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Salinity distribution in paddy root zone under subsurface drainage

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Abstract

One-dimensional convective dispersion solute transport model was solved by Crank–Nicholson finite difference scheme and was applied over the flow domain of subsurface drained paddy fields laid with tile drain at different spacings. The flow domain was divided into a number of stream tubes to predict salinities at different distances from drain centre, at different depths from the ground surface and at different times after the initiation of the operation of the subsurface drainage system. The sub division of the flow domain into a number of stream tubes was done for two purposes, viz. (i) to enable estimation of pore water flow velocity more appropriately with respect to the flow area within a stream tube and (ii) to enable comparison of predicted salinities with the observed values which were available within some of the stream tubes. The initial and the boundary conditions in solving one dimensional equation were based on the field investigated salinity values. In the solute transport model there are two essential input parameters, viz. the pore water velocity and the dispersion coefficient. The pore water velocity was calculated by dividing the Darcian velocity by the drainable porosity. The dispersion coefficient was fitted by trial and error till the average absolute deviation between the predicted and the observed salinities became minimum. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Solute transport; Solute concentration; Dispersion coefficient; Pore water velocity; Root zone salinity; Tile drain spacing

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1. Introduction

Salt distribution in the soil usually varies with both space and time. A change in the tile drain spacing changes the extent of soil volume to be leached and also changes the flow

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path length of the stream lines. Hence, it is evident that the salinity distribution over space and depth in a subsurface drained region will be a function of tile drain spacing. Most work on miscible displacement phenomena in soils has been limited to constant flow velocities and water contents(Youngs and Leeds-Harrison, 1990). These provide a means of determining hydro dynamic dispersion coefficients, evaluating macroscopic flow velocities and giving physical explanations for mixing phenomena which occur when salts flow through soils. For an inert system with zero distribution coefficient, undergoing steady-state uni-directional flow of water at constant moisture content (θ) and pore water velocity (V), the solute concentration as a function of time and space becomes

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial Z^2} - V\frac{\partial C}{\partial Z} \tag{1}$$

where C is the solute concentration (dS/m), t the time (days), Z the space co-ordinate (+ve downwards) (m), D is the dispersion coefficient ($\mathrm{m^2/day}$) and V is the pore water velocity (m/day).

The desalinisation process through leaching by surface irrigation water applied over subsurface drained saline fields in Sampla, Haryana, India was simulated by Rao and Leeds-Harrison (1991) for different water management scenarios aimed at increasing leaching efficiency. The Laplace equation was solved numerically to obtain the water flow pattern and a mass flow equation was applied to individual stream tubes to give the spatial and temporal distribution of salts. The major finding was that partial ponding improved desalinisation away from the drains and allowed a more efficient use of water.

The two-dimensional model of Kamra et al. (1991a,b) assumes, a steady-state water flow in the unsaturated and saturated zones and provides an exact-in-time finite element solution for solute concentrations as a function of time. The unsaturated and saturated zones of flow domains were discretized into linear quadrilateral finite elements. Linear basis functions were used for interpolation of concentration within an element. The predicted and observed salinities compared well except in the surface 20 cm soil layer. However, for a paddy crop the top 30 cm soil salinity decides the yield of crop, for which their study is not providing reliable information.

Ramaswamy (1993) used the one-dimensional convective-dispersion equation with zero distribution coefficient having no production term. His study was limited to the distribution of salts at different depths. In the present study, spatial distribution of salts under different tile drain spacings was investigated.

2. Description of the study area

The study area is located in Endakuduru village in Ghantasala mandal of Krishna district of Andhra Pradesh. The soils of the study area are heavy in texture and are underlain by deep sand beyond a depth of about 1.5 m. The reported soil salinity at times goes as high as 20 dS/m in the root zone. A high saline condition is also evidenced by white crust formation in the dry season. The physiography is nearly flat with a very gentle slope towards the Bay of Bengal which is about 15 km from the village. There are two distinct monsoons, one from June-to-August and the other from November-to-December.

Heavy rains in either of the above periods cause extensive surface waterlogging condition and *kharif* cultivation often suffers due to excess water in the *kharif*. The *rabi* cultivation suffers mainly due to high soil salinity.

There is a network of subsurface drainage systems executed at a constant average depth of 1.25 m with different spacings varying from 10 to 35 m over a total experimental area of about 4 ha. The system was executed during 1985–1987 and have been operated during the cropping seasons till date. The system helped in reducing the soil salinity to a great extent and as a result, their farmers were able to harvest as high as 4 t/ha of paddy from the area where practically nothing grew before introducing the subsurface drainage system. Consequent to the continuous crop activity, the soil physical condition also improved substantially over the years. This was evidenced by an increase in hydraulic conductivity from 0.144 m/day at the pre-drainage situation to 1.5 m/day after about 10 years of operation of the drainage system.

3. Methodology

The present study was carried out in two steps with the following assumptions:

- The soil is homogeneous and isotropic.
- The two-dimensional flow phenomenon in the saturated zone is adequately described by the Kirkham's steady-state equation.

In the first step, Kirkham's (1949) analytical solution (Eq. (2)) was used to find out the stream functions for the tile drainage system:

$$\Psi = 2q_f \sum_{-\infty}^{+\infty} (-1)^n \tan^{-1}\left[\tanh \pi \frac{(y-2nh)}{S} \text{ at } \frac{\pi x}{S}\right] \tan^{-1}\left[\tanh \pi \frac{(y-2d-2nh)}{S} \cot \frac{\pi x}{S}\right] \tag{2}$$

where

$$q_\text{f} = \frac{(t+d-r)}{f} \tag{3}$$

$$f = 2\ln \frac{\sinh(\pi(2d-r)/S)}{\sinh(\pi r/S)} - 2\sum_{n=1}^{\infty} (-1)^n \ln \frac{(\sinh^2(2\pi nh/S) - \sinh^2(\pi r/S))}{(\sinh^2(2\pi nh/S) - \sinh^2(\pi(2d-r)/S)} \tag{4}$$

where S is tile drain spacing (m), t the depth of ponding water (m), h the impermeable layer depth (m), r the radius of tile drains (m), d the depth of tile drains (m), n the number of iterations, q_f the flux coefficient, π has the value 22/7, Ψ the potential function and f is the variable used to calculate q_f.

Stream lines were plotted in the region between the drain and mid way between the two adjacent drains. Accordingly, the region was divided into a number of stream tubes. The quantity of water entering per unit length of drain tube per unit time (Q) was calculated by Hooghoudt's equation (Eq. (6)):

$$q = \frac{8\,Kd_e h_w + 4\,Kh_w^2}{S^2} \tag{5}$$

$$Q = qSl \tag{6}$$

where K is the hydraulic conductivity (m/day), d_e is equivalent depth (m), h_w is hydraulic head (m), l is length of lateral line (m), q is recharge rate (m/day) and S is tile drain spacing (m).

By assigning the same quantity of flow through each individual stream tube and considering different cross-sectional areas of different stream tubes at selected depths (0.1, 0.2, 0.3 and 0.4 m from ground surface), the average Darcian flow velocity in each tube was calculated. The pore water velocity was obtained by dividing the Darcian average flow velocity by the drainable porosity (0.0632), which was calculated from the long term observation of data on drain discharge, water table and time at the study area.

In the second step, the one-dimensional convective-dispersion equation (Eq. (1)) was used to find out the total soluble salt concentration in space and over the crop growing period, from surface to a depth of 50 cm, in individual stream tubes. This equation was solved by Crank–Nicholson finite difference scheme:

$$\frac{C_{i,j+1} - C_{i,j}}{\Delta t} = \frac{D}{2}\left(\frac{C_{i+1,j+1} - 2C_{i,j+1} + C_{i-1,j+1}}{\Delta z^2} + \frac{C_{i-1,j} - 2C_{i,j} + C_{i+1,j}}{\Delta z^2}\right) - V\left(\frac{C_{i+1,j} - C_{i-1,j}}{2\,\Delta z}\right) \tag{7}$$

where ΔZ is the spatial increment $= d_r/i - 1$ (m) Δt the time increment (day), d_r the root zone depth (m), i the number of spatial grid points, $(i = 2, 3, ., ., ., i-1)$ and j is the number of time steps, $(j = 1, 2, ., ., ., j)$. After replacing

$$\frac{\Delta t}{\Delta z^2} \text{ with } r, \quad \frac{\Delta t}{2\,\Delta z} \text{ with } S$$

Arranging all common terms into one side

$$-\frac{rD}{2}C_{i+1,j+1} + (rD+1)C_{i,j+1} - \frac{rD}{2}C_{i-1,j+1} = \left(\frac{rD}{2} - VS\right)C_{i+1,j} + (1 - rD)C_{i,j} + \left(\frac{rD}{2} + VS\right)C_{i-1,j} \tag{8}$$

As it is an iterative procedure to predict unknown values from known values, it was solved by a computer programmes written in FORTRAN. The initial conditions used to solve the programmes were the measured total soluble salts, expressed in terms of electrical conductivity, dS/m, at different locations and at different depths in the study area before the start of operation of drainage system. Five soil samples at different locations at different depths (0.1, 0.2, 0.3 and 0.4 m) were collected randomly and total soluble salt concentration was estimated as 3.14, 3.45, 4.22 and 4.50 dS/m, respectively. The average of these five locations was used as a uniform initial conditions throughout the study area. It was assumed that the presence of standing water at the time of soil sampling may have helped in stabilising the salt distribution over the entire field. the salt concentration of applied irrigation water was used as top boundary condition and soil salinity at 0.4–0.6 m depth was used as bottom boundary condition. The bottom boundary conditions on specified days, viz. 20, 30, 40, 60 and 65th day were compared with the predicted values. These days were selected based on the sensitivity stage of paddy crop to soil salinity.

A range of dispersion coefficient (*D*) values were selected based upon the Peclet number (0.5–2.0) which did not result in numerical oscillations while running the Crank–Nicholson scheme. For each value of dispersion coefficient selected, the average absolute deviation between the predicted and field observed values of electrical conductivity was found out. The value of dispersion coefficient at which the absolute deviation was found minimum, was used in further analysis. The field observed salinity values used for comparison were at four times with an interval of about 10 days in the paddy growing period of 120 days and three different depths at each time, for each stream tube.

4. Results and discussion

The stream functions calculated from the Kirkham's analytical solution were plotted against the distance away from the drain centre in each spacing (25 and 35 m) separately(sample plot in Fig. 1). In the construction of stream lines, the number of stream tubes were decided in such a way that locations of soil sampling for salinity lie well within any of the stream tubes. There were altogether 10 stream tubes in 25 m and 8 in 35 m spacing (Figs. 1 and 2). From these stream tubes, stream number 1, 2, 4, 6 and 10 in 25 m spacing and 1, 2, 3, 5 and 8 in 35 m spacing had observed salinity values which were used in subsequent analysis. The flow which enters per unit length of drain tube (*Q*) was calculated from Hooghoudt's equation. This discharge was halved to apply it to half spacing. The half spacing discharge in 25 and 35 m spacing is equal to 44.82 m^3/day and 24.38 m^3/day, respectively. This half spacing discharge is then divided by the corresponding number of stream tubes, to attribute equal amount of flow through each stream tube. Thus an amount of $44.82/10 = 4.48\,m^3$/day will drain through each stream tube in 25 m spacing and $24.38/8 = 3.05\,m^3$/day through each stream tube of 35 m spacing.

4.1. *Validation of the model in different spacings*

The solute transport model was initially validated with 25 and 35 m drain spacings where field observed salinity data were available at several distances (i.e. *S*/32, *S*/16, *S*/8, *S*/4 and *S*/2 m, where *S* is the drain spacing) from the drain and at several depths at certain specific times, over the growing period of paddy. After the model was validated on the basis of close agreement between the predicted and observed time and space distributed salinity values, the slainities at different distances away from the drain centre at a particular depth and time were averaged in each of the above two spacings separately. This was done to make use of the 10 and 15 m spacing salinity data which were available

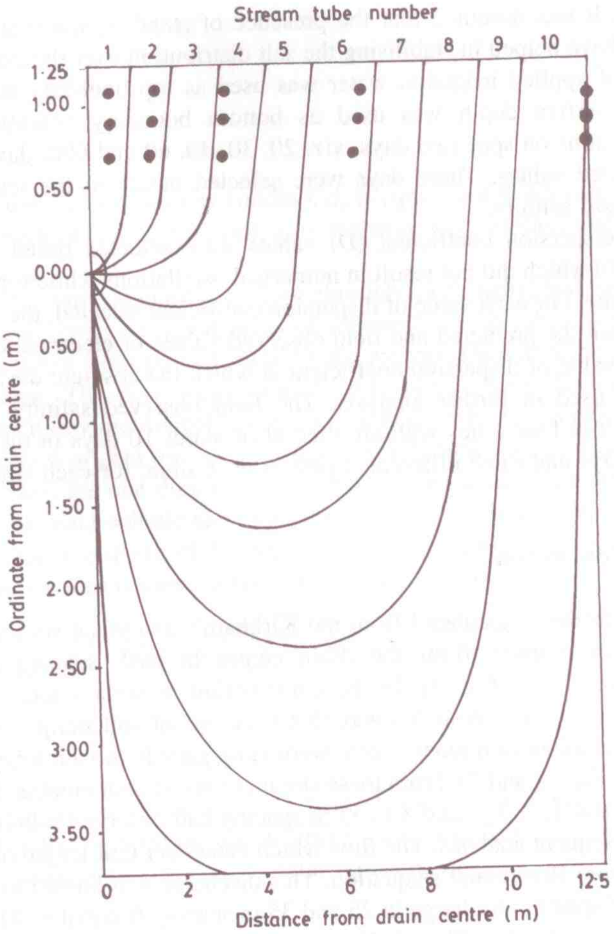

Fig. 1. Streamline and locations of soil salinity sampling (●) in 25 m drain spacing.

only at the half spacing at different depths and different time. The model was now validated with the above space average salinities of 25 and 35 m spacings and half spacing salinities of 10 and 15 m spacings.

4.1.1. Part I. Considering space distributed observed salinities under 25 and 35 m spacings

The solute transport model was validated by varying the value of dispersion coefficient starting with 0.001 m^2/day with an increment of 0.001 m^2/day, till the average absolute deviation between the observed and the predicted salinities was found minimum. The predicted salinities at different distances away from the drain centre in 25 and 35 m spacings are presented in Tables 1 and 2, respectively, along with the observed soil salinities. From these tables it can be seen that the predicted and observed salinities are

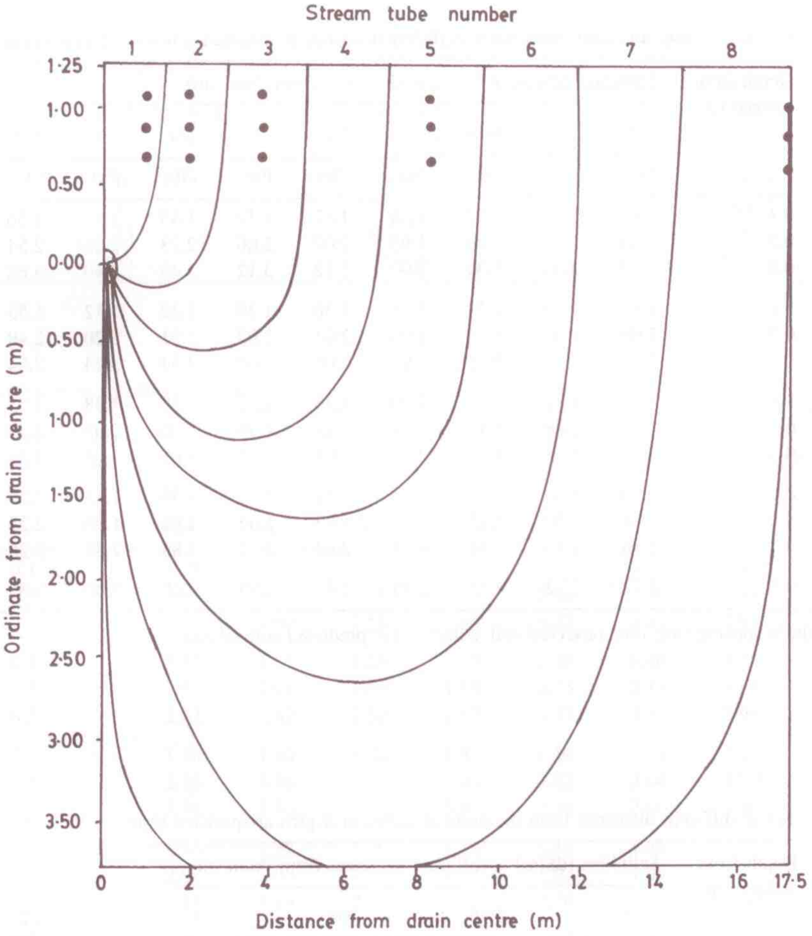

Fig. 2. Streamline and locations of soil salinity sampling (●) in 35 m drain spacing.

very closely matching, with average absolute deviation between them varying between 0.0008 and 0.0058 dS/m in 25 m spacing and 0.0042 and 0.0058 dS/m in 35 m spacing.

4.1.2. Part II. Considering average of space distributed salinities under 25 and 35 m spacings and the salinities at half spacing in case of 10 and 15 m drain spacing

By Kirkham's analytical solution stream function values were calculated and a single stream tube was constructed in the drained domain. The stream tube area at 0.1, 0.2, 0.3 and 0.4 m depth were calculated and were used in pore water velocity calculations. The flow entering per unit length of stream tube was calculated by Hooghoudt's equation. The fitted dispersion coefficients and the average absolute deviation between the predicted and observed salinities are presented in Table 3. The lower values of average absolute deviation indicates a close agreement between the predicted and observed salinities in all the spacings. When the deviations of 25 and 35 m spacings were compared with those of

Table 1
Soil salinities at different distances from drain at different depths at specified times in 25 m spacing[a]

Time (days)	Depth from surface (m)	Salinities (dS/m) at different distances from drain (m)									
		S/32		*S*/16		*S*/8		*S*/4		*S*/2	
		Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre
20	0.1	1.35	1.35	1.34	1.34	1.37	1.37	1.43	1.43	1.56	1.57
	0.3	2.00	1.99	1.96	1.96	2.07	2.06	2.23	2.23	2.54	2.53
	0.5	3.00	3.00	3.00	3.00	3.12	3.12	3.40	3.40	3.62	3.62
30	0.1	1.34	1.34	1.33	1.33	1.36	1.36	1.42	1.42	1.55	1.55
	0.3	2.00	1.96	1.93	1.93	2.01	2.02	2.21	2.20	2.49	2.49
	0.5	2.94	2.94	2.93	2.93	3.02	3.02	3.34	3.34	3.54	3.54
40	0.1	1.32	1.32	1.31	1.30	1.35	1.35	1.38	1.38	1.52	1.52
	0.3	1.87	1.88	1.83	1.84	1.98	1.98	2.06	2.06	2.38	2.38
	0.5	2.75	2.75	2.72	2.72	2.95	2.95	3.05	3.05	3.35	3.35
60	0.1	1.30	1.30	1.28	1.28	1.31	1.31	1.35	1.35	1.50	1.50
	0.3	1.78	1.79	1.75	1.76	1.83	1.83	1.96	1.96	2.32	2.32
	0.5	2.56	2.56	2.54	2.54	2.62	2.62	2.85	2.85	3.25	3.25
65	0.5	2.72	2.72	2.75	2.75	2.85	2.85	3.00	3.00	3.35	3.35

[a] *S*: drain spacing (m); obs: observed soil salinity; pre: predicted soil salinity.

Table 2
Soil salinities at different distances from the drain at different depths at specified times in 35 m spacing[a]

Time (days)	Depth from surface (m)	Salinities (dS/m) at different distances from drain (m)									
		S/32		*S*/16		*S*/8		*S*/4		*S*/2	
		Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre
20	0.1	1.28	1.28	1.28	1.27	1.29	1.29	1.31	1.31	1.33	1.33
	0.3	1.82	1.82	1.79	1.79	1.84	1.84	1.92	1.92	2.01	1.99
	0.5	2.88	2.88	2.87	2.87	2.90	2.90	3.10	3.10	3.21	3.21
30	0.1	1.26	1.28	1.26	1.26	1.28	1.29	1.30	1.31	1.32	1.33
	0.3	1.79	1.79	1.77	1.76	1.84	1.84	1.92	1.93	1.98	1.98
	0.5	2.81	2.81	2.79	2.79	2.91	2.91	3.12	3.12	3.20	3.20
40	0.1	1.26	1.26	1.24	1.25	1.26	1.27	1.30	1.29	1.30	1.31
	0.3	1.71	1.72	1.71	1.71	1.77	1.76	1.86	1.84	1.94	1.93
	0.5	2.64	2.64	2.66	2.66	2.72	2.72	2.91	2.91	3.08	3.08
60	0.1	1.23	1.24	1.22	1.24	1.22	1.25	1.27	1.28	1.28	1.30
	0.3	1.65	1.64	1.65	1.63	1.69	1.69	1.78	1.78	1.85	1.85
	0.5	2.44	2.44	2.46	2.46	2.54	2.54	2.76	2.76	2.89	2.89
65	0.5	2.65	2.65	2.67	2.67	2.72	2.72	2.94	2.94	3.12	3.12

[a] *S*: drain spacing (m); obs: observed salinity; pre: predicted salinity.

Table 3
Fitted dispersion coefficient values and average absolute deviation between predicted and observed salinities in 10, 15, 25 and 35 m spacings

S. no.	Spacing (m)	Dispersion coefficient (m^2/day)	Average absolute deviation (dS/m)
1	10	0.616	0.0083
2	15	0.238	0.0133
3	25	0.232	0.0033
4	35	0.0716	0.0083

Table 4
Average salinities at specified time in different spacings at different depths

Time (days)	Depth from surface (m)	Average salinties (dS/m) in different spacings (m)							
		10[a]		15[a]		25		35	
		Obs	Pre	Obs	Pre	Obs	Pre	Obs	Pre
20	0.1	1.35	1.34	1.26	1.26	1.41	1.41	1.30	1.29
	0.3	1.96	1.94	1.69	1.71	2.16	2.17	1.88	1.85
	0.5	2.89	2.89	2.58	2.58	3.23	3.23	2.99	2.99
30	0.1	1.32	1.33	1.25	1.25	1.40	1.40	1.28	1.28
	0.3	1.93	1.91	1.68	1.69	2.13	2.13	1.86	1.84
	0.5	2.82	2.82	2.52	2.52	3.15	3.15	2.97	2.97
40	0.1	1.38	1.40	1.32	1.31	1.38	1.38	1.27	1.27
	0.3	2.16	2.16	1.97	1.94	2.02	2.04	1.80	1.78
	0.5	3.36	3.36	3.14	3.14	2.96	2.96	2.80	2.80
60	0.1	1.36	1.37	1.26	1.29	1.35	1.35	1.24	1.25
	0.3	2.07	2.06	1.91	1.85	1.93	1.94	1.72	1.71
	0.5	3.13	3.13	2.92	2.92	2.76	2.76	2.62	2.62
65	0.5	3.60	3.60	3.33	3.33	2.93	2.93	2.83	2.83

[a] The salinity values are at half spacing; obs: observed salinities; pre: predicted salinities.

Part I, there is no much variation. The fitted dispersion coefficient values also did not vary much, and the values in Part II are 0.232 and 0.0716 m^2/day in 25 and 35 m spacings, respectively. The predicted and observed salinities are presented in Table 4.

5. Conclusions

In the present study, root zone salinity under different subsurface drain spacings were predicted using one-dimensional convective dispersion equation. Based on this study revealed that, by taking a number of stream tubes or even by taking a single stream tube in the flow domain the salinities predicted by the solute transport model are in very close agreement with the observed salinities. This can be seen from the lower values of average absolute deviation between the predicted and observed salinities (Tables 3 and 4). Hence, it can be concluded that the solute transport model can be used for reliable estimation of salinities at half spacing in tile drained area.

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