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Research Article

DESIGN OF CONTROLLED DRAINAGE-SUBIRRIGATION (CD-SI) SYSTEM IN WATERLOGGED RICE FIELDS OF BAPATLA

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Abstract: Chemical degradation of agricultural land sometime is a result of faulty irrigation water management besides being an inherent problem in several parts of the country. Such degradation may manifest in the formation of salinity, sodicity, acidity and toxic environment in the crop root zone. The result is loss is a reduction or loss of production. The water table could be maintained practically at desired level, during both monsoon and summer seasons using a unique drainage system i.e. Controlled drainage-Subirrigation system synonymously controlled and reversible drainage system or simply water table management. The scope of this paper is to discuss about the drain spacing related CD-SI system. Steady state Hooghoudt equation was used for the design of drainage spacing and similarly Moody and Ernst equation with convergence analysis was used for subirrigation mode spacing. The spacing arrived for controlled drainage mode was 27 m to that of subirrigation was 10.05 m respectively. Considering the feasibility of operation of both controlled drainage and subirrigation, the spacing of 10.05 m could be recommended for CD-SI system.

Keywords: *Controlled drainage, Subirrigation, Drain spacing, Hooghoudt's and Moody equation*

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Introduction

Irrigation development has created waterlogging and salinisation problems in many parts of the world. In many cases, the problems associated with shallow water tables were controlled by the installation of subsurface drainage pipe systems [1]. Subsurface drainage is used in both humid and arid areas to prevent waterlogging, provide aeration to ensure crop growth, and enhance the trafficability of soil, thus permitting timely soil preparation for planting and harvest. The efficiency of subsurface drainage depends on the design spacing between lateral drains, which involves the saturated hydraulic conductivity of the soil [2]. However, the positive developments in modern agriculture also have led to environmental side-effects where losses of nutrients in agricultural drainage water have become a major contributor to eutrophication. Therefore, nutrient and water management strategies are being emphasized from the last few decades. A conventional drainage system works with the same drainage intensity over time, whether there is a need for drainage or not. One of the challenges of on-going drainage research is to develop a ground-water control system that maintains the benefits of an efficient drainage system, ensuring maximum nutrient efficiency and crop yield, without removing more water than necessary. The problem of excessive drainage at certain times of the year can be overcome by using controlled drainage. The objectives of controlled drainage are:

Achieving optimum production conditions (water table and salinity (leaching) control, trafficability) at minimum costs (irrigation, input of fertilizers);

Obtaining optimum water quality and quantity downstream (control of transport of salts and other solutes, such as nitrogen and phosphorus by drainage water).

On the other side, subirrigation involves the application of water to the plant from beneath the soil surface. This method of irrigation supplies water for root uptake by capillary action and avoids wetting the soil surface. Subirrigation has shown to minimize soil compaction and reduce water usage resulting from excessive surface evaporation and runoff.

In view of above reasons, the present experiment was undertaken with the objectives to

Study of the design parameters in CD-SI system.

Design of lateral spacing with respect to controlled drainage and subirrigation system.

Determination of size of laterals and collector drains

Although drainage is in reality a non-steady state phenomenon, steady state drain spacing formulas are widely used for design and research purposes. One of the best-known formulas is that developed by Hooghoudt (1940) which is used widely both in the Netherlands and other countries. The formula is in very simple form because it gives a direct relationship between the discharge and the height of water table midway between the drains. Its use for design purposes, however, is rather complicated because the thickness of the equivalent layer is not given explicitly but as a function of the drain spacing. For this reason, one has to apply the method of trial and error for the computation of the spacing [3].

According to Hooghoudt's Equation, calculated drain spacing based on steady state conditions, where the water table depth remains constant, are based on the hydraulic conductivity of the soil, the drainage coefficient, and the hydraulic head above the drains.

Rollin *et al*. [4] discussed about the slots in the corrugated tubes through which water must percolate represent a small fraction of the total tube surface (1.0%). The slots are rectangular in shape (0-5mm × 5mm to 2mm × 15 mm) such that they cannot prevent movement of small diameter particles under a relatively high hydraulic gradient. The envelopes must be more permeable than the soil to be drained and must retain the soil in place without clogging. A further function of envelope materials by Dierickx [5] study is to decrease the entrance resistance of drain pipes has come into picture.

Controlled drainage can also be of advantage in humid regions to adjust the water level to crop water requirements as well as to workability and trafficability of the land [6]. The workability of a soil can be defined as being able to perform field operations at proper times without affecting it's structure. In poorly drained soils trafficability is decreased in that the soil requires long periods of time for moisture levels to fall sufficiently such that performing field operations does not adversely affect soil structure. Performing field operations on soils with high moisture contents tends to decrease the efficiency of the operation and do serious structural damage to the soil, such as compaction and reduced infiltration, which affects future crops.

Material and Methods

Design of CD-SI system

The main parameters considered in the design of drainage system are:

- Layout of the system
- Depth of installation of lateral and collector drain pipes
- Spacing of lateral pipe drains
- Sizes of lateral and collector drains
- Gradient of lateral and collector drains
- Outlets
- Structures for monitoring the performance of system
- Drainage materials

Layout of the System

The main design elements like drain spacing, depth and type of system are to be determined as per the topography should be made of the land and existing infrastructure. Optimum use of the existing topography in order to achieve as uniform depth to water table as possible throughout the field.

At study area, parallel gridiron type of layout was selected to suit to the topography as shown in [Fig-1]. On the northern side of the collector pipeline, 8 laterals with varying lengths of 20 to 30 m were installed as per the land topography. On Southern side of the collector pipe, 8 laterals of varying lengths of 23 to 41 m were laid.

Fig-1 Layout of laterals and collector pipe

Depth of Installation of Lateral and Collector Pipe Drains

At study area, the lateral pipes were placed at two depths of 50 cm and 60 cm from the ground level and the collector line was placed at 80 cm depth. A gravity outlet was provided in the study area was gravity outlet based on the topographical possibility.

Spacing of Lateral Pipe Drains for CD-SI system

a) Design of Controlled Drainage System

There are currently no specific design procedures for controlled drainage systems in either humid or arid regions. Of these, the Hooghoudt drainage formula is widely used in pipe drainage design practice, generally with good results [7]. For flow of groundwater to parallel field drains with following assumptions as two-dimensional flow, Uniform distribution of the recharge and homogeneous and isotropic soils. According to the Dupuit - Forchheimer theory, Darcy's equation and continuity principle, the drain spacing formula is computed as: The equivalent depth (d) represents the imaginary thinner soil layer [8] through which the same amount of water will flow per unit time as in the actual situation. Hence equation 1 can be rewritten as:

$$q = \frac{8KDh+4Kh^2}{L^2} \qquad (1)$$

Where, q = drain discharge (m/d)

h = height of the water table above the water level in the drain (m)

L = drain spacing (m)

D = depth to impervious layer below the drain level (m)

In case of two layers [9] with different K_a and K_b for top and bottom soil layers respectively. The h is replaced with D_d-D_w. There, equation 2 can be written as follows:

$$q = \frac{8Kdh+4Kh^2}{L^2} \qquad (2)$$

$$L^2 = \frac{8k_b\, d(D_d-D_w)+4k_a(D_d-D_w)^2}{q} \qquad (3)$$

b) Design of Subirrigation System for Spacing

The position and shape of the water table for steady-state subirrigation can be approximated by making the Dupuit-Forchheimer (D-F) assumptions and using the approach of Fox, *et al*.[10]. According to diagrammatic representation of Skaggs [11], the most common procedure is to maintain a constant water level elevation in the outlet. There, the water table assumes an elliptical shape under steady ET conditions. The maximum upward rate of water movement is dependent on water table depth as well as soil properties. Therefore, the drains should be placed close enough together to maintain some minimum water table elevation at the midpoint (x = L/2) during a period of maximum ET demand. Defining the difference between the water level at the drains and that midway between the drains is written as M= h_0-h_1. Then the spacing necessary to maintain in a specified 'e' at a given h_1 is

$$L = \left[\frac{4\,KM\,(h_o^2-h_1^2)}{e}\right]^{1/2} \qquad (4)$$

The equivalent water table elevations at the drain, $h_o=d_e+y_o$ and mid-way between the drains, $h_1=y_1+d_e$.

where L represents the distance between drains necessary for controlled drainage, K is the saturated hydraulic conductivity; m is the distance from drains line level to the water-table level measures at the middle of distance between drains.

The equivalent depth from the drain to the impermeable layer, 'de' can be calculated from equations presented by Moody[12] and substituted for the actual depth to the impermeable layer d, The h values are adjusted accordingly. Moody's equation for d/L< 0.3 can be written as follows:

$$L = \left[\frac{d}{1+\frac{d}{L}\left[\frac{s}{\pi}ln\frac{d}{r_e}-3.4\right]}\right]^{1/2} \qquad (5)$$

d is the distance from drains bottom to the impermeable layer; q is the drainage coefficient; de is the equivalent distance from drains bottom to the impermeable layer, re is the effective radius [11], considered lower than drain radius and considered for entrance resistance due to a finite number of openings in drain tube.

$$L = \left[\frac{4\,KM\,(2ho-M)}{e}\right]^{1/2} \qquad (6)$$

M = h_0-h_1 = h_0'-h_1'

The magnitude of e, increases with M, until the water table at the midpoint reaches the equivalent depth of the impermeable layer, h_1' = 0 for deeper midpoint water table depths (which can occur because the actual depth to the impermeable layer is greater than the equivalent depth). Ernst (1975) observed that this was inconsistent with the physics of flow since the maximum subirrigation rate should occur when the water table at the midpoint is deepest. Ernst's equation for the required drain spacings to maintain a given 'e' is obtained by

$$d_e = \left[\frac{4\,KM\,(2ho-\frac{ho}{ho}M)}{e}\right]^{1/2} \qquad (7)$$

c) Testing of additional drain spacing

In the design of drainage systems, a number of assumptions were made. In order to reduce the cost of the system and to see whether the spacing of the system could be increased beyond the design spacing, additional drain spacings were tested. A lower spacing than the design spacing was also included to see whether reclamation process could be hastened up with lower spacing and to see how much additional cost would be involved to achieve that. The lateral spacing of CD-SI system was shown in [Fig-2]. Layout and different views of inspection chamber was shown in [Fig-3].

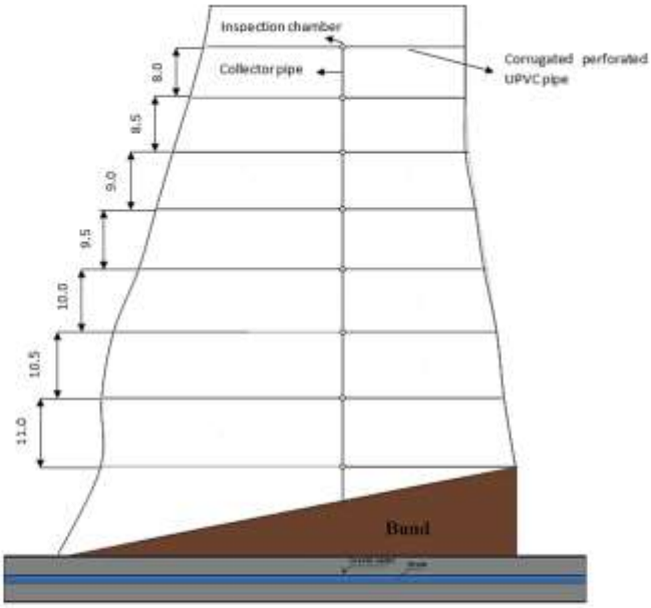

Fig-2 Experimental layout of controlled drainage-subirrigation system

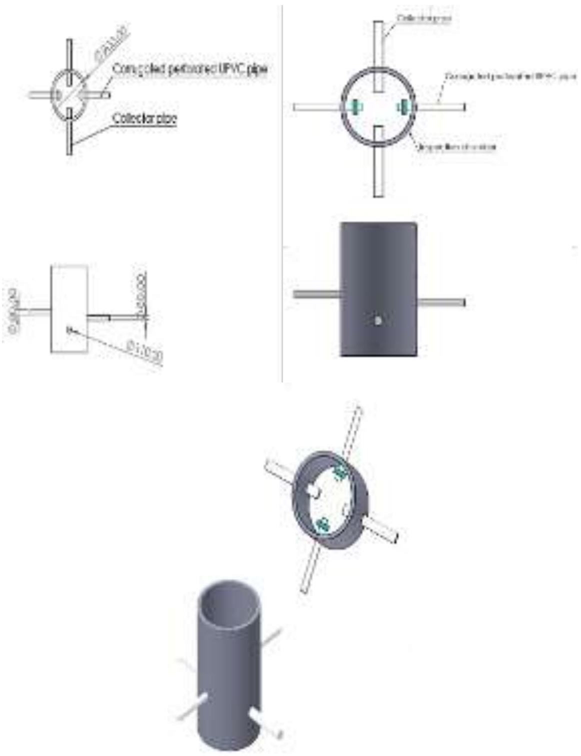

Fig-3 Layout and different views of inspection chamber

Size of the lateral drain and collector pipes for CD-SI system

Wessling's equation for uniform flow in smooth pipes and corrugated pipes derived from manning's equation were used to calculate the size of the drain pipes. The equations used are

For smooth pipes

$Q=89d^{2.714} i^{0.57}$ (8)

For corrugated pipes

$Q=38d^{2.67} i^{0.5}$ (9)

Where Q = discharge along the pipe = q x A (m^3/s)

D = internal diameter of pipe (m)

i = hydraulic gradient (m/m)

In general, for clay and cement concrete tiles, the minimum diameter prescribed is 100 mm, while for the PVC and PE pipes, it is 75 mm. Also for UPVC single wall corrugated perforated pipes the minimum diameter is 80 mm. The computed pipe diameter is to be rounded off to the next higher commercially available pipe size. Using the procedure suggested in Ritzema, the size of the lateral was fixed. The calculations done are as given below.

Size of the lateral pipe required to carry the design flow rate is given by

$d=1.548(nQ)^{0.375} S^{-0.188}$ (10)

Where n = manning's roughness coefficient

S = hydraulic gradient or slope (m/m)

$Q=qxLxB_{max}/24x3600$ (11)

Where q = drainage coefficient (m/day)

L = spacing of drain length (m)

B_{max} = maximum drain length (m)

Grade of lateral and collector pipes

A grade of 0.15% for lateral pipes and 0.25% for the collector pipes were provided to flow drain water from utmost point to the outlet.

Outlets

The drainage systems were designed to dispose the collected drain water into the natural drams passing along one of the boundaries of the field. At pilot area, an elevation difference of 80cm between the head end and tail end (outlet) was observed. Therefore, gravity outflow was possible to discharge the drain water and hence gravity outlet was designed. Care was taken to maintain elevation difference of 0.30 m between the lateral pipe and the collector pipe to facilitate collection of water samples from laterals and to measure discharge.

Structures for monitoring the performance of the system

The inspection chambers at junction points allow inspection and maintenance of the lateral drains as well as the collector as shown in [Fig-4]. At study area, 0.90m diameter RCC cement concrete rings were constructed with 2.54cm thickness. Also, after installation of rings, the bottom was sealed with 5cm thickness of concrete mixture. Al1 the inspection chambers were constructed up to a height of 1.0m above the ground surface to avoid falling of cattle and people in to them. Care was taken to keep the lateral pipes at a higher elevation than the collector pipe line in all the inspection chambers to facilitate free discharge water from the lateral pipes in to the inspection chambers.

Fig-4 Structures for monitoring drainage system

Drainage materials

The drainage materials include drainage pipes used as laterals and collector and the envelope materials wrapped around the laterals.

a) Pipe materials

The pipes made of corrugated perforated UPVC are more commonly being used as the lateral drain pipes. So, corrugated perforated UPVC pipes of 72/80mm size along with couplers, end caps as shown in [Fig-5] were procured from Gwalior Poly Pipes Ltd. and were used as laterals. PVC pipe of 110 mm diameter was used as the collector drain. Ball valves for lateral drains were used to control the water table. Zero sized chips as bedding material, Sand as additional filtering material were also used.

(a) Corrugated perforated UPVC pipes (b) Couplers, end cap and ball valve

Fig-5 Pipe materials

b) Envelope materials

Drain pipes are often surrounded by envelope materials. A wide variety of materials is used as envelopes for drainpipes, ranging from organic and mineral materials, to synthetic material and mineral fibres. Envelopes may be used to provide adequate bedding for the pipe, in order to increase its crushing strength or to prevent damage when filling the drain trench. More usually however, envelopes will be applied to prevent significant soil particle invasion into drain pipes and to avoid clogging of pipe inlets.

The advantages of using envelopes around drainage tubes are:

(a) Envelopes act as a filter to allow water entry but prevent migration of fine soil particles into drainage tubes.

(b) Envelopes effectively increase the inlet area of the system.

The property of envelopes to retain soil particles is called the filter function. Envelopes must be chosen in such a way that, once installed, no important soil particle invasion into the drain pipes occurs. The choice of an envelope is influenced by the nature of the soil material. Nylon mesh with 60 mesh size was used as envelope material for the present study as shown in [Fig-6]

(a) Stitched nylon mesh (b) Wrapping nylon mesh to lateral pipe

Fig-6 Envelope material

Results and Discussions

For adopting design of drainage system, pre drainage investigations were carried out at the experimental test site to provide information on some important physical and chemical parameters for the design of drainage system as shown in [Table-1].

Steady State Lateral Spacing Under Controlled Drainage System in the Study Area

For the study area, the values of K, h and dc are 0.709 m/day, 0.2 m and 2.96 mm/day respectively. Substituting the values in the above equation 2 and results shows that,

$L^2=8(0.709)\,d(0.2) + 4(0.709)(0.2)^2 / 0.00296$ (12)

$L^2= 383d+38.32$

Assuming L = 27 m

$x=2\pi D/L$

$x=2(3.14)(5.4)/27=1.25$ (13)

$$f(x) = \frac{\pi^2}{4x} + ln\frac{x}{2\pi} \quad (14)$$

$$f(x) = \frac{(3.14)^2}{4(1.25)} + ln\frac{1.25}{2(3.14)} = 0.36$$

$$d = \frac{\pi L/8}{ln\frac{L}{\pi r_0} + F(x)} \quad (15)$$

$$d = \frac{3.14\times 27/8}{ln\frac{27}{(3.14)(0.036)} + (0.36)} = 1.81$$

Substituting the d value in equ (4.2) and results

$L^2=383(1.81)+38.32$

L = 27.05 m

As the assumed value is nearer to the calculated value, the drain spacing value for the controlled drainage system can be taken as 27 m.

Table-1 *Design parameters found out after pre drainage investigation*

Parameter	Description
pH of soil	8.32
EC of soil	3.18 dS m^{-1}
ESP	30.5%
pH of canal water	7.18
pH of drain water	7.30
EC of canal water	1.50 dS m^{-1}
EC of drain water	2.43 dS m^{-1}
N	130 kg ha^{-1}
P	18 kg ha^{-1}
K	760 kg ha^{-1}
Bulk density	1.38 g cm^{-3}
Drainable porosity	2.98 %
Field capacity	30.6 %
Particle size distribution	Clay loam
1. Sand	45 %
2. Silt	25 %
3. Clay	30 %
Soil colour	Dark grey (7.5 YR 4/1) Hue: 7.5 YR, Value: 4, Chroma: 1
Drainage coefficient	2.96 mm/day

Design Spacing Under Subirrigation System in the Study Area

The hydraulic conductivity appears to decrease with depth so that it is restrictive to water movement below a depth of about 2.5 to 3.04 m. A drain depth of 0.6 m was selected, so that d = 2.44 m. The ET rate will usually not exceed 8.03 mm/day in study region. So, this value will be used as the design value for e. In order to maintain an upward flux of at least 8.03 mm/day, the water table should be maintained at depths within 0.3 m of the root zone. Taking a conservative estimate of the average root zone depth of 0.25 m, the midpoint water table should be held at a depth no greater than 0.5 m from the surface.

This would give an h1 = 3.04 – 0.5 = 2.54 m.

h1 = Difference between depth to impervious layer to height of water table above the water level in the drain.

The water table depth to be maintained at the drain depends on the root zone depth and crop tolerance for wet conditions. The effective root zone depth is assumed to be limited to 0.3 m for paddy [13]. The water table depth at the drains is 0.4 m was assumed. The saturated hydraulic conductivity was 0.709 m/day.

Then h0 = 3.04 – 0.4 = 2.64 m.

h0 = Difference between depth to impervious layer to effective root zone of the crop.

$$m = h_0 - h_1 = 2.64 - 2.54 = 0.1\ m.$$

From equ (4),

$$L = \left[\frac{4(0.709)(2.64^2 - 2.54^2)}{0.00803}\right]^{1/2} = 13.52m$$

From equ (5), Equivalent depth

$$d_e = \frac{2.44}{\left[1 + \frac{2.44}{13.78}\left(\frac{8}{3.14}\,ln\frac{2.44}{0.036}\,3.4\right)\right]} = 1.06m$$

$$h_o=Y_o+d_e=1.06+0.4=1.46m$$

y_0 is the depth from the desired water table depth to that of the supply pipe.

From equ (7),

$$L = \frac{4(0.709)(0.10)(2(1.46) - \frac{(1.46)}{(2.64)}(0.1))}{0.00803} = 10.05m$$

Therefore L = 10.05 m is considered as subirrigation drain spacing.

Size of Lateral Drain Pipe For Controlled Drainage System

For the present study area, L = 27 m.

From the literature studied, 'n' will vary according to type of channel and pipe material. The value of n is taken as 0.025.

S = 0.0015

Q = 0.00296 m/day

Bmax = 40 m

Substituting the above values in equation 10 and 11, we get

Q=0.00296x27x40/24x3600=0.000411 m^3/s

d=1.548((0.025)(0.0000411))$^{0.375}$(0.0015)$^{-0.188}$

d = 29.8 mm ≈ 30 mm.

Size of Lateral Drain Pipe For Subirrigation System

For 1 hp diesel engine, the discharge rate is 2 lps. As this was the case for subirrigation, i.e., water is pumping from collector to laterals. So, at the field level we are irrigating at a time for 4 laterals. Then the discharge for each lateral will become 0.5 lps. Substituting the above values in Equ (10), we will get

d=1.548((0.025)(0.0005))$^{0.375}$(0.0015)$^{-0.188}$

d = 76.20 mm.

Size of Collector Pipe for Controlled Drainage System

Using the Equation 10,11 and substituting the required values in the equations with considering pilot area of 80 m x 80 m. Taking n=0.011 for smooth pipes.

Q=0.00296x80x80/24x3600=0.0002192 m^3/s

d=1.548((0.011)(0.0002192))$^{0.375}$(0.0025)$^{-0.188}$

d = 37.33 mm.

Size of Collector Pipe for Subirrigation System

For 1 hp diesel engine, the discharge rate is 2 lps and substituting the values in Equation 10,

d=1.548((0.011)(0.002))$^{0.375}$(0.0025)$^{-0.188}$

d = 85.57 mm.

Therefore, the next higher commercially available diameters of 80 mm and 110 mm were fixed for laterals and collector pipe respectively. The design parameters for CD-SI system values are shown in Table 2.

Table-2 Design parameters of CD-SI system

SN	Design Parameter	Specification	
		Controlled drainage	Subirrigation
1	Drainage co-efficient	2.96 mm/day	-
2	Average hydraulic conductivity	0.709 m/day	0.709 m/day
3	Equivalent depth	1.81 m	1.06 m
4	Evapotranspiration rate	8.03 mm/day	8.03 mm/day
5	Hydraulic head	0.2 m	0.1 m
6	Effective radius	0.036 m	0.036 m
7	Drain spacing	27 m	10 m

Details of Treatments

The experiment was designed for the strip plot design with vertical factor and horizontal factor with three replications. The vertical factor indicates different depths *viz*., 50 cm and 60 cm. The horizontal factor indicates different drain spacings at 8, 8.5, 9.0, 9.5, 10, 10.5 and 11 m respectively. The experimental layout is as follows:

Table-3 *Layout of strip plot design*

	Replication 1		Replication 2		Replication 3	
	D1	D2	D1	D2	D1	D2
S1 (8.0 m spacing between drains)	x1	x2	x15	x16	x29	x30
S2 (8.5 m spacing between drains)	x3	x4	x17	x18	x31	x32
S3 (9.0 m spacing between drains)	x5	x6	x19	x20	x33	x34
S4 (9.5 m spacing between drains)	x7	x8	x21	x22	x35	x36
S5 (10.0 m spacing between drains)	x9	x10	x23	x24	x37	x38
S6 (10.5 m spacing between drains)	x11	x12	x25	x26	x39	x40
S7 (11.0 m spacing between drains)	x13	x14	x27	x28	x41	x42

Where x1, x2, ... x42 indicates yield values of respective treatment combinations. As per the procedure mentioned above, the spacing was arrived using steady state Hooghoudt's equation as 27 m for controlled drainage system. Similarly, for subirrigation system also using Moody's equation spacing for subirrigation system was calculated as 10 m for the study area. Hence, as discussed above, sub irrigation system mode was considered as a basis for choosing the design spacing of CD-SI system. For field practical sensitivity analysis, testing of additional drain spacings with 8.0, 8.5, 9.0, 9.5, 10.0, 10.5 and 11.0 m were considered for experimental layout preparation. Even though, the incremental spacing was just 0.5 m, which makes a big difference in subirrigation system with respect to the time of wetting the surface and capillary rise. This would certainly help in finding out economic analysis.

Conclusion

The design spacing were calculated separately for controlled drainage and subirrigation system using steady state Hooghoudt's equation and Moody's equation. The design spacing arrived are 27 m and 10.05 m respectively. To function under both the modes, 10.05 m is considered as system spacing. The system was installed successfully by following all the precautions to be followed.

Application of research: Based on the field investigations and crop drainage requirements the drainage system is designed and a layout plan is prepared to suit the field boundaries.

Research category: Design of drainage system, Agricultural Engineering.

Abbreviations: L- Drain spacing, de- Equivalent depth, d- diameter of lateral and collector pipes, Q- Discharge through pipes, dc- Drainage coefficient.

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Author Contributions: All author equally contributed.

Author statement: All authors read, reviewed, agreed and approved the final manuscript. Note-All authors agreed that- Written informed consent was obtained from all participants prior to publish / enrolment

Study area / Sample Collection: Jammulapalem, Bapatla

Cultivar / Variety / Breed name: Rice

Conflict of Interest: None declared

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Ethical Committee Approval Number: Nil

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