Field Evaluation of Unsteady Drain Spacing Equations for Optimal Design of Subsurface Drainage System under Waterlogged Vertisols of Maharashtra

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ABSTRACT

The field experiment was conducted at Agricultural Research Station, Kasbe Digraj, Dist. Sangli during *Adsali* sugarcane season of 2012-13 to 2013-14. The experiment was conducted by installing subsurface drainage system with 10, 20, 30 and 40 m drain spacing and 1 m drain depth. In view of different costs and effectiveness of subsurface drainage associated with the varying depths and spacings, field evaluation of unsteady drain spacing equations was important for finding out the optimal drain spacing equation among various equations. The field evaluation of unsteady drain spacing equations revealed that the van Schilfgaarde, Hammad, Modified Glover, Guyon and Integrated Hooghoudt's equation performed satisfactory for estimation of water table depths among seven unsteady drain spacing equations. The Glover-Dumm and Modified Glover-Dumm's equations were not performed satisfactory for estimation of water table depths. Among unsteady drain spacing equations, van Schilfgaarde's equation performed better and hence recommended for water table depth estimation and in turn for optimal design of subsurface drainage system under waterlogged vertisols of Maharashtra.

Key words: Field evaluation, Subsurface drainage, Unsteady drain spacing equations, Vertisols.

INTRODUCTION

Subsurface drainage system (SSDS) is a proven technology to combat the twin problems of salinization and waterlogging. However, the effectiveness of SSDS depends upon the optimal combination of drain spacing (DS) and drain depth (DD). In view to costs associated with the varying depths and spacings, it is necessary to evaluate the different unsteady state drain spacing equations for finding out the optimal combination of DS and DD as the inappropriate combinations may results in under or over drainage, less productivity and extra cost. The modifications in conventional SSDS design parameters indicated that there is need to optimize DS and DD to satisfy the drainage requirements under varying soil types, climates, crops, cropping intensities and water management practices. Before establishing guidelines for SSDS design for particular agro-hydrological condition, it is important to conduct field studies. Hence, this field set up on different combinations of DS and DD helps us to optimize the DS and DD. Further, the comparison of different unsteady state drain spacing equations with field evaluation allows SSDS designers to select the appropriate design formula for use under specific agro-hydrological conditions. Considering specific characteristics of the sugarcane and its water management practices in Vertisols, application of a suitable equation for planning of SSDS was of great importance.

Different researchers *viz*., Buckland *et al.* (1987), Firake (1987), Lal *et al.* (1989), Singh *et al.* (1992), Singh *et al.* (1999), Nasralla (2007) Tripathi *et al.* (2008), Kumar *et al.* (2013), Pali (2013), Naftchally *et al.* (2014), Pali (2015) and Yousef *et al.* (2016) etc. evaluated different steady and unsteady drain spacing equations in different soils and hydrological situations and most of them recommended unsteady drain spacing equations over steady drain spacing equations. Hussein (2015) also used unsteady drain spacing equation for Egyptian Vertisols. Hence, decided to evaluate unsteady drain spacing equations under waterlogged Vertisols of Maharashtra. Most of the researcher evaluated Modified Glover-Dumm, Hammad, Integrated Hooghoudt, Glover-Dumm, Modified Glover, van Schilfgaarde, Guyon, Luthin and Worstell, Dee zeeuw Hellinga and Massland's unsteady drain spacing equations under different soils and hydrological situations. Firake (1987), Lal *et al.* (1989), Singh *et al.* (1992), Kumar *et al.* (2013) and Pali (2013) reported the satisfactory field performance of Modified Glover,

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van Schilfgaarde and Integrated Hooghoudt's equation for design of SSDS in semi-arid conditions of India. The limited studies reported by researchers on field evaluation of drain spacing equations in sandy loam saline-waterlogged soils of Haryana and clay loams of Maharashtra emphasized the need of field evaluation of unsteady drain spacing equations to our agro-hydrological conditions especially for waterlogged Vertisols of Maharashtra as its drainage is the most important challenge in agricultural water management because of 40 to 70% clay content having the peculiar property of swelling and shrinking; very low infiltration rate and permeability; poor saturated hydraulic conductivity and drainable porosity. In view to above, seven unsteady drain spacing equations *viz.*, Glover-Dumm, Modified Glover-Dumm, Modified Glover, van Schilfgaarde, Integrated Hooghoudt, Hammad and Guyon's equations were selected for finding the most appropriate SSDS design equation through field evaluations at our soil, climate and agro-hydrological condition.

MATERIALS AND METHODS

Experimental site

In order to fulfill the objective of the study, the field experiment with four DS of 10, 20, 30 and 40 m and DD of 1.0 m. was installed on farmer's field at Village Mouje Digraj located 3 km away from Agricultural Research Station, Kasbe Digraj, Dist. Sangli (Maharashtra) during *Adsali* sugarcane seasons of 2012-13 to 2013-14. The experimental size of 216 m x 54 m was surveyed with Dumpy Level at 18 m x 18 m grid for the contour map and layout of SSDS. The parallel SSDS (gridiron) was installed as per layout by using 80 mm diameter perforated corrugated Poly Vinyl Chloride (PVC) drainage pipes with geo-textile synthetic filter as lateral drains and non-perforated corrugated PVC pipe of 80 mm diameter as a collector drain. These lateral drains were connected to the collector drain at a grade of 0.2%. The collector drain was laid on a uniform grade of 0.2%. The water table depth (WTD) was within 0.6 m in rainy season and 0.9 to 1.5 m in winter and summer season before installation of SSDS. The soil was clayey in texture as clay content was 59.73%. The pH and electrical conductivity of soil were 7.65 to 7.93 and 0.49 to 1.15 dS m^{-1} respectively.

Data collection

Saturated hydraulic conductivity of soil

The saturated hydraulic conductivity of soil (K_{sat}) in m day^{-1} was one of the most important input parameter required for field evaluation of different unsteady state drain spacing equations. For determination of K_{sat}, it was necessary to the study the heterogeneity of soil up to 370 cm as we need K_{sat} values up to 370 cm soil depth for evaluation of drain spacing equations. Accordingly, layer wise soil heterogeneity were studied by digging hole with 24 cm outer diameter post hole auger up to 370 cm depth and found heterogeneity at 0-130 cm, 130-250 cm, 250-300 cm and 300-370 cm. Hence, in-situ K_{sat} values were estimated with Hooghoudt's single auger hole method at five various places in the field at 0-130 cm, 130-188 cm, 188-250 cm, 250-300 cm and 300-370 cm soil depth. The water table was fluctuated between 0.50 to 1.0 m during the hydraulic conductivity test. The K_{sat} values of particular water transmitting layer that contributed flow to particular drains (depth of drain + Hooghoudt's equivalent depth) were calculated as a weighted K_{sat} of different soil layers. The single weighted K_{sat} values of particular water transmitting layer that contributed flow to particular drains were used for field evaluation of different unsteady state drain spacing equations.

Drainable porosity of soil

The drainable porosity of soil (*f*) was used to evaluate the drain spacing equations for DS of 10, 20, 30 and 40 m for different drain out periods. The *f* of the soil is not usually a constant, but besides other things, it is a function of WTD (Taylor, 1960) or in other words soil depth. In this study, *f* corresponding to different WTD was determined from water table drawdown and drain discharge measurements at the experimental site. It was calculated from the drain outflow measurements and its corresponding mid-span water table (MWT) heights above drain level by equation 1.

$$f = \frac{(Q \times t)}{A(h_o - h_t)} \qquad \ldots(1)$$

Where, Q is average drain outflow for drainage period during which the water table dropped from h_o to h_t in m^3 hr^{-1}, t is the total drain out time in hr, A is area drained in m^2, h_o is MWT height above drain level in m at t = 0 and h_t is MWT height above drain level in m at t >0.

Drainage coefficient

The drainage coefficient q (mm day^{-1}) was computed by equation 2.

$$q = \frac{Q}{A} \times 1000 \qquad \ldots(2)$$

Where, Q is average drain outflow for the certain drain out period in m^3 day^{-1} and A is area drained in m_2.

Depth to an impervious layer and Hooghoudt's equivalent depth

The depth to an impervious layer below soil surface (D) was recorded from the visible rock formation strata in irrigation well nearby the experimental area. Accordingly, the D was calculated. The D was assumed to be the same level at all points. The de was calculated by Moody's empirical equation (Moody, 1966) for each DS and DD combination,

a) When $0 < d/L \leq 0.3$,

$$\frac{d}{d_e} = 1 + \left\{\frac{d}{L}\left[8/\pi \times \ln\left(\frac{d}{r}\right) + \alpha\right]\right\} \qquad \ldots(3)$$

Where,

L= drain spacing (m), r is radius of drain pipe (m) and

$$\alpha = 3.55 - 1.6\left(\frac{d}{L}\right) + 2\left(\frac{d}{L}\right)^2 \qquad \ldots(4)$$

b) When d/L > 0.3,

$$\frac{L}{d_e} = 8\left\{\ln(L/r) - 1.15\right\}/\pi \qquad \ldots(5)$$

Field measurement of WTD and drain discharge

The WTD under different combinations of DS and DD was measured from piezometers, which were manually augured at L/2 (location of piezometers at distance of half of drain spacing from lateral drain), L/4 (location of piezometers at distance of a quarter of drain spacing from lateral drain) and L/0 (location of piezometers at a zero distance from lateral drain i.e., not exactly on drain but very close to lateral drain) at both the sides of lateral drain by using a 120 mm outside diameter auger to a depth of 1.7 m from the soil surface for periodically measurement of WTD after rainfall or irrigation. An 80 mm internal diameter PVC pipe with perforations was then lowered in each piezometer to a depth of 1.7 m, while ensuring that a 30 cm length was above the ground level to prevent runoff water from flowing in. End caps were fitted to both ends of the pipe to prevent the intrusion of materials into the piezometers. Coarse sand was backfilled throughout the whole perforated section of pipe. This was to prevent clogging of the perforations by clay and silt particles. WTD at each piezometer was measured by gradually lowering the locally made measuring meter with float in the piezometers until metered hollow pipe floats on water. On the other hand, drainage outflows (Q) in ml min^{-1} were manually measured at drainage outlet points, using a bucket and a stop watch. This observed daily WTD and corresponding drain outflows were used for statistical evaluation of drain spacing equations.

Theoretical considerations in unsteady drain spacing equations

The following unsteady drain spacing equations were evaluated,

Glover-Dumm's equation

Glover (Dumm, 1954 and Skaggs *et al*., 1973) developed the unsteady state flow theory for a case where the drains are placed above barrier (Fig 1). The water table between the drains was assumed to be flat horizontal surface at the start of each drainage cycle. The equation is,

$$L^2 = \frac{(\pi^2 K_{sat}\ dt)}{f \ln(4h_o/\pi h_t)} \quad \text{...(6)}$$

Where, K_{sat} is saturated hydraulic conductivity of soil, d is depth of impervious layer from the drain= $d_e+h_o/2$ in m and d_e is Hooghoudt's equivalent depth in m (Moody, 1966).

Modified Glover-Dumm's equation

Skaggs (1973) observed that the initial WT shape encountered in the field was more often parabolic than flat. They modified the initial condition accordingly and found a solution for spacing between drains that different from Glover-Dumm's equation only in that numerical constant $4/\pi$ was replaced by approximately 1.16. Thus, this results in the calculation of somewhat wider spacing between drains for the same rate of water table drop. The Modified Glover-Dumm's equation is as follows,

$$L^2 = \frac{(\pi^2 K_{sat}\ d_e t)}{f \ln(1.16\ h_o/h_t)} \quad \text{...(7)}$$

Integrated Hooghoudt's equation

Bouwer and van Schilfgaarde (1963) assumed that the instantaneous drainage rate midway between drains may be taken equal to the steady state drainage rate corresponding to the same water table elevation. Using Hooghoudt's steady state relationship, they obtained a transient drain spacing equation, which may be written as,

$$L^2 = \frac{(8 K_{sat}\ d_e\ t)}{Cf \ln\left\{\frac{h_o (h_t+2d_e)}{h_t (h_o+2d_e)}\right\}} \quad \text{...(8)}$$

Where, C is flux constant or correction factor defined as the ratio of the average flux between drains to the flux midway between drains. Typically C lies between 0.8 to 1. Hooghoudt's equivalent depth, d_e, must be used in Bouwer-van Schilfgaarde's equation as it is based on Dupuit-Forchheimer (D-F) assumptions.

van Schilfgaarde's equation

van Schilfgaarde (1963) proposed an unsteady subsurface drainage equation, which corrected for D-F assumptions and avoided the assumption of a constant thickness of the flow region. The following equation was proposed,

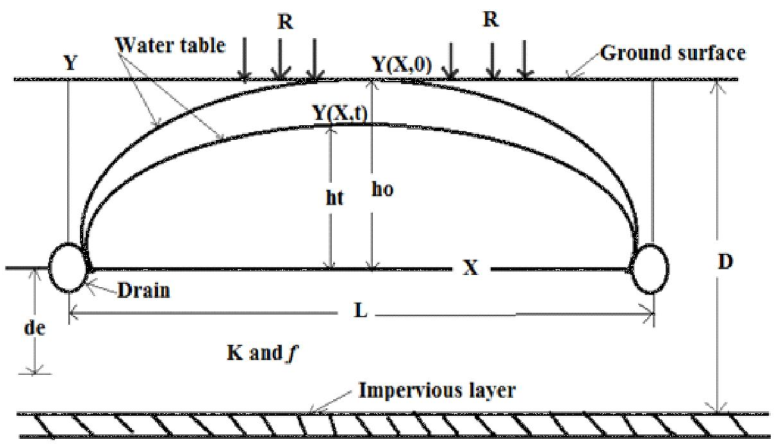

Fig 1: General principles of unsteady state drain spacing equations.

$$L^2 = 9\left\{1-\left(\frac{d_e}{d_e+h_o}\right)^2\right\}\left\{\frac{(K_{sat}\ (d_e+h_t)\ (d_e+h_o)\ t}{2\ f\ (h_o-h_t)}\right\} \qquad ...(9)$$

Modified Glover's equation

van Schilfgaarde (1964) derived following equation based on D-F assumptions for an initially parabolic water table,

$$L^2 = \frac{(9\ K_{sat}\ \ d_e\ t)}{f\ \ln\left\{\frac{(h_o\ (h_t+2d_e)}{(h_t\ (h_o+2d_e)}\right\}} \qquad ...(10)$$

Guyon's equation

Guyon's analysis is not based on the D-F assumptions, but on a more exact treatment of potential theory (Guyon, 1964 and van Schilfgaarde, 1965). For deeper impervious layer, he obtained the following drain spacing equation,

$$L_2 = \frac{(8.85\ K\ d_e\ t\ )}{f\ \ln\left\{\frac{h_o\ (h_t+1.8\ d_e)}{h_t\ (h_o+1.8\ d_e)}\right\}} \qquad ...(11)$$

Hammad's equation

Hammad (1962) derived his equation by using the potential theory. He made the assumptions that the receding water table between the drain tubes is nearly flat to derive equations for water table drawdown in both shallow and deep soils.

a) For shallow soils ($d/L < 0.25$), the spacing between drains is given by,

$$L = \frac{(2\ \pi\ K_{sat}\ t)}{f\ \ln\left(\frac{h_o}{h_t}\right)\ln\left(\frac{L^2}{(2\ \pi^2\ r\ d)}\right)} \qquad ...(12)$$

b) For deep soils ($d/L > 0.25$), the spacing between drains is

$$L = \frac{(2\ K_{sat}\ t)}{f\ \ln\left(\frac{h_o}{h_t}\right)\ln\left(\frac{L}{r}\right)} \qquad ...(13)$$

Statistical evaluation of drain spacing equations

The predicted and observed MWT heights were compared by the percent deviation (PD), percent error (PE), mean absolute error (MAE), root mean square error (RMSE) and correlation coefficient (R^2) to find out the appropriate drain spacing equation.

$$PD = \frac{Pi-Oi}{Oi} \times 100\% \qquad ...(14)$$

$$PE = \frac{\sum_{i=1}^{n} Pi - \sum_{i=1}^{n} Oi}{\sum_{i=1}^{n} Oi} \times 100\ \% \qquad ...(15)$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}(Oi - \bar{O})\ (Pi - \bar{P})\right)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2\ \sum_{i=1}^{n}(Pi - \bar{P})^2} \qquad ...(16)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Oi-Pi)^2}{n}} \qquad ...(17)$$

Table 1: Observed and predicted MWT heights above drain by different unsteady drain spacing equations for SSDS with DS: 10 m and DD: 1 m.

Δt (days)	t (days)	Oi MWT height (m)	Pi MWT height by Glover-Dumm's eqn.(m)	Pi MWT height by Modified Glover -Dumm's eqn.(m)	Pi MWT height by Modified Glover's eqn. (m)	Pi MWT height by Integrated Hooghoudt's eqn (m)	Pi MWT height by van Schilfgaarde's eqn. (m)	Pi MWT height by Guyon's eqn. (m)	Pi MWT height by Hammad's eqn.(m)
0.808	0.81	0.5015	0.7282(45.20%)	0.6853(36.64%)	0.5799(15.62%)	0.5735(14.35%)	0.5786(15.37%)	0.5791(15.47%)	0.6199(23.61%)
0.976	1.78	0.4185	0.5740(37.15%)	0.5366(28.21%)	0.4566(9.10%)	0.4519(7.98%)	0.4799(14.67%)	0.4563(9.02%)	0.4852(15.93%)
1.017	2.80	0.4570	0.4770(4.37%)	0.4449(-2.66%)	0.3795(-16.95%)	0.3755(-17.84%)	0.4024(-11.95%)	0.3794(-16.99%)	0.4038(-11.64%)
1.977	4.78	0.4305	0.3795(-11.85%)	0.3784(-12.11%)	0.3144(-26.97%)	0.3020(-29.85%)	0.3879(-9.91%)	0.3141(-27.04%)	0.3981(-7.53%)
1.013	5.79	0.3720	0.4893(31.52%)	0.4567(22.77%)	0.3894(4.68%)	0.3851(3.52%)	0.4131(11.05%)	0.3892(4.62%)	0.4151(11.57%)
1.000	6.79	0.3395	0.4308(26.88%)	0.3998(17.76%)	0.3421(0.77%)	0.3390(-0.14%)	0.3610(6.32%)	0.3421(0.76%)	0.3606(6.21%)
Average		**0.4198**	**0.5131(22.21%)**	**0.4836(15.10%)**	**0.4103(-2.29%)**	**0.4045(-3.67%)**	**0.4371(4.26%)**	**0.4100(-2.36%)**	**0.4471(6.36%)**

Note: Numbers in parentheses represents the PD between the predicted and observed (actual) MWT heights.

Table 2: Observed and predicted MWT heights above drain by different unsteady drain spacing equations for SSDS with DS: 20 m and DD:1m.

Δt (days)	t (days)	Oi MWT height (m)	Pi MWT height by Glover-Dumm's eqn.(m)	Pi MWT height by Modified Glover-Dumm's eqn.(m)	Pi MWT height by Modified Glover's eqn.(m)	Pi MWT height by Integrated Hooghoudt's eqn.(m)	Pi MWT height by van Schilfgaarde's eqn.(m)	Pi MWT height by Guyon's eqn. (m)	Pi MWT height by Hammad's eqn.(m)
0.808	0.81	0.6995	0.92510(32.25%)	0.85968(22.90%)	0.73420(4.96%)	0.72810(4.09%)	0.73300(4.79%)	0.73390(4.92%)	0.77017(10.10%)
0.976	1.78	0.6350	0.81667(28.61%)	0.75785(19.35%)	0.64825(2.09%)	0.64285(1.24%)	0.67900(6.93%)	0.64805(2.06%)	0.67965(7.03%)
1.017	2.80	0.7053	0.73052(3.58%)	0.67875(-3.76%)	0.58065(-17.67%)	0.57490(-18.48%)	0.61495(-12.80%)	0.58050(-17.69%)	0.61345(-13.02%)
1.977	4.78	0.6860	0.62985(-8.19%)	0.61475(10.39%)	0.51600(-24.78%)	0.49885(-27.28%)	0.62300(-9.18%)	0.51575(-24.82%)	0.62510(-8.88%)
1.013	5.79	0.6115	0.79890(30.65%)	0.74145(21.25%)	0.63420(3.71%)	0.62875(2.82%)	0.6656(8.86%)	0.63412(3.70%)	0.66585(8.89%)
1.000	6.79	0.5515	0.70128(27.16%)	0.65160(18.15%)	0.55762(1.11%)	0.55195(0.08%)	0.59225(7.39%)	0.55756(1.10%)	0.59000(6.98%)
Average		**0.6481**	**0.7671(19.01%)**	**0.7173(11.25%)**	**0.6118(-5.10%)**	**0.6042(-6.26%)**	**0.6513(1.00%)**	**0.6116(-5.12%)**	**0.6574(1.85%)**

Note: Numbers in parentheses represents the PD between the predicted and observed (actual) MWT heights

Table 3: Observed and predicted MWT heights above drain by different unsteady drain spacing equations for SSDS with DS: 30 m and DD: 1 m.

Δt (days)	t (days)	Oi MWT height(m)	Pi MWT height by Glover-Dumm's eqn.(m)	Pi MWT height by Modified Glover-Dumm's eqn.(m)	Pi MWT height by Modified Glover's eqn.(m)	Pi MWT height by Integrated Hooghoudt's eqn.(m)	Pi MWT height by van Schilfgaarde's eqn.(m)	Pi MWT height by Guyon's eqn.(m)	Pi MWT height by Hammad's eqn.(m)
0.808	0.81	0.8065	1.0839(34.40%)	0.99680(23.60%)	0.85650(6.20%)	0.85315(5.78%)	0.85630(6.17%)	0.85650(6.20%)	0.87555(8.56%)
0.976	1.78	0.7350	0.9700(31.97%)	0.89371(21.59%)	0.76765(4.44%)	0.76337(3.86%)	0.79350(7.96%)	0.76765(4.44%)	0.79085(7.60%)
1.017	2.80	0.8003	0.8713(8.88%)	0.80400(0.47%)	0.69045(-13.72%)	0.68570(-14.31%)	0.72120(-9.88%)	0.69050(-13.71%)	0.71675(-10.43%)
1.977	4.78	0.7750	0.8099(4.50%)	0.76705(-1.03%)	0.65270(-15.78%)	0.63825(-17.65%)	0.74815(-3.46%)	0.65280(-15.77%)	0.73738(-4.85%)
1.013	5.79	0.7025	0.9233(31.43%)	0.85170(21.24%)	0.73138(4.11%)	0.72660(3.43%)	0.76075(8.29%)	0.73130(4.10%)	0.75730(7.80%)
1.000	6.79	0.6465	0.8313(28.58%)	0.76700(18.64%)	0.65890(1.92%)	0.65420(1.19%)	0.68945(6.64%)	0.65890(1.92%)	0.68445(5.87%)
Average		**0.7443**	**0.9150(23.29%)**	**0.8467(14.08%)**	**0.7263(-2.14%)**	**0.7202(-2.95%)**	**0.7616(2.62%)**	**0.7263(-2.14%)**	**0.7604(2.42%)**

Note: Numbers in parentheses represents the PD between the predicted and observed (actual) MWT heights.

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |Oi - Pi| \quad ...(18)$$

Where,

n is number of observations, Oi is observed MWT height above drain at Julian day i, $\bar{O}$ is arithmetic mean of observed daily MWT height above drain, Pi is predicted MWT height above drain at Julian day i and $\bar{P}$ is arithmetic mean of predicted daily MWT height above drain.

RESULTS AND DISCUSSION

Prediction of mid-span water table heights by unsteady drain spacing equations

It is observed from Table 1, 2, 3 and 4 that the average observed MWT heights under DS of 10, 20, 30 and 40 m with DD of 1.0 m were 0.4198, 0.6481, 0.7443 and 0.9130 m, respectively. The average predicted MWT heights by Glover-Dumm, Modified Glover-Dumm, Modified Glover, Integrated Hooghoudt, van Schilfgaarde, Guyon and Hammad's equation under DS of 10, 20, 30 and 40 m with DD of 1.0 m were 0.5131, 0.4836, 0.4103, 0.4045, 0.4371, 0.4100, 0.4471 m; 0.7671, 0.7173, 0.6118, 0.6042, 0.6513, 0.6161, 0.6574 m; 0.9150, 0.8467, 0.7263, 0.7202, 0.7616, 0.7263, 0.7604; and 1.1161, 1.0308, 0.8850, 0.8785, 0.9250, 0.8850 and 0.9250, respectively. Further, among these seven unsteady drains spacing equations; Modified Glover, Integrated Hooghoudt, van Schilfgaarde, Guyon and Hammad's equation predicted the average MWT heights nearer to average observed MWT heights under all four drain spacings as the average percent deviation for these five equations were within the allowable limit of ±10% variations (Table 1, 2, 3 and 4). Whereas, the MWT heights predicted by Glover-Dumm and Modified Glover-Dumm's equations looking most of the time largely away from the observed MWT heights under all four drain spacings as these equations recorded the higher average percent deviation values beyond the allowable limit of ±10% variations (Table 1, 2, 3 and 4). This was due to the fact that Glover-Dumm considered flat water table at the start of each drainage cycle and these equations are derived for isotropic and homogeneous soil. However, the experimental soil was heterogeneous and multi-layered vertisols. Whereas, the satisfactory performed equations considered the parabolic WT and avoided the assumption of a constant thickness of the flow region.

Evaluation of unsteady drain spacing equations

It is observed from Table 5 and 6 that the statistical parameters *viz*., PE, MAE and RMSE recorded by Glover-Dumm and Modified Glover-Dumm's equations were more than the allowable limit of ±10% variations. Hence, these two equations can be out rightly discarded for drainage design of waterlogged, heterogeneous and deep impervious multi-layered Vertisols. The statistical parameters *viz*., PE, MAE and RMSE values recorded under Modified Glover, Guyon, Integrated Hooghoudt, van Schilfgaarde and

Table 4: Observed and predicted MWT heights above drain by different unsteady drain spacing equations for SSDS with DS: 40 m and DD: 1 m.

Δt (days)	t (days)	Oi MWT height (m)	Pi MWT height by Glover-Dumm's eqn. (m)	Pi MWT height by Modified Glover -Dumm's eqn.(m)	Pi MWT height by Modified Glover's eqn. (m)	Pi MWT height by Integrated Hooghoudt's eqn. (m)	Pi MWT height by van Schilfgaarde's eqn. (m)	Pi MWT height by Guyon's eqn. (m)	Pi MWT height by Hammad's eqn. (m)
0.808	0.81	0.9738	1.26620(30.03%)	1.16110(19.24%)	0.99920(2.61%)	0.99665(2.35%)	0.99920(2.61%)	0.99920(2.61%)	1.01280(4.01%)
0.976	1.78	0.9148	1.18460(29.50%)	1.08920(19.07%)	0.93642(2.37%)	0.93250(1.94%)	0.96190(5.15%)	0.93650(2.38%)	0.95860(4.79%)
1.017	2.80	0.9640	1.08540(12.59%)	1.00120(3.86%)	0.86010(-10.78%)	0.85420(-11.39%)	0.89805(-6.84%)	0.86000(-10.79%)	0.89215(-7.45%)
1.977	4.78	0.9395	1.00780(7.27%)	0.94815(0.92%)	0.80910(-13.88%)	0.79360(-15.53%)	0.91225(-2.90%)	0.80920(-13.87%)	0.89780(-4.44%)
1.013	5.79	0.8713	1.11340(27.79%)	1.02750(17.93%)	0.88230(1.27%)	0.87630(0.58%)	0.92160(5.78%)	0.88230(1.27%)	0.91590(5.12%)
1.000	6.79	0.8145	1.03900(27.56%)	0.95740(17.54%)	0.82285(1.03%)	0.81765(0.39%)	0.85715(5.24%)	0.82300(1.04%)	0.85115(4.50%)
Average		**0.9130**	**1.1161(22.46%)**	**1.0308(13.09%)**	**0.8850(-2.90%)**	**0.8785(-3.61%)**	**0.9250(1.51%)**	**0.8850(-2.89%)**	**0.9214(1.09%)**

Note: Numbers in parentheses represents the PD between the predicted and observed (actual) MWT heights.

Table 5: Statistical parameters for different unsteady drain spacing equations under SSDS with varying DS.

Drain spacing equations	PE (%) under SSDS with different DS				Average PE (%) from DS of 10 to 40m	MAE (m) under SSDS with different DS				Average MAE (m) from DS of 10 to 40m
	DS:10m DD:1m	DS:20m DD:1m	DS:30m DD:1m	DS:40m DD:1m		DS:10m DD:1m	DS:20m DD:1m	DS:30m DD:1m	DS:40m DD:1m	
Glover-Dumm	22.22	18.35	22.93	22.25	21.44	0.11	0.14	0.17	0.20	0.16
Modified Glover-Dumm	15.19	10.68	13.76	12.90	13.13	0.09	0.10	0.11	0.12	0.11
Modified Glover	-2.27	-5.60	-2.42	-3.06	-3.34	0.06	0.06	0.06	0.05	0.06
Integrated Hooghoudt	-3.66	-6.77	-3.24	-3.78	-4.36	0.05	0.06	0.06	0.05	0.06
van Schilfgaarde	4.12	0.49	2.32	1.32	2.06	0.05	0.05	0.05	0.04	0.05
Guyon	-2.34	-5.63	-2.42	-3.06	-3.36	0.06	0.06	0.06	0.05	0.06
Hammad	6.49	1.43	2.16	0.92	2.75	0.06	0.06	0.06	0.05	0.06

Table 6: Statistical parameters for different unsteady drain spacing equations under SSDS different DS.

Drain spacing equations	RMSE (m) under SSDS with different DS				Average RMSE(m) from DS of 10 to 40 m	R^2 under SSDS with different DS				Average R^2 from DS of 10 to 40 m
	DS:10m DD:1m	DS:20m DD:1m	DS:30m DD:1m	DS:40m DD:1m		DS:10m DD:1m	DS:20m DD:1m	DS:30m DD:1m	DS:40m DD:1m	
Glover-Dumm	0.13	0.16	0.19	0.22	0.18	0.39	0.03	0.15	0.19	0.19
Modified Glover-Dumm	0.10	0.11	0.13	0.14	0.12	0.44	0.05	0.18	0.22	0.22
Modified Glover	0.07	0.09	0.07	0.07	0.08	0.42	0.04	0.17	0.21	0.21
Integrated Hooghoudt	0.07	0.09	0.08	0.08	0.08	0.40	0.03	0.15	0.19	0.19
van Schilfgaarde	0.05	0.06	0.05	0.05	0.05	0.53	0.14	0.30	0.41	0.35
Guyon	0.07	0.09	0.07	0.07	0.08	0.42	0.04	0.17	0.21	0.21
Hammad	0.06	0.06	0.06	0.05	0.06	0.56	0.17	0.29	0.38	0.35

Hammad's equation were within the allowable limit of ±10% variations, indicating satisfactory field performance for prediction of MWT height and in turn to design of SSDS. Further, the highest R^2 was recorded by van Schilfgaarde and Hammad's equation. Among all the unsteady drain spacing equations, van Schilfgaarde's equation performed better as compared to other unsteady drain spacing equations. The performance order of different unsteady drain spacing equation on the basis of PD, PE, MAE, RMSE and R^2 values were van Schilfgaarde > Hammad > Modified Glover > Guyon > Integrated Hooghoudt > Modified Glover-Dumm > Glover-Dumm's equation.

Firake (1987) reported the performance order of different unsteady drain spacing equation as Modified Glover-Dumm, Hammad, Integrated Hooghoudt, Glover-Dumm, van Schilfgaarde and Guyon's equation for clay loam soils of Maharashtra. Pali (2013) also reported the satisfactory field performance of Modified Glover, Integrated Hooghoudt and van Schilfgaarde's equation in saline soils of Haryana. Kumar *et al.* (2013) also reported the order of performance of different unsteady drain spacing equations as Modified Glover, van Schilfgaarde, Integrated Hooghoudt and Glover-Dumm for arid climatic regions of Rajasthan. They further reported that Glover-Dumm equation recorded PD between -33.31 to -31.55% and should not be applicable for drainage design. Lal *et al*. (1989) and Singh *et al*. (1992) also found the better performance of van Schilfgaarde's equation for drainage design. Sarwar and Feddes (2000) also mentioned that the non-steady state approach proved successful in analyzing the complex interactions between irrigation and drainage components. Schuh (2008) reported in "Potential Effects of Subsurface Drainage on Water Appropriation and the Beneficial Use of Water in North Dakota" that van Schilfgaarde's equation was commonly used in irrigated areas, or for areas where rainfall was commonly intense and of short duration. This type of rainfall situation and irrigated condition is common in our areas. Hence, van Schilfgaarde's equation performed better among all unsteady drain spacing equations for predicting MWT heights under irrigated and waterlogged Vertisols. Pali (2015) found the satisfactory field performance of Van Schilfgaarde's equation for design of SSDS in saline and waterlogged soils of Haryana. Hammad's equation performed next to Van Schilfgaarde's equation because he derived this equation for deep impervious layered soils and the experimental soil was 18 m deep impervious layer below ground surface. Chandra and Shyamsundar (2007), Nasralla (2007) and Naftchally *et al*. (2014) also recommended the unsteady state approach for drainage design. Hussein (2015) also used unsteady drain spacing equation for Egyptian Vertisols.

CONCLUSION

The experiment on field evaluation of seven unsteady drain spacing equations under subsurface drainage system with varying drain spacing and depth in waterlogged Vertisols conducted at Agricultural Research Station, Kasbe Digraj, Dist. Sangli (M.S.), India concluded that van Schilfgaarde, Hammad, Modified Glover, Guyon and Integrated Hooghoudt's equation performed satisfactory. Hence, these five unsteady drain spacing equations are suggested for prediction of mid-span water table heights under waterlogged Vertisols. Whereas, Modified Glover-Dumm and Glover-Dumm's equations indicated statistically poor field performance and can be out rightly discarded for design of subsurface drainage system under waterlogged, heterogeneous and deep impervious layered Vertisols of Maharashtra.

Among seven unsteady drain spacing equations, the following van Schilfgaarde's unsteady state drain spacing equation is recommended for better estimation of mid-span water table heights and in turn for the design of subsurface drainage system in terms of drain spacing and depth under waterlogged, heterogeneous and deep impervious layered Vertisols of Maharashtra.

$$L^2 = 9\left\{1 - \left(\frac{d_e}{(d_e+h_o)}\right)^2\right\}\left\{\frac{K_{sat}\,(d_e+h_t)\,(d_e+h_o)\,t}{2\,f\,(h_o-h_t)}\right\}$$

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