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Optimization of Subsurface Drain Spacing and Depth for Sugarcane under Waterlogged Vertisols of Canal/Lift Irrigated Areas of Maharashtra, India

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Abstract

The problems of waterlogging, salinity and sodicity of Vertisols declined the productivity of different crops especially sugarcane in recent decades of Maharashtra. Subsurface drainage is required to combat the twin problems of irrigation induced soil salinity and waterlogging. The field experiments for increasing sugarcane productivity in waterlogged Vertisols through subsurface drainage system were conducted at Agricultural Research Station, Kasbe Digraj, Sangli, Maharashtra (India) during 2012-13 to 2017-18. Four drain spacings (10, 20, 30 and 40 m) as main factor and three drain depths (0.75, 1.0 and 1.25 m) as sub-factor in split plot design were included for achieving objectives. The results revealed that 40 m drain spacing recorded significantly highest pooled mean height of sugarcane, milleable cane height, No. of internodes, No. of milleable canes per clump, cane yield followed by 30, 20 and 10 m. Whereas, the significantly highest pooled mean height of milleable cane, weight of single milleable cane, cane yield, CCS (%) and sugar yield were observed under 1.25 m drain depth followed by 1.0 and 0.75 m. The economic analysis revealed that 40 m drain spacing and 1.25 m depth recorded significantly highest pooled mean of B:C ratio, gross and net monetary returns. The interaction effect was non-significant. Thus, the drain spacing of 40 m and 1.25 m depth are recommended for optimum drainage, less NO_3-N losses, economically optimal growth, yield and quality dynamics of sugarcane under waterlogged Vertisols of canal/lift irrigated areas of Maharashtra, India.

Key words: Drain depth, Drain spacing, Subsurface drainage system, Sugarcane, Waterlogged Vertisols

Introduction

Irrigated agriculture in India as well as in the world is under stress due to twin problems of waterlogging and soil salinity (Valipour, 2014; Ambast *et al.,* 2007). In India, out of 6.74 Mha salt affected soils, almost half of the area (3.1 Mha) is suffering from irrigation induced salinity in different canal commands (Kamra and Sharma, 2016: Fagodiya *et al.,* 2022). More than 1.1 Mha areas under black cotton soils (Vertisols and associated soils) in different states of India are facing waterlogging and salinity problems. Vertisols cover an area of 26 Mha in India, and are predominant in the states of Madhya Pradesh (10.7 Mha), Maharashtra (5.6 Mha), Karnataka (2.8 Mha), Andhra Pradesh (2.2 Mha), and Gujarat (1.8 Mha) (Bhattacharyya *et al.,* 2013). These soils are generally deep to very deep and heavy texture with clay content varying from 40-70%. Because of their inherent physio-chemical and hydrological characteristics such as narrow workable moisture range, deep and wide cracks; poor internal drainage, low hydraulic conductivity, less infiltration rates and drainable porosity poses serious problems even at low salinity level. In black cotton soils (Vertisols and associated soils), Sugarcane is a major cash crop cultivated in Maharashtra. Further, around 70% of the total water available through irrigation system for farming in Maharashtra state is used for only sugarcane crop having around only 5 to 6% of the total cultivable land of the state and creating waterlogging, salinity and sodicity problems (CACP, 2012). The problems of waterlogging, salinity and sodicity declined the productivity of different crops and fertility of Vertisols in recent decades of Maharashtra. The best example is that of sugarcane as the productivity of sugarcane reduced from 150 Mg ha^{-1} in 1970's during the initial stages of introduction of irrigation to 50-

60 Mg ha^{-1} in 2000's after waterlogging and salinity of soil (Rathod *et al.*, 2011). In all such cases, Vertisols, where productivity is either low or the lands have become unproductive; drainage improvement through subsurface drainage system (SSDS) along with application of suitable amendments is required (Mukhopadhyay *et al.*, 2023). The need of drainage provisions in irrigation projects has been well acknowledged by the researchers worldwide and now a days it is considered as an integral part of large irrigation schemes. However, the effectiveness of SSDS depends upon the optimal combination of drain spacing (DS) and drain depths (DD).

Farmers of Sangli and Kolhapur districts in Maharashtra are using SSDS with drain spacing of 10-20 m for saline, saline-sodic, sodic and waterlogged soils. But this increased the initial adoption cost of SSDS, drained excess water and created moisture deficit conditions during summer season under the canal/lift irrigation systems with high irrigation interval of 25-30 days due to rotational supply of water. Sometimes, farmers are using ball valves at the outlet of SSDS for control of excess drainage of water as well as nutrients. Karegoudar *et al.* (2019), Nash *et al.* (2014) and Singh *et al.* (2000) reported NO_3-N losses under closely spaced drains. Randall (2004) studied the SSDS characteristics during 15-year period on a Webster clay loam soil in Minnesota and reported that the DS less than 27.4 m had observed more than 50% nitrate losses. Carter and Camp (1994) reported that there was no statistically significant cane sugar yield advantage to subsurface drains spaced closer than 42 m in clay loam soil of Louisiana. Boonstra *et al.* (2002) also reported that the sugarcane yield recorded in control, 30, 45 and 60 m drain spaced treatments with 0.9 m drain depth were 80, 115, 105 and 84 Mg ha^{-1}, respectively at Ukai-Kakrapar Command (Gujarat), India. It is found from above reviews that SSDS increased the productivity of sugarcane under waterlogged and saline soils. However, the results reported by Karegoudar *et al.* (2019), Singh *et al.* (2000), Nash *et al.* (2014) and Randall (2004) about nutrient losses through closely spaced drains; and drain spacings suggested by Camp and Carter (1994), Boonstra *et al.* (2002) and Raju *et al.* (2016) are in contraction whether to choose closely spaced or widely spaced drains for better sugarcane productivity under waterlogged-saline soils. Further, these results are creating misunderstanding among farmers as well as scientists regarding drain spacing. This emphasized the need for further verification of these results for the benefit of the farming community of Maharashtra, India.

Materials and Methods

Experimental details

The experimental soil was clayey in texture with average clay content of 59.73%. The field capacity, permanent wilting point and bulk density of soil were 39.24%, 18.90% and 1.30 gm cc^{-1}, respectively. The pHs and electrical conductivity of soil (ECe) were 7.65 to 7.93 and 0.49 to 1.15 d*S* m^{-1} respectively. The water table depth was within 0.30 m in rainy season and 0.6 to 1.54 m in winter and summer season. The average saturated hydraulic conductivity of soil was 0.096 m/day. The quality of irrigation was C_1S_1 (low salinity and sodium hazards) in *Kharif* and C_2S_1 (medium salinity and low sodicity hazards) in both *rabi* and summer season.

The field experiment for evaluating the effect of subsurface drain spacing and depth of drain for sugarcane under waterlogged Vertisols of Maharashtra was carried out during 2012-13 to 2017-18 with two Adsali plant canes (16-18 months crop duration) and one ratoon (12 months crop duration) at Agricultural Research Station, Kasbe Digraj, Sangli district (M.S.), India. Experiment was carried out in split plot design with four DSs as a main factor and three DDs as sub-factor. The four DSs of 10, 20, 30 and 40 m and three DDs of 0.75, 1.00 and 1.25 m were taken under split plot design and replicated three times. This formed the twelve combinations of DS and DD.

SSDS with different combinations of DS and DD

Treatments		Description
$L_{10}D_{1.25}$	:	DS 10 m and DD 1.25 m
$L_{10}D_{1.0}$	:	DS 10 m and DD 1.0 m
$L_{10}D_{0.75}$	:	DS 10 m and DD 0.75 m
$L_{20}D_{1.25}$	:	DS 20 m and DD 1.25 m

$L_{20}D_{1.0}$	:	DS 20 m and DD 1.0 m
$L_{20}D_{0.75}$	:	DS 20 m and DD 0.75 m
$L_{30}D_{1.25}$	:	DS 30 m and DD 1.25 m
$L_{30}D_{1.0}$	:	DS 30 m and DD 1.0 m
$L_{30}D_{0.75}$	:	DS 30 m and DD 0.75 m
$L_{40}D_{1.25}$	:	DS 40 m and DD 1.25 m
$L_{40}D_{1.0}$	:	DS 40 m and DD 1.0 m
$L_{40}D_{0.75}$	:	DS 40 m and DD 0.75 m

The experimental size of 216 m × 54 m was surveyed with Dumpy level at 18 m × 18 m grid for preparation of the contour map and layout of SSDS. The parallel SSDS (gridiron) was installed as per layout of 12 treatment combinations of DSs and DDs 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 slope of 0.2%. The collector drain was laid on a uniform grade of 0.2%. The concrete inspection chambers having 0.9 m diameter and 2.5 m height with ladder and top cover were installed for collection of drain discharge periodically from each treatment combination. The two *Adsali* canes (Variety: CoM-86032) planted at a spacing of 1.37 m × 0.3 m spacing during August, 2012 to December, 2013 and August, 2016 to December, 2017 and one ratoon were taken during January, 2014 to February, 2015. The agronomic practices, irrigation applications, fertilizer applications and plant protection practices were common to all treatments. The following physical, chemical and hydrological properties of soil; growth, yield, quality and economic parameters of sugarcane under different combinations of DS and DD were recorded during the investigation.

Determination of physical properties of waterlogged vertisols

The bulk density with core sampler method (Dastane, 1967), particle density of soil by Pycnometer method (Blake, 1965) and total porosity of soil calculated by using particle density and bulk density of soil (Brady and Weil, 1996) at initial and after harvest of sugarcane i.e., 18 months after drainage at 0-30, 30-60, 60-90 and 90-120 cm soil depth. Further, bulk density, particle density and total porosity of soil were averaged for 0-120 cm soil profile and used for studying the percent improvements observed due to SSDS with 12 different combinations of DSs and DDs.

Determination of chemical properties of waterlogged vertisols

The chemical properties of soil *viz.*, pHs by Potentiometric (Jackson, 1973) and electrical

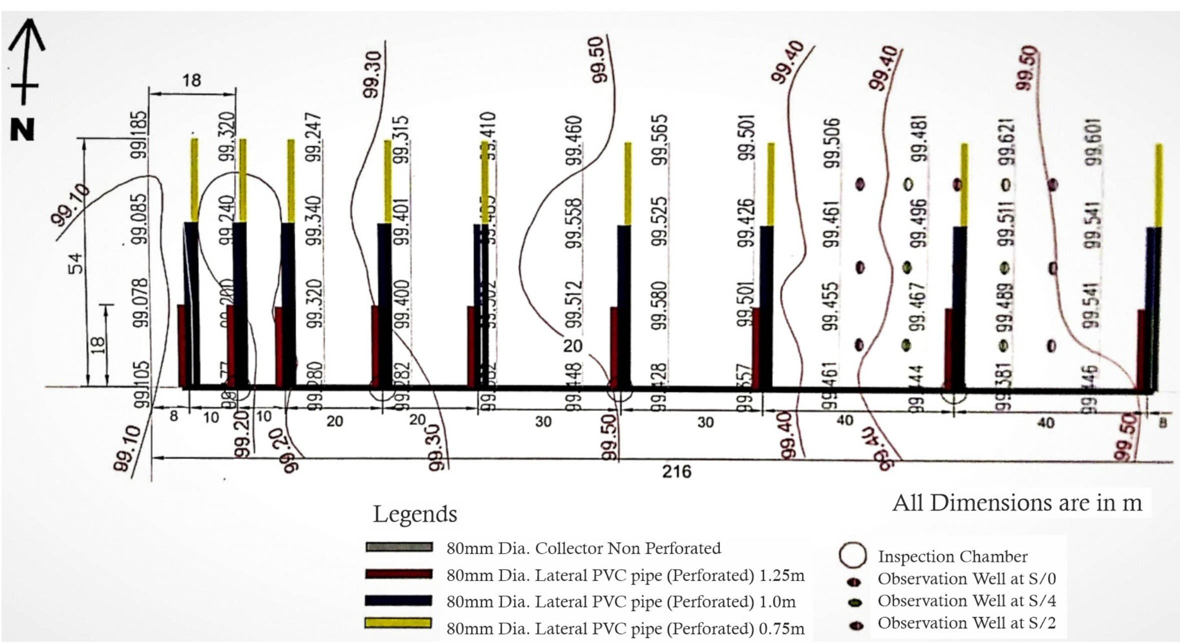

Fig. 1 Contour plan and layout of SSDS with different combinations of DS and DD

conductivity (ECe) of soil with Conductometric (Jackson, 1973) at different soil depths (0-30 cm, 30-60 cm 60-90 cm and 90-120 cm) were determined at initial and after harvest of sugarcane (18 months after drainage). The pHs and ECe of soil were averaged for 0-120 cm soil profile and used for calculating the percent improvements under SSDS with 12 different combinations of DSs and DDs.

Determination of hydrological properties of waterlogged vertisols

The methods used to determine the hydrological properties of soil such as drainage coefficient, mid-span water table (MWT) height, the saturated hydraulic conductivity and drainable porosity of soil are given below,

Drainage coefficient

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

$$q = \frac{Q}{A} \times 1000 \qquad \ldots(1)$$

Where,

Q = average drain outflow for the certain drain out period, m^3 day^{-1}

A = area drained, m^2

Field measurement of water table depths and drain discharges

Five piezometers were installed to record the water table depth across the subsurface drain for each combination of depth and spacing. One piezometer was installed on lateral drain and remaining at a distance of half and quarter of drain spacing at both 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 WTDs 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. WTDs at each piezometer were 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 m^3 day^{-1} were manually measured at drainage outlet points, using a bucket and a stop watch.

Saturated hydraulic conductivity of soil

It was necessary to the study the heterogeneity of soil for determination of saturated hydraulic conductivity of soil (K_{sat}) in m day^{-1}. 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 0-30 cm, 30-130 cm, 130-250 cm, 250-300 cm and 300-370 cm. It was, therefore, in-situ K_{sat} values at four various places in the field at 0-130 cm, 130-250 cm, 250-300 cm and 300-370 cm soil depth were determined by Hooghoudt's single auger hole method. The K_{sat} values of particular water transmitting layer (depth of drains + Hooghoudt's equivalent depth, de) contributed flow to drains for particular DS and DD combinations were calculated before and after harvest of sugarcane as a weighted K_{sat} of different soil layers. The 'de' was calculated by Moody's empirical equation for each DS and DD combination as d/L > 0.3.

$$\frac{L}{de} = 8\left\{\ln(L/R) - 1.15\right\}/\pi \qquad \ldots(2)$$

Where,

L= drain spacing, m

r = radius of drain pipe, m

Drainable porosity of soil

The drainable porosity of soil (f) is not usually a constant, but besides other things, it is a function of water table depth (WTD) or in other words soil depth (Taylor, 1960). The time of drawdown and shape of the WT depends on the particular way in which f is related to WTD. Thus, it is convenient and often necessary in drawdown studies to express f as a function of WTD. In this study, f corresponding to different WTDs was determined from WT drawdown and drain discharge measurements at the experimental site. It was calculated from the drain outflow measurements and its corresponding MWT heights above drain level by using equation 3.

$$f = \frac{Q \times T}{A\,(ho - ht)} \quad \ldots(3)$$

Where,

Q = average drain outflow for the drainage period during which the WT dropped from ho to ht, m^3 hr^{-1}

t = total drain out time, hr

A = area drained, m^2

ho = MWT height above the drain level at t = 0, m

ht = MWT height above the drain level at t= t, m

Growth parameters of sugarcane

Height of sugarcane: The height of sugarcane was recorded from ground level to the end of the last fully opened leaf from randomly selected nine sugarcanes (3 sugarcanes on above lateral area, 3 on the L/2 area i.e., DS/2 and 3 on L/4 area *i.e.*, DS/4 at harvest {510 days after planting (DAP)}. The average height of these nine sugarcanes was recorded as height of sugarcane in cm.

Milleable cane height: The milleable cane height was recorded from ground level to the base of the last fully opened leaf (last node) from randomly selected nine milleable canes (3 milleable canes on lateral area, 3 on L/2 area and 3 on L/4 area at harvest (510 DAP). The average height of these nine milleable canes was recorded as milleable cane height in cm.

***Number of internodes per milleable cane*:** Number of internodes present on milleable cane was recorded from base of cane stalk to fully opened leaf base. The average number of internodes of nine randomly selected milleable canes was recorded at harvest of sugarcane.

***Average intermodal length*:** The milleable cane height measured at harvest was divided by the number of internodes of each cane and recorded as average intermodal length, expressed in cm.

Yield and quality dynamics of sugarcane

***Number of milleable canes per clump*:** The number of milleable canes per clump was recorded at harvest. The number of milleable canes was counted randomly of nine eye buds (3 clumps on lateral area, 3 clumps on L/2 and 3 clumps on L/4 area. The average number of milleable canes from nine clumps was recorded as number of milleable canes per clump.

***Cane diameter/ girth of milleable cane*:** The diameter of cane (cm) was recorded at harvest. This was recorded from exactly central internodal portion of top, middle and bottom internodes using Vernier Caliper and expressed in centimeter. The values of top, middle and bottom portion of nine canes were selected and averaged.

Milleable cane weight: The weights of nine randomly selected milleable canes were recorded at harvest and the average of those was worked out and expressed as single cane weight in Kg.

***Cane yield*:** All milleable canes in the net plot were cut close to the ground level. The green tops and trash were removed and cane yield per net plot was recorded. The net plot for different treatment was different because of the drainage effect of different combinations of subsurface DS and DD on sugarcane growth. The sugarcane yield was calculated by converting the yield of net areas to one hectare and expressed in Mg ha^{-1}.

***Commercial cane sugar percentage* (CCS %):** It is the amount of white commercial sugar obtained from cane juice after removing total soluble solids. It was calculated by using the following formula.

CCS (%) = [Sucrose (%) – Brix (%) – Sucrose (%) × 0.40] × 0.73 …(4)

Sugar yield or commercial cane sugar (CCS)

Sugar yield (Mg ha^{-1}) was calculated by using the following formula as suggested by Sastry and Venkatachari (1960),

$$\text{Sugar yield (Mg ha}^{-1}) = \frac{\text{CCS (\%)} \times \text{Sugarcane yield (Mg ha}^{-1})}{100}$$

Where, CCS = Commercial cane sugar (%)

Economic feasibility of SSDS with different DS and DD

Following economic parameters were worked out to find the suitable combination of DS and DD.

Initial adoption cost of SSDS with different combinations of DS and DD: The initial costs on adoption of SSDS were worked out for each treatment and their replications. The initial cost of SSDS includes purchase cost of different materials, labour and consultancy charges required for preparation of contour and layout of SSDS; excavation and installation of SSDS. The maintenance of SSDS was required from one year after installation of SSDS.

Cost of sugarcane production: The total cost of sugarcane production was calculated by adding the yearly cost of SSDS in cost of cultivation of sugarcane. Maintenance cost on SSDS was also added from second year after installation of SSDS while calculating the cost of sugarcane production.

Gross monetary returns: The gross monetary returns per hectare were worked out by considering the yield of main produce and by produce from different treatments with prevailing market price of sugarcane and by produce.

N*et monetary returns:* The net monetary returns per hectare were calculated by deducting the cost of sugarcane production per ha from gross monetary returns per hectare.

Benefit: Cost ratio: The benefit: cost ratio (B:C ratio) was worked out by dividing the cost of sugarcane production to the gross monetary returns in each treatment under study.

Statistical analysis

The split plot design with four main factors and three sub-factors with three replications were used for statistical analysis of growth, yield and quality dynamics of sugarcane (Panse and Sukhatme, 1967).

Results and Discussion

Growth, yield and quality dynamics of sugarcane under SSDS with different combinations of DS and DD

It is observed from Table 1 to 3 that the significant differences in pooled mean of height of sugarcane, milleable cane height, No. of internodes, weight of single milleable cane, No. of milleable canes

Table 1. Effect of SSDS with different DSs and DDs on growth dynamics of sugarcane under waterlogged Vertisols

Treatments	Height of sugarcane (cm)				Height milleable cane (cm)				No. of internodes				Length of internodes (cm)			
	2013-14	2014-15	2017-18	Pooled Mean	2013-14	2014-15	2017-18	Pooled Mean	2013-14	2014-15	2017-18	Pooled Mean	2013-14	2014-15	2017-18	Pooled Mean
DS																
L_1 (10 m)	423.81	337.12	446.17	402.37	243.39	155.60	256.50	218.50	25.61	17.08	22.22	21.64	9.63	9.15	11.60	10.13
L_2 (20 m)	443.36	349.07	468.00	420.14	273.92	175.18	280.56	243.22	27.17	18.18	23.33	22.89	10.19	9.63	12.11	10.64
L_3 (30 m)	461.44	357.45	479.72	432.87	295.44	188.78	306.44	263.56	28.50	19.12	25.06	24.22	10.43	9.88	12.30	10.87a
L_4 (40 m)	480.39	368.16	491.33	446.63	313.11	200.88	339.11	284.37	29.19	19.61	27.39	25.40	10.75	10.25	12.46	11.15a
SE±	2.74	3.11	4.54	3.50	4.17	2.01	4.20	4.03	0.31	0.22	0.46	0.35	0.13	0.13	0.24	0.15
CD at 5%	9.48	10.74	15.70	10.21	14.42	7.10	14.54	11.75	1.08	0.76	1.59	1.03	0.45	0.45	NS	0.45
DD																
D_1 (0.75 m)	442.00	346.64	465.17	417.94	266.08	170.73	281.21	186.24	26.65	17.81	23.50	22.65	10.11	9.57	12.02	10.99
D_2 (1.0 m)	452.13	352.43	470.04	424.87a	280.48	179.20	295.25	195.58	27.56	18.46	24.50	23.51a	10.20	9.69	12.12	11.09
D_3 (1.25 m)	462.63	359.78	478.71	433.71a	297.83	190.40	310.50	207.55	28.65	19.22	25.50	24.46a	10.44	9.92	12.20	11.25
SE±	2.77	2.83	3.42	3.37	4.77	1.42	4.76	2.62	0.38	0.27	0.48	0.42	0.17	0.17	0.19	0.25
CD at 5%	8.29	8.48	10.26	9.56	14.31	4.26	14.27	5.28	1.13	0.80	1.43	1.21	NS	NS	NS	NS
Interaction																
DS × DD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 2. Effect of SSDS with different DSs and DDs on yield dynamics of sugarcane under waterlogged Vertisols

Treatments	Weight of single milleable cane (kg cane^{-1})				No. of milleable canes /clump				Girth of cane (cm)			
	2013-14	2014-15	2017-18	Pooled mean	2013-14	2014-15	2017-18	Weighted mean	2013-14	2014-15	2017-18	Pooled mean
DS												
L_1 (10 m)	1.68	1.12	1.99	1.60	11.28	8.31	12.67	10.86	9.64	9.28	9.12	9.35
L_2 (20 m)	1.83	1.22	2.07	1.71	11.78	8.86	13.00	11.36	9.62	9.27	9.48	9.46
L_3 (30 m)	1.98 a	1.32 a	2.24 a	1.85 a	12.03	9.50	13.06	11.66	9.50	9.17	9.45	9.37
L_4 (40 m)	2.13 a	1.42 a	2.31 a	1.95 a	13.19	10.53	14.33	12.81	9.47	9.15	9.69	9.44
SE±	0.06	0.04	0.065	0.05	0.09	0.19	0.29	0.14	0.16	0.13	0.13	0.13
LSD (p=0.05)	0.19	0.13	0.22	0.14	0.32	0.65	1.00	0.29	NS	NS	NS	NS
DD												
D_1 (0.75 m)	1.79	1.19	1.92	1.43	11.65	8.94	12.54	10.22	9.57	9.22	9.34	9.38
D_2 (1.0 m)	1.91 a	1.27 a	2.13	1.54	12.15	9.38	13.21	10.70 a	9.55	9.21	9.38	9.38
D_3 (1.25 m)	2.03 a	1.35 a	2.41	1.65	12.42	9.58	14.04	10.95 a	9.57	9.22	9.58	9.46
SE±	0.05	0.03	0.08	0.05	0.16	0.14	0.50	0.20	0.12	0.10	0.09	0.12
LSD (p=0.05)	0.15	0.10	0.23	0.10	0.47	0.41	NS	0.41	NS	NS	NS	NS
Interaction												
DS×DD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS= not significant

Table 3. Effect of SSDS with different DSs and DDs on CCS (%), cane and sugar yield under waterlogged Vertisols

Treatments	CCS (%)				Cane yield (Mg ha^{-1})				Sugar yield (Mg ha^{-1})			
	2013-14	2014-15	2017-18	Pooled Mean	2013-14	2014-15	2017-18	Weighted Mean	2013-14	2014-15	2017-18	Pooled Mean
DS												
L_1 (10 m)	13.96	13.09	13.95	13.67	122.92	73.82	141.68	87.03	17.17	9.67	20.14	15.66
L_2 (20 m)	14.10 a	13.23 a	14.00	13.78	153.25	91.25	168.90	107.64	21.62	12.08	24.64	19.45
L_3 (30 m)	14.17 a	13.30 a	14.22 a	13.90 a	179.69	107.30	200.85 a	126.54	25.47	14.28	29.83	23.19 a
L_4 (40 m)	14.28 a	13.41 a	14.28 a	13.99 a	201.48	118.49	214.04 a	140.12	28.80	15.91	29.65	24.79 a
SE±	0.06	0.06	0.05	0.05	4.59	2.48	11.28	3.72	0.62	0.32	0.82	0.68
LSD (p=0.05)	0.21	0.20	0.17	0.15	15.87	8.60	39.03	7.92	2.14	1.09	2.85	1.97
DD												
D_1 (0.75 m)	13.98	13.11	14.01	13.70	147.66	87.04	153.41	102.18	20.66	11.42	21.47	13.86
D_2 (1.0 m)	14.07	13.20	14.10	13.79	163.43	96.65	179.52	113.56	23.03	12.78	25.92	15.63
D_3 (1.25 m)	14.33	13.46	14.23	14.01	181.91	109.46	211.35	128.20	26.10	14.75	30.80	18.01
SE±	0.04	0.04	0.03	0.05	3.80	2.01	9.66	3.50	0.53	0.27	0.85	0.46
LSD (p=0.05)	0.13	0.13	0.09	0.13	11.38	6.04	28.97	7.06	1.60	0.80	2.56	0.93
Interaction												
DS × DD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

per clump, CCS (%), cane yield and sugar yield were observed under DS (main factor) and DD (sub-factor). However, the interaction effect of drain spacing and depth on growth, yield and quality dynamics of sugarcane was non-significant. The DS of 40 m recorded significantly maximum pooled mean height of sugarcane (446.63 cm), milleable cane height (284.37 cm), No. of internodes (25.40), No. of milleable cane per clump (12.81 Nos.), cane yield (140.12 Mg ha^{-1}) followed by DS of 30 m, 20 m and 10 m (Table 1 to 3). Whereas, 30 m DS was performed at par with 40 m drain spaced treatment for length of internodes, weight of single milleable cane, CCS (%) and sugar yield. The girth of internodes was non-significant under DSs. This might be due to less NO_3-N losses through slow drainage under higher spaced drains. The drainage coefficient observed under treatment combination of 10 m DS with 1.25 m DD and 40 m DS with DD of 1.25 m were 6.93 mm day^{-1} and 2.18 mm day^{-1}respectively (Table 6). Sugarcane growth was adversely affected due to excess losses of nitrogen in the form of NO_3-N through excess drainage under closely spaced drains. Excess drainage of around 50% of Nitrogen and 17% of irrigation water were recorded from paddy fields in Saline clay loam soils of Tungabhadra Project (TBP) Command Area of Karnataka, India (Karegoudar, *et al*. 2019). Nash *et al.* (2014) reported annual NO_3-N loss through tile drainage water with SSDS ranged from 28.3 to 90.1 kg N ha^{-1}. Nangia *et al*. (2009) also observed that a tile DD of 1.5 m and increasing the tile DS from 27 to 40 m reduced NO_3-N losses by 50% (while reducing crop yield by 7%) Randall (2004) reported that the SSDS characteristics during 15-year period on a Webster clay loam soil in Minnesota showed that more than 50% of the annual nitrate loss occurred in 10% and 18% of the days drainage occurred when tile DS was 15.2 and 27.4 m, respectively. This was extremely important that the DS less than 27.4 m had observed more than 50% nitrate losses (Randall, 2004). Further, nitrogen requirement of *Adsali* sugarcane crop (16-18 months crop period) was very high i.e., 400 kg ha^{-1} for present experimental soil site. Hence, the sugarcane pooled yield trend observed under different DS were 40 m DS (140.12 Mg ha^{-1}) > 30 m DS (126.54 Mg ha^{-1}) > 20 m DS (107.64 Mg ha^{-1}) > 10 m DS (87.03 Mg ha^{-1}). These results are very useful for farming community. Because they always misunderstood that closer spaced drain gives more yield. Further, they don't know about the losses of nitrogenous fertilizers. The second reason might be due to less water stress on sugarcane growth by slow drainage in higher spaced drains under high irrigation interval period (generally 25-30 days) adopted by the co-operative lift irrigation schemes. Generally, irrigation interval for furrow irrigation was 10-12 days in summer, 18-20 in winter and 14-15 days in rainy season in Maharashtra. But due to rotational supply system of lift/canal irrigated sector of Maharashtra, farmers can get irrigation water generally after every 25-30 days. Under this situation, if SSDS was installed; it removes 4 to 10% of irrigated water just within 2 to 3 days. Hence crop may face the deficit water stress during later stages or 5-10 days before irrigation. The third reason may be the spatial variability in salinity of the experimental soil (0.4 to 1.15 dS m^{-1}). However, the critical salinity tolerance limit of sugarcane was 1.71 dS m^{-1} (FAO, 1985). The fourth reason might be that sugarcane appears to be exceptionally resistant to waterlogging, with standing periods of up to 14 days of shallow standing water or saturated soil in a Florida study (Glaz and Morris 2010; Glaz et al. 2004). Hence, slow drainage by higher spaced drains may not adversely affect the sugarcane yield. But as per FAO guidelines on crop yield response to water, the yield response factor (Ky) of sugarcane is greater than one (>1.2) indicating more sensitivity towards water deficit with proportional larger yield reductions when water use is reduced because of stress (Doorenbos and Kassam, 1979). Hence, DS of 10 m recorded significantly lowest pooled yield of sugarcane (87.03 Mg ha^{-1}). Camp and Carter (1994) reported that there was no statistically significant sugarcane yield advantage to subsurface drains spaced closer than 42 m; the DS recommended for draining Jeanerette silty clay loam soil in Louisiana was 42 m. Tiwari and Goel (2017) also reported that the DS should be within 20-50 m for fine textured soils in semi-arid regions.

Further, the significantly highest pooled mean height of milleable cane (207.55 cm), weight of single milleable cane (1.65 kg), cane yield (128.20 Mg ha^{-1}), CCS (14.23%) and sugar yield (18.01 Mg ha^{-1}) were observed under DD of 1.25 m followed by 1.0 m and 0.75 m DD (Table 1 to 3). Further, the DD of 1.0 m was performed at par with 1.25 m DD for height of sugarcane, No. of internodes per cane and No. of milleable canes per clump. The length and girth of internodes were non-significant under different DD. These might be due to different rate of WT drop under different DD (Table 6). The percent improvement in physico-chemical and hydrological properties of soil were more under deep drains for a given spacing, and provided faster and better congenial condition at greater soil depth for deep rooted crops like sugarcane (Table 6). The opposite condition was observed for shallow drained treatments. Hence, shallow depth recorded significantly lowest growth, yield and quality parameters of sugarcane as compared to deep drains (Table 1 to 3). Tiwari and Goel (2017) reported that the DD of SSD should be more than 1.2 m for optimum crop growth and to avoid breakages of pipes by heavy loaded vehicles may be sugarcane tractors and other vehicles. The DD of 0.9 to 1.2 m below ground surface were increasingly used in humid and semi-arid climates (Abu-zeid, 1992). In India, Ritzema *et al.* (2008) and Srinivasulu *et al.* (2005) noted that under gravity flow conditions, DD can be reduced to 0.9 to 1.0 m. Sarwar and Feddes (2000) also reported that deeper drains performed technically better in relation to crop growth and soil desalinization.

Economic feasibility of SSDS with different combinations of DS and DD for cultivation of sugarcane under waterlogged vertisols

As presented in Table 4, the economic analysis of SSDS with varying DS and DD revealed that the DS of 40 m recorded significantly highest pooled mean of gross monetary returns (Rs 379571.20 ha^{-1}), net monetary returns (Rs. 237707.20 ha^{-1}) and B: C ratio (2.55) followed by DS of 30 m, 20 m and 10 m. The higher spaced drain recorded superior economics as compared to closely spaced drains. This was due to the fact that closely spaced drains required more initial investment on SSDS as compared to widely spaced drains for a given drain depth (Table 5). Further, the yield of sugarcane also recorded higher under widely spaced drains of 40 m as compared to closely spaced drains of 10 m for a given drain depth (Table 3). In case of drain depth, 1.25 m recorded significantly highest pooled mean of gross monetary returns (Rs. 347299.70 ha^{-1}), net monetary returns (Rs. 203851 ha^{-1}) and B:C ratio (2.33) followed by DD of 1.0 and 0.75 m as the deeper drains provided faster and better physico-chemical and hydrological properties of soil at greater soil depth for deep rooted crops like sugarcane and thereby the higher yield (Table 3, 4 and 6). The interaction effect of DS and DD was non-significant. The results of B: C ratio is corroborated with the findings of Raju *et al*. (2017) who observed up to 134% increase in B:C ratio

Table 4. Economic feasibility of SSDS with different DSs and DDs for sugarcane under waterlogged Vertisols

Treatments	Gross monetary returns (Rs ha^{-1})				Net monetary returns (Rs ha^{-1})				B:C ratio			
	2013-14	2014-15	2017-18	Weighted mean	2013-14	2014-15	2017-18	Weighted mean	2013-14	2014-15	2017-18	Pooled mean
DS												
L_1 (10 m)	332980.79	199989.87	384455.56	235780.10	92794.54	82722.97	136529.39	86875.21	1.39	1.70	1.55	1.55
L_2 (20 m)	415158.92	247197.07	457544.93	291579.70	178982.05	135178.03	214946.80	147654.50	1.76	2.21	1.89	1.95
L_3 (30 m)	486778.80	290678.96	544100.70	342780.40	251358.62	179955.85	302813.63	200033.60	2.07	2.62	2.25	2.31
L_4 (40 m)	545814.38	320982.89	579849.35	379571.20	311213.92	211159.50	339478.40	237707.20	2.33	2.92	2.41	2.55
SE±	12425.08	6735.84	30558.04	10069.28	12425.08	6735.84	30558.04	10069.28	0.05	0.06	0.13	0.08
LSD (p=0.05)	42996.46	23309.07	105744.74	21461.67	42996.46	23309.07	105744.74	21461.67	0.18	0.21	0.44	0.23
DD												
D_1 (0.75 m)	400021.89	235781.41	415601.64	276595.40	163749.74	123647.09	172886.32	133787.60	1.70	2.11	1.71	1.87
D_2 (1.0 m)	442734.54	261834.76	486320.87	307655.50	206131.04	149369.08	243267.58	164516.10	1.88	2.34	2.01	2.08
D_3 (1.25 m)	492793.24	296520.43	572540.40	347299.70	255881.07	183746.10	329172.27	203851.50	2.08	2.64	2.36	2.33
SE±	10284.40	5458.65	26181.04	9483.67	10284.40	5458.65	26181.04	9483.67	0.04	0.05	0.11	0.06
LSD (p=0.05)	30832.63	16365.02	78490.74	19138.81	30832.63	16365.02	78490.74	19138.81	0.13	0.15	0.32	0.13
Interaction DS × DD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 5. Cost of sugarcane production and initial investment on adoption of SSDS with different DSs and DDs

Sr. No.	Items	$L_{10}D_{0.75}$	$L_{10}D_{1.0}$	$L_{10}D_{1.25}$	$L_{20}D_{0.75}$	$L_{20}D_{1.0}$	$L_{20}D_{1.25}$	$L_{30}D_{0.75}$	$L_{30}D_{1.0}$	$L_{30}D_{1.25}$	$L_{40}D_{0.75}$	$L_{40}D_{1.0}$	$L_{40}D_{1.25}$
1	Initial investment on SSDS (Rs ha^{-1})	219238	233268	247297	126175	133789	139135	107700	114116	120531	88547	93623	98699
2	Yearly cost of SSDS considering 25 years life of SSDS (Rs ha^{-1} $year^{-1}$)	8769.52	9330.70	9891.88	5047.00	5351.56	5565.40	4308.01	4564.63	4821.25	3541.87	3744.91	3947.95
3	Cost of sugarcane cultivation (Rs ha^{-1}) 2013-14	230856	230856	230856	230856	230856	230856	230856	230856	230856	230856	230856	230856
4	Cost of ratoon (Rs ha^{-1}) 2014-15	105000	105000	105000	105000	105000	105000	105000	105000	105000	105000	105000	105000
5	Cost of sugarcane cultivation (Rs ha^{-1}) 2017-18	235587	235587	235587	235587	235587	235587	235587	235587	235587	235587	235587	235587
6	Cost of maintenance of SSDS needed from 2014-15 and onwards (Rs ha^{-1} $year^{-1}$)	2936.20	2936.20	2936.20	1697.72	1697.72	1697.72	1158.48	1158.48	1158.48	1078.48	1078.48	1078.48
7	Cost of sugarcane production 2013-14 (Rs ha^{-1}) = Sr.No.2+3	239625.52	240186.7	240747.88	235903	236207.56	236421.4	235164.01	235420.63	235677.25	234397.87	234600.91	234803.95
8	Cost of sugarcane production 2014-15 (Rs ha^{-1}) = Sr.No.2+4+6	116705.72	117266.9	117828.08	111744.72	112049.28	112263.12	110466.49	110723.11	110979.73	109620.35	109823.39	110026.43
9	Cost of sugarcane production 2017-18 (Rs ha^{-1})= Sr.No.2+5+6	247292.72	247853.9	248415.08	242331.72	242636.28	242850.12	241053.49	241310.11	241566.73	240207.35	240410.39	240613.43

Table 6. Drainage coefficient, drainable porosity, bulk density, soil desalination and water table under SSDS with different combinations of DS and DD

Sr. No.	Treatments	Average drainage coefficient (mm.d^{-1})	Drainable porosity (%)	Improvement in bulk density of soil after drainage (%)	Improvement in soil porosity after drainage (%)	Desalination of soil after drainage (%)	Depth of average water table (m), 10 days after heavy rainfall of 147 mm
1.	$L_{10}D_{1.25}$	6.93	10.58	20.76	13.74	55.53	0.693
2.	$L_{10}D_{1.0}$	4.07	10.14	20.00	13.56	57.92	0.549
3.	$L_{10}D_{0.75}$	1.49	3.87	18.60	12.30	59.44	0.355
4.	$L_{20}D_{1.25}$	4.05	6.96	17.82	11.80	36.73	0.472
5.	$L_{20}D_{1.0}$	2.78	5.07	17.13	11.37	46.30	0.332
6.	$L_{20}D_{0.75}$	1.04	2.50	15.97	11.18	49.38	0.216
7.	$L_{30}D_{1.25}$	2.86	5.48	16.51	10.90	31.47	0.335
8.	$L_{30}D_{1.0}$	2.00	4.96	15.51	10.49	33.86	0.235
9.	$L_{30}D_{0.75}$	0.80	1.99	13.81	8.51	41.43	0.178
10.	$L_{40}D_{1.25}$	2.18	4.91	16.36	10.88	25.26	0.125
11.	$L_{40}D_{1.0}$	1.90	4.43	14.89	9.99	27.84	0.072
12.	$L_{40}D_{0.75}$	0.72	1.65	12.58	8.40	39.18	0.042

for sugarcane crop. Raju *et al.* (2015) and, Chinnappa and Nagaraj (2007) also recorded similar results.

Finally, DS of 40 m and DD of 1.25 m were found economically optimal among other DSs and DDs for sugarcane under waterlogged Vertisols of Maharashtra. Carter and Camp (1994) also suggested 42 m for sugarcane for silty clay loam soil. Talukolaee *et al.* (2016) also recommended 30 m DS and DD of 0.9 m instead of 15 m DS and DD of 0.65 m for optimum properties of soil and higher canola yield in Iran. Tiwari and Goel (2017) also reported that the DS should be within 30-50 m for fine textured soils, DD > 1.2 m and drainage coefficient of 2 mm day^{-1} for semi-arid regions. In this investigation the highest sugarcane yield was obtained under DS of 40 m, DD of 1.25 m and drainage coefficient of 2.18 mm day^{-1} which was nearer to recommended drainage coefficients of 2 mm day^{-1} for semi-arid regions. Hence, the previous research works supported the present research outputs as well.

Conclusions

The narrow workable soil moisture range and very low hydraulic conductivity have always been considered as hurdles in getting potentially higher crop outcomes from highly fertile Vertisols. The heavy waterlogging condition in these soils during rainy season sometimes makes it impossible to carry out farm operations and hence causes land to leave fallow. Further, the irrigated *Vertisols* are highly prone to soil degradation if proper irrigation water management and drainage infrastructure are not in place. In Maharashtra, the canal and lift irrigation schemes are supplying continuous water supply but creating twin problems of waterlogging and salinity. The optimum drainage is the only possible solution to minimize these soil constraints. The present study evaluated subsurface drainage system with four drain spacings of 10, 20, 30 and 40 m and three drain depths of 0.75, 1.00 and 1.25 m for finding out the optimal combination of drain spacing and drain depth for optimum growth of sugarcane under waterlogged Vertisols of Sangli, Maharashtra. To conclude, the losses of NO_3-N with excess drainage of irrigation water through subsurface drainage system with closely spaced drains reported by Karegoudar, *et al*. (2019), Nash *et al.* (2014), Nangia *et al*. (2009), Randall (2004), and Singh *et al.* (2000) have been played a decisive role. Hence, in this study, the subsurface drainage system with 40 m drain spacing and 1.25 m drain depth has been recommended for optimum drainage, less NO_3-N losses and, economically higher cane/sugar yield under lift/canal irrigated Vertisols of Sangli district in Maharashtra, India.

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