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Performance Evaluation of Subsurface Drainage System with the Strategy to Reuse and Disposal of its Effluent for Arid Region of India

VINOD KUMAR TRIPATHI[1], S.K.GUPTA[2] AND PRADEEP KUMAR[3]

[1]*Directorate of Water Management, Bhubaneswar - 751 023*
[2]*AICRP on Use of Saline Water, CSSRI, Karnal - 132 001*
[3]*Water Technology Centre, IARI, New Delhi - 110 012*

ABSTRACT

Disposal of drainage effluent is a major issue associated with subsurface drainage system. Without proper disposal of drainage effluent, environmental problems may arise which may nullify the advantages and act as a stumbling block in the expansion of drainage in the country. In order to estimate the quantity of drainage effluent the Glover-Dumm equation is found to be most appropriate on the basis of average error and root mean square error. An assessment of drain discharge for entire year on daily basis has been done through its disposal to pond. The main design assumptions in this study are that the depth of water in pond at any time does not exceed 2.0 m and storage at the end of year (June) is less than 0.1 m. The evaporation pond area under the assumptions is found to be 8 percent of the drained land for arid region. The management options for disposal of saline drainage effluent considered are closure of pumping, reuse of drainage effluent for irrigation and the combination of two. In absence of a safe drain disposal outlet, evaporation ponds seem to be a viable option for the disposal and reuse of drainage effluents.

Key words: Subsurface drainage, drainage effluents, evaporation pond, reuse

Introduction

Inter-basin transfer of water has been a major thrust area such that canals networks are now a major source of irrigation in the arid and semi-arid regions. It is now well established that seepage from the canals and other distribution structures and inefficient use of irrigation water has led to the development of waterlogging and soil salinity in many irrigation commands. The problem is quite widespread and it is assessed that about 5.6 million ha of land has gone out of cultivation in irrigation commands (Tyagi and Minhas, 1998). To reclaim and manage waterlogged salt affected lands, drainage seems to be most appropriate intervention. Besides many advantages, drainage helps to maintain edaphic environment that is favorable to crop production. During extensive and intensive field testing of the system, it has been observed that one of the major environmental issue in implementing drainage is to find out a suitable outlet for the disposal of drainage effluent as saline drainage effluent is commonly a by-product of any drainage system. The disposal of the effluent should be made in such a manner that there are no adverse effects on the soil and water resources of the region and environment at the disposal site remains undisturbed. The possible alternatives for effluent disposal are sea, rivers, deep aquifer and evaporation ponds. Effluents can also be reused for irrigation and agro-plantations.

Disposal of saline drainage effluent to the sea is uneconomical for inland areas, which are located far away from the sea. Disposal into the rivers has several implications. A major limitation is that the discharge to the river could be limited and that too in a specific time frame, i.e. only during the monsoon season. In other seasons, river water is the main source for domestic and industrial supplies to down stream urban areas and therefore, not much saline drainage effluent could be discharged. Disposal to the deep aquifer requires favourable geo-hydrological conditions. Scientific geo-hydrological investigations must precede before any such arrangement is finalized as otherwise it may cause contamination of the groundwater, which would be more serious environmental problem.

In many situations particularly in land locked areas such as many parts of north-west India, evaporation ponds would be an appropriate means for disposal and reuse of the drainage effluent. Dutta *et al.* (2000) reported that construction of evaporation ponds to temporarily store drainage effluent was technically possible while maintaining the financial feasibility of the investments in drainage. A number of earlier studies provide a fairly wide range of estimate of the area required to temporarily store the drainage effluent in on-farm evaporation ponds. Gupta and Oosterbaan (1987) developed a theoretical approach to assess the size of the tank and concluded that about 10% of the area was required for a pond where average depth of water in the pond was about 1.7 m. Rao and Rao (1990) on the other hand suggested that a tank covering an area of 5% of the total drained area would be sufficient, if appropriate management options were incorporated. The evaporation ponds have been extensively used to dispose drainage effluents in the U.S.A., the Australia and other countries. This system of disposal has not yet become popular mainly because the design procedure for this kind of structure has not been well investigated and verified. The cost of the system is also, in some cases, an impediment in the application of this technology. Nevertheless in many cases, it would be the only option for drainage effluent disposal and reuse. Reuse of drainage effluent has been well-investigated subject in this country. With the information being generated in other projects on use of saline water in agriculture, many techniques are now available which favour the reuse of drainage water for crop production and for agro-plantations. For the purpose of this study, these options have been utilized as management options to reduce the area of an evaporation pond under consideration. In view of this, present study was carried out to evaluate performance of various unsteady state drainage design models for arid conditions and develop a design procedure for evaporation pond.

Materials and methods

Location

The subsurface drainage system has been installed in 1996 at the farm of Agricultural Training Center, Loonkaransar, Bikaner, Rajasthan, India. This farm is situated 2 km north of Loonkaransar town on the National Highway No. 15, about 72 km away from Bikaner and is located between 28°30' and 28°32' north latitude and 73°45' and 73°46' east longitude. The farm is falls in the command area of Kanwar Sain lift canal, a part of Indira Gandhi Nahar Pariyojana. The total area of the farm is 77.23 ha. The horizontal subsurface drainage system on farm is installed on the area of about 40 ha, and is divided into 24 plots of 125×125 m each (1.5ha). The climate of the area is classified as arid. The minimum temperature during winter can go below 5°C, while the summers are very hot and dry with a maximum temperature of around 45°C. Sand and dust storms are a common feature of the area. At present pigeon pea, groundnut, green gram, wheat and musturd are generally grown in this area.

Rainfall

Rainfall at Loonkaransar is low and the average annual rainfall is 238mm. For the estimation of hydraulic head and drain discharge by various equations rainfall of Loonkaransar was proposed to be utilized. Due to non-availability of data the rainfall data of the nearest gauging station Bikaner have been utilized. Out of the ten years, a year (1998-99) with maximum rainfall (347.5 mm) has been chosen for the present study.

Drainage experimental plot

The subsurface drainage system is designed to drain the deep percolation losses resulting from applied irrigation water so as to maintain a safe water table depth. A drainage coefficient of 1.0 mm/day is adopted for the design of subsurface drainage system. Laterals are placed at a depth of 1.6m with a drain spacing of 125m. Depth of collector drain is 2.0m. The difference between depth of lateral and collector drain at their junction facilitates monitoring of the drain discharge and quality of water from individual lateral. Drainable porosity of this site has been taken as 0.14 and depth of impermeable gysiferous layer from drain level is 3.4m. The average hydraulic conductivity of the area is taken as 1.0 m/day for present study. The experimental area has moderately rapid infiltration rate of about 8.4 cm/h. The infiltration test conducted at several sites indicated that basic infiltration rate ranges from 2.0 to 18.0 cm/h.

Drain flow data

Hydraulic head and drain discharge data for the year 1999 is collected from Indo–Dutch Network Project Sub-centre, Hanumangarh, Rajasthan.

Recharge to Water Table

Main factors for the recharge to water table considered are rainfall and irrigation. Rainfall less than 5.0 mm is neglected assuming that it would not lead to recharge. For rainfall higher than 5.0 mm, it was assumed that 60 percent of the rainfall contributes to shallow water table, in the area. The fields being bunded from all sides, surface runoff is quite less in this area as compared to the non bunded areas. Such a situation is also favourable for leaching of salts and is a desirable proposition.

Generally irrigation is provided to *rabi* crops, but if there is low rainfall in the rainy season one or two irrigation are necessary to prevent crop damage. In the present study, only *rabi* season irrigation was considered. It was also assumed that in *kharif* season rainfall is more critical to the drainage system than irrigation and therefore, any irrigation that is given would not raise the water table to critical level. Depth of irrigation in the area is 60 mm per irrigation and is applied at an interval of 21 days (wheat crop) through surface irrigation. If there is rainfall, the interval is accordingly extended. It was considered that conveyance and deep percolation loss in these sites are 40 percent of the depth of irrigation (Rao and Kamra, 1991) which is contributing to ground water table.

Estimation of hydraulic head and drain discharge

Assumption made that the water table was at drain level at the time of start of the rainy season (July) and never goes below the drain level. If the hydraulic head or the water table comes above ground level then it is treated at ground level assuming that water in excess goes as runoff. Hydraulic head and drain discharge were estimated by the three unsteady state models as discussed below:

The Glover-Dumm equation

Assuming initially the shape of the water table being a fourth degree parabola, the Glover-Dumm equation is used to calculate the water table midway between the drains as follows:

$$h_t = h_0 \, e^{-\alpha \Delta t} \qquad \ldots(1)$$

a = reaction factor (day^{-1})

Δt is time period during which water table drops from h_0 to h_t in days.

Adopting instantaneous recharge condition on any day by rainfall or irrigation, hydraulic head depends upon the recharge factor or percentage deep percolation losses, which decides as to what percentage of rainfall/irrigation water contributes to the rise in groundwater table. If initial water table is at the drain level and rainfall or depth of irrigation applied is R_I then recharge is

$$\text{Recharge} = R_I \times \text{Fac} \qquad \ldots(2)$$

Fac = Rainfall recharge factor or percentage deep percolation loss which is less than 1.0

Due to this recharge increment in hydraulic head

$$\Delta h = \frac{Recharge}{\mu} \qquad \ldots(3)$$

μ = drainable pore space

For 1st time interval $h_0 = \Delta h$ because water table is initially at the drain level.

By applying this h_0 in eq. (1), hydraulic head after a time period say t day will be h_t.

During recession period, if any rainfall or irrigation occurs then hydraulic head calculated by eq. (3) should be added to the water table on that day by assuming instantaneous recharge condition.

Drain discharge is directly related to the hydraulic head so that by knowing hydraulic head, drain discharge can be calculated by the following equation:

$$q_t = 6.89 \frac{K h_t d_e}{L^2} \quad \ldots(4)$$

The De Zeeuw – Hellinga equation

In this equation non-uniform recharge is divided into shorter time periods in which recharge to the ground water can be assumed to be constant. The change in drain discharge is proportional to excess recharge (R–q),

$$\frac{dq}{dt} = \alpha(R - q) \quad \ldots(5)$$

where

$$\alpha = \frac{\pi^2 K d_e}{\mu L^2} = \text{reaction factor (day}^{-1}\text{)}$$

By this equation, hydraulic head and drain discharge will be as:

$$h_t = h_{(t-1)}\, e^{-\alpha \Delta t} + \frac{Recharge}{0.8\mu\alpha}\left(1 - e^{-\alpha\Delta t}\right) \quad \ldots(6)$$

here recharge is calculated in the same manner as in the Glover-Dumm equation using eq. (2)

Δt is time interval for calculation of depth to water table from h_{t-1} to h_t.

$$q_t = q_{(t-1)}\, e^{-\alpha\Delta t} + Recharge\left(1 - e^{-\alpha\Delta t}\right) \quad \ldots(7)$$

when water table is at the drain level, $q_{t-1} = 0$ and $h_{t-1} = 0$ so that for the first day of recharge hydraulic head and drain discharge will be as follows:

$$h_t = \frac{Recharge}{0.8\mu\alpha}\left(1 - e^{-\alpha\Delta t}\right) \quad \ldots(8)$$

$$q_t = Recharge\left(1 - e^{-\alpha\Delta t}\right) \quad \ldots(9)$$

At the time of recession, second term of eq. (6) and (7) will be zero, and this equation will behave like the Glover – Dumm equation.

The Kraijenhoff Van de Leur-Massland equation

Applicability of this equation is valid for various recharge conditions. In the present study, an intermittent recharge condition has been considered. For the computation of hydraulic head and drain discharge at the end of any arbitrary day, it is essential to account for the recharge of each preceding days. Recharge for each day is taken as given by eq. (2). Let for t^{th} day hydraulic head is

$$h_t = \frac{1}{\mu}\left(C_1 R_t + C_2 R_{t-1} + C_3 R_{t-2} + \ldots\ldots\ldots\ldots\ldots\ldots C_t R_1\right) \quad \ldots(10)$$

where

$C_1 = c_1 j$,

$C_2 = (c_2 - c_1)\, j$,

$C_t = (c_t - c_{t-1})\, j$

$$c_t = \frac{4}{\pi}\sum_{n=1,-3,5}^{\infty} \frac{1}{n^3}\left(1 - e^{\frac{-n^2 t}{1/\alpha}}\right) \quad \ldots(11)$$

Similarly discharge rate is

$$G_t = \left(G_1 R_t + G_2 R_{t-1} + G_3 R_{t-2} + \ldots\ldots\ldots\ldots\ldots\ldots G_t R_1\right) \quad \ldots(12)$$

where

$G_1 = g_1$,

$G_2 = (g_2 - g_1)$,

$G_t = (g_t - g_{t-1})$

$$g_t = \frac{8}{\pi^2}\sum_{n=1,3,5}^{\infty} \frac{1}{n^3}\left(1 - e^{\frac{-n^2 t}{1/\alpha}}\right) \quad \ldots(13)$$

In this way, hydraulic head and drain discharge was calculated for the entire year. To avoid complexity in various values, a computer programme has been prepared and used.

Comparison of observed and estimated value

Estimated value of hydraulic head and drain discharge from different equations are compared with the observed or corrected data. Two performance indicators namely, Average Error (AE) and Root Mean Square Error (RMSE) were used, which compared the observed and the simulated values. AE and RMSE were calculated using Equations 14 and 15 respectively. The AE indicates whether the model is over or under predicting; for a perfect simulation, AE should be zero. The RMSE measures the average precision of the simulation and should be as small as possible. (Nash & Sutcliffe, 1970).

$$AE = \sum_{i=1}^{n} \left(P_i - O_i\right) / n \qquad \text{...(14)}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \left(P_i - O_i\right)^2 / n} \qquad \text{...(15)}$$

where,

P = Predicted values;

O = Observed values;

n = Total no of observations

Design of Evaporation Pond

It has been observed that in land locked areas, evaporation pond could be one of the most appropriate alternative for the disposal of saline drainage effluent. Considering drain discharges as estimated by the Glover-Dumm equation, the procedure for the design of an evaporation pond has been developed and the area required for the pond as a percentage of drained area has been calculated. The main design assumptions (Tripathi *et al.*, 2003) in this study are that the depth of water in pond at any time does not exceed 2.0 m and storage at the end of year (June) is less than 0.1 m.

Results and Discussions

Comparative performance of equations

Three equations namely the equation derived from the exact Glover-Dumm equation, the De Zeeuw-Hellinga and the Massland were choosen to identify an equation that best assessed the hydraulic heads and drain discharges for an arid station. The AE and RMSE between the observed and predicted values were used to select the most appropriate equation. The average error for hydraulic head varied from -0.044 to 0.043 while it varied from 0.066 to 0.317 for drain discharge. In both cases, the average error is lowest for the Glover-Dumm equation. Comparative performance in terms of RMSE is lowest for same equation (Table 1). Thus, it is clear that overall Glover-Dumm equation performs better than the two other unsteady state drainage equations as it can predict accurately the drain discharge with reasonably good accuracy of hydraulic heads. Better performance of the Glover-Dumm equation is also reported by French and O' Callaghan (1966), Rawat (2001), RAJAD (1995). In view of this, the Glover-Dumm equation has been used in the prediction of drain discharge for design of evaporation ponds as well as in assessing management options.

Annual water table

Annual water table hydrograph (Fig. 1) shows that water table is always below 1.20 m in the rainy season and varies from 0.8 to 1.1 m in the

Table 1. Comparative performance of equations

Equation	Hydraulic Head		Drain Discharge	
	AE	RMSE	AE	RMSE
Glover-Dumm	-0.044	0.092	0.066	0.195
De Zeeuw-Hellinga	0.082	0.107	0.267	0.385
Massland	0.043	0.103	0.317	0.414

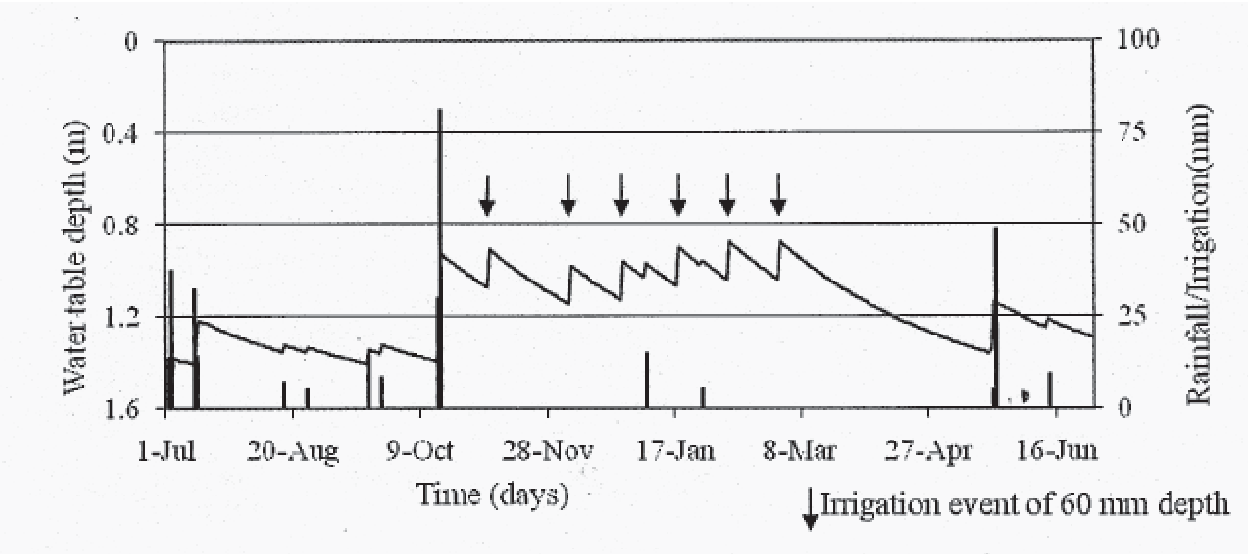

Fig. 1. Annual water table hydrograph

rabi season. The main reason for the high water table in *rabi* season compared to rainy season is due to deep percolation losses as a result of irrigation at this site. The preliminary investigations have also led to conclusions that installation of subsurface drainage system at this site is only to prevent the waterlogging resulting from deep percolation losses.

Prediction of monthly drain discharge

Daily drain discharge predicted by the Glover-Dumm equation is reported on monthly basis in mm/day (Table 2). It is observed that deep percolation is having more pronounced effect on drain discharge than rainy season. Maximum drain discharge is observed in *rabi* season which is 0.697 to 0.748 mm/day in the months of November to February compared to rainy season when the drain discharge is in the range of 0.321 to 0.466 mm/day.

Area and water balance of evaporation ponds

It is known that drain discharge increases with increasing rainfall. Thus, evaporation pond area required to store drainage effluent would also increase with increase in rainfall because more space is needed to store drainage effluent. The pond area for the Loonkaransar site is assessed to be 8.0 percent for maximum rainfall year. Tanji

Table 2. Monthly average drain discharge (mm/day)

Month	Drain discharge
July	0.322
August	0.321
September	0.279
October	0.466
November	0.697
December	0.624
January	0.726
February	0.748
March	0.718
April	0.490
May	0.365
June	0.451
Average	0.517

et al. (1985) have also suggested that about 33 percent of area for an evaporation pond under non-reuse condition would be required to dispose off drainage water. For the Loonkaransar site, Denecke (1998) reported that the evaporation pond area should be about 4 to 7 ha for an area of 40 ha, where subsurface drainage has been installed. The present study suggests that an evaporation pond area of about 3.5 ha, lower than the value suggested by Denecke would be sufficient to dispose off the drainage effluent at this site. Water balance in the pond as per the assessed area reported in Table 3. From July to October, month wise water input is equal to or

Table 3. Water balance in pond

Month	Input (m^3)	Output (m^3) Evaporation (m^3)	Seepage (m^3)	Balance (m^3)	Depth of water (m)
July	3992.80	7047.17	1984.00	0.00	0.00
August	3980.40	5725.82	1984.00	0.00	0.00
September	3348.00	5256.96	1920.00	0.00	0.00
October	5778.40	4844.93	1984.00	0.00	0.00
November	8364.00	2983.68	1920.00	3460.32	0.11
December	7737.60	1982.02	1984.00	7231.90	0.23
January	9002.40	1982.02	1984.00	12268.29	0.38
February	8377.60	2784.77	1792.00	16069.12	0.50
March	8903.20	4991.74	1984.00	17996.58	0.56
April	5880.00	6748.80	1920.00	15207.78	0.48
May	4526.00	8955.78	1984.00	8794.00	0.27
June	5412.00	9377.28	1920.00	2908.72	0.09

less than the output and maximum water balance (17996.58 m^3) occurs in the month of March with the depth of 0.56 m.

Management of Drainage Effluent

From the foregoing discussion, it is essential to manage the drainage effluent in a practical manner such that the size of the evaporation pond could be reduced to a minimum. These options should either reduce the input to the pond or increase the output from the pond. There are a limited number of options available when trying to decide where and how much drainage water could be disposed. The common available options are, return the water either to the drained land as a part of leaching water, irrigation water, or dispose it off to a river or to the ocean. The options in land locked areas are even limited. Considering the situations of such areas, two important and practically applicable management options are to reduce input by closure of the pump in an appropriate month or months, increase output by applying the drainage water for irrigation in the drained area. A combination of the two options can also work simultaneously. So that pond area 8% under without management options can be minimized upto 2.6% with the application of both management options. The reuse potential of drainage effluents depends upon the water quality. If the salinity of water is less than or equal to 9 dS m^{-1}, all the post showing irrigation to wheat could be given with the drainage effluents without any detrimental effect on the crop or the land. If it is above 9 dS m^{-1} but less than 15 dS m^{-1}, drainage effluent could be used in conjunction with fresh water (Sharma *et al*., 1991).

Conclusions

This study was done to investigate the applicability of the Glover-Dumm, the De Zeu Hellinga and the Massland equations in designing of subsurface drainage system for arid regions of India. The Glover-Dumm equation has been found appropriate for assessing the hydraulic heads and the drain discharge. Therefore, this equation is suggested for use to predict hydraulic heads and drain discharge on daily basis for the design of drainage structures including evaporation ponds for the disposal of drainage effluents. For the maximum rainfall conditions which are considered critical, the pond area for the Loonkaransar site is 8.0 percent of the drained land, which can be minimized upto 2.6% by applying management options.

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