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*Original Article*

# Comparative Study of the Spacing of Subsurface Drains in the Eastern Gandak Project Using Different Criteria

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***Abstract*** - *Irrigation is an age-old practice in India. A sizable proportion of irrigated areas have suffered due to waterlogging and salt-related problems. The proper provision of drains in irrigated command areas differed or was postponed in many projects, including the Eastern Gandak project in Bihar, India. Keeping this in view, the spacing of sub-surface drains in the Eastern Gandak project has been determined. A comparative study was made using different steady-state and unsteady-state criteria. The study reveals that the irrigation schedule has a very high influence on the estimation of drain spacing, especially for unsteady-state conditions. In addition, it is observed that the spacing using Donnan's approach is consistently larger than that from Hooghoudt's approach for steady-state conditions. Also, the spacing estimated from these two models is correlated with* $r^2 = 0.7648$*. Further, for the unsteady-state approach, the spacing estimated from the van-Schilfgaarde approach varies from 1.45 to 1.85 times the spacing determined using Glover-Dumm's approach. However, these two approaches have a good correlation with* $r^2 = 0.9734$*. Hooghoudt's approach uses the concept of equivalent depth (*$d_e$*), which is less than the actual depth of the barrier layer from the level of the drain. Therefore, it is recommended to use Hooghoudt's equation for steady state condition and Glover-Dumm's equation for unsteady state condition in the study area and other projects of the state of Bihar and elsewhere in India. The sub-drains do not require repairs and maintenance once the envelope is properly designed and placed around the drain tube.*

***Keywords*** - *Barrier layer; Subsurface drain spacing; Equivalent depth; Steady state criteria; Unsteady state criteria.*

## 1. Introduction

Waterlogging reduces soil aeration, whereas salinity increases the osmotic potential of soil solution, leading to a lower crop yield (Singh, 2015). Crop yield reduction varies from 10% to 100% for different crops for soil salinity varying between 1.5 to 27 dS/m (FAO, 2018). CSSRI (2010) and IDNP (2002a) estimated salt-affected areas in India to be 6.7 and 8.4 million ha, respectively. Irrigation and drainage are the most significant input factors to increase the yield of crops per unit of farmland (Bos et al., 2006). Subsurface drainage is important to combat waterlogging and soil salinity (Ritzema et al., 2007). So far, subsurface drainage systems have been installed in about 18,000 ha of India (Nijland et al., 2005). After installing subsurface drains, crop yield has increased significantly in several parts of India, such as 69%, 64%, 54% and 136% for rice, cotton, sugarcane, and wheat, respectively (Ritzema et al., 2007). Most of the drainage equations are based on the Dupit-Forchheimer assumptions. These assumptions allow the researcher to reduce the two-dimensional flow to one-dimensional flow by assuming parallel and horizontal streamlines.

For centuries, land drainage was a practice based on the local experience and gradually developed into an art with more applicability. The credit goes to Darcy (1856), due to whom theories were developed and land drainage became an integral component of engineering science, Russel (1934), Hooughoudt (1940), Ernst (1962) and Kirkham (1972). However, the performance of the land drainage system is not only evaluated based on a crop production perspective, but increasingly from an environmental perspective too.

Despite various studies highlighting the importance of subsurface drainage in mitigating these problems (Ritzema et al., 2007), there remains a gap in systematically determining the optimal spacing of subsurface drains under different hydrological conditions. While previous studies have focused on general drainage solutions, few have compared steady-state and unsteady-state drainage models to recommend the most suitable approach for the Eastern Gandak region. Moreover, the impact of irrigation scheduling on drain spacing has not been extensively analyzed, which is crucial for designing efficient drainage systems.

To address this gap, this study conducts a comparative analysis of subsurface drain spacing using different steady-state and unsteady-state criteria, including Hooghoudt's and Donnan's equations for steady-state conditions and Glover-Dumm's and van Schilfgaarde's approaches for unsteady-state conditions.

By evaluating these models in the context of the Eastern Gandak Project, this research provides insights into the most effective drainage design parameters tailored to the region's specific hydrogeological conditions. The findings aim to enhance drainage planning strategies and improve agricultural productivity in waterlogged command areas in Bihar and similar regions in India.

## 2. The Study Area

The Gandak Project is one of the major multi-purpose projects in India, covering a culturable command area of 14.04 lakh ha distributed in the states of Uttar Pradesh and Bihar (Singh et al., 2002). The project also covers some areas of Nepal. The command area lies between longitude 830 15' and 850 15' East and latitude between 250 40' and 270 25' North.

The estimated area, which is waterlogged during the Kharif season, is 6.07 lakh ha and during the Rabi season, 2.41 lakh ha. The total salt-affected area in the Gandak command is 2.24 lakh ha (Singh et al., 2002). As per the Central Water Commission of India, 4 lakh ha of land has been estimated to have saline-alkali soils, resulting in a loss of about 0.4 million tonnes of food grains every year. However, the increasing rate of waterlogging is estimated at 3000 ha/year, and the salt-affected area is rising at a rate of 36000 ha/year, as per Singh et al. (2002). Therefore, the study of the prospects of subsurface drainage in the Gandak Command area is a significant futuristic issue.

The climate of the command area is tropical, humid, and sub-humid. The normal average rainfall of the command area is about 1200 mm. About 85.64% of total rainfall occurs during the southwest monsoon, i.e. June to October. The maximum temperature recorded is 42°C. The average relative humidity values in the morning and evening are 67% and 59%, respectively.

About 70% of the Gandak Project area is under cultivation. 4.3% of the land is covered by forests, and 14.11% of the area is under tree crops and permanent pastures. 88.3% of the cropped area is under food grains comprising mostly rice (43.2%), wheat (28.5%), maize (7.8%), pulses (7.0%), barley (0.5%) and sugarcane (5.4%) etc.

The soil texture in the upland consists of sandy loam and loam, while the predominant soil texture of mid uplands is silt loam. The lowlands have silty clay loam, sandy loam and clay loam as dominant soil textures. The topography of the area is plain. The general slope of the region is from northwest to southeast.

Bhagwanpur Distributary is a tail-end distributary of the Eastern Gandak Irrigation Project. It offtakes from the Vaishali Branch Canal near Saraiya (Latitude 26.15° N, Longitude 85.03° E). Vaishali Branch Canal originates from Tirhut Main Canal, which starts from the Gandak Barrage at Balmikinagar. All the canals in this project are mainly ridge canals.

The command area of Bhagwanpur distributary lies between a latitude of 26001'N to 25052'N and a longitude of 85009'E to 85014'E. The proposed Gross Culturable Area under Gandak Phase II for Bhagwanpur Distributary was 4691 ha in 1981. However, the estimated command area of Bhagwanpur Distributary using Google Earth Pro is approximately 4530 ha. Bhagwanpur Distributary was constructed under Gandak phase II i.e. 1981 onwards. Almost 40 – 50 small and medium villages benefit from agriculture from this distributary.

The total length of Bhagwanpur Distributary is 21.1 km. It covers three blocks in Bihar, India, i.e. Saraiya block in Muzaffarpur district and Vaishali and Lalganj blocks in Vaishali district. Bhagwanpur Distributary covers 7- 8% of its length in each Saraiya and Lalganj block, and almost 85% is in Vaishali block. The location map of the study area is given in Figure 1.

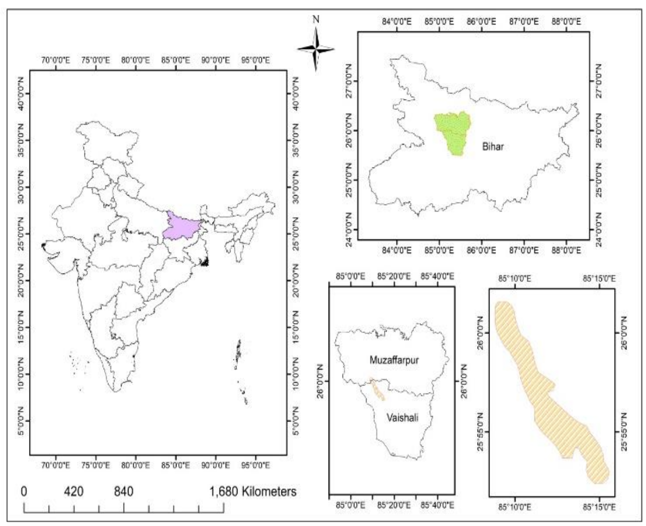


**Fig. 1 Location map of the command area of Bhagwanpur distributary**

## 3. Materials and Methods

The methodology for selecting drain spacing is shown in the flowchart given in Figure 2.

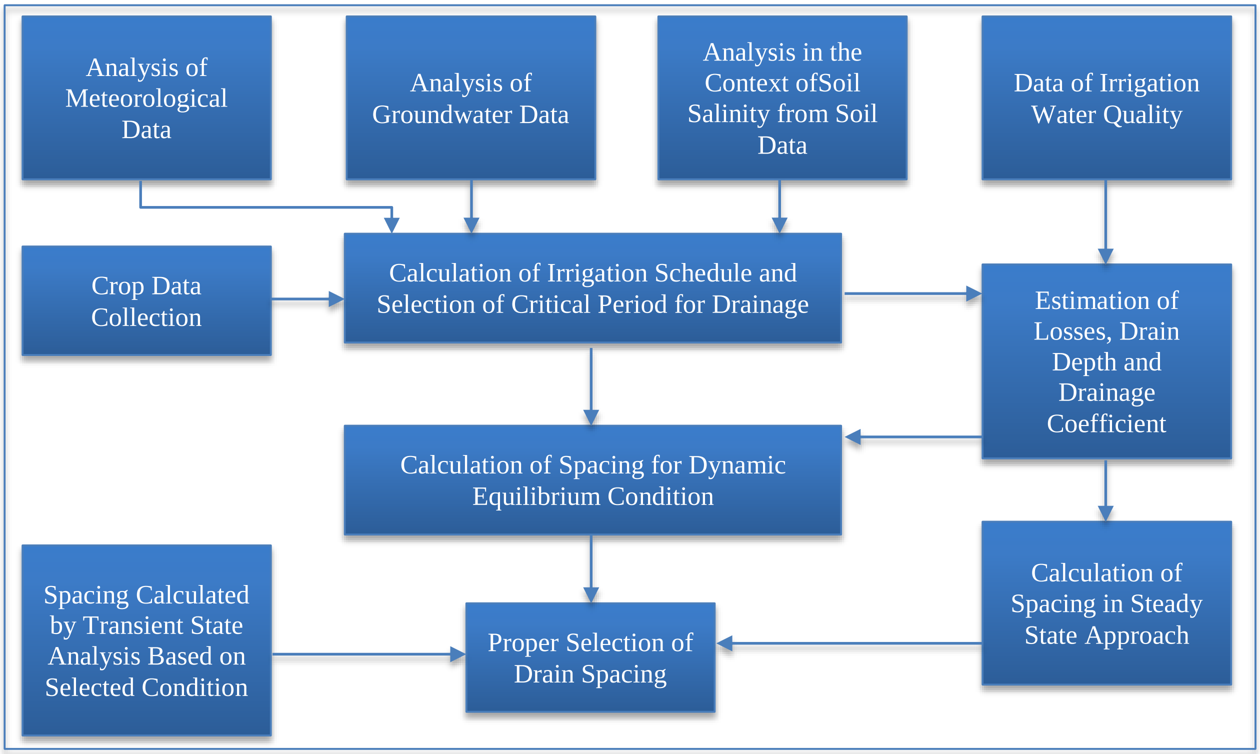


**Fig. 2 Flowchart for the selection of drain spacing**

Irrigation Scheduling has been done using the software CROPWAT 8.0 (FAO 46, 1992). Further, Bhushan et al. (2018) have reported the groundwater fluctuations in the command area of the Bhagbanpur distributary of the Eastern Gandak project in Bihar. Singh and Roy (2024, 2024a) have stressed the need for participatory irrigation management to successfully function drainage systems in different command areas in Bihar, India. They have also described in detail the pertinent issues related to the drainage of irrigated agriculture in Bihar. Different data needed for the irrigation scheduling are meteorological data, crop data and soil data. 75% dependable rainfall was calculated as given in Table 1. For this study, a 75% dependable value has been estimated using the meteorological data from 1981 to 2016, which were collected from the Agro-Meteorological Department of Indian Agricultural Research Institute, Pusa, Bihar, India, as given in Table 2.

**Table 1. 75% dependable and average monthly rainfall values**

| Month | Rainfall (mm) | |
|---|---|---|
| | 75% Dependable | Average |
| January | 0 | 8.3 |
| February | 0 | 11.8 |
| March | 0 | 5.4 |
| April | 0 | 18.6 |
| May | 35.7 | 114.2 |
| June | 82.7 | 149.2 |
| July | 153.4 | 309.8 |
| August | 128.9 | 266.4 |
| September | 127.8 | 221.8 |
| October | 7.1 | 56.1 |
| November | 0 | 5.2 |
| December | 0 | 4.9 |

**Table 2. 75% dependable and average reference ET values**

| Month | $ET_0$ (mm/day) | |
|---|---|---|
| | 75% Dependable | Average |
| January | 1.4 | 1.35 |
| February | 2.01 | 1.96 |
| March | 3.01 | 2.95 |
| April | 4.06 | 3.95 |
| May | 4.62 | 4.54 |
| June | 4.5 | 4.33 |
| July | 3.89 | 3.81 |
| August | 3.94 | 3.86 |
| September | 3.57 | 3.50 |
| October | 3.19 | 3.09 |
| November | 2.22 | 2.15 |
| December | 1.49 | 1.43 |

### *3.1. Selection of Crop*

Maize is a very well-grown staple crop in this area. That's why this crop was selected for the present study. The growth of this crop is very well observed in areas having annual rainfall of 1000 to 1150 mm. As per rainfall data collected, the mean annual rainfall in the study area for the last 36 years is 1171.5 mm. Therefore, the selection of maize crops is justified for the present study. Crop data are as given in Table 3.

**Table 3. Crop data input for maize in the CROPWAT 8.0 for calculation of irrigation scheduling (FAO "crop information", 2018)**

| Stages | Initial Stage | Development Stage | Mid-Season Stage | Late Season Stage |
|---|---|---|---|---|
| Days | 20 | 30 | 45 | 30 |
| Crop Coefficient (Kc) | 0.3 | | 1.2 | 0.5 |
| Rooting depth (m) | 0.3 | | 1 | 1 |
| Critical Depletion (Fraction) | 0.15 | | 0.1 | 0.1 |
| Yield Response Factor | 0.4 | 0.4 | 1.3 | 0.5 |

### *3.2. Irrigation Water Quality*

As given in Table 4, the average electrical conductivity of irrigation water ($EC_{iw}$) value for water samples is 0.475 dS/m, which is less than 2.0 dS/m. Therefore, the quality of irrigation water supplied by the Bhagwanpur Distributary is good.

**Table 4. Electrical conductivity of irrigation water**

| Sample No. | Temp. ($^0$C) | EC (μs/cm) | EC (dS/m) | Average EC (dS/m) |
|---|---|---|---|---|
| 1 | 26.1 | 359 | 0.359 | 0.475 |
| 2 | 25.5 | 368 | 0.368 | |
| 3 | 25.7 | 528 | 0.528 | |
| 4 | 25.7 | 579 | 0.579 | |
| 5 | 25.6 | 481 | 0.481 | |
| 6 | 25.7 | 536 | 0.536 | |

### *3.3. Soil Data*

For the present study, soil samples had been collected from five places, i.e. Saraiya (Latitude 26.15° N, Longitude 85.03° E), Keshopur (Latitude 25.95° N, Longitude 85.12° E), Dharampur (Latitude 25.96 N°, Longitude 85.17° E), Bishunpur (Latitude 25.94° N, Longitude 85.18° E) and Lalpura (Latitude 25.86° N, 85.24° E). Soil samples were analysed in the laboratory, as shown in Table 5. Hydraulic conductivity and drainable porosity values were estimated based on soil texture. Apart from this, the electrical conductivity of soil saturation extract ($EC_e$) of the mixture of five soil samples (i.e. $EC_e$= 1.185 dS/m) was also determined to estimate the leaching requirement of the soil.

**Table 5. Physical and chemical properties of soil**

| | Saraiya | Keshopur | Dharampur | Bishunpur | Lalpura |
|---|---|---|---|---|---|
| Field Capacity (%) | 22.172 | 22.237 | 22.201 | 20.424 | 18.967 |
| Permanent Wilting Point (%) | 0.962 | 1.630 | 4.268 | 4.252 | 1.938 |
| Soil-Moisture Available (mm/meter) | 212 | 206 | 179 | 161 | 170 |
| Na (meq/100gm) | 0.19 | 0.18 | 0.19 | 0.18 | 0.18 |
| Ca (meq/100gm) | 0.7 | 0.6 | 1.12 | 1.84 | 0.84 |
| Mg (meq/100gm) | 0.2 | 0.4 | 0.56 | 0.8 | 0.38 |
| pH | 8.1 | 8.3 | 7.6 | 7.9 | 7.3 |
| Available P (kg/ha) | 3.22 | 4.06 | 4.39 | 3 | 3.1 |
| Available K (kg/ha) | 34.4 | 57.23 | 92.62 | 112.56 | 39.53 |
| Total Organic Carbon (%) | 0.68 | 0.58 | 0.68 | 0.48 | 0.49 |
| ESP (%) | 17.43 | 15.25 | 10.16 | 6.38 | 12.85 |
| % Sand | 2 | 12 | 9 | 6 | 8 |
| % Clay | 3 | 9 | 11 | 3 | 8 |
| % Silt | 95 | 79 | 80 | 91 | 84 |
| Soil Texture | Silt | Silt Loam | Silt Loam | Silt | Silt |

## 4. Approaches to Solve the Problem of Subsurface Drainage

### *4.1. Steady State Approach*

Steady-state theory assumes that the recharge rate is uniform and steady, and the recharge is equal to the discharge through the drainage system (Ritzema et al., 2006). A simplified diagram for steady state theory is given in Figure 3. Some of the popular approaches are discussed below.

#### *4.1.1. Hooghoudt's (1940) Equation*

The most accepted steady-state equation for subsurface drainage is Hooghoudt's Equation (1940) as Equation (1).

$$L^2 = \frac{4KH(2d+H)}{q} \tag{1}$$

Where,
L = spacing between two parallel drains (m),
K = Saturated hydraulic conductivity (m/day),
H = Hydraulic head above drain level (m),
d = Equivalent depth of impervious layer (m),
q = Drainage coefficient (m/day)

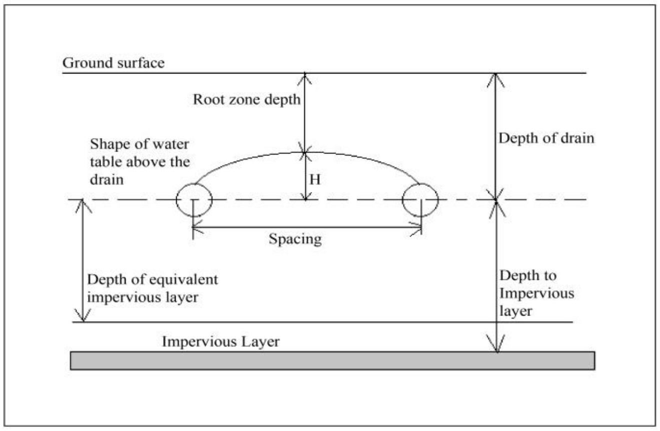


**Fig. 3 A simplified diagram for steady state approach**

*4..1.2. Convergence Correction in Hooghoudt's Equation*

Due to the convergence of flow near the drain, the depth of the impervious layer (D) is to be replaced by an equivalent depth of the impervious layer (d). Generally, d < D and d is a function of L, D and $r_0$, where $r_0$ is the equivalent radius of drainpipes as given in Equation (2).

$$d = \frac{\pi D L^2}{[\pi(L-2D)^2 + 8LD ln\left(\frac{2D}{u}\right)]} \tag{2}$$

Where,
d = Equivalent depth of impervious layer (m),
D = depth of impervious layer (m),
L = Spacing calculated from Hooghoudt's equation,
u = Wetted perimeter = $\pi r_0$ (Assuming the drain to be half full)

*4..1.3. Donnan's (1946) Equation*

The equation is generally used in the irrigated areas of the USA. It was independently developed by Donnan in 1946. The Equation (3) is given as,

$$L^2 = \frac{4K(b^2-a^2)}{q} \tag{3}$$

Where,
L = spacing between two drains (m),
K = Saturated hydraulic conductivity (m/day),
q = Drainage coefficient (m/day),
b = (D+H) = distance between groundwater level and impervious layer (m),
a = D = depth of impervious layer (m)

***4.2. Unsteady or Transient State Approach***

In this approach, the water table is the function of both space and time. Flow towards the drain is also not steady and constant. Two important transient state equations that have been used in this paper are as described below. (Pali, 2013)

*4.2.1. Glover-Dumm Equation (Ritzema et al., 2006)*

Dumm invented the differential equation solution to predict the fall of the horizontal water table after it had risen instantaneously to a height of $h_0$ above the drain level. His solution was based on the formula developed by Glover, describing the lowering of the water table as a function of time, place, drain spacing and soil properties, as given in Equation (4).

$$L = \pi\left(\frac{Kdt}{f}\right)^{0.5}\left(ln1.27\frac{h_0}{h}\right)^{-0.5} \tag{4}$$

Where d = Equivalent depth of the impervious layer and t is the time the drawdown occurs from $h_0$ to h in the centre of two drains and above the drain level. Other parameters have been defined earlier. In 1960, this equation was modified by Glover, assuming the shape of the water table to be of a fourth-order parabola and was stated as below. This is called the Glover-Dumm Equation (5).

$$L = \pi\left(\frac{Kdt}{f}\right)^{0.5}\left(ln1.16\frac{h_0}{h}\right)^{-0.5} \tag{5}$$

*4.2.2. Van Schilfgaarde's (1963) Equation*

Van Schilfgaarde (1963) proposed an unsteady state subsurface drainage equation, which was corrected for Dupuit-Forchheimer assumptions and avoided the assumption of a constant thickness of the flow region as given in Equation (6).

$$S = 3A\left[\frac{K(d+h)(d+h_0)t}{2f(h_0-h)}\right]^{1/2} \tag{6}$$

Where, A= 〖[1- 〖{d/(d+h_0 )}〗^2]〗^(1/2), L = spacing between two parallel drains (m), K = saturated hydraulic conductivity (m/day), t = Time in days between initial and final water table, h0 = initial water table height from drain level (m), h = final water table height from drain level (m), and f = Specific yield (in decimal)

A simplified diagram of the transient state approach is given in Figure 4, with notations for different parameters.

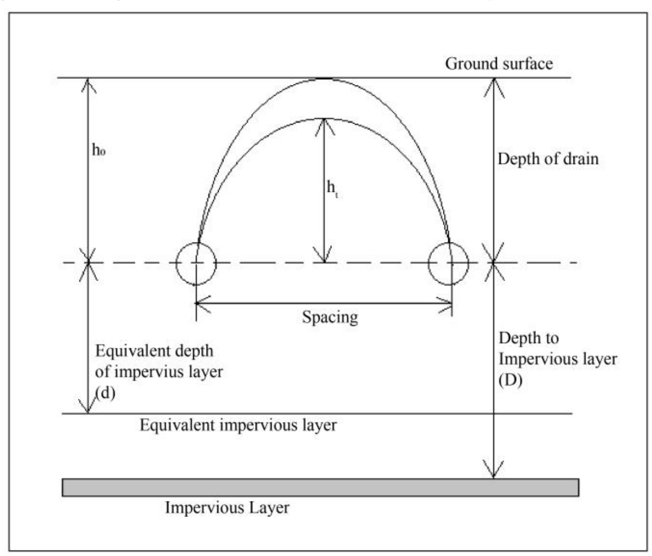


**Fig. 4 Simplified diagram for transient state analysis**

*4.2.3. USBR Method (USBR Drainage Manual, 1993)*

It is a method based on transient state analysis. The main objective of this method is to keep the groundwater table at dynamic equilibrium. If the annual discharge is not equal to the annual recharge, the water table tends to rise year after year. When annual discharge and recharge are almost equal, the range or cyclic annual water table fluctuation becomes reasonably constant. This condition of the groundwater table is defined as "dynamic equilibrium". Mainly, there arise two types of situations, i.e. drain above the barrier and drain on the barrier, as shown in Figure 5 (i.e. drain on barrier case occurs when $d/y_0 \leq 0.1$ and drain above barrier case occurs when $d/y_0 \geq 0.8$). Where d = depth of impermeable layer, $y_0$ & H= initial height of water table, and y& Z = final height of water table.

The two most important graphs utilised in the USBR approach are the plot between specific yield and hydraulic conductivity and the curves showing the relationship of parameters needed for drain spacing calculation using transient flow theory.

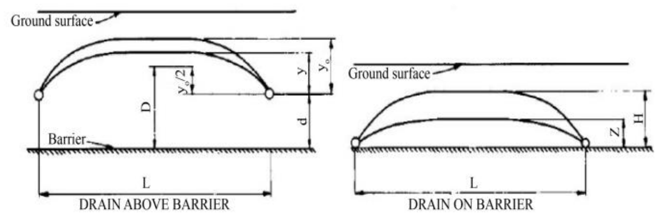


**Fig. 5 Position of drains for impermeable layer (USBR drainage manual, 1993)**

## 5. Drainage Coefficient

It is defined as the depth of water to be removed in 24 hours (Luthin, 1959). The accurate estimation of DC is required to design any subsurface drainage system. Generally, for steady-state subsurface drainage conditions, the DC value varies between 1 mm/day and 5 mm/day. Some recommended subsurface drain spacings are given in Table 6 based on the values of drainage coefficient and course of activities.

**Table 6. Option for selection of drainage coefficient (Source: RAJAD, 1995)**

| Option | DC (mm/day) | Description | Recommended Drain Spacing (m) |
|---|---|---|---|
| I | 0 | No Drainage | - |
| II | < 1 | Subsurface drainage for salinity control only | 60 to 70 |
| III | 1 to 2 | Salinity control and some waterlogging control during monsoon | 40 to 60 |
| IV | 2 to 3 | Salinity control and significant waterlogging control during monsoon | 30 to 50 |
| V | > 3 | Salinity control and best waterlogging control during monsoon | 30 to 50 |

***5.1. Selection Criteria of Drainage Coefficient for Transient State Analysis***

Different crops have different tolerance periods to waterlogging. To save the crop from aeration problems, a 30 cm lowering of the water table within 2 days is implemented as the main objective of the transient state approach.

***5.2. Process for Calculation of Drain Depth***

As per Smart et al. (1992), it is assumed that the water table will rise mainly due to three factors, namely, deep percolation loss (DPL), water conveyance loss (WL) and leaching requirement (LR) as given in Equation (7)-(10).

$$\boldsymbol{DPL = r_1(\frac{SMD}{E_a} - SMD)} \tag{7}$$

Where r1 = 0.9 to 1.0 (the fraction of excess irrigation water which recharges the groundwater table),

SMD = Soil Moisture Deficit ≈ Maximum Net Irrigation Requirement (mm),

$E_a$= Field application efficiency = 70% (assumed in the present case)

In this study, the $r_1$ value has been modified to 0.5. Because keeping this value between 0.9 and 1.0 predicts the deep percolation loss to be around 40%, much higher than in normal conditions. For silt loam, deep percolation is 18% of surface irrigation as per USBR Drainage Manual, 1993. Therefore, for $r_1$ = 0.5, DPL is approximately 21% of surface irrigation, which is acceptable. Therefore, $r_1$ = 0.5 has been assumed.

$$\textbf{Water conveyance loss} = \boldsymbol{r_2(\frac{SMD}{E_a E_c} - \frac{SMD}{E_a})} \tag{8}$$

$$\boldsymbol{LR = \frac{EC_{iw}}{5EC_e - EC_{iw}} * \frac{1}{L_e}} * \text{SMD} \tag{9}$$

$$\textbf{Water Table Rise (WTR)} = \frac{DPL+WL+LR}{f} * \mathbf{1.5} \quad (10)$$

Where f = drainable pore space.

Therefore, the Depth of Drain = WTR + height of capillary fringe + root zone depth + additional depth allowance (= 0.1 to 0.2 m).

### *5.3. Crop Water Requirement*

The entire calculation procedure of CROPWAT 8.0 is based on two FAO publications of Irrigation and Drainage Series, namely, No. 56 "Crop Evapotranspiration - Guidelines for computing crop water requirements" and No. 33 titled, "Yield Response to Water". Penman-Montieth's method was used to calculate reference crop evapotranspiration. This program uses a flexible menu system and is user-friendly.

### *5.4. Agricultural Drainage Planning and Program (ADPP)*

It is a menu-driven computer program that assists in analysing and designing existing and proposed drainage systems. There are two components of the software: one is the transient state analysis component for the computation of drain spacing, and the other one is the uncertainty analysis component for the evaluation of potential cost and performance. Different transient-state equations have been used in the transient state analysis component, as developed by Lee Dumm, Ray Winger Jr. and Robert Glover of the U.S. Bureau of Reclamation. In this model, Hooghoudt's correction for convergence is used. The output of this program gives the drain spacing for the condition of dynamic equilibrium, and it also shows the water table fluctuation throughout the year.

## 6. Results and Discussion

### *6.1. Irrigation Schedule*

It was calculated using CROPWAT 8.0 software by giving input for 75% dependable monthly reference evapotranspiration, 75% dependable monthly rainfall, crop data, and soil data. Three conditions have been assumed by the software as given below.

a) Timing of irrigation: Irrigate at critical depletion
b) Application of irrigation: Refill the soil moisture up to the field capacity
c) Field application efficiency: 70%

The theoretical irrigation schedule is given in Table 7, from which the following parameters are obtained.

| | | |
|---|---|---|
| Total Gross Irrigation | = | 370.4 mm |
| Total Net Irrigation | = | 259.3 mm |
| Actual Water used by the Crop | = | 404.0 mm |
| Potential Water used by the Crop | = | 404.0 mm |
| Efficiency Irrigation Schedule | = | 100.0% |
| Total Rainfall | = | 465.1 mm |
| Effective Rainfall | = | 157.8 mm |
| Total Rain Loss | = | 307.3 mm |
| Moisture Deficit at Harvesting | = | 10.9 mm |
| Actual Irrigation Requirement | = | 246.2 mm |
| Rainfall Efficiency | = | 33.9% |

**Table 7. Theoretical irrigation schedule and amount of irrigation for maize Crop as per CROPWAT 8.0**

| No of Irrigation | Date | Day No. | Net Irrigation (mm) | Gross Irrigation | Flow (Litre/sec/ha) |
|---|---|---|---|---|---|
| 1 | 15 Jun | 1 | 8.9 | 12.7 | 1.47 |
| 2 | 22 Jul | 38 | 17.6 | 25.1 | 0.08 |
| 3 | 31 Jul | 47 | 18.7 | 26.7 | 0.34 |
| 4 | 6 Aug | 53 | 18.6 | 26.5 | 0.51 |
| 5 | 10 Aug | 57 | 18.6 | 26.5 | 0.77 |
| 6 | 16 Aug | 63 | 18.7 | 26.7 | 0.52 |
| 7 | 20 Aug | 67 | 18.7 | 26.7 | 0.77 |
| 8 | 26 Aug | 73 | 18.2 | 26.1 | 0.50 |
| 9 | 30 Aug | 77 | 18.2 | 26.1 | 0.75 |
| 10 | 6 Sep | 84 | 17.8 | 25.4 | 0.42 |
| 11 | 10 Sep | 88 | 17.8 | 25.4 | 0.73 |
| 12 | 16 Sep | 94 | 17.1 | 24.4 | 0.47 |
| 13 | 20 Sep | 98 | 17.1 | 24.4 | 0.71 |
| 14 | 1 Oct | 109 | 16.5 | 23.5 | 0.25 |
| 15 | 10 Oct | 118 | 16.9 | 24.1 | 0.31 |
| Harvest | 17 Oct | 125 (End) | | | |

This irrigation schedule is much more realistic. The irrigation interval in the case of a practical irrigation schedule is larger than that of the theoretical irrigation schedule, which is acceptable in the real field. The total number of irrigations is 15 in CROPWAT 8.0, and the water depth applied per irrigation varies from 8 mm to 19 mm. But, in practice, keeping this schedule is not possible. For the cultivation of the maize crop in Bhagwanpur Distributary, it was learnt from local farmers that 5 to 6 irrigations are given to the maize crop during monsoon. For each irrigation, the depth of applied water varies between 50 mm to 75 mm. Therefore, this theoretical irrigation schedule is modified per the field's practical requirement, as given in Table 8.

**Table 8. Actual irrigation schedule in CROPWAT 8.0**

| No of Irrigation | Date | Day No. | Net Irrigation (mm) | Gross Irrigation | Flow (Litre/sec/ha) |
|---|---|---|---|---|---|
| 1 | 15 Jun | 1 | 60 | 85.7 | 9.92 |
| 2 | 4 Jul | 20 | 50 | 71.4 | 0.44 |
| 3 | 3 Aug | 50 | 50 | 71.4 | 0.28 |
| 4 | 23 Aug | 70 | 50 | 71.4 | 0.41 |
| 5 | 22 Sep | 100 | 50 | 71.4 | 0.28 |

| | | | | | |
|---|---|---|---|---|---|
| Harvest | 17 Oct | 125(End) | | | |

### 6.2. Estimation of Drainage Coefficient and Drain Depth

It is assumed that the water table will rise mainly due to three factors, namely, Deep Percolation Loss (DPL), Water Conveyance Loss (WL) and Leaching Requirement (LR). The different combinations of these three factors will lead to critical conditions. The results of these combinations are shown in Table 9. For the subsurface drains, the drainage coefficient (DC) value may vary between 1 mm/day and 5 mm/day. For scenario C, the drainage coefficient value lies within this range. Therefore, acceptance of scenario C for the selection of DC value is justified.

In Table 10, the depth of the drain is shown for different schedulings. For the actual irrigation schedule, the depth of the drain = 1.97 m and for the theoretical irrigation schedule, the depth of the drains = 1.48 m. The reason behind the lower depth in the theoretical irrigation schedule is that the corresponding NIR is lower, and as a result, less water table build-up occurs.

From Table 10, one can see that the irrigation schedule significantly influences the estimation of the drain and drainage coefficient depth. Results from the theoretical irrigation schedule are more acceptable than the practical irrigation schedule as the drainage coefficient for the theoretical schedule is critical and higher than the actual schedule. Therefore, the values of the parameters selected for analysis in this study are the depth of drain (DD) = 1.48 m ≈ 1.5 m and the drainage coefficient (DC) = 2.64 mm/day.

**Table 9. Drainage coefficients derived from analytical approach**

| Scenario | Approach | DC (mm/day) | | Remarks |
|---|---|---|---|---|
| | | Actual | Theoretical | |
| A | Deep Percolation from Irrigation only | 0.64 | 1.00 | 21.4% Deep Percolation |
| B | Deep Percolation + Leaching Requirement | 1.02 | 1.58 | 12.42% excess water for leaching |
| C | Deep Percolation + Water Conveyance Loss + Leaching Requirement | 1.69 | 2.64 | 56.5% contribution to groundwater |

**Table 10. Comparison of results between practical and actual irrigation schedule**

| Irrigation Schedule | Depth of Drain (m) | Drainage Coefficient (mm/day) |
|---|---|---|
| Actual | 1.97 | 1.69 |
| Theoretical | 1.48 | 2.64 |

As per Ritzema et al. (2007), deep drains have several drawbacks. Firstly, the deeper the drains, the higher the installation charge. Secondly, deeper drains can only be economically installed with mechanical construction practices, which are not always easily available. Thirdly, deep drains lower the water table during the irrigation season. However, shallower drains maintain the optimum water table for crops, resulting in better salinity control and higher crop yield. Therefore, the selection of the drain depth for the theoretical irrigation schedule is justified.

### 6.3. Estimation of Drain Spacing for the Steady-state Approach as per Hooghoudt's (1940) Equation and Donnan's (1946) Equation

Assumed root zone depth for maize = 1.0 m;
Depth of drain = 1.5 m;
Drainage coefficient = 2.64 mm/day
Hydraulic head above drain level = 0.5 m

Hooghoudt, 's drain spacings are as given in Table 11, from which it is observed that the drain spacing varies between 52.13 m to 103.9 m for the present case. Keeping the other parameters fixed, it is seen in Tables 11 and 12 how drain spacing changes as per K values and D values. With increasing depth of the impervious layer, spacing changes at a higher rate. On the other hand, the change in spacing value is slower in case of a change in hydraulic conductivity values. This observation indicates that the depth of the impervious layer and the depth of the drains are the most sensitive parameters in the estimation of drain spacing.

**Table 11. Calculated spacing by hooghoudt's equation based on different parameters**

| Hydraulic conductivity (m/day) | Depth of impervious layer (D) | | |
|---|---|---|---|
| | 5 m | 10 m | 15 m |
| 0.5 | 52.13 | 60.25 | 62.5 |
| 0.6 | 58.1 | 68.3 | 71.85 |
| 0.7 | 63.6 | 75.75 | 80.56 |
| 0.85 | 71.16 | 86.05 | 92.68 |
| 1.00 | 78.09 | 95.52 | 103.9 |

**Table 12. Calculated spacing by donnan's equation based on different parameters**

| Hydraulic conductivity (m/day) | Depth of impervious layer (D) | | |
|---|---|---|---|
| | 5 m | 10 m | 15 m |
| 0.5 | 63.06 | 88.18 | 107.48 |
| 0.6 | 69.08 | 96.53 | 117.74 |
| 0.7 | 74.62 | 104.26 | 127.17 |
| 0.85 | 82.22 | 114.9 | 140.14 |
| 1.00 | 89.18 | 124.62 | 152.00 |

When comparing the two steady-state theories, as shown in Figure 6, it is found that there exists a good correlation between the two theories, and the correlation coefficient is 0.7648. The Donnan's spacing is on the higher sides because in this equation, the flow of water towards the drain is assumed to be horizontal. However, the water flow towards the drain is curvilinear, and the concept of equivalent depth of the impervious layer arises. As the path becomes curved, the length of flow increases and as a result of this, the hydraulic gradient decreases. As the hydraulic gradient decreases, a lower spacing is needed. That is why Hooghoudt's spacing is lower than Donnan's spacing.

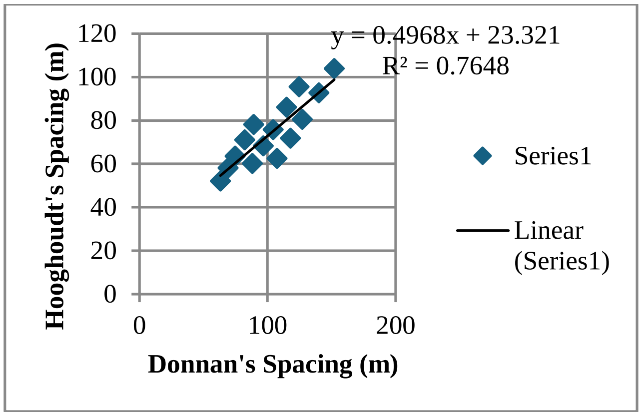


**Fig. 6 Correlation between the spacings as per Hooghoudt and Donnan's equations**

### *6.4. Transient State Approach as per Glover-Dumm's (1954 and 1964) Equation and van Schilfgaarde' (1963) Equation*

It is observed from Table 13 and Table 14 that the spacing calculated by using the van Schilfgaarde equation is consistently higher than the spacing calculated by using the Glover-Dumm equation. Also, it was found that van Schilfgaarde's spacing varies between 1.45 to 1.85 times the Glover-Dumm's spacing with an average of 1.58 times. The reason behind this variation lies in the theory of these two equations. In the Glover-Dumm equation, the flow region is assumed to be of constant thickness, wherthis assumption is not there eas in van Schilfgaarde's equahere. The variation in spacing from these two equations is shown in Table 15. In Figure 7, the relationship between Glover-Dumm and van Schilfgaarde models has been derived. Plotting the spacing on both axes, it is found that both the models are highly correlated with each other as the value of the coefficient of determination ($r^2$) is equal to 0.9734.

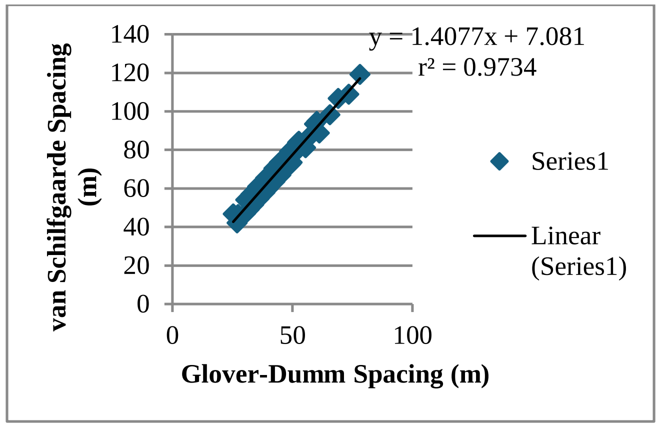


**Fig. 7 Relation between Glover-Dumm and Van Schilfgaarde spacing**

**Table 13. Calculated spacing by Glover-Dumm equation**

| Specific yield (f) | 0.05 | | | 0.07 | | | 0.09 | | |
|---|---|---|---|---|---|---|---|---|---|
| D(m) | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 |
| K=0.5 m/day | 39.94 | 44.53 | 44.54 | 32.03 | 34.01 | 32.65 | 26.96 | 27.39 | 25.31 |
| K=0.6 m/day | 44.82 | 51.11 | 52.10 | 36.15 | 39.46 | 38.78 | 30.58 | 32.10 | 30.51 |
| K=0.7 m/day | 49.31 | 57.21 | 59.17 | 39.94 | 44.53 | 44.54 | 33.91 | 36.49 | 35.43 |
| K=0.85 m/day | 55.50 | 65.66 | 69.03 | 45.15 | 51.56 | 52.62 | 38.5 | 42.6 | 42.34 |
| K=1.0 m/day | 61.16 | 73.44 | 78.18 | 49.93 | 58.05 | 60.15 | 42.70 | 48.25 | 48.81 |

**Table 14. Calculated spacing by Van-Schilfgaarde equation**

| Specific yield (f) | 0.05 | | | 0.07 | | | 0.09 | | |
|---|---|---|---|---|---|---|---|---|---|
| D(m) | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 |
| K=0.5 m/day | 59.95 | 69.89 | 73.43 | 49.19 | 55.63 | 57.05 | 42.28 | 46.61 | 46.86 |
| K=0.6 m/day | 66.6 | 78.79 | 83.81 | 54.79 | 63.03 | 65.53 | 47.2 | 53.03 | 54.09 |
| K=0.7 m/day | 72.72 | 87.03 | 93.45 | 59.95 | 69.9 | 73.45 | 51.75 | 59 | 60.9 |
| K=0.85 m/day | 81.15 | 98.41 | 106.85 | 67.05 | 79.4 | 84.5 | 58 | 67.28 | 70.43 |
| K=1.0 m/day | 88.87 | 108.9 | 119.23 | 73.56 | 88.16 | 94.8 | 63.71 | 74.93 | 79.3 |

**Table 15. Variation of spacing in Van-Schilfgaarde from Glover-Dumm equation**

| Specific yield (f) | 0.05 | | | 0.07 | | | 0.09 | | | Variation from Glover spacing |
|---|---|---|---|---|---|---|---|---|---|---|
| D(m) | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 | |
| K=0.5 m/day | 1.50 | 1.57 | 1.65 | 1.54 | 1.64 | 1.75 | 1.57 | 1.70 | 1.85 | 1.5 – 1.85 |
| K=0.6 m/day | 1.49 | 1.54 | 1.60 | 1.52 | 1.60 | 1.69 | 1.54 | 1.65 | 1.77 | 1.49 – 1.77 |
| K=0.7 m/day | 1.47 | 1.52 | 1.58 | 1.50 | 1.57 | 1.65 | 1.53 | 1.63 | 1.72 | 1.47 – 1.72 |
| K=0.85 m/day | 1.46 | 1.5 | 1.55 | 1.48 | 1.54 | 1.61 | 1.51 | 1.58 | 1.66 | 1.46 – 1.66 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| K=1.0 m/day | 1.45 | 1.48 | 1.52 | 1.47 | 1.52 | 1.57 | 1.49 | 1.55 | 1.62 | 1.45 – 1.57 |

**Table 16. Calculated spacing by USBR method in ADPP software**

| Specific yield (f) | 0.05 | | | 0.07 | | | 0.09 | | |
|---|---|---|---|---|---|---|---|---|---|
| D(m) | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 |
| K=0.5 m/day | 116 | 148 | 166 | 148 | 192 | 220 | 180 | 238 | 274 |
| K=0.6 m/day | 129 | 165 | 187 | 164 | 214 | 246 | 198 | 265 | 306 |
| K=0.7 m/day | 140 | 181 | 205 | 178 | 233 | 271 | 215 | 289 | 336 |
| K=0.85 m/day | 156 | 201 | 231 | 198 | 261 | 305 | 239 | 323 | 377 |
| K=1.0 m/day | 171 | 222 | 256 | 216 | 286 | 333 | 261 | 355 | 413 |

### *6.5. Dynamic Equilibrium Approach Using ADPP Software*

Spacing has been calculated for dynamic equilibrium based on a theoretical irrigation schedule using ADPP software, which is based on the USBR method, and the results are shown in Table 16. From this, it is observed that the USBR spacing is much higher than the spacing calculated by other unsteady approaches. The dynamic equilibrium of the groundwater table is shown in Figure 8.

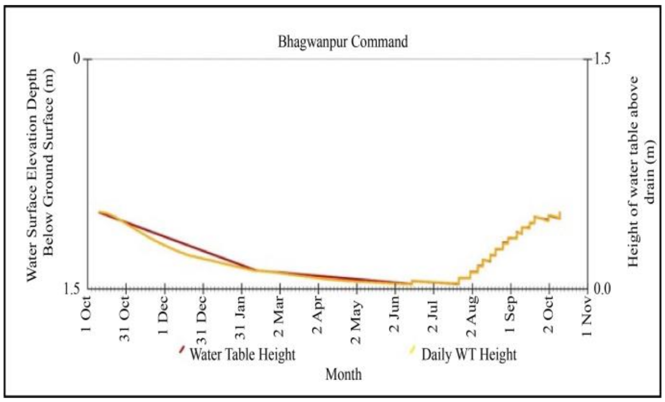


**Fig. 8 Groundwater fluctuation as an output in ADPP software**

**Table17. Drain spacing calculated by different methods**

| Method | Range of Spacing (m) |
|---|---|
| Hooghoudt's Equation with convergence correction | 60.25 – 95.52 |
| Donnan's Equation without convergence correction | 88.18 – 124.62 |
| Glover Dumm Equation | 34.01 – 58.05 |
| Van Schilfgaarde Equation | 55.63 – 88.16 |
| USBR Method is based on the concept of Dynamic Equilibrium | 192– 286 |

### *6.6. Comparison of Spacings Calculated by Using Different Methods*

It has been observed in other parts of the Gandak sub-basin that the depth of the impervious layer varies mostly between 10 m to 15 m, and the specific yield value varies between 5 to 12 per cent. Therefore, for an average condition, the depth of the impervious layer is assumed to be equal to 10 m and specific yield is assumed to be equal to 7% in the present study.

Also from past studies, it is noted that the efficient methods for calculating drain spacing are Hooghoudt's equation for steady state condition and Glover - Dumm equation for transient state condition. Therefore, approximate drain spacing in a range of 55 m to 65 m can be provided. Calculated drain spacings based on both steady and unsteady for average conditions are given in Table 17.

## 7. Conclusion

The study enhances subsurface drainage design by integrating steady-state and unsteady-state models, optimizing irrigation scheduling, and incorporating soil-specific data for improved drain spacing estimation. Unlike conventional approaches that rely on singular models, this research compares multiple equations, validates results through correlation analysis, and applies dynamic equilibrium analysis using ADPP software.

Including detailed soil classification and logarithmic water loss analysis refines hydraulic conductivity and drainage coefficient estimates, leading to more accurate and practical recommendations. The findings offer a cost-effective solution for mitigating waterlogging and salinity, ultimately improving agricultural productivity and water management in the Eastern Gandak Project and similar regions.

The following conclusions and recommendations have been made based on the above results and discussion.

- The command area of Bhagwanpur Distributary is facing a problem with soil salinity. Though the ECe value does not indicate salinity, ESP and pH values indicate it. The average electrical conductivity of soil saturation extract in the study area is 1.185 dS/m. Average ESP and pH values are 12.41% and 7.38, respectively. With the increasing rate of soil salinity, subsurface drainage implementation can be a solution to increase crop production.
- The irrigation schedule directly affects the estimation of DD and DC. The approaches of actual and theoretical irrigation schedules show the result. Since DC is an important parameter for the design of subsurface drains, the critical DC value should be based on the theoretical irrigation schedule. The estimated values DD and DC for the study area are 1.5 m and 2.64 mm/day, respectively.
- Based on the results, the range of spacing recommended

for the study area is 55 m to 65 m. This spacing is taken such that it remains within the range of spacing calculated by Hooghoudt's equation and Glover-Dumm's equation, as these two equations are the most widely used throughout the world. In the present study, the Hooghoudt's spacing varies from 52.13 m to 103.9 m, and the Glover–Dumm's spacing varies between 25.31 m to 78.18 m.

- The comparison of two steady-state equations, i.e. Hooghoudt's equation and Donnan's equation, shows a good coefficient of determination of 0.7648.
- The comparison of the two unsteady state equations, namely, Glover-Dumm's and van-Schilfgaarde's equations, shows an excellent correlation between them, with the coefficient of determination equal to 0.9734.

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