SIMULATION OF DRAINAGE AND REUSE SYSTEM FOR WATERTABLE MANAGEMENT OF CANAL IRRIGATED AREAS A CASE STUDY

Ranvir Kumar[1] Joginder Singh[2]

ABSTRACT

The introduction of canal irrigation in the semi-arid regions of the Haryana State of India underlain with saline ground water in early sixties led to the rise in water levels at an annual rate of 0.3 to 1.0 m and secondary salinization adversely affecting crop production. To develop feasible technologies for the reclamation of such areas, a pilot study on sub-surface tile drainage systems was undertaken in an area at the Haryana Agricultural University Farm having shallow water levels and high salinity. The drains with three spacings (24, 48, 72 m) were placed at a depth of 2.5 m. The water levels, drainage rates and soil salinity data from the study area growing vegetable crops (egg plant, tomato and potato) were used to calibrate the Field Agricultural Irrigation and Drainage Simulation (FAIDS) model for the period 1985-1989 and validate it for the period 1989-93. A number of simulations were also carried out to finalize optimum drain configuration (spacing x depth) under existing agro-hydrological conditions. The drain configurations of 75 m x 2 m (Ist option) and 100 m x 2.5 m (2nd option) performed equally well based on salinity in the root zone and crop performance. In both the options, relative evapotranspiration (ET_a/ET_p) of 0.81 was attained during the third year of operation of the drainage system under normal rainfall conditions. The occurence of a maximum one-day rainfall event (1 in 10 years) during the fifth year resulted in the failure of one out of three crops in both the options in that year indicating the necessity of integration of a surface drainage system with the subsurface drainage under abnormal rainfall events. The existing inland basin

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drainage conditions did not permit the disposal of drainage effluent. The reuse system was therefore, integrated with the drainage system. A model RESBAL was coupled with the calibrated and validated model FAIDS and run for eight years to optimally design a series of connected reservoirs for the disposal of drainage effluent from an area provided with a subsurface drainage system. The possibility of the reuse of the disposed water for irrigation, aqua culture and salt harvesting was also studied comprehensively in order to maintain proper salt balance in the root zone. On the basis of this study, subsurface drainage systems coupled with surface drainage systems are being extended in Haryana to over 2000 ha of the farmers' land severely affected with waterlogging and soil salinity using a tile-laying trenching machine.

INTRODUCTION

Haryana is located in the north-western part of India between latitude 27° 39′ and 30° 55′ N and longitude 74° 28′ and 77° 37′ E with a total land area of 44200 km^2. The state lies on the watershed between the Ganges and the Indus river basins. The Yamuna river which forms the eastern boundary is a tributary to the Ganges and the Ghaggar river which flows along the north-western boundary belongs to the Indus basin. About 80 per cent of the state area is agricultural land and nearly 57 per cent of the cultivated land is irrigated through canal and ground water. The large scale canal irrigation in the south-western part of the state through the Bhakra Irrigation System during the early sixties led to the rise in ground water table in nearly 60 per cent of the area. The areas experiencing the rise in water levels are primarily underlain by brackish and saline ground waters which are not usable for irrigation purposes. Haryana, with its location between the Himalayan mountains on the north-east and the Thar desert on the south-west, is mainly an extensive closed basin (Anonymous, 1986). A topographical depression exists in the centre with its axis passing through Delhi-Rohtak-Hisar and Sirsa on the regional scale and ground water moves towards this depression. The state also forms the water divide between the Indus and the Ganges basins. The climate in the problem areas varies from arid to semi-arid with an annual precipitation of 300-500 mm, most of which is received in the monsoon period (July to September). The losses from the irrigation system through conveyance and water application, unfavourable geo-hydrological conditions and poor ground waters are the major factors contributing to the rise in water levels.

During the last three decades, the water table in the canal irrigated areas has risen at a rate of 30 to 100 cm annually. In nearly 400,000 hectares, the watertable has already come within 3 m of the ground surface, resulting in the degradation of the land resource due to waterlogging and secondary salinization (Anonymous, 1983). According to a study, it is expected that in the next three decades the area under critical water table depth will register a four-fold increase if no curative measures are undertaken.

Therefore, in order to develop feasible drainage and reclamation technologies, studies were undertaken at a pilot scale on the University Farm, Hisar, a part of the inland drainage basin. It is essential to develop suitable simulation models to transfer the results from these studies to other problematic areas. The calibrated and validated model would in turn help in deciding the drain depth and spacing under various cropping, soil and hydrological conditions to maintain a favourable salt and water balance for the proper agricultural production. The present paper primarily deals with the calibration and validation of the Field Agricultural Irrigation and Drainage Simulation Model - FAIDS (Roest, et.al., 1991) by using water levels, drainage discharge and soil salinity data generated from horizontal tile drainage studies at the vegetable farm during the period 1985-1993. The calibrated model was used to simulate number of options to decide the optimum drain spacing and depth under existing agro-hydrological conditions including a once in 10 years 1-day maximum rainfall event which occurred in the fifth year. In view of the absence of a natural outlet, the drainage system should be integrated with the builtin provision for the storage and reuse of the drainage effluent on a long term basis for maintaining a favourable salt-water balance in the area. The model FAIDS in combination with a reservoir balance model has been used to design an integrated reuse system at the Farm.

The Model

The FAIDS model is a simulation model describing water and salt movement in the unsaturated system consisting of effective root and capillary zones and the upper part of the saturated system and simulates for one time step and one crop the irrigation water application, evapotranspiration, drainage and salinity changes

(Roest, et al. 1991). The following fluxes are estimated on a daily basis:

- infiltration of water from the soil surface due to irrigation or rainfall;
- percolation to the water table;
- evapotranspiration from soil and crop;
- capillary rise from the water table into the root zone;
- drainage through a possible sub-surface drainage system;
- seepage/leakage from/into the underlying aquifer.

The overview of the different fluxes as represented in the model are shown in Fig.1

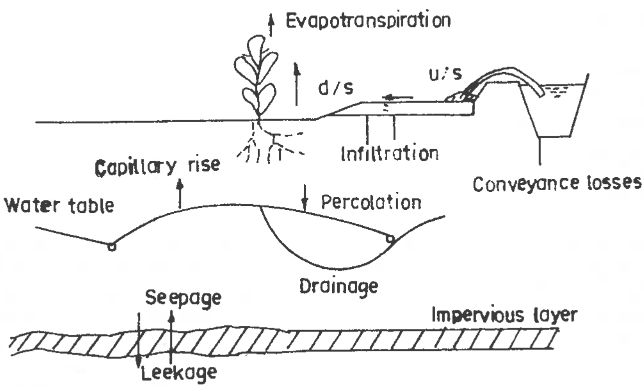

Figure 1. Overview of fluxes considered in the FAIDS model

In the model, two reservoirs for the soil system, namely unsaturated (above water level) and saturated (below water level) are considered and both can be partitioned uniformly into a number of layers (Fig. 2).

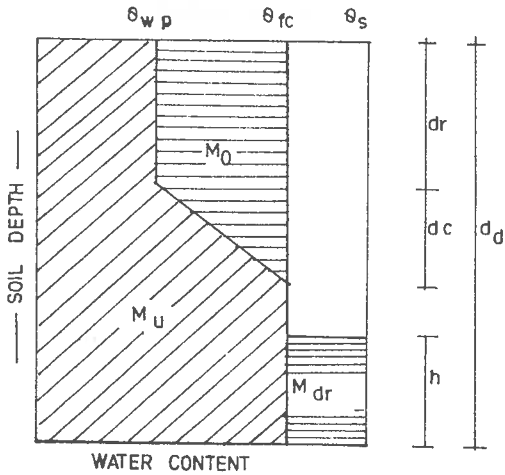

Figure 2. Schematization of soil profile

In the unsaturated reservoir, the maximum quantity of water which can be extracted by plant roots is the amount available between field capacity and wilting point. Below the effective root zone depth, half of this quantity is assumed available for evapotranspiration by capillary rise. The maximum available amount of soil moisture in a soil profile is given below:

$$M_o = (d_r + 1/2 d_c)\ (\theta_{fc} - \theta_{wp}) \qquad (1)$$

Where:

M_o = maximum available soil moisture for evapotranspiration when soil is at field capacity (m);
d_r = effective root zone depth (m)
d_c = thickness of capillary zone (m)
θ_{fc} = soil water content at field capacity ($m^3.m^{-3}$)
θ_{wp} = soil water content at wilting point ($m^3.m^{-3}$)

The soil moisture which is not available for evapotranspiration is given by:

$$M_u = d_d\ \theta_{fc} - \{ (d_r + 1/2 d_c)\ (\theta_{fc} - \theta_{wp}) \} \qquad (2)$$

Where:

M_u = soil moisture which is not available for evapotranspiration (m)
d_d = drain depth (m)

In the saturated reservoir, the amount of drainable water is directly related to drainable porosity and average watertable depth and given by:

$$M_{dr}\ (t) = \mu\ h(t) \qquad (3)$$

Where:

$M_{dr}(t)$ = amount of drainable water (m);
μ = $(\theta_s - \theta_{fc})$ = drainable porosity ($m^3.m^{-3}$);
θ_s = saturated soil moisture fraction ($m^3.m^{-3}$);
$h(t)$ = watertable elevation above drain level at any time (m).

The surface flow irrigation (border strip) is considered as a two-dimensional process. The transport of salts either as downward movement due to recharge and leaching, or as upward movement due to evapotranspiration and seepage is modelled by subdividing the soil profile into a number of layers. Through the boundary of each layer, transport of salts takes place by mass transport of water. For both rainfall and irrigation, the fluxes between the different layers are determined on the basis of the water balance of each layer.

Input and Output Parameters: The basic input parameters used in the model are grouped in four categories:

Soil: Infiltration rate, moisture content at saturation, field capacity and wilting point and initial soil moisture content and soil salinity at different depths (unsaturated and saturated zone)

Plant: Plant height, soil cover, root zone and critical leaf water potential

Hydrological: Hydraulic conductivity, depth of impervious layer, aquifer resistance, piezometric pressure, initial water table depth and ground water salinity, method of irrigation and depth and quality of each irrigation during crop growth period, depth and spacing of drains (in case of a drainage system);

Climatic: Daily maximum and minimum temperature, rainfall, relative humidity, day length, wind velocity, evaporation from U.S. Class 'A' pan.

Daily actual and maximum evapotranspiration, capillary flux, leakage/seepage from the aquifer, depth of water stored in the root zone, water table, drainage discharge and its quality, soil moisture content and soil salinity at different depths are the main output parameters of FAIDS.

The model was calibrated by using the water levels, drain discharges and soil salinity in the area drained by horizontal tile drainage system with different spacings growing vegetable crops (brinjal (egg-plant)-tomato-potato) from 1985 to 1989 at the University Farm, Hisar (Kumar and Singh, 1999). The model was validated for another four years i.e 1989 to 1993.

Model Simulation

After successful calibration and validation of the model, a number of simulations for a period of five years considering normal rainfall and also incorporating a once in ten years maximum one day rainfall (Kumar et. al., 1995; Kumar, 1994) during the fifth year of simulation were carried out to determine optimum drain spacing and depth based on relative evapotranspiration, (ET_a/ET_p) and soil salinity in the upper 30 cm and 100 cm soil depth for vegetable crops. A number of lateral spacing and depth combinations were considered. The results of simulations are given in Tables 1 and 2.

The drain configuration of 100 m x 2.5 m and 75 m x 2.0 m results in almost identical relative evapotranspiration values in the third year considering the normal rainfall situation (Table 1). However, the average soil salinity (EC_e, electrical conductivity of saturation extract) of the upper 30 cm and 100 cm soil depth in case of the former was higher (2.16 and 3.10 $dS.m^{-1}$) as compared to the latter (1.99 and 2.86 $dS.m^{-1}$). The threshold values for the vegetable crops considered ranged between 1.8 and 2.0 $dS.m^{-1}$ (Maas, 1990, Mangal et. al., 1988). Considering the relative evapotranspiration and the ease for installation, 75 m x 2.0 m drain configuration is better than 100 m x 2.5 m. If the drain depth is further reduced in case of 75 m spacing, soil salinity increases considerably resulting in significant reduction in relative evapotranspiration. At shallower depths, the water table remains very close to the ground surface thus creating unfavourable conditions for plant growth.

A maximum one-day rainfall event (1 in 10 years) in the fifth year of simulation resulted in severe waterlogging conditions (Fig.3) reducing relative evapotranspiration considerably in drain configurations of 100 m x 2.5 m and 75 m x 2.0 m. Therefore both these configurations pose a serious risk of crop damage in case of heavy rainfall events during a particular year. Therefore, it is of paramount importance to combine surface drainage with subsurface drainage system in view of the limited infiltration capacity of the soil

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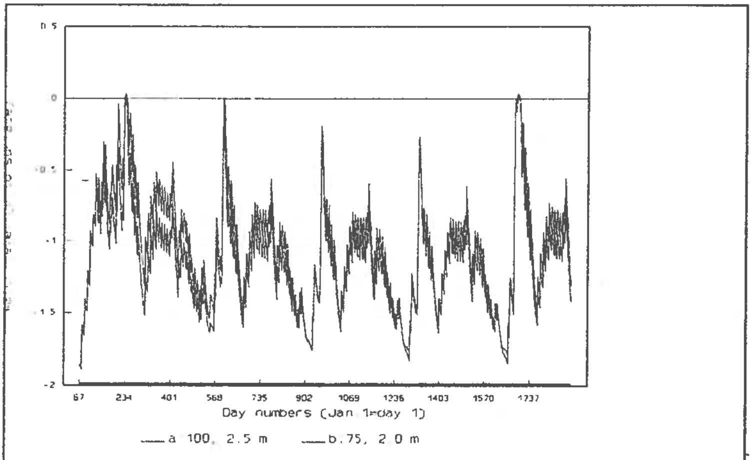

Figure 3. Simulated water levels with different drain configurations including maximum 1-day rainfall (1 in 10 years) during fifth year

Table 1: Relative Evapotranspiration (ET_a/Et_p) under different drain configurations

Sr. No.	Drain configuration (mxm)	Years				
		I	II	III	IV	V
1.	100x2.5	0.32	0.58	0.81	0.82	0.82
2.	100x2.5*	0.32	0.58	0.81	0.81	0.61
3.	75x2.5	0.50	0.77	0.78	0.79	0.79
4.	75x2.5*	0.50	0.77	0.78	0.79	0.61
5.	50x2.5	0.49	0.76	0.76	0.77	0.77
6.	25x2.5	0.49	0.75	0.75	0.75	0.75
7.	100x2.0	0.18	0.57	0.60	0.62	0.63
8.	75x2.0	0.35	0.78	0.81	0.81	0.82
9.	75x2.0*	0.35	0.78	0.81	0.81	0.61
10.	75x1.5	0.23	0.57	0.61	0.63	0.64
11.	75x1.0	0.04	0.11	0.28	0.30	0.30

In the case of the 100 m x 2.5 m drain configuration, there will be a savings of around 25 per cent of lateral pipe length, but it will be offset due to the higher initial cost of the trencher and additional dewatering costs. The cost of installation per hectare for 75 m x 2 m drain configuration is around US$ 1000 whereas for the other configuration, US$ 1025 (Anonymous, 1996). Therefore, techno-economically, the 75 m x 2 m drain configuration is the best option and is being adopted on a large scale (2000 ha) on the farmers' fields.

Table 2. Average soil salinity (EC_e) of different depths (30 and 100 cm) under different drain configurations

Sr.No.	Drain configuration (mxm)	Years				
		I	II	III	IV	V
1.	100x2.5	3.03 (7.1)	2.44 (4.0)	2.16 (3.1)	1.97 (2.6)	1.84 (2.3)
2.	100x2.5*	3.03 (7.1)	2.44 (4.0)	2.16 (3.1)	1.97 (2.6)	1.63 (2.1)
3.	75x2.5	2.41 (5.8)	1.58 (2.7)	1.29 (1.9)	1.14 (1.5)	1.06 (1.3)
4.	75x2.5*	2.41 (5.8)	1.58 (2.7)	1.29 (1.9)	1.14 (1.5)	0.93 (1.1)
5.	50x2.5	2.11 (5.3)	1.09 (1.9)	0.92 (1.2)	0.86 (1.0)	0.83 (0.9)
6.	25x2.5	2.09 (5.3)	0.99 (1.7)	0.83 (1.0)	0.79 (0.9)	0.78 (0.8)
7.	100x2.0	3.59 (8.2)	2.86 (5.0)	2.65 (3.9)	2.50 (3.4)	2.41 (3.0)
8.	75x2.0	2.80 (6.6)	2.23 (3.6)	1.99 (2.9)	1.88 (2.4)	1.70 (2.1)
9.	75x2.0*	2.80 (6.6)	2.23 (3.6)	1.99 (2.9)	1.82 (2.4)	1.49 (1.9)
10.	75x1.5	3.21 (7.8)	2.73 (4.6)	2.54 (3.7)	2.44 (3.2)	2.37 (2.9)
11.	75x1.0	4.89 (9.2)	3.79 (6.0)	3.28 (4.8)	3.08 (4.1)	2.96 (3.7)

* one-day maximum rainfall (1 in 10 years)
Values in ( )pertain to average EC_e of 100 cm depth

RESBAL Model

The RESBAL model determines the optimum size and operation schedule of a series of reservoirs using an iterative procedure. It calculates the water level and salt concentration in a series of reservoirs based on the drainage effluent received from FAIDS. It is assumed that the first reservoir receives a certain discharge on the basis of drainage rate; its quality is calculated by FAIDS over a certain period from the given area on a daily basis. The open water evaporation from each reservoir is calculated by the Penman method in the model RESBAL. The daily rainfall are read from the same output file of FAIDS and leakage from the reservoir is estimated on the basis of specified piezometric head, leakage resistance and water level in the reservoir.

The model has a builtin provision to specify the maximum level beyond which the specific reservoir starts spilling into the next reservoir. Irrigation uptakes on a 10-day basis are specified for each reservoir. The minimum water level to be maintained in the reservoir is also defined for fish culture. The salt concentration is considered constant within it during a specified time step. When the reservoir loses water to evaporation, the quality of the evaporated water is considered fresh and the resultant salt concentration of the leftover water in the reservoir is estimated. The salt concentration of the inflowing, outflowing water, irrigation uptake and leakage is considered for the specified time step (daily basis).

The FAIDS model was used in conjunction with RESBAL to decide design specifications and an operation schedule for three connected reservoirs for irrigation, fish culture and salt harvesting for a 315 ha area at the University Farm (Singh and Kumar, 1998). The model was run for wheat-cotton rotation, with drain spacing of 72 m and depth 2 m for a period of eight years (1985-92) having four years (1985, 1988, 1990 and 1992) above normal, normal (1986 and 1991) and below normal rainfall (1987, 1989). The drainage rates and salt concentrations (output from FAIDS) were read by RESBAL. The salinity of the drainage effluent varied between 4 to 5.5 dS/m. The three reservoirs were proposed to be interconnected in series by an inverted syphon with the possibility of irrigation uptake from the first two reservoirs. In the first two reservoirs, irrigation water would not be drawn once the water level dropped to 0.7 m. This limit was introduced to grow fish in the first two reservoirs (Garg, 1994). The size of the different reservoirs was decided on the basis of salt concentration, minimum water level, irrigation uptake and no spill from the last reservoir.

The annual inflow, outflow and irrigation uptake in all three reservoirs are given in Table 3. The temporal variation in water level and water salinity in the three reservoirs are shown in Figures 4, 5 and 6. The water could be drawn from the first reservoir during all the years with different levels of uptakes. An additional irrigation could be applied in 30 to 350 ha depending upon drainage discharges. In the case of second reservoir, the irrigation uptake was possible only during three years out of eight years which was sufficient for additional irrigation in 15-160 ha. It was possible to grow fish in first reservoir during the entire period, whereas in the second reservoir, the fish culture could be followed in three years only. In the third reservoir, however, fish could be raised only during one year. The salt concentration initially in all the reservoirs was around 5 dS/m. During the summer months (April to June) when the wheat crop is harvested (first week of April) and the cotton crop just sown (3rd and 4th week of May) and the day temperature ranges between 35 and 45 degrees celsius, the drainage effluent from the drainage systems reduces considerably. The water level (depending on the year) specifically in the second and third reservoirs gets depleted due to high evaporation (8-20 mm/day) resulting in high salinity. In the present situation, a very high concentration (60-80 dS/m) was obtained during fourth and sixth year in the second and third reservoirs. The salt could be scraped, stored in bags and disposed of safely in the sea (around 600 km away from the study area) in order to maintain a favourable salt balance in the project area.

The final sizes of these reservoirs were 250 m x 200 m x 2 m;150 m x 200 m x 2 m and 250 m x 200 m x 2 m.

Table 3. Inflow (In), outflow (Out) and irrigation uptake (Irr) from all three reservoirs during the simulation period 1985 - 1992. (All values in 10^3 m^3.

	Reservoir 1			Reservoir 2			Reservoir 3		
Year	In	Out	Irr	In	Out	Irr	In	Out	Irr
1985	359	145	132	145	53	42	53	-	-
1986	233	4	210	4	-	8	-	-	-
1987	166	-	145	-	-	-	-	-	-
1988	346	139	132	139	87	-	87	-	-
1989	309	86	238	86	6	97	6	-	-
1990	8	-	58	-	-	-	-	-	-
1991	58	-	18	-	-	-	-	-	-
1992	76	-	38	-	-	-	-	-	-

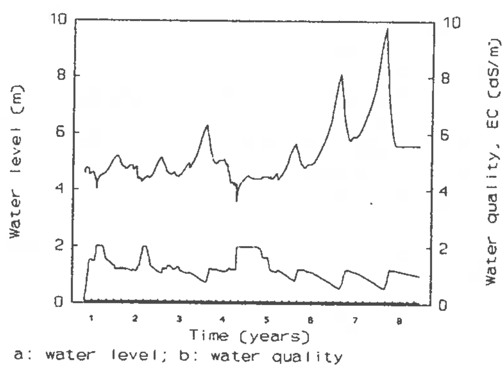

Figure 4. Temporal variation of water level and quality in the first reservoir.

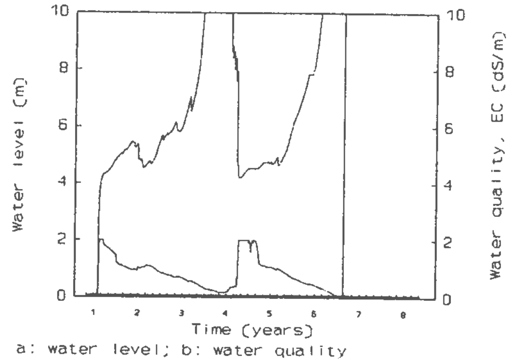

Figure 5. Temporal variation of water level and quality in the second reservoir.

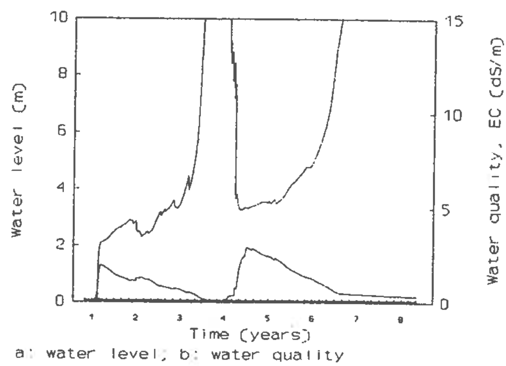

Figure 6. Temporal variation of water level and quality in the third reservoir.

SUMMARY AND CONCLUSIONS

Based on various simulation runs, the drain configuration (spacing x depth) of 75 m x 2 m depth was found to be satisfactory to maintain a favourable salt and water balance and for sustainable agricultural production. The drainage model in conjunction with the reservoir model was used to decide design specifications and an operation schedule for three connected reservoirs utilized for irrigation, fish culture and salt harvesting at the University Farm covering an area of 315 ha. The total area under the reservoirs was estimated to be about 4 percent of the total drained area. It was possible to draw water for irrigation from the first reservoir during all the simulated eight-year period and for three years from the second reservoir. The fish could be raised during all the eight years in the first reservoir and for four years and one year in the second and third reservoirs respectively.

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