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The Suitability of Controlled Drainage and Subirrigation in Paddy Fields

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Abstract: DRAINMOD, an agricultural water management simulation model, was used to investigate the suitability of controlled drainage/subirrigation scenarios in 52 ha of northern Iran paddy fields which planted in April to September and the rest of the time being waterlogged and pounded and could not be cultivated because of high water table, low permeable top soils and unsuitable drainage systems. The model as run for 30 year climate data. Various drain depth and spacing combinations and different weir setting were simulated. Simulation results showed that the xcess soil moisture was the main factor for yield reduction and the best conditions of controlled drainage and subirrigation were obtained when the depth of weir setting was the same as drain depth and these systems acted as conventional drains. Based on results, controlled drainage and subirrigation were not suitable because of high rainfall in the region. But the conventional controlled drainage system can be used for these fields, so that in wet season the system acts like a conventional or free drainage system and in paddy rice growth periods, it operates as controlled drainage by installing a weir setting outlet drain.

Key words: DRAINMOD, paddy fields, controlled drainage, subirrigation

INTRODUCTION

High water table, low permeable top soils and unsuitable drainage systems caused northern Iran paddy fields planted April to September and the rest of the time being waterlogged and pounded and could not be cultivated. Because of such problems, paddy rice cultivation is not an economic job for farmers, so that their land use condition is being changed. Use of agricultural water management systems including controlled drainage, subirrigation and conventional drainage (NRCS, 2001) in these fields can be useful because in one hand decreases the water use and provides more suitable conditions for cultivation, plant growth and harvesting and on the other hand, decreases N and other nutritive and chemical materials from these lands. The process called controlled drainage occurs when a structure is used in outlet drain to conserve water by reducing drainage outflows and when no additional water is pumped in. During dry periods, water may be pumped into the control outlet where it moves back through the drainage network, thus it can raise the water level in the field. In this model the system is being used for subirrigation. The final design of the drainage/subirrigation system should be evaluated using the water management simulation model, DRAINMOD (Evans and Skaggs, 1996). DRAINMOD is a deterministic field scale model developed by R.W. Skaggs at North Carolina State University. It has been developed and tested for use in humid regions characterized by the presence of a shallow water table. Approximate methods were used to simulate the water movement processes to avoid prohibitive amounts of computer time for long-term simulations due to the application of numerical solutions to nonlinear differential equations (Borin *et al*., 2000). The basis for the model is a water balance on a thin section of soil located midway between drains and extended from the impermeable layer to the soil surface which can be written for a time increment Δt as (Skaggs, 1980):

$$\Delta v_a = D+ET+DS-F \quad (1)$$

Where ΔV_a is the change of water free pore space or air volume (cm), D is drainage (or Subirrigation) from the soil profile (cm), ET is evapotranspiration (cm), DS is deep seepage (cm) and F is infiltration entering to the soil profile (cm). A water balance is also computed at the soil surface for each time increment using:

$$P = F+\Delta S+RO \quad (2)$$

where P is precipitation (cm), ΔS is the change in volume of water stored on the surface (cm) and RO is the surface runoff (cm).

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Hooghoudt's steady-state equation was selected for use in DRAINMOD to calculate drainage rate (El-Sadek *et al.*, 2001). This equation is as follows:

$$q = \frac{8kd_e m + 4km^2}{L^2} \tag{3}$$

where, q is drainage rate (cm h^{-1}), d_e is the equivalent depth of the restrictive layer below the drain (cm), m is the water table height above the drain (cm) in the soil plot which is assumed to be located at a point midway between ditches, K is effective lateral saturated hydraulic conductivity (cm h^{-1}) and L is distance between drains (cm).

The Green-Ampt equation (1911) was used in the model to calculate infiltration rate. This equation may be written as:

$$f = B + \frac{A}{F} \tag{4}$$

Where, f is infiltration rate (cm h^{-1}), A and B are parameters that depend on soil properties and F is cumulative infiltration (cm).

DRAINMOD uses equations 5 to 9 to calculate relative yield.

$$yR = \frac{y}{y_0} = yR_w \times yR_d \times yR_p \times yR_s \tag{5}$$

$$yR_w = \frac{y_w}{y_0} \tag{6}$$

$$yR_d = \frac{y_d}{y_0} \tag{7}$$

$$yR_d = \frac{y_d}{y_0} \tag{8}$$

$$yR_d = \frac{y_d}{y_0} \tag{9}$$

Where yR is the relative yield, y is the yield for the given year, y_0 is the optimum long term average yield and the subscripts w, d, p and s represent relative yields due to excess water conditions, deficient soil water, planting date delay and salinity stresses.

DRAINMOD has been tested to predict water table elevations and subsurface drain flow in many parts of the world for different soils, crops and climates (Mostaghimi and McMahan, 1989; Shukla *et al.*, 1994; Madramootoo *et al.*, 1995; Borin *et al.*, 2000; He *et al.*, 2002; Fausey, 2004; Khalil *et al.*, 2004). Generally, results showed that DRAINMOD can be used to predict water table depth and drainage discharge. Wang *et al.* (2006) run DRAINMOD to predict and compare drain flow for three drain spacing and crop yield for four drain spacing at the Southeastern Purdue Agricultural Center and concluded that the model can be used to study the efficiencies of different drain spacing and to guide the drain spacing design for specific soils. Jin *et al.* (2005) used DRAINMOD to simulate water table depth in two soils of the Red River of the North Basin in the Northwest Minnesota. DRAINMOD simulations showed that a simple calibration of the model by adjusting monthly ET factors was sufficient to allow the model to simulate the high water tables associated with large summer rainfall events.

The objective of this study was to find the best condition of controlled drainage and subirrigation based on DRAINMOD simulations. To obtain this aim different combination of drain depth and spacing were simulated and the results were investigated based on Sum of Excess Water (SEW), depth of water table, number of working days and relative yield.

MATERIALS AND METHODS

The site and drainage design: The research was conducted in 52 ha of northern Iran paddy fields i.e., Amol region (36.58° N, 52.17° W), located at Mazandaran province. The elevation above sea level is 5.5 m. Average annual rainfall and temperature are approximately 865 mm and 17°C, respectively. The soil at the site is loamy in upper layers. The site has a surface drainage system with open ditches spaced 200-400 m apart. The water table elevations were investigated using observation wells during Oct., 2004 to March, 2005. Measurements of water surface in observation wells were carried out weekly or following rainfall events. The water table depth measured in the observation wells were converted into water table elevations using the ground surface elevations data of topographic surveying. The mean of water table elevations was 24 cm.

Model inputs: The main input data and parameters required for DRAINMOD include weather data, drainage system parameters, soil properties and crop parameters.

DRAINMOD was run for 30-year (1974-2004) climate data which include hourly rainfall and daily maximum and minimum air temperature. Hourly rainfall was not available but daily rainfall was measured on the site for 1994-2004 and the rest was obtained from Babolsar weather station approximately 30 km away. The daily rainfall was distributed through the day according to the region rainfall distribution. The daily maximum and minimum temperature were collected from the experimental site weather station when available (1994-2004) or from Babolsar weather station.

The maximum surface storage were estimated based on Skaggs, (1980) to be 2.5 mm that represents good surface drainage. The hydraulic conductivity of 5 layers can be used in DRAINMOD, so the soil profile was divided into 5 layers: (0-35 cm), (35- 60 cm), (60-150 cm), (150-240 cm) and (240-310 cm) based on relatively uniform properties within each layer.

The measured hydraulic conductivity for each layer is 9.21, 4.4, 4.75, 5.42 and 2.3 cm h^{-1}, respectively. The impermeable layer depth was found approximately 3 m using the criterion of 0.1 to 0.2 weighted average

Table 1: Coefficients for the Green-Ampt infiltration equation as a function of water table depth

Water table depth (cm)	A (cm^2 h^{-1})	B (cm h^{-1})
0	0.00	9.21
10	1.29	9.21
20	2.58	9.21
40	4.83	8.61
60	6.05	7.21
100	9.23	6.59
200	43.09	6.59
1000	43.09	6.59

Table 2: Time distribution of effective rooting depth

Days after planting	Root depth (cm)
1	3
10	3
20	10
30	20
40	31
50	42
70	45
80	43
90	32
100	24
110	15
120	7

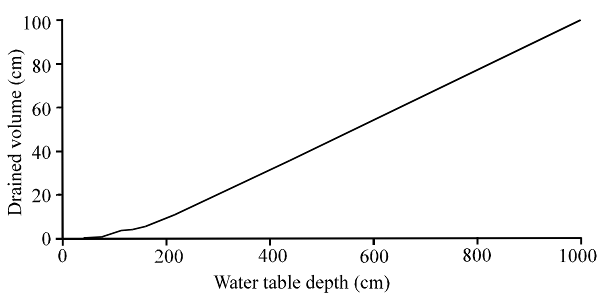

Fig. 1: Drainage volume- water table depth relationship in the soil profile

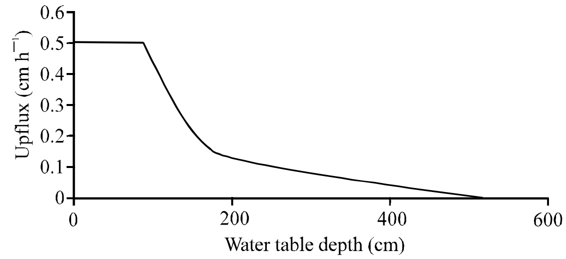

Fig. 2: Upflux -water table depth relationship in the soil profile

hydraulic conductivity of upper layers. The soil water retention characteristics were measured using the standard pressure plate method for each horizon of the soil layers. These values are used in the SOILPREP program to estimate volume drained, upflux and Green-Ampt infiltration parameters versus water table depth relationship. The volume drained and upflux plotted These values are obtained based on crop growth stage Where x_i is the water table depth on day i and n is the number of days in the growing season.versus water table depth and is given in Fig. 1 and 2 and the Green-Ampt parameters are tabulated in Table 1. DRAINMOD requires maximum effective rooting depth and effective rooting depth-time distribution for each crop. These values are obtained based on crop growth stage coefficients (Skaggs, 1980) and are given in Table 2.

RESULTS AND DISCUSSION

To obtain the best condition of controlled drainage and subirrigation, different combination of drain depth and spacing were simulated. Among the simulation results, 4 parameters are selected as objective functions including; Sum of Excess Water (SEW), working days, water table depth and relative yield. To compute sum of excess water, SEW_{35} is used because of the need for more free space in soil profile to maintain rainfall and prevent surface runoff. SEW_{35} is the sum of excess water table rises above the 35 cm which is ordinarily expressed in cm/day and may be defined as follows:

$$SEW_{35} = \sum_{i=1}^{n}(35 - x_i) \quad (10)$$

Where x_i is the water table depth on day I and n is the number of days in the growing season.

Regardless of the paddy rice growth drainage requirements, drainage is much necessary to winter cropping in northern Iran paddy fields. So, in simulations

Table 3: Results of controlled drainage and subirrigation simulations

			Controlled drainage				Subirrigation			
Drain depth (m)	Weir Setting (m)	Drain spacing (m)	SEW_{35} (cm)	Working days	Water table (cm)	Relative yield (%)	SEW_{35} (cm)	Working days	Water table (cm)	Relative yield (%)
		10	385	52	54	48.9	390	47	52	47.7
		20	395	52	53	47.1	400	50	51	46.4
1	0.6	30	411	52	51	45.1	415	51	49	44.5
		40	433	51	49	42.3	439	49	47	41.5
		50	451	50	47	38.6	466	48	45	37.9
		60	474	49	44	30.7	506	46	41	30.2
		10	380	55	56	49.8	381	49	53	47.7
		20	391	55	55	47.7	398	52	52	46.6
1.1	0.6	30	406	54	54	45.8	415	51	51	44.6
		40	419	52	52	42.9	437	50	49	42.0
		50	441	51	50	38.1	464	49	47	38.6
		60	472	50	45	33.4	503	47	44	30.0
		10	371	60	58	50.3	388	50	54	47.9
		20	386	58	56	48.3	397	53	53	46.8
1.2	0.6	30	393	57	54	46.1	413	54	51	44.8
		40	424	55	52	43.6	418	53	49	42.8
		50	434	53	50	39.8	441	51	47	39.1
		60	470	50	47	35.1	497	50	44	33.6
		10	367	64	60	51.8	362	51	56	50.3
		20	382	60	58	48.8	379	53	55	49.1
1.3	0.6	30	382	58	56	46.7	382	55	52	47.3
		40	412	56	53	44.4	397	53	50	46.2
		50	422	54	51	41.2	424	52	49	42.5
		60	446	51	48	36.1	457	50	46	37.8

Table 4: DRAINMOD simulations of relative canola yield under wet, dry, delay and overall plant stresses

			Relative yield (%)			
Drain depth (m)	Weir setting (m)	Drain spacing (m)	Wet	Delay	Dry	Overall
Controlled drainage 1.2	0.6	40	43.6	100	100	43.6
Subirrigation 1.1	0.6	30	44.6	100	100	44.6

Table 5: DRAINMOD simulations of relative canola yield under wet, dry, delay and overall plant stresses for different weir depths

			Relative yield (%)			
Drain depth (m)	Weir setting (m)	Drain spacing (m)	Wet	Delay	Dry	Overall
Controlled drainage						
1.2	0.6	40	43.6	100	100	43.6
1.2	0.8	40	53.8	100	100	53.8
1.2	1.0	40	61.6	100	100	61.6
1.2	1.2	40	69.2	100	100	69.2
Subirrigation						
1.1	0.6	30	44.6	100	100	44.6
1.1	0.8	30	54.7	100	100	54.7
1.1	1.0	30	64.0	100	100	64.0
1.1	1.1	30	68.5	100	100	68.5

the aim was investigation of objective parameters for wet seasons. One of the major crop cultivated is canola which is used in the model. In each scenario, 4 drain depths (1, 1.1, 1.2 and 1.3 m) and 6 drain spacing (10, 20, 30, 40, 50 and 60 m) were simulated. The average of total SEW_{35}, working days, water table depth and relative yield for wet seasons of 1994-2004 are tabulated in Table 3. There was no difference significantly ($p>0.05$) between means of SEW_{35}, working days, water table depths and relative yields for all drain spacing in each drain depth. Total SEW_{35} for 180 days was higher than 360 cm that represents more than 2 cm excess water for each day in both subirrigation and controlled drainage. The weir depth of 0.6 m caused that the water table remained nearly constant for all spacing with standard deviation of about 1.5-6.5 cm for controlled drainage and 4.5-5.5 cm for subirrigation. This high water table was detrimental to crop growth and resulted in yield reduction of about 48.2-69.3% of potential yield under ideal conditions for controlled drainage and 49.7-70% reduction for subirrigation for drain spacing 10-60 m. Although controlled drainage gave better results than subirrigation but neither controlled drainage nor subirrigation had a satisfactory result. In each drain depth the best condition of SEW35, working days, water table depth, and the highest relative yield was obtained in 10 m drain spacing. In each scenario the results became worse by increasing the drain spacing. To investigate the reason of the low relative yield in controlled drainage and subirrigation, one combination (for controlled drainage model 40 m drain spacing and 1.2 m drain depth and for subirrigation 30 m drain spacing and 1.1 m drain depth) of drain depth and spacing for each scenario was selected and used in all further simulations. Then the relative canola yield under different stresses including wet, dry, delay and overall stresses were simulated and the results are tabulated in Table 4.

The delay and deficient soil water (dry) stresses had no effect on relative yield and the yield reduction was as a result of wet stress. To obtain the optimum depth for weir setting and the maximum relative yield in each scenario, the relative yield are simulated in 4 weir setting depths of selected scenarios as shown in Table 5.

As it can be observed in Table 5, having increased weir depth from 0.6 to 1.2 m, the relative yield increased about 37% and was equal to the relative yield of conventional drainage with 1.2 m drain depth and 40 m drain spacing. Also in subirrigation model, by increasing weir depth from 0.6 to 1.1 m the relative yield increased about 35% and was equal to the conventional drainage of 1.1 m drain depth and 30m drain spacing. By increasing the weir depth to the drain depth, the relative yield reduction was due to excess soil moisture. This shows better drainage requirement with narrower drain spacing or deeper drain depths.

CONCLUSIONS

Investigation of water table depths in 52 ha of northern Iran paddy fields showed that the drainage systems are necessary for these fields cultivation in wet seasons. So controlled drainage and subirrigation scenarios were studied using an agricultural water management simulation model, DRAINMOD, to obtain the best condition of these scenarios. The model was run for 30-year climate data. In each scenario different combination of drain depths and spacing were simulated. To obtain the maximum relative yield, various weir setting for both controlled drainage and subirrigation were selected. To investigate simulations results 4 parameters including SEW_{35}, working days, water table depth and relative yield were defined as the objective functions. Simulation results showed that any combination of drain depth and spacing had not given suitable results for objective functions. By increasing weir depth from 0.6 to drain depth in each scenario, this system operates as a conventional drainage, the relative yield increased and was equal to the conventional drainage relative yield which has a drain depth and spacing equal to those systems. In all simulations the relative yield reduction was due to soil excess water. Based on results controlled drainage and subirrigation were not suitable because of high rainfall in the region. But the conventional controlled drainage system can be used for these fields, so that in wet season the system acts like a conventional or free drainage system and in paddy rice growth periods, it operates as controlled drainage by installing a weir setting in outlet drain.

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