Estimating the Volume of Subsurface Drainage Water under Different Crops

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Large-scale subsurface drainage projects are being implemented in different states of India for reclamation of waterlogged saline soils. Various options for management of saline drainage water like disposal into stream or river, reuse for cropping or agro-forestry and evaporation ponds have been tried on pilot scale field studies with different degrees of success. Information on expected rate and volume of drainage water from subsurface drainage projects would be useful for comparative evaluation of different disposal/management options and to design structures for conveyance or storage of drainage water. The parameters of De Zeeuw-Hellinga equations, appropriate for simulation of watertable depth and drain discharge in homogeneous soils, were modified in this study to be applicable for two layered stratified soils. The simulated results compared favourably with field observations of an experimental subsurface drainage site at Hisar (Haryana) during the recession phase of drainage. Peak discharge rate and volume of drainage water were simulated based on 10 years meteorological and irrigation data for different kharif (cotton, sorghum and bajra) and rabi (wheat, berseem, barley, mustard and oat) crops at the experimental site. Due to occurrence of high intensity rain during rainy season, peak rate of drainage was higher in kharif crops than in rabi crops. Berseem, cotton, sorghum and wheat generated considerably larger drainage volumes than the remaining kharif and rabi crops.

Keywords : Subsurface drainage, De Zeeuw-Hellinga equations, Watertable, Drain discharge, Crop water requirement

NOTATION

d : equivalent depth of the soil below drain level, m
h_e : entrance head loss, m
h_t : height of watertable midway between two lateral drains at time t, m
h_{t-1} : height of watertable midway between two lateral drains at time $t-1$, m
K : hydraulic conductivity, m/day
L : length of drain, m
Q : total drain discharge over length L, m^3/day
q_t : lateral drain discharge at time t, m/day
q_{t-1} : lateral drain discharge at time $t-1$, m/day
R : constant recharge during time interval Δt, m
r_e : entrance resistance, days/m
S : half drain spacing, m
t : time, days
ρ : drainable pore space, –
α : reaction factor, d^{-1}

INTRODUCTION

Water logging and often-associated soil salinity adversely affect the crop productivity and sustainability of irrigated agriculture in many states of India. It is estimated that 8.5 Mha land area in India has been affected by soil salinity and alkalinity[1]. About 0.7 to 1.0 Mha area in semi-arid regions of north west India, comprising the state of Punjab, Haryana, north western Rajasthan and western Uttar Pradesh, is afflicted by waterlogging and soil salinity problems and the affected area is increasing alarmingly[2]. For reclamation and management of waterlogged salt-affected soils, large-scale subsurface drainage projects are being implemented in certain states of India and a few more projects are expected in near future. Provision of drainage for removal of excess water and salt from the root zone would generate large quantum of drainage water, which would need safe disposal to minimize downstream degradation of soil and water regimes. Pilot scale experimental field studies on various management options of saline drainage water, like disposal into stream or river, reuse for cropping or agro-forestry, evaporation ponds have been attempted at different locations in the country with varying degrees of success. Whatever the option for disposal of drainage effluent, information on expected rate and volume of drainage water from subsurface drainage projects is critical.

In the present study, the parameters of the De Zeeuw Hellinga equations[3] applicable for homogeneous condition were modified to simulate watertable depth and drain discharge under non-homogeneous conditions. The equations with modified parameters were applied to estimate the volume of drainage water from a subsurface drainage system operational at Central Institute for Research on Buffaloes (CIRB) farm, Hisar. A subsurface drainage system was installed in 40 ha area at CIRB farm during 1990 with disposal of its drainage water into an evaporation pond of 1 ha surface area. Subsurface drains were installed at 75m and 100m spacing and 1.75m depth[4]. Simulated results were first compared with field observations for recession phase of drainage. Long term simulations on water table depth and drain discharge were performed based on 10 years meterological data, prevalent agronomic and irrigation practices for different *kharif* (cotton, sorghum and bajara) and

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This paper (redrafted) was received on December 3, 2001. Written discussion on this paper will be received until March 31, 2003.

rabi (wheat, berseem, barley, mustard and oat) crops in the area. These simulations were used to estimate peak discharge rate and mean drainage volume per unit cultivated area of different crops. The generated information can be useful to evaluate management or disposal options of drainage water and for design of different structures necessary for its conveyance or storage.

MATERIALS AND METHODS

Features of the subsurface drainage system at CIRB farm Hisar, modification of parameters of De Zeeuw Hellinga equations for non-homogeneous soil conditions, field validation and long-term simulation of peak drainage rate and seasonal drainage volume for different crops under subsurface drained conditions are discussed in the following subsections.

Subsurface Drainage System

Drainage investigations in the area indicated soils to be silty loam up to 1.5m depth and loamy below, with silt loam layers mixed with loamy sand at certain locations. Infiltration rate of soil varied from 2 cm/day to 8 cm/day while hydraulic conductivity (K), determined by auger-hole method, ranged from 0.12 m/day to 1.85 m/day. The K values were statistically analyzed and the value at 50% log probability level *ie*, 0.5 m/day was selected for design of drainage system. The depth to impervious layer ranged between 4.0 m to 5.0 m from ground surface. The depth of impervious layer below drain was taken as 2.75 m for which an equivalent depth of 2.20 m was estimated[5]. A subsurface drainage system for the amelioration of 40 ha waterlogged saline soils was designed on the basis of Hooghout's steady state drainage equation. Using a drainage coefficient of 1.5 mm/day and equivalent depth of 2.20 m, a drain spacing of 71.8 m was computed. Design drain spacing of 75 m , drain depth of 1.75 m and slope of 0.1 % were adopted for subsurface drainage system at CIRB, Hisar[4]. An evaporation pond of 1 ha area and 2 m depth was constructed for disposal of saline drainage water.

Simulation of Watertable Depth and Drain Discharge

Soils in the study area were non-homogeneous, recharge to drainage system was intermittent and consequent flow to drains was unsteady. Steady state Hooghoudt equation or unsteady state Glover Dumm's equation[5] applicable for homogeneous soil conditions had limited scope for predicting watertable depth and drain discharge in the project area. De Zeeuw Hellinga equations[3], also applicable for unsteady state conditions for homogeneous soils, with proposed modified parameters were applied for non-homogeneous soils conditions to improve predictions on water table depth and drain discharge at subsurface drainage system at CIRB, Hisar.

De Zeeuw Hellinga equations

De Zeeuw-Hellinga equations[3] for simulating drain discharge and water table depth in homogeneous soil are presented below. To simulate drain discharge over a period with non-uniform recharge, the period is divided into time intervals of equal length *eg* days.

$$q_t = \left(q_{t-1}\, e^{-\alpha \Delta t}\right) + R\left(1 - e^{-\alpha \Delta t}\right) \qquad (1)$$

$$h_t = \left(h_{t-1}\, e^{-\alpha \Delta t}\right) + \frac{R\left(1 - e^{-\alpha \Delta t}\right)}{\left(0.08\ \rho \alpha\right)} \qquad (2)$$

where, q_t, h_t and q_{t-1}, h_{t-1} are the drain discharge (m/day) and watertable height midway between drains m at time t and $t-1$ respectively, R is the recharge, m, ρ is the drainable pore space (–) and t is the time days, while the reaction factor α , d^{-1} is given by

$$\alpha = \frac{\pi^2\ K d}{\rho S^2} \qquad (3)$$

where K is hydraulic conductivity, m/day, d is the equivalent depth of the soil below drain level, m and S is the half drain spacing, m

De Zeeuw Hellinga Equations for Stratified Soil Layers

Soils under field conditions are generally not homogeneous, though individual layers in a stratified soil can be treated as homogeneous. At the study site, the top soil layer of about 1.0 m depth was relatively more pervious, followed by a comparatively less pervious middle layer (in which drains are installed), underlain further by the least pervious lower zone. Simulations by De Zeeuw Hellinga equations using average soil properties of three stratified layers gave good results when water table fluctuation range was within the top porous layer. At lower depth ranges of watertable fluctuations, there were differences in the observed and simulated values, perhaps due to sudden reduction in hydraulic conductivity and an increase in entrance resistance to flow[6]. To improve simulated results on watertable depth and drain discharge during a phase when watertable fluctuated in the less pervious middle layer, parameters (reaction factor and drainable pore space) of De Zeeuw Hellinga equations were determined by using soil properties of middle and lower layer. Using parameters of these layers, the simulation of watertable depth in the middle layer improved; the simulations on drain discharge were further improved by incorporating the effect of entrance resistance which can be defined as

$$r_e = \frac{h_e \times L}{Q} \qquad (4)$$

where r_e, h_e, L and Q are entrance resistance, days/m, entrance head loss, m, length of drain, m and total drain discharge over length L, m^3/day, respectively. It is seen from equation (4) that r_e is inversely proportional to drain discharge Q and consequently to hydraulic head, h since Q is proportional to h during the receding watertable conditions. This implied that r_e can influence Q at small hydraulic heads. At large hydraulic heads (when watertable fluctuated within the top porous zone), the impact of entrance resistance was negligible and the De Zeeuw-Hellinga equations predicted drain discharge and watertable depth fairly accurately. The effect of entrance resistance, however, became prominent in the depth range of middle zone or below when hydraulic head was relatively small. Under

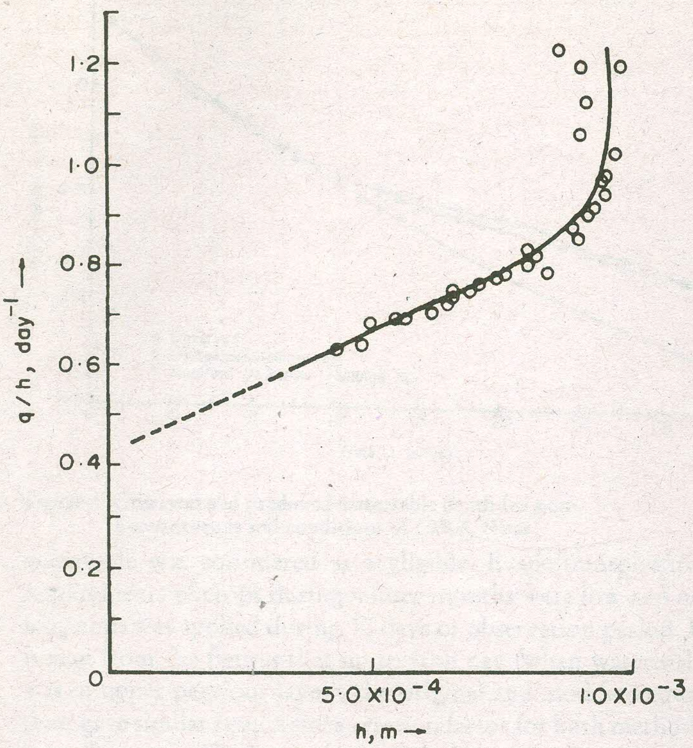

Figure 1 A plot of (drain discharge q/hydraulic head h) v/sh

such conditions, the effective heads causing lateral flow at times $(t + n - 1)$ and $(t + n)$ were obtained by subtracting entrance head loss, h_e at these times from the corresponding hydraulic heads. The drain discharge q in m/day was consequently obtained as

$$q_{(t+n)} = q_{(t+n-1)} \frac{\left(h_{(t+n)} - h_{e\,(t+n)}\right)}{\left(h_{(t+n-1)} - h_{e\,(t+n-1)}\right)} \qquad (5)$$

Though h_e may vary with time, an average constant value of 0.1 m was used in the analysis in absence of information on the exact nature of its variation. Equation (5) was used to simulate drain discharge at Hisar field site when the watertable fluctuated in the depth range of the middle layer.

De Zeeuw Hellinga equations for stratified soils were tested with field data of CIRB farm, Hisar and were used for long term simulation of watertable depth and drain discharge for different crops. These equations do not consider root density and root water uptake pattern from different layers. Recharge was determined indirectly from the estimated evapo-transpiration requirement of crops. The purpose of the study was to estimate the approximate rate and volume of drainage water before the installation of subsurface drainage project using basic soil data available from drainage investigations. In water balance analysis, 20% of the rainfall and 35% of irrigation were assumed to contribute to groundwater recharge for Hisar region[7]. In addition, it was also assumed that small amount of pre-monsoon and winter rains would not be contributing to groundwater .

Table 1 Mean hydraulic conductivity, *K* drainable porosity, ρ and reaction factor α of soils at CIRB, Hisar

Layer depth, m	K	ρ	α
De Zeeuw Hellinga equations			
Upper layer (< 1.0 m)	0.91	0.145	0.028
Below the upper layer (> 1.0 m)	0.91	0.145	0.028
De Zeeuw Hellinga equations with modified parameters			
Upper layer (< 1.0 m)	0.91	0.145	0.028
Below the upper layer (> 1.0 m)	0.45	0.14	0.015

RESULTS AND DISCUSSION

Field Validation of Simulated Results

Hydraulic conductivity K_a (above drain) and K_b (below drain) in drainage project area were determined using data on lateral drain discharge q, m/day and watertable elevation h, m at midway between drains. A plot of q/h and h (Figure 1), shows upward sloping trend upto a certain value of head. Results indicated K_a to vary from 1.18 m/day to 2.28 m/day while K_b varied from 0.035 m/day to 0.129 m/day. The average hydraulic conductivity of whole soil mass was estimated as 0.91 m/day. The average drainable pore space (ρ) was taken as 0.15 for upper 1.0 m depth and 0.14 for the lower layers[8]. The average hydraulic conductivity and drainable porosity values of the whole soil mass were used for simulations by De Zeeuw Hellinga equations. In case of De Zeeuw Hellinga equations with modified parameters the average hydraulic conductivity and drainable porosity of the whole soil mass or of only the middle and bottom layers were used when water table fluctuated in the top and middle depth zones respectively (Table 1).

Simulated drain discharge and watertable depths using original De Zeeuw Hellinga equations and the proposed approach for stratified soils were compared with the observed data and are presented in Figures 2 and 3 for the period from 30th December 1995 to 28th January 1996. Two rain events of 1.8 mm and 3.5 mm were experienced on 14th and 15th January respectively. As rainfall amounts were small the contribution to

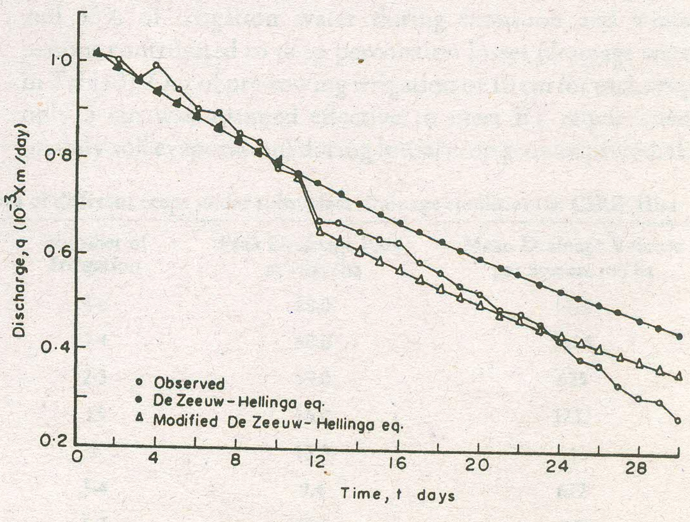

Figure 2 Observed and predicted drain discharge for non- homogeneous soil conditions of CIRB, Hisar

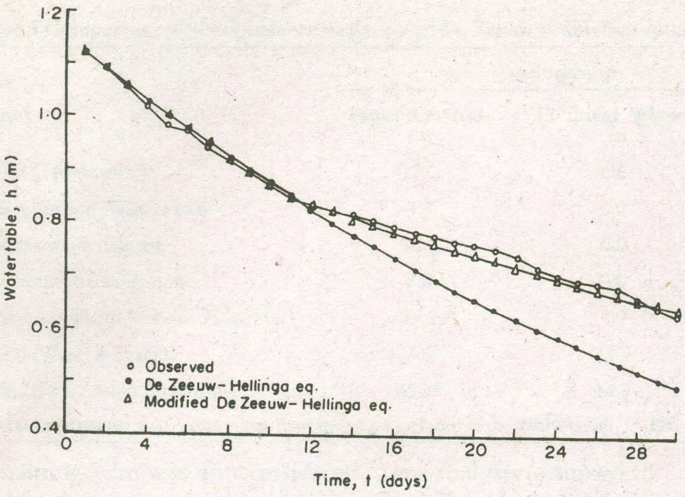

Figure 3 Observed and predicted watertable depth for non-homogeneous soil conditions of CIRB, Hisar

watertable was considered as negligible. Evapo-transpiration requirements of crops during winter months were low and no irrigation was applied during 30 days of observation period. It is seen from the figures that up to 10th day (when watertable was in upper pervious layer), the original and modified equations gave similar results since reaction factor for both methods was the same. However, from 11th day onwards when watertable was falling through middle layer, the predictions by equations with modified parameter matched better with the field observations. This was primarily due to a more realistic estimation of reaction factor and incorporation of the effect of entrance resistance. The maximum absolute net deviation between observed and estimated discharge reduced from 1.71 m/day (with original equations) to 0.0017 m/day (with modified parameters). Corresponding deviations for watertable depths were reduced from 0.095 m to 0.000025 m. In brief, the equations with modified parameters predicted discharge and watertable regime more realistically under conditions when the recharge was intermittent, flow to drains unsteady and soil non-homogeneous.

Long-term Simulation of Subsurface Drainage Rate and Volume

Long term watertable depth and drain discharge were simulated for different *kharif* (cotton, sorghum and bajra) and *rabi* (wheat, berseem, barley, mustard and oat) crops in the region considering evapo-transpiration requirements[9, 10], daily rainfall based on 10 years (1984-1994) record and prevalent irrigation practices. Hydraulic conductivity and drainable pore space values indicated in Table 1 were used during simulations.

Groundwater depth at the time of pre-sowing irrigation was taken as the initial watertable depth. Calendar dates of irrigations including of pre-sowing irrigation were identified. Whenever rainfall was approximately equal to irrigation depth, irrigation was either cancelled or postponed. Moisture holding capacity of soil was determined by taking field capacity and wilting point as 18% and 7.5% respectively. Sum of rainfall and irrigation exceeding the moisture holding capacity was taken as recharge to the watertable. Long-term simulations were carried out separately for each crop considering its irrigation requirements. The maximum simulated drain discharge of 10 results was taken as the peak discharge rate. Mean drainage volume was determined as average of simulated values of 10 years under different *kharif* and *rabi* crops. Results of long term simulations in terms of peak drainage rate and mean drainage volume under different crops are presented in Table 2.

Table 2 indicates that peak rate of drainage was higher in case of *kharif* crops like cotton, sorghum and bajra due to occurrence of high intensity rain events during rainy season. Peak drainage rates for *rabi* crops were considerably low compared to *kharif* crops since groundwater recharge during *rabi* season occurred mainly due to irrigation excess. Drainage volume was highest in berseem crop for which more frequent irrigations were applied. Of the studied crops, berseem, cotton sorghum and wheat generated considerably large volumes compared to remaining *kharif* and *rabi* crops.

Example water balance analysis for a *kharif* (sorghum) and a *rabi* (wheat) crop based on procedure[10] and De Zeeuw simulations are presented in Table 3. The average rainfall amounts during sorghum and wheat crop period were 37.6 cm and 4 cm, respectively. The pre-monsoon and monsoon rainfall amounts during sorghum crop were 4.6 cm and 33 cm, respectively. Two and six irrigations of 7 cm each were given to sorghum and wheat crops respectively. It was assumed that 20% of rainfall and 35% of irrigation water during monsoon and winter seasons contributed to deep percolation losses (drainage water in Table 3). Out of pre-sowing irrigation of 10 cm for each crop, only 5 cm was assumed effective to meet ET requirements (mainly soil evaporation) during initial crop growth period, the

Table 2 Simulated peak drainage rate and mean drainage volume per unit area of different crops under subsurface drainage conditions at CIRB, Hisar

Crop	Sowing Date	Crop Period, days	ET, cm	Number of Irrigation	Peak Drainage Rate, m^3/day/ha	Mean Drainage Volume per Season, m^3/ha
Cotton	5th May	174	85	4-6	88.0	1498
Sorghum	15th May	164	50	3-4	58.0	1205
Bajra	1st July	128	50	2-3	39.0	625
Berseem	5th October	183	90	15	15.0	1733
Mustard	20th October	183	15	2	13.3	643
Oat	10th October	178	30	3-4	9.4	672
Wheat	10th November	156	35	5-7	13.8	1104
Barley	20th November	147	30	3-4	13.8	789

Table 3 Comparison of water balance analysis and De Zeeuw simulation results

Input	Sorghum			Wheat		
	Input Amount, cm	Drainage Water, cm	ET, cm	Input Amount, cm	Drainage Water, cm	ET, cm
Rainfall (monsoon)	33.0	6.6	26.4	—	—	—
Pre-monsoon/Winter rain	4.6	0.0	4.6	4.0	0.0	4.0
Pre-sowing Irrigation	10.0	0.0	5.0	10.0	0.0	5.0
Pre-monsoon Irrigation	7.0	0.0	7.0	—	—	—
Irrigation (during monsoon/winter)	14.0	4.9	9.1	42.0	14.7	27.3
Total (Water balance)	68.6*	11.5	52.1	56.0*	14.7	36.3
Total (Dee Zeeuw Equations)	69.9*	14.9	50.0	51.0*	11.0	35.0

* 5 cm unaccounted water from pre-sowing irrigation included in the total amount; ** 20% of monsoon rainfall and 35% of normal irrigation water

remaining 5 cm was not considered in the analysis (assumed to replenish or redistribute moisture in the soil profile). Similarly it was assumed that pre-monsoon inputs (rain and irrigation) as well as winter rain were utilized fully to meet ET requirements of crop and resulted in no drainage. The contributions of surface runoff, sub-surface inflow, capillary rise were also assumed to be negligible and were neglected in the analysis. It is seen that the simulated and water balance results for these two crops are in close agreement. A similar approach was used for other crops to derive final results of Table 2.

While designing the subsurface drainage system, the fraction of area to be put under various crops during different seasons can be envisaged. Peak drainage rate and drainage volume from subsurface system can be more realistically estimated by using approach discussed in this paper. Peak drainage rate would be useful in the design of conveyance system like main surface or pipe drain to carry drainage effluent from the project area to the disposal site. Estimates of drainage volume are helpful in designing the storage capacity of structures for evaporation or for reuse for irrigation of crops or agro-forestry.

CONCLUSIONS

The parameters of De Zeeuw Hellinga equations for simulating watertable depth and drain discharge were modified to incorporate the effects of non-homogeneous soil and intermittent recharge conditions. Non-homogeneous soil conditions were represented by different homogeneous soil layers. The parameters were modified by incorporating the effect of reduction in hydraulic conductivity and drainable pore space and an increase in entrance resistance to flow at smaller discharge values. The equations were validated with field data. Long term simulation of watertable depth and drain discharge under different crops in the drainage area provided estimates of the expected peak rates and volume of drainage water from subsurface drainage projects. Peak drainage rates were higher in *kharif* crops like cotton, sorghum and bajra than in *rabi* crops. Berseem, cotton, sorghum and wheat generated considerably larger volumes of drainage water than the remaining *kharif* and *rabi* crops. The generated information is useful in the management of drainage effluent, in particular for the design of conveyance and storage structures.

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