of water through their unlined banks and beds (Ayers et al., 1987). Furthermore, frequent irrigation applications also tend to keep the water table close to soil surface, and this combined with normal fertilizer applications, causes a slow salinization of the root zone, and affects crop yields. The natural drainability of these soils, as such, cannot cope with this man-caused problem. If this phenomenon is not checked on time through the installation of interceptor drains and subsurface drainage systems, most of the farmland that was very productive at one point becomes unproductive. Then the farmers either have to change their cropping practices or, in some cases, they cannot grow any crop at all (Gupta et al., 1993).

Waterlogging problems in arid and semi-arid regions are usually associated with high salinity problems. Salinity build-up in the soil has an adverse effect on crop yield because of a large number of factors. The processes involved are complicated, and interrelated with such factors as crop species, soil properties and salinity of irrigation water and subsurface drainage (Kandil et al., 1995). Computer simulation models are developed to describe this comprehensive system. DRAINMOD is one of the well known drainage simulation model to characterize the response of the soil water regime to various combinations of surface and subsurface water management.

DRAINMOD is a computer model that simulates response of the soil water regime to various combinations of surface and subsurface water management systems (Skaggs, 1980). It can be used to predict water table depth, subsurface drainage conditions, evapotranspiration and surface runoff affected by the various drainage, weather and soil property data.

The model has been subsequently tested in many parts of the world. Some of the field tests were carried out using DRAINMOD in Ohio (Skaggs et al., 1981; Nolte et al., 1983; Desmond et al., 1996), Georgia (Shirmohammadi et al., 1991), Illinois (Mostaghimi et al., 1985; Kurien et al., 1997), Louisiana (Fouss et al., 1987; Fouss et al., 1989), Iowa (Sanoja et al., 1990), Australia (Cox et al., 1994), Canada (Madramootoo 1990; Shukla et al., 1994), Italy (Bixio and Bortolini, 1997), Mexico (Quej and Palacios-Valez, 1996) and also Turkey (Cizikci et al., 2001; Kale, 2004; Kale et al., 2004).

The fields in this study region which are in Bala-Koprukoy Basin were opened irrigation in 1970. Until mid-1980, the irrigation land ratio was not more than 50% because of the inadequate system component, some field problems or uneducated farmers. In recent years, this ratio is much more than before but the farmers are faced to the different problems at this time. The most important problem in this area is that there is no efficient drainage system. Thus high water table, waterlogging and soil salinity problems are getting increase year by year because of excess irrigation and/or mismanagement of irrigation system.

The purpose of this study is to predict the effect of the tested parameters of drainage system using DRAINMOD simulations on the crop yield.

MATERIALS AND METHODS

Description of study site

The Central Anatolia Region, located in the centre of Turkey, covers approximately 19% of the land in Turkey, with a surface area of 151,000 km^2. The experimental site is located in Ankara-Bala of Central Anatolia region of Turkey. Average annual rainfall is 350 mm and annual pan evaporation is 1255 mm. The field experiment carried out on 1475 ha plot area (Figure 1).

According to the soil analysis results, top soil textures were silty clay loam and deeper soil textures were clay. The lateral saturated hydraulic conductivity was measured in the field using the auger holes method (Boast, 1971) and small-undisturbed core samples were taken for constant head permeameter test in the laboratory. Irrigation waters are diverted from Kesikkopru Dam Lake on the Kızılırmak River. This dam is used for energy and irrigation. Irrigation water quality is high saline and non-alkaline. Wheat and barley are grown commonly in study area. However, the yields for these crops are irregular and the optimum yield and production for crops have not been obtained in drought years. In addition, corn and dry bean are also grown in experiment site.

Model description

DRAINMOD is a computer model developed by Dr. R.W. Skaggs at North Carolina State University. DRAINMOD simulates the hydrology of poorly drained, high water table soils on an hour-by-hour, day-by-day basis for long periods of climatological record. The model predicts the effects of drainage and associated water management practices on water table depths, the soil water regime, drainage outflows, and crop yields. The main inputs data and parameters required for DRAINMOD include weather data, drainage system parameters, soil properties, crop, and trafficability parameters. A detailed description of DRAINMOD can be found in Skaggs (1978) and Skaggs (1982).

Model inputs and collected field data

Soil, crop and irrigation inputs were obtained from Bala Station of General Directorate of Agricultural Enterprise for research studies.

Weather inputs

DRAINMOD requires daily maximum and minimum air temperature, hourly rainfall amounts and potential evapotranspiration (PET) data. Climatological data were obtained from Bala meteorology station. Potential evapotranspirations (PET) were calculated by Penman-Montieth method. PET data were used directly in the model.

Soil inputs

Soil inputs are soil water content versus pressure head (pf curve), lateral conductivity of each soil layer, Green and Ampt infiltration parameters versus water table depth, volume drained versus water table depth and upward flux versus water table depth. Disturbed and undisturbed soil samples had been taken in the field for laboratory analysis. Impermeable layer was found generally 4 m. Soil texture and hydraulic conductivity are given in Table 1.

The soil water characteristic data for the predominant soil type were determined on soil cores using pressure plate tests, which allowed a calculation of the volumetric water content at suction pressures of 10, 20, 33, 63, 346, and 1500 kPa (pF curve in Figure 2).

The infiltration parameters, volume drained versus water table depth and upward flux versus water table depth can be estimated with the soil preparation program.

Initial soil salinity, irrigation water salinity, dispersion coefficient and crop salt tolerance parameters require as salinity input in the model.

Crops input data

The crop input data is that are rooting depths, SEW (the amount of excess soil water), trafficability inputs (trafficable conditions in the field), planting delays, excess soil water stress, deficient soil water stress and salinity stress.

The Equation (1) was used by DRAINMOD for computing crop relative yields.

$$YR = Y/Y_o = YR_p * YR_w * YR_d * YR_s \quad (1)$$

Where YR is the relative yield, Y is the yield for a given year, Y_o is the optimum long term average yield, YR_p is the relative yield that would be obtained if only reduction due to planting date delay is considered, 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 the only reductions are due to deficient soil water and YR_s is the relative crop yield if the only reductions are due to soil salinity.

An excessive accumulation of salts in the soil profile causes a decline in productivity. Mass and Hoffman (1977) indicate that each increases in soil salinity (salinity was expressed in terms of the electrical conductivity of the saturated paste) in excess of the

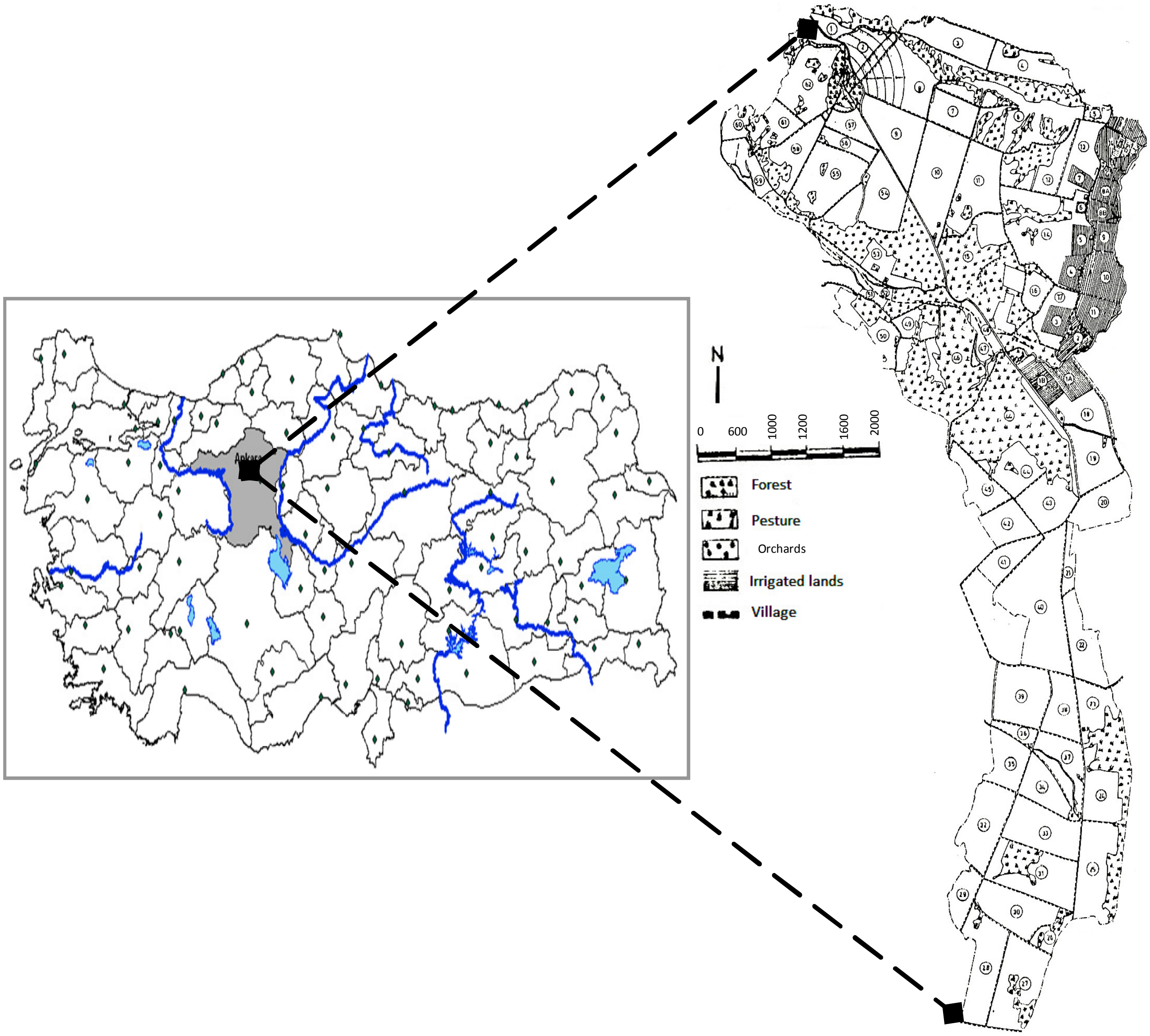

Figure 1. Experimental field site.

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

Soil depth (cm)	K (cm/h)	Texture
0-23	0.59	C
23-54	0.33	C
54-102	0.54	C
102-140	0.20	C
140-180	0.45	C

concentrations that initially begin to affect yield will cause a proportional decrease in yield. They have proposed the equation to express this effect:

$$YR_s = 100 - b^* (EC_e - a) \quad (2)$$

Where YR_s is the relative crop yield (%), 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

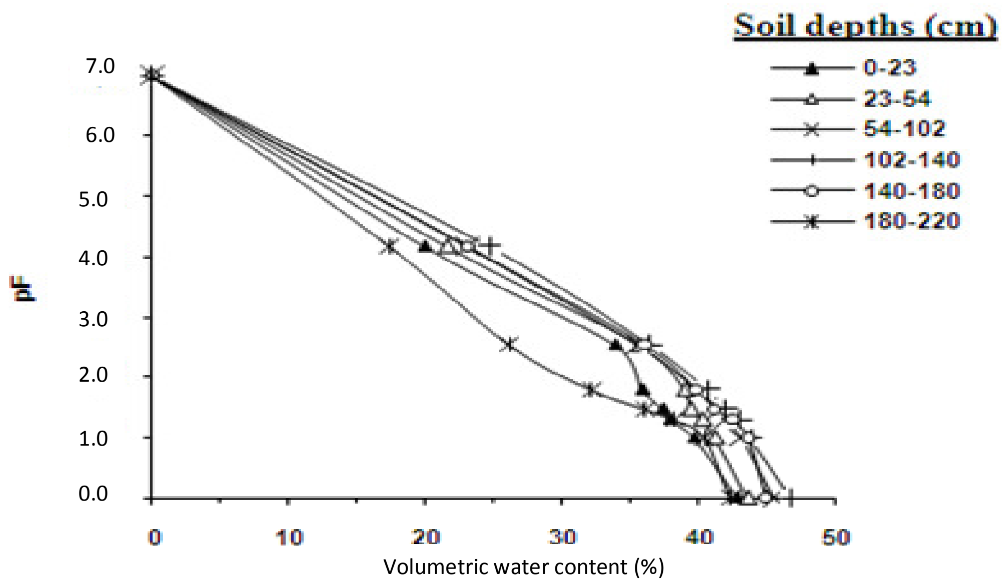

Figure 2. Soil water characteristics (pF curves).

Table 2. Time distribution of effective rooting depths.

Winter wheat root depth			Corn root depth		
Month	**Day**	**Root depth (cm)**	**Month**	**Day**	**Root depth (cm)**
10	20	3.0	1	1	3.0
11	15	3.0	4	16	3.0
12	30	5.0	5	4	4.0
4	15	8.0	5	17	15.0
4	30	10.0	6	1	25.0
5	10	10.0	6	20	30.0
6	1	15.0	7	18	30.0
6	20	15.0	8	20	20.0
7	20	3.0	9	24	10.0
			9	25	3.0
			12	31	3.0

m^{-1} and 12% per dS m^{-1}) and (6.0 dS m^{-1} and 7.1% per dS m^{-1}) respectively.

Dispersivity has been derived by Neuman (1990) in Equation (3):

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

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

The order of crops grown in the rotation was corn and winter wheat. The simulations were performed for 10 years. An effective rooting depth as a function of time is used in DRAINMOD to define the zone from which water can be removed to meet the ET demand. The effective root depths for crops were measured in the growing season. Relative yield to stresses due to planting delay, excessive and deficient soil water conditions along with stress-day factors were taken from Evans et al. (1990), Evans and Skaggs (1992), Skaggs (1998) and Seymour (1986).

While more research is needed to determine crop parameters, they are directly available for some crops, such as corn (Evans and Skaggs, 1993) and can be estimated, based on data in the literature for others (FAO 33). For this region wheat planting dates are generally 15 to 20 October, harvesting dates 15 to 20 July, planting dates of corn are 10 to 15 May and harvesting dates 15 to 20 October. According to planting and harvesting date two periods is specified in the model a spring and fall period, for calculating trafficable conditions in the field.

DRAINMOD requires maximum effective rooting depth and effective rooting depth–time distribution for each crop. Maximum effective rooting depths were used 90 cm for wheat and 60 cm for corn. Skaggs (1982) suggested using 60% of the actual maximum rooting as the maximum rooting depth in the model because most of the water would be taken up near the surface. A value of 3 cm was used for the fallow periods to reflect the soil depth from which water could be evaporated in the absence of a crop (Skaggs et al., 1981). Effective rooting depth–time distribution for each crop was given Table 2. Other crop and trafficability parameters are listed in

Table 3. Crop and trafficability parameters.

Crop and trafficability parameter	Winter wheat	Corn
Length of growing season (day)	270	154
Last day of year to plant without yield loss	305 (1 Nov.)	140 (20 May)
Period to count wet and dry days (month/day)	9 /30 - 7/1	5/10 - 10/5
Days required to prepare seedbed and plant (day)	2	
Lower limit of water content in the root zone (cm^3/cm^3)	0.176	
Limiting water table depth for no crop damage (cm)	30	
Minimum water-free pore space needed to work the soil (cm)	1.5	
Minimum daily rainfall to stop field operations (cm)	0.5	
Minimum time after rainfall before work can restart (day)	1	
Starting hours for working	8 a.m.	
Ending hours for working	8 p.m.	

Table 4. Irrigation date and applied irrigation water amount (mm).

Irrigation date for corn	Irrigation water amount (mm)	Irrigation date for wheat	Irrigation water amount (mm)
23 June	43.4	25 October	88
15 July	171.6	20 May	88
6 August	132.0	15 June	79
28 August	132.0		
19 September	113.1		

Table 5. Water table depths for ten years in experimental site (cm).

Months/Years	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Average
October	126	145	165	89	114	103	93	150	113	86	120
November	147	124	154	88	132	99	123	130	107	92	122
December	114	152	149	87	121	93	102	133	101	102	115
January	100	128	137	90	127	107	85	109	97	95	107
February	99	107	63	67	112	85	98	113	85	88	86
March	97	99	92	82	131	102	76	105	88	65	94
April	85	106	91	115	135	88	66	99	73	62	92
May	83	94	79	93	98	73	62	95	68	56	78
June	77	81	87	55	92	64	57	93	64	50	73
July	75	75	88	47	74	59	42	72	61	46	65
August	77	84	74	54	82	73	67	94	66	49	83
September	96	106	80	78	108	97	87	127	101	65	99

Table 3.

Irrigation data

Total irrigation water requirement for corn is 590 to 600 mm in the Bala basin. According to carried out irrigation projects on this area irrigation scheduling for corn and wheat were given Table 4.

RESULTS

In the experiment site there is no considerable drainage problem in the winter-time due to the semi-arid climate conditions. Generally in this region evapotranspiration is high and rainfall is not enough for plant water requirement. For this reason, irrigation is definitely essential for the crop production. Irrigation water applications of farmers are not conscious in the experiment site. Thus, water table level is getting increase in irrigation seasons. Monthly water table fluctuations for 10 years are given in Table 5. Depending on the application of the excess irrigation water under insufficient drainage conditions, soil salinity also is

Table 6. Simulated relative yield results of winter wheat*.

Year	Stress day index		Plant date	Plant delay	Harvest date	Relative yields (%)				
	Excess	Drought				Excess	Drought	Delay	Salinity	Overall
2001	9.6	0.0	293	0.0	198	91.5	100	100	100	91.5
2002	9.8	0.0	293	0.0	198	90.2	100	100	100	90.2
2003	9.6	0.0	293	0.0	198	91.4	100	100	100	91.4
2004	9.1	0.0	293	0.0	198	93.0	100	100	100	90.3
2005	8.9	0.0	293	0.0	198	94.4	100	100	100	90.4
2006	9.3	0.0	293	0.0	198	92.2	100	100	100	91.2
2007	9.5	0.0	293	0.0	198	91.2	100	100	100	94.4
2008	9.8	0.0	293	0.0	198	90.4	100	100	100	92.2
2009	9.9	0.0	293	0.0	198	90.3	100	100	100	93.0
2010	9.6	0.0	293	0.0	198	91.7	100	100	100	91.7
Average	9.5	0.0	293	0.0	198	91.6	100	100	100	91.6

*It is presented only 50 cm drain depth, 20 m drain spacing simulation results for wheat in this table in order to show model yield output.

Table 7. Simulated relative yield results of corn*.

Year	Stress day index		Plant date	Plant delay	Harvest date	Relative yields (%)				
	Excess	Drought				Excess	Drought	Delay	Salinity	Overall
2001	0.0	12.6	145	0.0	295	100	100	100	92.6	92.6
2002	0.0	12.9	145	0.0	295	100	100	100	90.4	90.4
2003	0.0	13.4	145	0.0	295	100	100	100	87.2	87.2
2004	0.0	13.5	145	0.0	295	100	100	100	86.7	86.7
2005	0.0	13.8	145	0.0	295	100	100	100	85.1	85.1
2006	0.0	13.6	145	0.0	295	100	100	100	84.7	84.7
2007	0.0	13.5	145	0.0	295	100	100	100	82.4	82.4
2008	0.0	13.5	145	0.0	295	100	100	100	80.2	80.2
2009	0.0	13.6	145	0.0	295	100	100	100	79.4	79.4
2010	0.0	13.7	145	0.0	295	100	100	100	75.2	75.2
Average	0.0	13.4	145	0.0	295	100	100	100	84.4	84.4

*It is given only 50 cm drain depth, 20 m drain spacing simulation results for corn in this table in order to show model yield output.

increasing and accumulating in the soil profile.

DRAINMOD computer model was used to simulate drainage system design parameters to provide crop needs to sustain high yields for Bala Basin in Turkey. Yields of individual crops were predicted for each growing season. Analysis option of the model was used to determine optimum drainage system parameters, which provided maximum crop yield.

Simulation were performed for six drain depths (50, 100, 120, 140, 160 and 180 cm) and ten drain spacing (from 20 to 200 m with 20 m interval) using by analysis option of the model. Yield results for wheat and corn growing season were simulated for 10 years period.

To demonstrate DRAINMOD relative yield outputs, first set of the design parameters which is drain depth 50 cm and drain spacing 20 m were presented in Tables 6 and 7 for wheat and corn respectively.

Results showed that crop was affected by water logging. Wheat yields decreased because of the excess water on the soil profile. Wheat yield were not affected negatively by soil salinity and drought for considered drain system parameters.

Corn yield decreased because of the salinity stress. Initial soil salinity values were obtained from collected soil samples in experimental area. For drainage set exampled earlier (Table 7) average initial soil salinity (2001) were used 2.26, 2.21, 2.32, 2.37 and 2.45 dS m^{-1} for 0-20, 20-40, 40-60, 60-80 and 80-100 cm soil depths respectively. Model run for the projection of ten years and average soil salinity were found 3.78 3.45 3.67 3.79 4.48 dS m^{-1} for 0-20, 20-40, 40-60, 60-80 and 80-100 cm soil depths respectively. Stress due to excessive soil water conditions did not limit yields. Salinity stress indexes were given by model as if drought stress occurred. Because model assuming that crop would not benefit from available soil water due to osmotic effect of salinity.

Model was run for all alternative drain depths and drain spacing for 10 years to identify alternative of subsurface drainage system that would satisfy maximum crop productions. Simulated average relative yields of winter wheat for specified drain depths and drain spacing were given in Table 8 and shown in Figure 3.

Table 8. Relative yields for winter wheat at different drainage system parameters.

Drain spacing (m)	Drain depths (cm)					
	50	100	120	140	160	180
	Relative yields of winter wheat (%)					
20	91.6	92.4	91.8	92.1	92.0	90.9
40	91.2	92.4	92.5	92.5	92.2	91.2
60	91.5	92.6	93.6	92.5	91.8	91.5
80	91.7	92.9	94.8	91.8	91.2	91.6
100	92.4	93.1	95.6	92.1	91.2	91.4
120	92.6	95.8	96.5	93.4	91.5	90.2
140	92.7	96.6	98.8	93.4	91.8	88.9
160	92.9	95.5	99.9	94.6	92.1	86.7
180	93.0	94.1	97.1	93.6	92.6	86.5
200	93.1	93.8	95.9	92.1	91.8	86.4

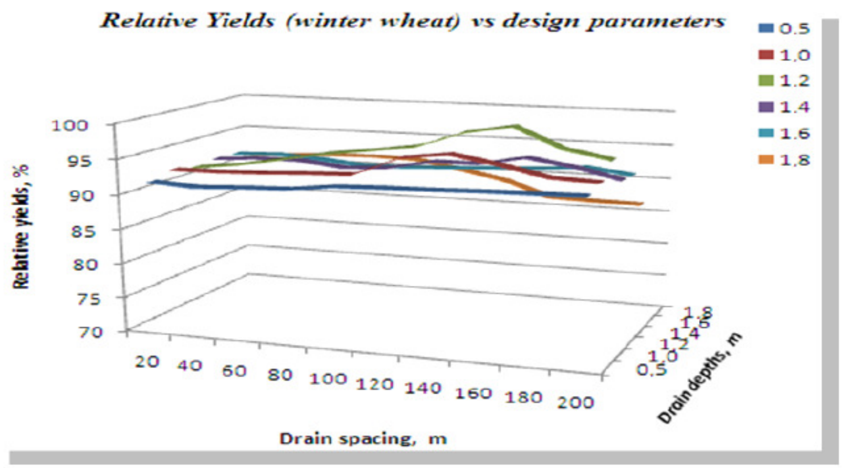

Figure 3. Relative yields for winter wheat at different drainage system parameters.

Relative wheat yield results show that significant reduction was not observed for all design parameters (at the most 14%). The reason of the wheat yield reduction was waterlogging for narrow drain spacing and shallow drain depths. When drain depths were more than 1.2 m and drain spacing more than 160 m, crop yields started to be affected by drought stress that is to say the excess drainage conditions happened.

Average relative yields of corn for all alternative drain depths and drain spacing were given in Table 9 and shown in Figure 4.

The reason of corn yield reduction was that of high soil salinity level in root zone. The results of corn relative yields showed that soil salinity level in root zone causes 5 to 40% drop in yield.

DISCUSSION

Maximum crop yields were, however, obtained for both wheat and corn at 120 cm drain depth and 160 m drain spacing which provides 90% of corn yield and approximately 100% of wheat yield. The results could be accepted for optimum drainage design parameters in Bala Basin.

In general approach, drainage spacing could be increased thus reducing the cost by changing drain depth. The effect of drainage spacing and depths on crop yields, an economical analysis should be conducted to determine the water management system design that would optimize long-term profits. However estimating optimum drainage design parameters using by model to provide maximum crop yield are the most appropriate tool for decision makers before application of the drainage system on the field.

Results of simulations presented herein clearly showed that there were the interdependence of drainage requirement and soil salinity. This supports the often stated proposition that drainage, irrigation and salinity for arid lands should be considered a component of water

Table 9. Relative yields for corn at different drainage system parameters.

Drain spacing (m)	Drain depths (cm)					
	50	100	120	140	160	180
	Relative yields of corn (%)					
20	84.4	87.2	88.6	87.5	72.1	70.2
40	85.6	87.5	88.9	87.6	73.2	75.8
60	86.4	87.8	89.1	87.9	75.9	78.6
80	87.3	87.8	89.4	88.2	76.2	70.5
100	87.5	88.1	89.5	88.5	66.5	69.6
120	88.1	88.3	89.7	88.8	66.3	64.2
140	88.2	88.5	89.7	89.1	65.2	61.2
160	88.2	88.5	90.1	89.1	64.6	59.8
180	87.1	87.8	90.3	89.2	64.2	58.4
200	86.5	87.1	90.5	87.6	63.7	57.5

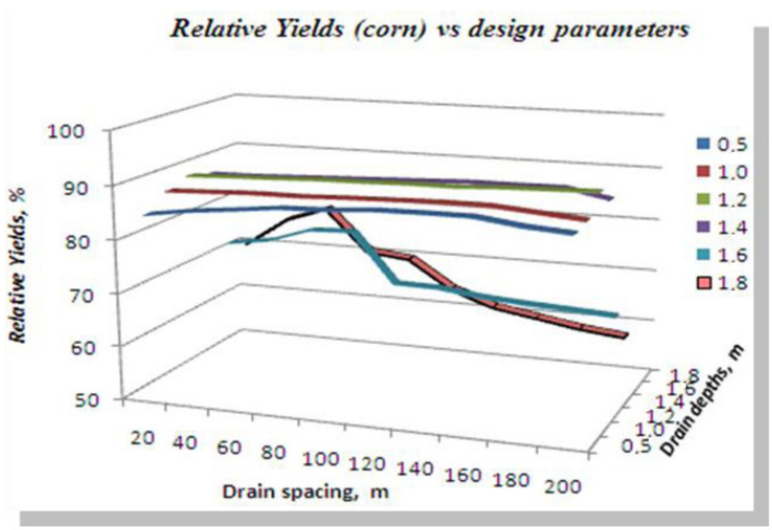

Figure 4. Relative yields for corn at different drainage system parameters.

management system and that design of each component should depend on the others.

Conclusions

The water management model DRAINMOD was used to simulate drainage system design parameters to provide crop needs to sustain high yields for Bala Basin in Turkey. Soil and site parameter data of experimental area were obtained from research studies which were carried out in related field. Soil water conditions and soil salinity level were simulated for crop rotation of corn and winter wheat. Yields of individual crops were predicted for each growing season. Results of the simulations were analyzed to identify alternatives of subsurface drainage system that would satisfy maximum crop productions. Results of the simulations were analyzed to identify effects of subsurface drainage system that would satisfy maximum crop productions. According to the simulation results 90% corn yield and 99.9% wheat yield were obtained with drain spacing 160 m and drain depth 120 cm which are recommended for Bala Basin as an optimum drainage system parameters. Results showed that soil salinity level and salinity stress can be reduced and yield can be increased by installing drainage system. According to model predictions, if current conditions remain without drainage system in this basin, salinity will be very important factor for limiting crop productivity. The greatest attention must be given to reduce salt loading either through installation of drainage systems or changes in irrigation systems and management strategy.

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