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Evaluating the Spacing in Free and Controlled Subsurface Drainage Systems in Saline *Vertisols* of the Tungabhadra Project Command Area, Karnataka, India

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Abstract

Performance of subsurface drainage (SSD) systems mainly depends on free movement of drainage effluent to the surface drain through the gravity outlets as it influences the rate of reclamation of waterlogged saline soils. Farmers at the tail end of the Tungabhadra project (TBP) command who often face scarcity of water especially at the later part of the crop growth period are in practice of blocking the outlets so as to retain water in the field for the crop. This practice has led to the inefficient SSD network in the command. To overcome this practice, Controlled Drainage (CD) system wherein a slight modification to the existing Free Drainage (FD) system was designed at Agricultural Research Station, Gangavathi, Karnataka, India. A comparative field study was conducted to evaluate the effectiveness of FD and CD systems with 50 and 60 m spacing in waterlogged saline *Vertisols* within the TBP command area. The FD and CD treatments have been applied since the installation of the SSD system. The data of seven seasons revealed that in both the spacing, rate of reclamation was faster under FD system. However, CD system saved irrigation water by 28% to 35% and also reduced drainage water volume by 39% to 70%. Apart from this, the CD system also reduced the movement of nitrate by 42% to 70% with maintaining shallow water depth as compared to FD system. The B: C ratio under FD system for 60 and 50 m spacing was 1.66 and 1.73, respectively, whereas slightly less effective CD system in terms of reclamation by leaching has reasonably good B: C ratio of 1.55 and 1.56 for 60 and 50 m spacing, respectively. The study revealed that 60 m drain spacing with CD system could be a viable option to address water shortage by reducing drainage discharge, seasonal salt and water balance and nutrient loss in the tail-end areas of the TBP command.

Keywords: Controlled drainage, Depth to watertable, Salt removal, Salt and water balance, Nitrogen loss

Introduction

Water, as elixir of life is essential for the survival of all ecosystems, deserves our utmost care and management. The average rainfall of the country is about 1200 mm, but it is erratic and ill distributed. The northern parts of the Karnataka receive an average annual rainfall of about 550 mm which is not sufficient to irrigate all the crops. With this background, the government took steps to build a dam in 1953 across the Tungabhadra River in order to give supplemental irrigation to these lands. Before the construction of the dam, scientific team planned the cropping pattern which was decided based on the availability of water in the reservoir (105.78 TMC). Based on localization principles, crop with lower water requirements (such as those traditionally grown in dry land areas) should grow in the upper region (91%), while water-intensive crops like paddy (8%) and sugarcane (4%) should be grown in the lower region or tail-end areas (CADA, 2013), where excess water can be optimally utilized. The farmers of this region followed the same cropping pattern till the 1980s. However, Godavari district farmers (migrated from Andhra Pradesh state) violated the cropping pattern and introduced the paddy-paddy system in many regions of the command. The excessive seepage from paddy fields in the upstream areas made cultivation of light irrigated crops impossible in the downstream region. Then farmers started to grow paddy by modifying their land (Check basin method), resulted in to increased area from 29000 ha (8%) to 150000 ha (41%), especially in upper and middle regions where canal water was easily available. The violation of cropping pattern in these regions, not only created water shortage but also faced the problem of secondary salinization on an area of about 96215 ha in the tail end of the command (CADA, 2013).

In order to reclaim these lands, TBP-CADA (Tungabhadra Project- Command Area Development Authority) has taken up subsurface drainage (SSD) works but the farmers made it defunct to avoid over draining of irrigation water through SSD system from the paddy fields. To overcome these problems adopting controlled drainage (CD) approach (Karegoudar *et al.*, 2019) to the existing drainage (FD) system was identified as the best solution as it can save 17 % irrigation water and reduce 64% of drainage water in the command.

This type of practice already adopted in many countries and proved to be the best watertable management practice (Gilliam *et al.*, 1979) to maintain shallow (Doering *et al.*, 1982) groundwater table which in turns helped to minimized the drainage outflow (Gilliam & Skaggs, 1986).The similar kind of practice was carried out and drainage outflow was minimized by 24% in maize (Drury *et al.*, 1996), 79% to 94% in potato (Wesstrom *et al.*, 2001), 40% in corn (Fausey, 2004) and 94% (Zhonghua *et al.*, 2006) and 35% (Kornay, 1997) in rice. Hamidreza *et al.* (2018) reported that, controlled drainage system not only reduced the nitrate flow by 15%, 9%, and 8% but also reduced phosphorus flow by 38%,36%, and 39% compared FD system under wheat, barley, and maize crops, respectively in Moghan plain of northwest Iran. Similarly, Evans *et al.*, (1989) also reported that adopting CD system reduced the annual transport load of total nitrogen by 46.5% and total phosphorus load by 44%. The effect of CD approach varies with season to season, according to Amatya *et al. (*1998) drainage outflow was reduced by 88% during summer and 39% during spring seasons. Similarly, Wahba *et al.* (2001) observed that in the Western Delta of Egypt the drainage outflow was reduced by 68% and 28% thereby reducing nitrate loss by 73% and 32% in summer and winter season, respectively as compared to FD treatment. Some studies (Amatya *et al.*, 1998; Ayars *et al.*, 2005; Ayars *et al.*, 2006; Doering *et al.*, 1982 and Karegoudar *et al.*,2019) also reported that, the prolonged use of CD approach especially during cropping season avoided salt deposition at lower depths due to reduced salt movement.

In view of this background, Controlled Drainage (CD) system wherein a slight modification to the existing Free Drainage (FD) system with 50 and 60 m spacing was laid out at Agricultural Research Station, Gangavathi to address soil salinity and water scarcity issues in the tail-end area of the command.

Materials and Methods

Study area description

The study was carried out at Agricultural Research Station, Gangavathi (N 15° 27'14.1", E 76°32' 06.12" to N 15°27'12.1", E 76°32' 06.4") which comes under TBP command (Fig. 1). The soil of the study site is dominantly clay loam with weathered calcareous parent material (Manjunath *et al.*, 2004). Rice was transplanted at the study site in *kkharif* and *rabi*/summer (R/S) season.

The study sites were divided into two equal plots with FD and CD systems, and each system was served by three lateral drains at 1 m (IDNP, 2002) depth with a spacing of 50 m (2.8 ha) and 60 m (4.0 ha). Under both the spacing, the collector drains (100 mm diameter PVC corrugated plastic pipe) were installed perpendicular to the surface drain (Nala) at 1.10 m (IDNP, 2002) depth. The slope of lateral drains was maintained from 0.1% to 0.2% and were connected to the respective manhole (Chamber). Manholes were interconnected through collector drains whose slopes were 0.2% to 0.3%, and finally, the effluent was discharged into the Nala *via* lateral, manhole, collector and drainage outlet (Fig.2).

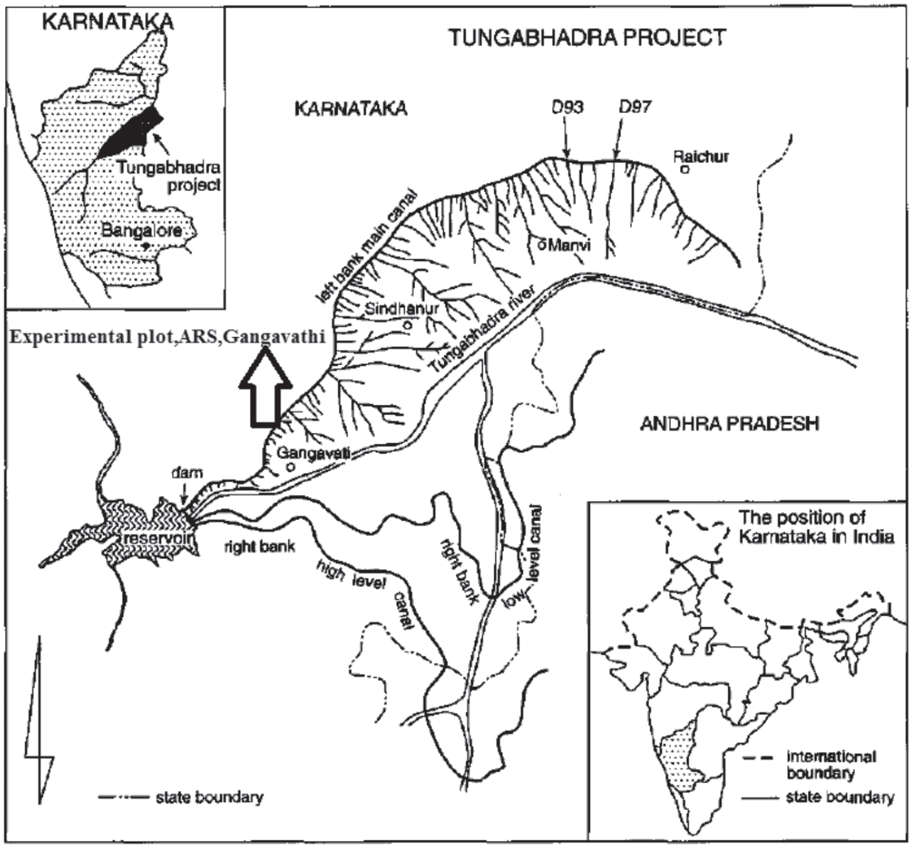


Fig. 1 Location Map of Tungabhadra Irrigation Project

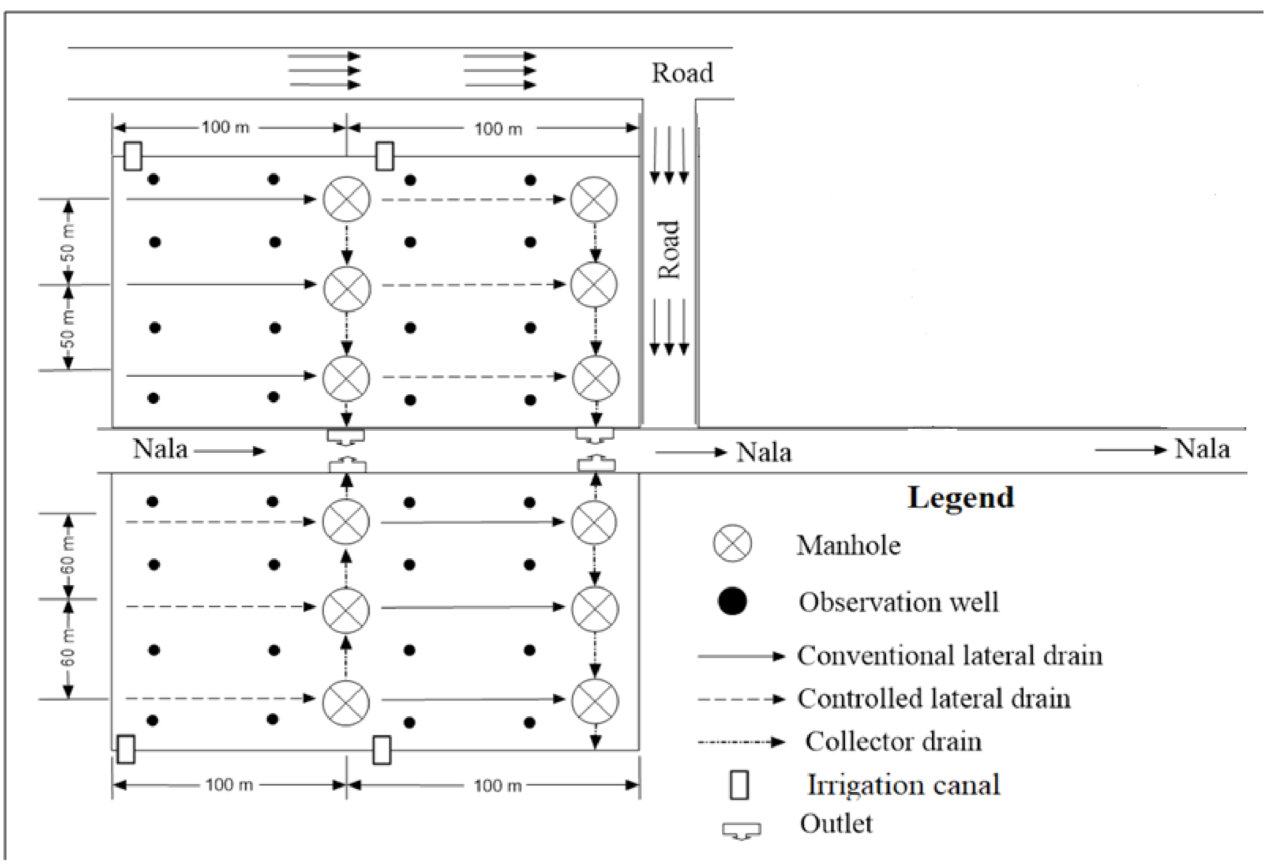
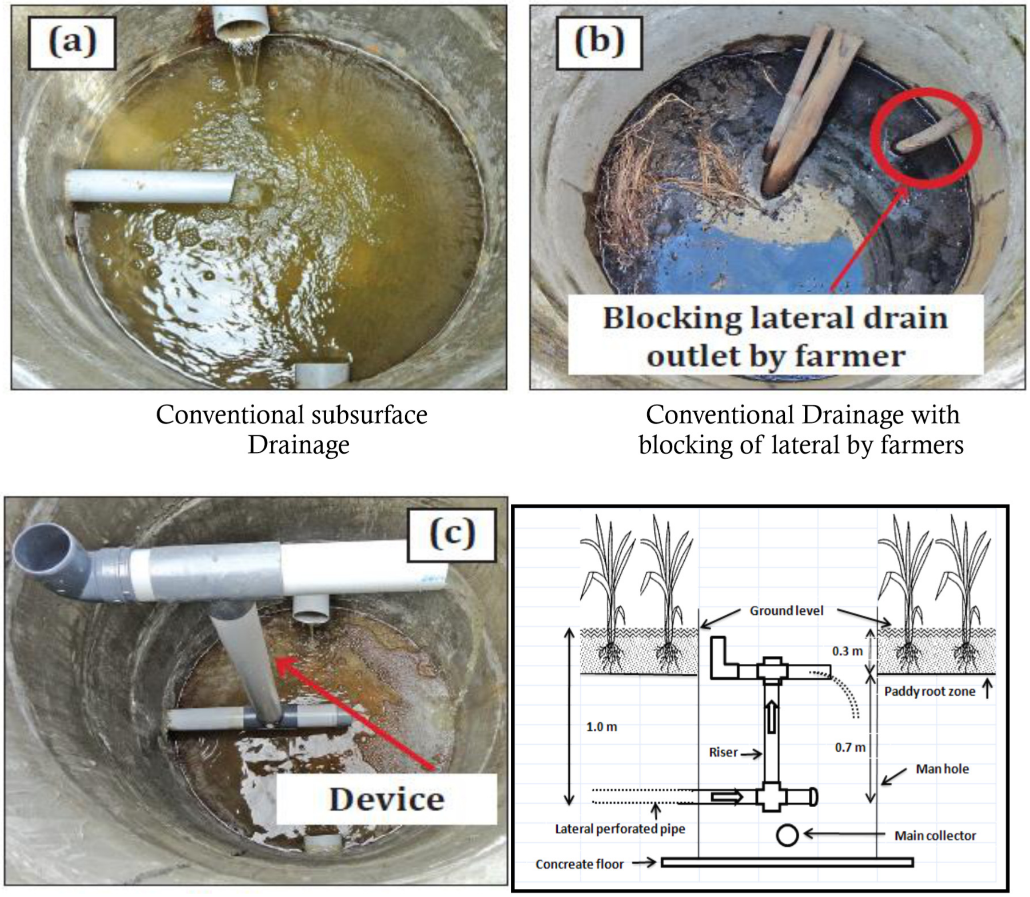


Fig. 2 Experimental field layout



Conventional subsurface Drainage

Conventional Drainage with blocking of lateral by farmers

Controlled Subsurface Drainage

Schematic diagram of Controlled Subsurface Drainage

Fig. 3 Adopted Controlled Drainage Subsurface System to overcome drawbacks of Conventional Subsurface Drainage system (Karegoudar *et al.*, 2019)

Installation of the controlled drainage device

In the controlled drainage system, groundwater table control consisted of a small device connected to the existing outlet of the lateral drain in the manhole (Fig.3). Further, the small device comprised two horizontal PVC (polyvinyl chloride) pipes (80 mm dia) and riser. The first horizontal PVC pipe was fitted at the bottom to the lateral drain and its end was closed with an end cap. To maintain a desired groundwater table depth in the paddy field, say, at 0.30 m, a 0.70 m long riser pipe was provided from the bottom horizontal PVC pipe through a T-section. The other horizontal PVC pipe was fitted to the riser pipe to serve as a lateral drain at 0.30 m depth from the soil surface in the case of the controlled drainage system to restrict the drain outflow by blocking the actual drain under the conventional SSD system. The controlled drainage system compared to the existing SSD system required an additional cost of about Rs.1000 per ha.

Data acquisition

The depth of irrigation water applied in each treatment during seven seasons from 2013 to 2019 was measured for each irrigation event using Parshall flume. The rainfall during the growing seasons was measured using a rain gauge. The volumetric method of flow measurement was adopted and daily discharge at all lateral drains was manually measured using a bucket and stop watch during the drainage events. The drain discharge was converted to the drain depth (mm) and then the average drainage depth was calculated for both FD and CD systems. Water samples collected during flow events were analyzed for pH, EC and nitrate-nitrogen (NO_3-N) concentration. The NO_3-N losses were determined through reduction of nitrate present in water to ammonia by adding Devardas's alloy and alkali, where the reduction from ammonia is distilled into fresh boric acid and titrated against 0.01 N sulphuric acid (H_2SO_4). The mathematic equation used for NO_3-N is given below

$$\text{Nitrate nitrogen (meq l}^{-1}) = \frac{(Tv \times 0.01 \text{ of N } H_2SO_4 \times 1000)}{(\text{vol.aliquot taken})}$$

The nitrate concentrations from the outlets were multiplied by their respective monthly drain flow depths and expressed the total load in kilogram per hectare basis (Mejia and Madramootoo, 1998).

In order to assess the impact of the conventional and controlled drainage on ground/ perched water level, the water levels were monitored fortnightly in sixteen observation wells (Fig. 2) installed at two positions viz., at one third length of lateral and at two third distances of lateral length. The PVC pipes fitted with the end cap at top were used as the observation wells for monitoring the ground water table. Observation wells were installed in a 10 cm dia. hole to a depth of 1 m. The PVC pipes with perforations all over the pipe periphery were lowered in to the augured hole and the space around were filled with sand and gravel. The water table was measured manually by tape and average daily water level in each treatment was recorded.

Rice (BPT 5204 & Gangavati sona) was transplanted in both *Kharif* and *Rabi/summer* season at the experimental site. During the growing seasons 150 kg ha^{-1} of nitrogen, 75 kg ha^{-1} of phosphorous, 75 kg ha^{-1} of potash and 20 kg ha^{-1} of zinc sulphate ($ZnSO_4.7H_2O$) fertilizers were used as per the local recommended dose of fertilizers. Similar agronomic practices were followed for paddy in both the systems.

Soil samples from 44 georeferenced locations were collected to a depth of 90 cm with 15 cm increment using GPS and analyzed for initial soil pH and soil salinity (EC, dS m^{-1}) on a 1:2.5 soil water suspension and the EC so obtained was converted to ECe (dS m^{-1}) i.e., EC of saturation paste extract by multiplying EC with a conversion factor 2.66 which was worked out for these soils at ARS, Gangavathi. Soil samples to a depth of 90 cm were also collected at the end of each cropping season and analyzed for soil salinity appraisal.

Paddy yield was recorded at ten locations by harvesting crop from 2 m x 2 m area from each SSD site and expressed the yield as q ha^{-1}. As far as economic evaluation is considered, payback period, the simple rate of return, and the internal rate of return on the investment was calculated for each spacing. The cost of installation of the SSD system (Karegoudar *et al.*, 2022) considering the nominal length (upto 200m) of surface drainage (Nala) cleaning for 50 and 60 m drain spacing was Rs. 96661 and Rs. 83005 per hectare, respectively.

Statistical analysis

Three-way repetitive measures of ANOVA were used to analyze the experiment, which is repeated in specific time intervals (1^{st} month, 2^{nd} month, 3^{rd} month). Here the total variability of the experiment can be divided into between-treatments variability (within-subject effects, excluding individual differences and treatments variability) (Quene &Van den bargh, 2004). Here are three factors viz., method (FD and CD system), spacing (50 m and 60 m), and seasons (R/S'13-14, Kharif-14, Kharif-15, Kharif-16, Kharif-17, Kharif-18 & Kharif-19) were used for the analysis. Parameters like drainage discharge, irrigation water salinity, Salinity of drainage effluent, NO_3-N losses through drainage discharge, Soil salinity (EC_e) at different soil depth (cm) were analyzed by three-way repetitive ANOVA using "rstatix" software algorithm adopted under r software. The crop yield was analyzed using two-way repeated ANOVA.

Results and Discussion

Drainage discharge

The drain discharge was collected from the outlet of each treatment over seven seasons. Irrespective of the spacing, the drain discharge was higher in the case FD compared to the CD system. The drain discharge under FD system varied from 0.61 to 3.04 mm d^{-1} and 0.36 to 1.86 mm d^{-1} with a mean value of 1.88 and 0.87 mm d^{-1} at 50 and 60 m spacing, respectively (Table 1). Similarly, under CD system drain discharge varied from 0.16 to 1.23 mm d^{-1} and 0.14 to 1.25 mm d^{-1} with a mean value of 0.55 and 0.53 mm d^{-1} (Fig. 4) at 50 and 60 m spacing respectively. Analyzing the drain discharge using repeated measures of ANOVA over recurrent *kharif* seasons showed that factors like season and methods are significantly different. But significant difference (P=0.061) in drainage discharge was not observed under different spacing. Moreover, the interactive effects between spacing vs. method, season vs. SSD method, and three-way interactions were significantly different. Overall, results of the data collected for seven seasons depicted that 70% and 39% reduction in drainage discharge under CD treatment as compared to FD treatments for 50 and 60 m spacing, respectively. The rate of downward deviation is -0.140 mm d^{-1} per season in 50 m and -0.147 mm d^{-1} for 60 m respectively under CD method.

Drainage water salinity

The drainage water salinity was measured for each treatment over seven seasons and it was higher in the case of FD compared to CD system for both 50 and 60 m spacing. The average drainage water salinity under FD system varied from 1.55 to 3.05 dS m^{-1} and 1.76 to 4.79 dS m^{-1} with a mean value

Table 1. Drainage discharge (mm d^{-1}) as influenced by free (FD) and controlled (CD) SSD system

Season	50 m		60 m	
	FD	CD	FD	CD
Rabi/Summer 13-14	2.4	1.23	1.86	1.25
Kharif-14	2.03	0.42	0.97	0.6
Kharif-15	2.61	0.81	0.87	0.56
Kharif-16	3.04	0.66	0.93	0.5
Kharif-17	1.26	0.18	0.6	0.35
Kharif-18	1.25	0.37	0.48	0.3
Kharif-19	0.61	0.16	0.36	0.14
Average	1.88	0.55	0.87	0.53
Effect	F-value	P-value	Significance	
Spacing	14.95	0.061	NS	
SSD Method	1124.90	0.001	**	
Season	9.82	0.000	**	
Spacing: SSD Method	69.54	0.014	*	
Spacing: Season	3.49	0.031	*	
SSD Method: Season	7.17	0.002	**	
Spacing: SSD Method: Season	3.88	0.022	*	

*Significant at 5 %, **Significant at 1 %, NS-Non Significance at 5 %

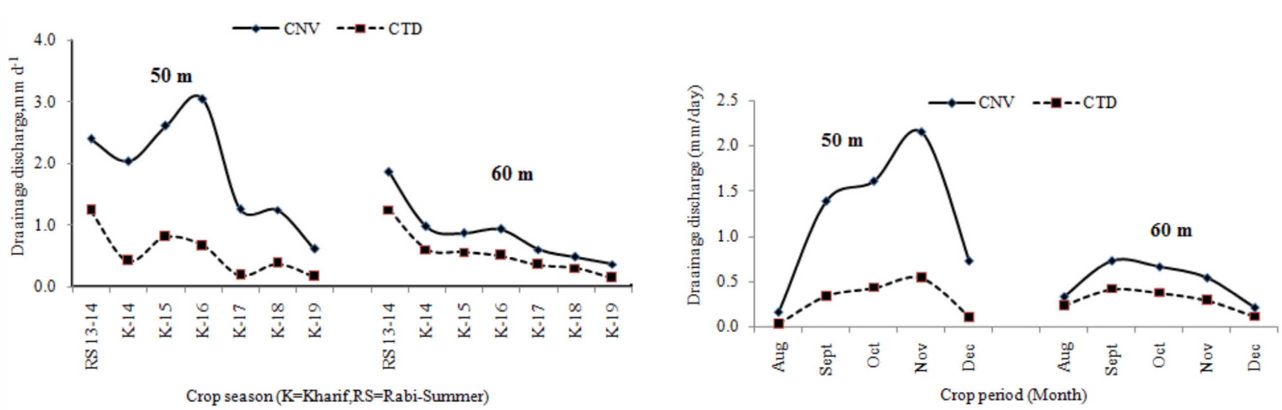


Fig. 4 Season-wise and monthly average drainage outflow in conventional and controlled SSD under different spacing

of 2.09 and 2.89 dS m^{-1} at 50 and 60 m spacing, respectively (Table 2). Similarly, under CD system drain water salinity varied from 1.34 to 3.07 and 1.59 to 3.31 dS m^{-1} with a mean value of 1.93 and 2.37 dS m^{-1} at 50 and 60 m spacing, respectively (Fig.5). The monthly drainage water salinity was maximum during October and November months which coincided with monsoon rains and minimum during December month due to removal of irrigation water from the paddy fields as crop reach to maturity which causes the low salinity level. The collected drain drainage samples were analyzed statistically and found that all factors, including their interactions, showed significant results for drainage water salinity. The results clearly showed that the average salinity level was 8% and 18% higher due to higher flow rate under FD system would help the faster movement of soluble salts than corresponding with CD systems at 50 and 60 m spacing respectively.

Seasonal salt balance under different drain spacing

The salt balance was worked out over seven seasons by considering the amount of salts added through irrigation water plus fertilizer as an input and salt removed through FD and CD system at 50 and 60 m spacing (Tables 3a and 3b) as an output. The electrical conductivity of irrigation water (canal water) applied varied from 0.05 to

Table 2. Electrical conductivity of drainage effluent in dS m^{-1} as influenced by the spacing of free drainage (FD) and controlled drainage (CD) SSD system

Season	50 m		60 m	
	FD	CD	FD	CD
Rabi/Summer 13-14	3.05	2.02	4.79	2.74
Kharif-14	2.51	3.07	2.48	1.59
Kharif-15	1.97	1.76	2.14	1.86
Kharif-16	1.55	1.48	2.65	1.84
Kharif-17	1.98	2.21	3.81	2.68
Kharif-18	1.81	1.65	1.76	2.55
Kharif-19	1.73	1.34	2.63	3.31
Average	2.09	1.93	2.89	2.37
Effect	F-value	p-value	pd”.05	
Spacing	28.545	0.033	*	
SSD Method	66.507	0.015	*	
Season	16.015	4.29E-05	**	
Spacing: SSD Method	75.893	0.013	*	
Spacing: Season	16.123	4.15E-05	**	
Method: Season	4.971	0.009	**	
Spacing: SSD Method: Season	21.743	8.61E-06	**	

*Significant at 5%, **Significant at 1%, NS-Non Significance at 5%

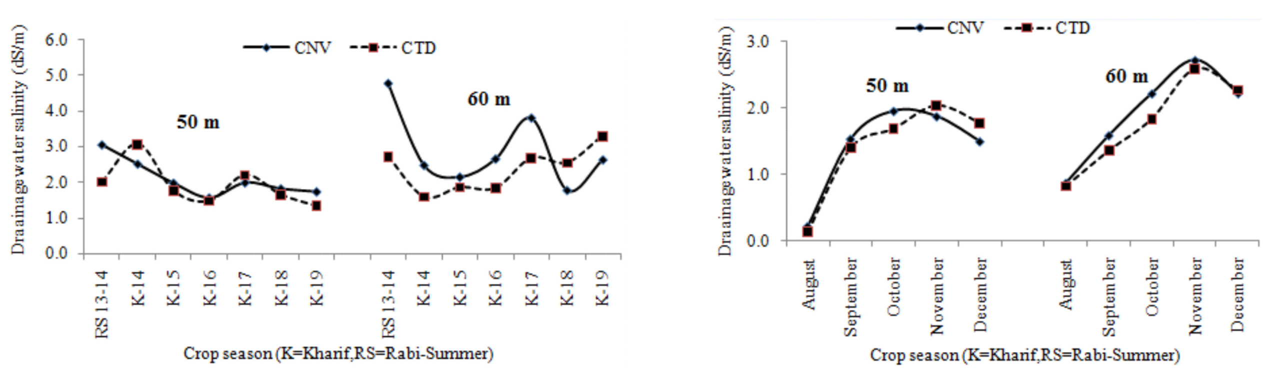


Fig. 5 Season-wise and monthly average drainage water salinity (dS m^{-1}) for the conventional and controlled SSD under different spacing

0.19 dS m^{-1}, which was multiplied by a standard factor of 640 to get the salt load in mg L^{-1} (ppm). The recommended dose of fertiliser i.e. 150, 75 and 75 kg ha^{-1} of N, P and K, respectively was applied and therefore, the amount of salt added through fertilizer alone was 0.045 Mg ha^{-1} per season. The combined average salt load added through irrigation and fertilizers over seven crop seasons under FD and CD system was 0.91 and 0.69 Mg ha^{-1}, respectively at 50 m spacing and 0.79 and 0.56 Mg ha^{-1}, respectively at 60 m spacing. Similarly, average salt load removed through drainage discharge over seven crop seasons under FD and CD system was 2.34 and 0.64 Mg ha^{-1}, respectively at 50 m spacing and 1.23 and 0.52 Mg ha^{-1}, respectively at 60 m spacing. The data of seven seasons indicated that under FD system, salt load added through irrigation and fertilizers was 24% and 29% higher at 50 and 60 m spacing, respectively whereas salt load removed through drainage discharge was 73% and 58% higher at 50 and 60 m spacing, respectively as compared to CD system. The salt removal was maximum during October and November months whereas 50 m spacing gave higher salt removal due to a higher volume of drain discharge than 60 m spacing under both FD and CD systems. Similarly, cumulative amount of salt added through irrigation and fertilizers and, salt discharged through drainage was also higher (Fig.6) under FD compared to corresponding CD system (Hornbuckle *et al.*, 2004; Ayars *et al.*, 2006). The data clearly indicates that, under both the spacing reclamation was faster under FD as compared to CD system but considering the farmers' tendency of blocking the system, adopting CD approach would be the better option as at least salt is leached to some extent through the system.

Seasonal water balance under different drain spacing

The seasonal water balance of the study area was worked out by considering the volume of irrigation water and rainfall as an input and volume of drainage water discharging as an output (Table 4a and 4b). The average depth of irrigation water used over seven seasons under FD system was 125 and 97.8 cm at 50 and 60 m spacing, respectively whereas under CD system it was 110 and 81.7 cm at 50 and 60 m spacing, respectively. This data indicates that the CD system saved 27 cm (28%) and 28 cm (35%) depth of irrigation at 50 and 60 m spacing, respectively. Similarly, average volume of drainage outflow over seven seasons under FD system was 179 and 51 at 50

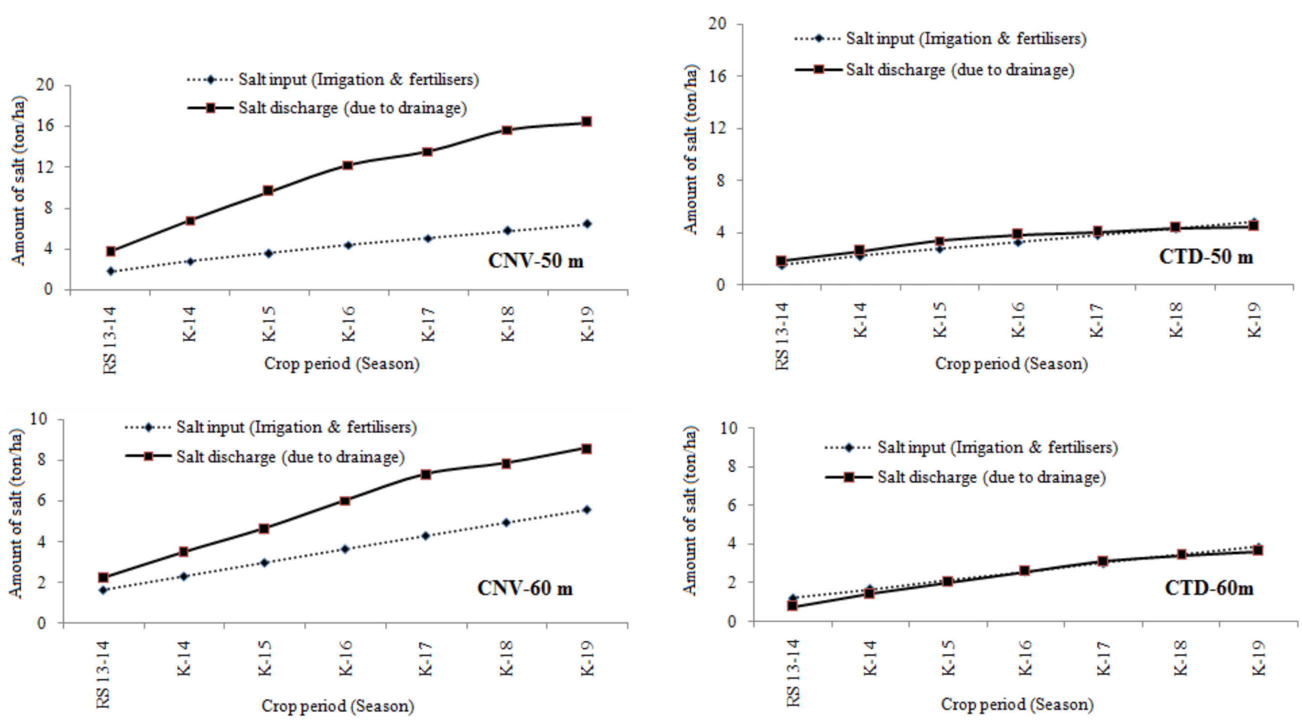


Fig. 6 Cumulative salt input and discharge showing leaching and storage of salts under conventional and controlled SSD spacing

Table 3a. Seasonal salt balance (Mg ha^{-1}) in free (FD) and controlled (CD) SSD system under 50 m spacing

S. No.	Salt balance component	FD								CD							
		R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg.	R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg.
1	Salt added through irrigation	1.77	0.92	0.73	0.76	0.64	0.65	0.61	0.61	1.43	0.68	0.43	0.42	0.38	0.40	0.39	0.59
2	Salt added through fertilizer	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
3	Total amount	1.81	0.96	0.78	0.81	0.69	0.69	0.65	0.91	1.48	0.72	0.54	0.54	0.50	0.52	0.50	0.69
4	The difference in salt input of conventional and controlled									0.33	0.24	0.23	0.27	0.19	0.18	0.15	0.23
5	Salt removed through the drainage	3.68	3.08	2.87	2.56	1.35	2.09	0.75	2.34	1.79	0.81	0.76	0.46	0.19	0.33	0.12	0.64
6	The difference in salt output of conventional and controlled	1.89	2.27	2.11	2.10	1.16	1.76	0.63	0.63								

R/S - Rabi/Summer, K-*Kharif*

Table 3b. Seasonal salt balance (Mg ha^{-1}) in free (FD) and controlled (CD) SSD system under 60 m spacing

S. No.	Salt balance component	FD								CD							
		R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg.	R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg.
1	Salt added through irrigation	1.57	0.62	0.62	0.63	0.60	0.60	0.59	0.75	1.15	0.41	0.41	0.41	0.40	0.40	0.39	0.51
2	Salt added through fertilizer	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
3	Total amount	1.62	0.67	0.67	0.67	0.65	0.65	0.63	0.79	1.20	0.46	0.46	0.46	0.44	0.44	0.43	0.56
4	The difference in salt input of conventional and controlled									0.42	0.21	0.21	0.22	0.21	0.20	0.20	0.24
5	Salt removed through the drainage	2.25	1.26	1.16	1.36	1.29	0.54	0.74	1.23	0.77	0.65	0.61	0.54	0.52	0.32	0.23	0.52
6	The difference in the salt output of conventional and controlled	1.48	0.61	0.55	0.82	0.77	0.22	0.51	0.71								

R/S - Rabi/Summer, K-*Kharif*

Table 4a. Seasonal water balance (mm) in free (FD) and controlled (CD) SSD system under 50 m spacing

S. No.	Water balance component	FD								CD							
		R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg.	R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg.
1	Irrigation water applied	1380	1300	1040	1084	913	922	745	1055	1120	963	708	699	646	673	649	780
2	Rainfall		228	225	124	255	123	430	231		228	225	124	255	123	430	231
3	Total input	1380	1528	1265	1208	1168	1045	1175	1253	1120	1191	933	823	901	796	1079	978
4	The difference in the input of Conventional and controlled									260	337	332	385	267	249	96	275
5	Drainage outflow	216	248	235	274	113	112	55	179	108	51	73	59	16	33	14	51
6	Reduction in drainage outflow									108	197	162	215	97	79	41	128
7	Total input-drainage outflow (Water storage)	1164	1280	1030	934	1055	933	1120	1074	1012	1140	860	764	885	763	1065	927

R/S - Rabi/Summer, K-*Kharif*

Table 4b. Seasonal water balance (mm) in free (FD) and controlled (CD) SSD system under 60 m spacing

S. No.	Water balance component	FD								CD							
		R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg	R/S-13-14	K-14	K-15	K-16	K-17	K-18	K-19	Avg
1	Irrigation water applied	1227	887	883	894	854	853	730	904	902	584	585	585	561	567	548	619
2	Rainfall		228	225	124	255	123	430	231		228	225	124	255	123	430	231
3	Total input	1227	1115	1108	1018	1109	976	1160	1102	902	812	810	709	816	690	978	817
4	The difference in the input of Conventional and controlled									325	303	298	309	293	286	182	285
5	Drainage outflow	167	87	78	84	54	43	32	78	112	54	50	45	31	27	13	47
6	Reduction in drainage outflow									55	33	28	39	23	16	19	30
7	Total input-drainage outflow (Water storage)	1060	1028	1030	934	1055	933	1128	1024	790	758	760	664	785	663	965	769

R/S - Rabi/Summer, K-*Kharif*

and 60 m spacing, respectively whereas under CD system it was 78 and 47 mm at 50 and 60 m spacing, respectively. The above data indicated that the CD system not only saved irrigation water but also reduced 128 mm (70%) and 31 mm (39 %) drainage water outflow as compared to FD system at 50 and 60 m spacing, respectively. The results clearly showed that the use of CD system in TBP command could be a key strategy to address the issue of irrigation water shortage for paddy crop, particularly at the tail end of the command.

Table 5. Average depth to the water table (cm) as influenced by different subsurface drainage spacing under free (FD) and controlled (CD) SSD system

Month	50 m		60 m	
	FD	CD	FD	CD
Canal ON period (*Kharif* season)				
August	13.2	9.3	14.1	10.1
September	14.1	10.2	12.3	9.8
October	15.6	10.7	12.4	9.1
November	16.4	11.3	13.1	9.4
December	21.7	13.1	18.7	14.1
Average	19.1	13.8	16.8	12.7
Canal ON period (*Rabi* season)				
January	13.1	9.5	13.4	9.8
February	12.5	9.1	13.1	9.3
March	16.7	9.8	14.9	10.1
Average	14.1	9.5	13.8	9.7
Canal non-operational period (after *rabi*)				
April	33.2	33.1	36.1	31.7
May	89.4	87.3	95.7	89.5

Effect of subsurface drainage spacing on watertable depth

The watertable depth was measured in observation wells at two days interval and it was converted into monthly mean. The monthly mean depth to watertable during crop period (July to December) under FD system varied from 13.2 to 21.7 cm and 12.3 to 18.7 cm, with a mean value of 19.1 and 16.8 cm at 50 and 60 m spacing, respectively whereas under the CD system it was 9.3 to 13.1 cm and 9.1 to 14.1 cm with a mean value of 13.8 and 12.7 cm at 50 and 60 m spacing respectively. Similarly, during the *rabi* season, in the FD system, the monthly mean depth to the water table was 14.1 and 13.8 cm as against 9.5 and 9.7 cm under the CD system at 50 and 60 m spacing, respectively (Table 5 and Fig.7). The results of the seven-season data indicated that controlled drainage system maintained a shallower depth of water table both in Kharif and rabi season as compared to the conventional drainage system at both 50 and 60 m spacing. During the non-operational period of canal (After April), the monthly mean depth to water table under a FD system varied from 33.2 to 89.4 cm and 36.1 to 95.7 cm as against 33.1 to 87.3 cm and 31.7 to 89.5 cm under a CD system at 50 and 60 m spacing respectively. Usually during the harvesting stage, accessories of CD system were removed and the system was maintained like FD system so that soil trafficability can be improved.

Nitrate-Nitrogen (NO_3-N) loss

Analyzing Nitrate-Nitrogen loss (NO_3-N) through drainage discharge under FD and CD system showed significant results between seasons at a 5% significance level. Similarly, the interactive effects between spacing vs. season, method: season, and spacing: SSD Method: season were significantly different at a 5% significance level.

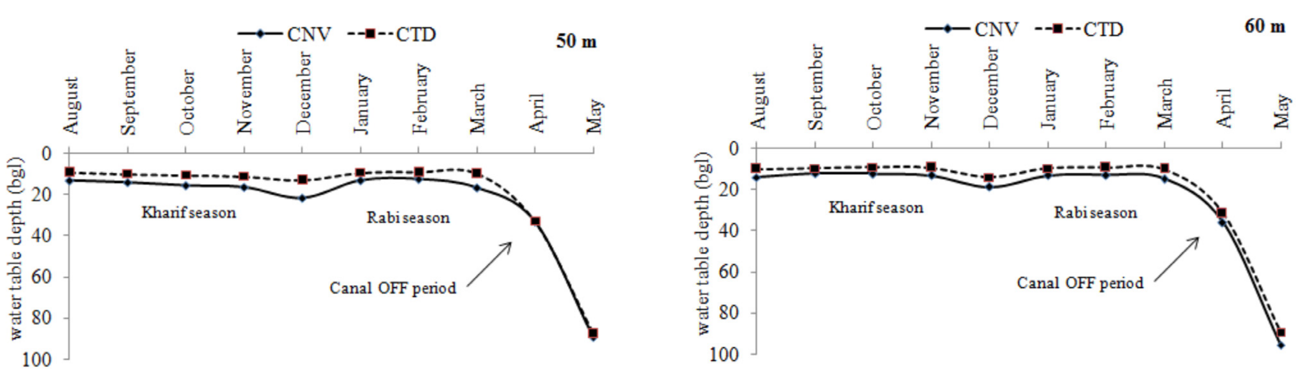


Fig. 7 Variation in depth to water table under conventional and controlled SSD

However, spacing and SSD methods showed non-significant results in NO_3-N loss.

The average flow-weighted NO_3-N concentration in drainage discharge was 7.5 and 6.45 mg L^{-1} for 50 m spacing and 6.47 and 6.23 mg L^{-1} for 60 m spacing under FD and CD systems, respectively (Table 6). The average concentration of drainage effluent was slightly higher under FD system *i. e.* 14% and 4% at 50 and 60 m spacing, respectively due to a high drainage discharge rate. Observed monthly NO_3-N concentration through drainage discharge was maximum during October and November months which coincided with monsoon rains, and usually minimum during December month due to cut down of irrigation water at crop maturity stage (Fig. 8).

The NO_3-N loss in kg ha^{-1} through drainage discharge showed that factors like season, spacing, and SSD method are significantly different at a 5% significance level. Similarly, the interactive effects between spacing vs. SSD Method, method vs. season, and spacing vs. SSD method vs. season were significant at 5%. (Table 6). The NO_3-N loss through drainage effluent was significantly higher under FD than CD systems for both 50 m (70% higher) and 60 m (42% higher) spacing. The highest NO_3-N loss occurred in October and November months under FD in both the spacing compared to the CD system (Fig. 8). The NO_3-N concentrations between FD and CD treatments were more or less similar but lower nitrate load under CD could be attributed to a reduction of

Table 6. NO_3-N losses through drainage discharge under free (FD) and controlled (CD) SSD system

Season	NO_3-N (mg L^{-1})				NO_3-N (kg ha^{-1})			
	50 m		60 m		50 m		60 m	
	FD	CD	FD	CD	FD	CD	FD	CD
Rabi/Summer 13-14	10.17	7.72	13.23	12.42	20.9	16.54	9.88	6.48
Kharif-14	8.3	7.34	5.8	5.15	15.24	2.57	6.97	3.99
Kharif-15	6.88	5.74	4.78	3.88	15.36	3.33	3.7	1.88
Kharif-16	7.78	7.12	6.26	5.95	20.03	3.89	6.09	3.16
Kharif-17	10.54	11.56	8.31	8.56	12.07	1.63	4.68	2.72
Kharif-18	6.26	4.22	5.15	5.21	12.13	1.01	3.54	1.95
Kharif-19	2.58	1.43	1.77	2.47	1.91	0.19	0.77	0.42
Average	7.5	6.45	6.47	6.23	13.95	4.17	5.09	2.94

Effect	F-Value	p-value	P<0.05	F-Value	p-value	P<0.05
Spacing	0.35	0.62	NS	38.28	0.03	*
SSD Method	7.97	0.11	NS	110.01	0.01	*
Season	14.08	0.00	*	13.19	0.00	*
Spacing: SSD Method	6.14	0.13	NS	45.43	0.02	*
Spacing: Season	3.06	0.05	*	1.22	0.36	NS
Method: Season	8.11	0.00	*	4.46	0.01	*
Spacing: SSD Method: Season	3.46	0.03	*	5.20	0.01	*

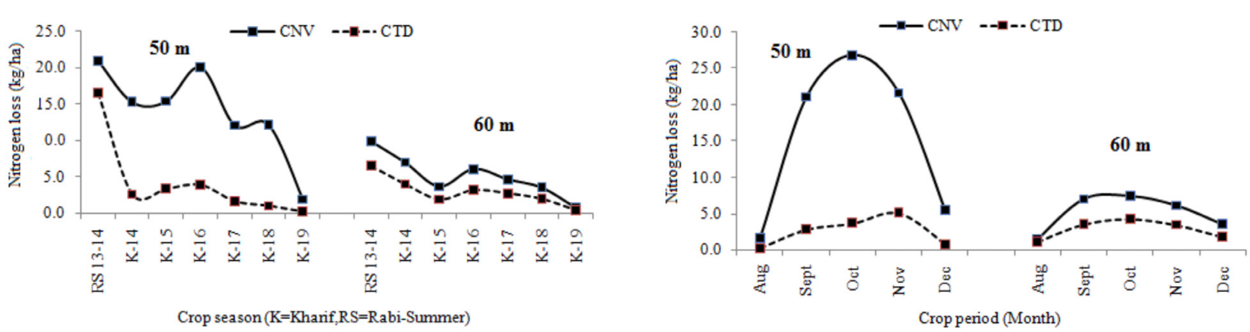


Fig. 8 Season-wise and monthly NO_3-N loss (kg ha^{-1}) for the conventional and controlled SSD under different spacing

drainage volume rather than a reduction in nitrate concentrations. The similar results were also reported by (Drury *et al.*, 1996; Wahba *et al.*, 2001; Wesstrom *et al.*, 2001; Fausey, 2004; Karegoudar *et al.*, 2019). The result of the data clearly shows that regulation of drainage discharge not only addresses the issue of water shortage but also increase the denitrification (Hamidreza *et al.*, (2018) rate by reducing the environmental pollution.

Soil salinity

The analysis of soil salinity at different soil depths (cm) as influenced by FD and CD system at 50m and 60 m spacing showed significant results between depth, SSD method, season and all possible interactions at 1% level of significance. The soil salinity up to 90 cm depth at the end of each season under both FD and CD system as is shown in Table 7a and 7b. The mean root zone soil salinity (0-30cm) significantly reduced (Fig. 9) from initial to Kharif-19 season. In case of FD system, the reduction was from 8.26 to 1.25 dS m^{-1} and from 4.7 to 0.61 dS m^{-1} for 50 and 60 m spacing, respectively whereas it was 8.97 to 1.37 dS m^{-1} and 6.14 to 1.22 dS m^{-1} under CD system at 50 and 60 m spacing, respectively. The mean soil salinity was also reduced under other depths as compared to initial soil salinity.

Under CD plots, due to regulation of drain discharge, higher concentration of salts was observed at 30-90 cm depth during initial seasons, however, in subsequent years it showed decreasing trend. The rate of soil salinity reduction was higher for 50 m spacing as compared to 60 m spacing as higher drain discharge of 50 m spacing lead to faster movement of salts through the profile. The adoption of CD system does not hold good in an aerobic situation (Hornbuckle *et al.*, 2004; Ayars *et al.*, 2005; Ayars *et al.*, 2006; Ghannam *et al.*, 2016) as soil salinity level increases in the crop root zone due to capillary rise. Whereas in a saturated conditions of paddy fields, salts get pushed downward resulting into decrease in root zone salinity (0-30 cm) (Fig. 9). Therefore, the farmers of the tail end can adopt this technology to the existing FD system without accumulation of salts at root zone depth (0-30 cm).

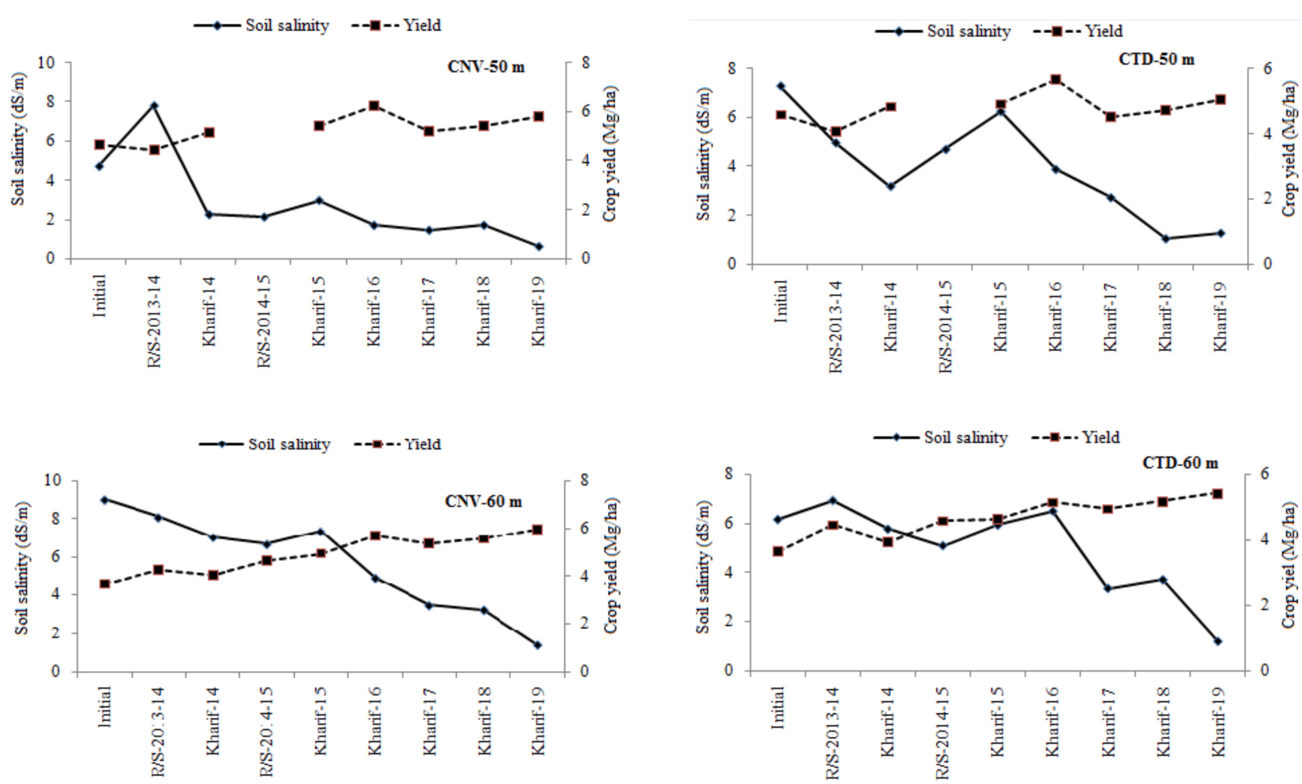


Fig. 9 Influence of conventional and controlled SSD on soil salinity (0-30 cm) and crop yield

Table 7a. Soil ECe (dS m[-1]) at different soil depths (cm) as influenced by free (FD) and controlled (CD) SSD system at 50m spacing

Season	FD				CD			
	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90
Initial	4.31	5.1	5.93	5.25	6.28	8.31	12.01	13.85
Rabi/Summer 13-14	7.8	7.79	8.1	7.96	3.72	6.22	8.32	10.9
Kharif-14	2.5	1.98	3.72	5.33	1.87	4.52	6.95	6.63
R/S-2014-15	2.2	3.23	3.74	4.42	4.14	5.28	8.64	9.02
Kharif-15	2.56	3.36	3.06	2.91	4.87	7.63	9.28	6.86
Kharif-2016	1.41	1.97	2.58	5.14	3.93	3.84	5.59	6.54
Kharif-2017	1.44	1.44	1.48	1.68	1.91	3.54	1.78	5.44
Kharif-2018	1.17	1.19	2.99	2.9	1.3	2.09	5.43	7.96
Kharif-2019	1.27	1.98	2.77	3.07	3.55	3.26	5.88	9.31
Average	2.74	3.12	3.82	4.30	3.51	4.97	7.10	8.50

Effect	F-Value	p-value	Significance
Depth	87.065	2.88E-21	**
SSD Method	87.412	1.54E-08	**
Season	10.154	2.65E-11	**
Depth: SSD Method	28.786	1.84E-11	**
Depth: Season	2.76	2.15E-05	**
Method: Season	2.976	0.004	**
Depth: SSD Method: Season	2.833	1.26E-05	**

Table 7b. Soil ECe (dS m[-1]) at different soil depths (cm) as influenced by free (FD) and controlled (CD) SSD system at 60m spacing

Season	FD				CD			
	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90
Initial	7.69	10.25	11.01	11.55	5.99	6.29	6.43	6.1
Rabi/Summer 13-14	7.8	8.33	7.76	8.93	6.58	7.24	6.53	6.67
Kharif-14	6.83	7.2	7.46	7.31	5.47	6.02	7.12	7.46
Rabi/Summer 14-15	5.62	7.67	8.35	9.47	4.39	5.78	5.43	5.68
Kharif-15	6.51	8.15	9.33	10.03	5.34	6.48	6.93	6.75
Kharif-2016	3.96	5.83	6.44	6.48	5.71	7.24	8.64	7.9
Kharif-2017	3.06	3.83	7.45	6.97	3.34	3.37	5.84	8.58
Kharif-2018	2.85	3.58	7.21	8.79	2.79	4.62	5.02	6.31
Kharif-2019	3.33	3.96	12.19	11.38	2.91	3.58	7.61	7.07
Average	5.29	6.53	8.58	8.99	4.72	5.62	6.62	6.95

Effect	F-Value	p-value	Significance
Depth	130.35	1.7E-25	**
SSD Method	14.72	1.0E-03	**
Season	10.71	7.0E-12	**
Depth: SSD Method	11.08	7.8E-06	**
Depth: Season	12.12	1.4E-35	**
Method: Season	3.47	1.0E-03	**
Depth: SSD Method: Season	2.47	1.6E-04	**

Grain yield

The crop yield was not significantly affected by the drainage methods as well as drain spacing. This shows that at par grain yield can be possible in CD system with additional environmental benefits. The root zone soil salinity (0-30 cm) was decreased with increasing grain yield under both FD and CD systems (Fig.9). The decreased soil salinity over the seasons resulted in to the increased grain yield. For FD system, the yield was increased from 46.8 to 58 q ha^{-1} and 45.8 to 50.4 q ha^{-1} for 50 and 60 m drain spacing, respectively whereas in CD system it was increased from 36.3 to 59.4 q ha^{-1} and 36.5 to 54.2 q ha^{-1} for 50 and 60 m drain spacing. The grain yield was higher 50 m spacing compared to 60 m spacing under both FD and CD system. Further, irrespective of the spacing, 15.0 and 9.0 % marginally higher grain yield was observed under FD compared to CD systems over the seven cropping seasons at 50 and 60 m drain spacing, respectively (Table 8). Ghannam *et al.* (2016) reported that higher crop yield was observed under CD over FD system. But in our case, the paddy yield was slightly higher under FD than CD system due to faster reclamation process.

Economic analysis

The economic feasibility of the investment in SSD systems was found to be profitable even though the investment was very high. The initial investment cost of the SSD system was worked out to be Rs. 96661 and Rs. 83005 for 50 and 60 m drain spacing, respectively. The adoption of a CD system to the existing SSD required an additional cost of about Rs. 1000 ha^{-1}. Looking into economics for a period of 20 years (Table 9), the projected data revealed higher B:C ratios,

Table 8. Variation of crop yield (q ha^{-1}) as influenced by the spacing of free (FD) and controlled (CD) SSD system

Season	FD		CD	
	50 m	60 m	50 m	60 m
Initial	46.8	36.3	45.8	36.5
Rabi/Summer 13-14	44.4	42.4	40.6	44.5
Kharif-14	51.4	40.2	48.3	39.4
Rabi/Summer 14-15	52.1	46.3	48.6	45.8
Kharif-15	54.3	49.2	49.1	46.3
Kharif-16	62.3	56.4	56.7	51.43
Kharif-17	52.0	53.4	45.3	49.4
Kharif-18	54.0	55.3	47.2	51.6
Kharif-19	58.0	59.4	50.4	54.2
	52.81	48.77	48.00	46.57
Effect	F-value	P-Value	Significance	
SSD Method	3.09	0.09	NS	
Spacing	1.89	0.18	NS	
SSD Method: Spacing	0.42	0.52	NS	

Table 9. Economics of free (FD) and controlled (CD) SSD system (20 years life period)

Treatment	Drain spacing (m)	Total returns, Rs/ha	The total cost of cultivation, Rs/ha	Net returns, Rs/ha	Net Present Value, Rs/ha	BCR	IRR (%)	Payback period (seasons)
FD	50	164421.00	78583.00	85838.00	419005.00	1.73	62	1.84
	60	159404.00	77900.00	81504.00	372341.00	1.66	49	2.15
CD	50	148354.00	78583.00	69770.00	324355.00	1.56	51	1.88
	60	146604.00	77900.00	68704.00	311371.00	1.55	47	2.14

positive NPV, a higher value of IRR, and a lesser payback period at all the different spacing under FD compared to CD systems. Based on economic analysis (BCR and payback period), it is evident that 50 m drain spacing appears to be suitable for the study region. Considering the additional yields gained, the amount spent on land reclamation through the SSD system could be reimbursed in about 2-3 seasons, indicating that the system is quite remunerative and cost-effective.

Conclusions

The data on experimental results on FD and CD systems with 50 and 60 m spacing for a period of seven seasons revealed that adoption of CD approach to the existing FD system significantly reduced the drain discharge but the rate of salt leaching was lower in CD system compared to FD system. Nevertheless, there were numerous advantages of a CD system like saving of irrigation water, reduction in the nitrate-nitrogen loss and ability to maintain shallow water table depth for paddy crop under both *kharif* (5.3 and 4.1 cm) and *rabi* seasons. The monthly drain discharge, drainage water salinity, salt removal, and loss of nitrate-nitrogen was maximum during October and November months and minimum during December month under both FD and CD system. Regarding water shortage and economic feasibility, 60 m lateral drain spacing with CD system appears adaptable/feasible in the study area. It was expected that FD and CD systems would give similar economic benefits in the long term. However, for 60 m spacing the SSD should be operated under FD system for initial 3-4 years to reduce soil salinity and thereafter CD approach can be adopted. Considering the saving of irrigation water with reduced drainage volume and NO_3-N loss, the CD system appeared to be a more environmentally friendly strategy.

Impact of this project

Controlled subsurface drainage could save about 20% (240 mm) of irrigation water per season compared to conventional subsurface drainage system. Therefore, an additional area of about 19200 ha could be supplemented with this saved water which in turn may add about 0.0576 MT (@ 3t ha^{-1}) to the food grain production of the command area. Similarly, controlled drainage system could reduce NO_3-N losses by about 50% resulting in to the savings of Rs.68.80 lakh per season on account of urea fertilizer in TBP command area.

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