Desalinization of a salt-affected soil in plots of various sizes under two modes of water application

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SUMMARY

Leaching in a salt-affected, permeable, sandy loam soil was evaluated under continuous and intermittent ponding conditions in 2×2 m (S_1), 4×4 m (S_2) and 6×6 m (S_3) plots. The soil contained large amounts of soluble salts throughout the profile to the water table, chiefly chlorides and sulphates of sodium, calcium and magnesium. The leaching curves did not differ significantly between S_1, S_2 and S_3 plots under continuous ponding but did under intermittent ponding. The leaching efficiency decreased sharply with increased plot size. The leaching efficiency in S_1 plots was significantly greater with intermittent than with continuous ponding, but the reverse was true in S_3 plots. The displacement of the resident soil solution in S_1 plots under intermittent ponding was nearly piston-like. With increased plot size, it tended to deviate from this behaviour. The leaching curves from S_3 plots (this size being reasonable in farmers' fields) were compared with those obtained from numerical solution of a simplified steady-state salt transport model. The model also included a source term, solubility rate constant, for the slightly soluble salts present in the experimental soil. The pore water velocity was estimated from field capacity and time-averaged infiltration rate. The effective dispersion coefficient and solubility rate constant were estimated by a least-squares minimization technique. A reasonably good agreement was obtained between simulated and experimental leaching curves. For practical purposes, this simple model may be adequate to predict leaching in salt-affected soils similar to the one under consideration.

INTRODUCTION

Problems of soil salinity are widespread in the world, both in regions with humid climates, e.g., Holland, Sweden, Hungary and the U.S.S.R., and in arid or semi-arid regions, e.g., the south-western U.S.A., India and Middle East (Elgabaly, 1971; Dahiya & Dahiya, 1977). It is estimated that one-third of the irrigated land in the world is affected by these problems (Bresler, McNeal & Carter, 1982). About 4×10^4 ha of land annually become unfit for agricultural production because of salinization problems (Evans, 1974).

Many salt-affected soils are saline-sodic throughout the soil profile with chlorides and sulphates of sodium, calcium and magnesium as soluble salts. Shallow and fluctuating water tables are responsible for the creation of such soils. Reclamation of these soils requires lessening of soluble salts in the root zone by leaching to a level safer to crops (Dahiya, 1978). A reliable quantitative estimate of (*a*) the extent of leaching accomplished by a given quantity of water at disposal; and (*b*), conversely, the amount of water needed (leaching requirement) to accomplish the desired level of leaching is an important factor governing reclamation and management of these soils. Such an estimation would also be useful in planning and modifying present irrigation systems in these areas to prevent further salinity development. Empirical leaching curves and some leaching models, ranging from relatively simple to rather complex ones, have been found adequate to make such an estimation. A recent review by Pal & Poonia (1982) surveys most of these empirical rela-

tionships and models. A detailed account of them is given by Bresler *et al.* (1982) in their book on salt-affected soils.

In these studies, mostly conducted in soil columns (e.g. Dahiya & Abrol, 1974; Kirda, Nielsen & Biggar, 1974; Dahiya, Singh, Singh & Hajrasuliha, 1980) and micro-plots in the fields (e.g. Miller, Biggar & Nielsen, 1965; Oster, Willardson & Hoffman, 1972; Dahiya, Malik & Singh, 1981, 1982), the leaching efficiency was found to be significantly higher when water was ponded intermittently rather than continuously on the soil surface. In other studies, salt removal was, however, found to be independent of mode of water application (Leffelaar & Sharma, 1977; Dahiya, Singh, Richter & Singh, 1984).

In practice, reclamation of soils is carried out on large plots which are manageable on farmers' fields. Spatial variability of soil salinity, as also of other soil properties, increases with an increase in area (see review of Dahiya, Richter & Malik, 1984). Thus, any attempt made on development of a reclamation technology for these soils based on the results of laboratory and micro-plot experiments would probably be fruitless unless the validity of such results was examined on practically manageable large plots. Also, application of leaching models in many practical situations on salt-affected soils is likely to be restricted by the confounding effect of the spatial structure of solute mobility in large fields (Dahiya, Richter & Malik, 1984).

In the present study, leaching behaviour of a permeable, sandy loam soil having salt-laden profiles extending to the water table (a situation met by most of the soils under consideration) was evaluated in plots of three different sizes under continuous and intermittent ponding conditions. The observed data were compared with those predicted with a simplified steady-state salt transport model.

MATERIALS AND METHODS

Field experiment

The experiment was conducted from January to February 1981 at Haryana Government Agricultural Farm, Hansi, situated in the south-west part of Haryana state in northern India. The area is almost flat: slope varies from 0·10 to 0·35%. Canal irrigation has been practised for more than 50 years. The climate is semi-arid, with mean annual rainfall of 350 mm, 70% of which falls between July and September. The water table is highly fluctuating, varying from 1 m deep in September to several metres in June. The essential properties of the selected soil are given in Table 1. The soil is classified as Natric Camborthid.

Leaching was accomplished in the following plots: (1) 2×2 m (S_1); 4×4 m (S_2); and (3) 6×6 m (S_3). The modes of water application were: (1) continuous ponding (CP) with 60 cm water; and (2) intermittent ponding (IP) with 60 cm water. In the latter case, 5 cm water was added on every alternate day. These treatments were replicated three times to give a total of 18 plots. A fairly uniform salty piece of land was selected by preliminary sampling

Table 1. *Composition of soil*

Property	Depth (cm)				
	0–20	20–40	40–60	60–80	80–100
$pH_{1:2}$	7·9	8·0	8·2	8·6	8·6
$EC_{1:2}$(mmhos/cm)	6·1	6·5	7·0	7·3	7·1
Texture	Sandy loam	Sandy loam	Loamy sand	Loamy sand	Loamy sand
$CaCO_3$(%)	0·1	0·2	1·6	3·6	4·8
ESP	39	46	52	55	58
CEC (m-equiv/100 g)	7·2	8·0	8·7	9·6	9·8
Bulk density (g/cm³)	1·64	1·56	1·52	1·50	1·47
Soluble salts (m-equiv/l) in 1:2 soil-water extract					
Calcium	21	18	11	6	4
Magnesium	10	6	4	4	6
Sodium	30	41	55	63	61
Chloride	42	54	61	60	62
Sulphate	19	11	9	13	9
Bicarbonate	3	5	6	6	6
Water content (cm³/cm³)					
Before leaching	0·196	0·207	0·210	0·216	0·228
While leaching	0·330	0·286	0·282	0·280	0·271

and plots of the required size were made on it in a randomized fashion. The coefficient of variation of salt content in this piece of land was 3·3–10·3 % for different depths. Bricks were laid down around each plot to avoid saline soil falling into it from the ridges. A channel was dug around each plot and water was added to it while leaching was in progress to minimize the lateral movement of water.

The soil had a very impermeable compact layer with a thickness of 10–15 cm below the fluffy salt layer present on the soil surface. This is mainly because of the fact that the salty piece of land was lying barren for the last several decades, as no crop can grow on it. The layer was broken up with a spade prior to the commencement of leaching. The plots were levelled sufficiently to give a uniform distribution of irrigation water. Leaching was accomplished with good quality canal water that contained a negligible amount of soluble salts.

Soil samples were collected before leaching started and after 10, 20, 40 and 60 cm of water had infiltrated into the soil. Samples were taken to a depth of 100 cm at 20 cm intervals. Individual samples for a given depth taken at several positions in each plot were combined, and averages from three replicates are presented here. The bulk density was found by core sampling.

Soil samples were analysed for water content and electrical conductivity (EC) of 1:2 soil–water extract. From the EC values, concentration of total soluble salts in the soil solution was estimated (Richards, 1954).

Model description

In the system under consideration, the soil profile remains appreciably moist throughout the year. As can be seen from Table 1, average water content prior to leaching was 0·21 cm³/cm³. This is because of the presence of (a) hygroscopic salts in the soil; and (b) shallow water table. The water content at greater depths remains quite constant in such soils even though irrigation and rainfall may change the water content distribution near the soil surface for some time. Also during leaching, profile water content was nearly constant. Hence, water movement through soil under such conditions may be considered steady (quasi-stationary). Previous field studies also support this assumption (Leffelaar & Sharma, 1977; Khosla, Gupta & Abrol, 1979; Dahiya *et al.* 1981, 1982; Dahiya, Malik & Richter, 1983). The experimental (Table 1) and other such soils (Dahiya & Dahiya, 1977) contain appreciable amounts of slightly soluble salts like gypsum and lime. Since such salts can greatly affect the concentration of total soluble salts in soil solution, their solubility was also accounted for in the transport model. The interaction of these salts with soil

solution was assumed to be irreversible during leaching.

Movement of non-reactive solutes in one-dimensional profile under steady-state conditions may be described by the convective–dispersive solute transport equation:

$$\frac{\delta C}{\delta t} = D\left(\frac{\delta^2 C}{\delta x^2}\right) - v\frac{\delta C}{\delta x} + K, \qquad (1)$$

where C = soil solution salt concentration (m-equiv/cm³), v = average pore water velocity (cm/day) given by Darcian flux q (cm/day) divided by volumetric water content θ (cm³/cm³), D = effective dispersion coefficient (cm²/day), x = distance from the soil surface (cm), t = time (days), and K = solubility rate constant for sparingly soluble salts (m-equiv/day).

We used here a simple explicit finite-difference solution of equation (1) as in an earlier report (Richter, Scharpf & Wehrmann, 1978):

$$\frac{C_{t+\Delta t} - C_t}{\Delta t} = D\frac{C_{x+\Delta x} - 2C_x + C_{x-\Delta x}}{\Delta x^2}$$
$$- v\frac{C_x - C_{x-\Delta x}}{\Delta x} + K \quad (2)$$

to get $C_{t+\Delta t}$. The initial and boundary conditions consist of

$$C(x > 0, 0) = C_0, \quad C(0, t > 0) = 0. \qquad (3)$$

C and C_0 are average values for the profile and these were reasonably uniform down the profile (Table 1). The calculation process was formulated as Dialogprogram in BASIC for a table (micro) computer.

Values of v, D and K in the model were determined as follows.

A time-averaged water flux rate, q, was determined from the total amount of water infiltrated divided by the total infiltration time. Cumulative infiltration was estimated by subtracting the value of cumulative pan evaporation from the total amount of water applied. Previous experience (e.g. Dahiya *et al.* 1981, 1982, 1983) as well as data from this study showed that irrespective of mode of water application, leaching in such structureless soils takes place at a volumetric water content nearly equivalent to field capacity, i.e. $\theta = \theta_{fc}$. For the present field, this value was 0·29 cm³/cm³ for 100 cm soil depth (Table 1). The use of these estimated values of q and θ gave average pore water velocity of 8·3 and 35·9 cm/day for intermittent and continuous ponding respectively.

Because of the complex nature of solute transfer through porous media, which depends upon the geometric configuration of the pores, the soil water content, the flow velocity of soil water, the concentration of solutes and the composition of solutes,
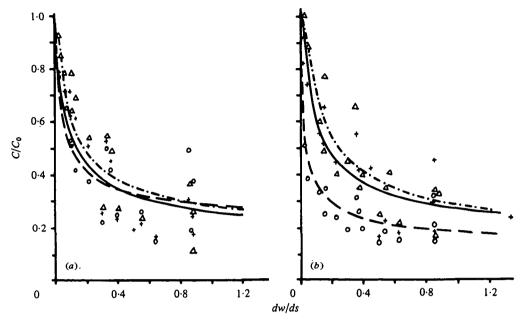
Fig. 1. Leaching curves showing effect of plot size (S_1, 2×2 m; S_2, 4×4 m; S_3, 6×6 m) under (a) continuous ponding (CP, and (b) intermittent ponding (IP). S_1, - -, $\bigcirc$; S_2, ——, +; S_3, -·-·-, $\triangle$.

generally empirical relations are used to estimate D (e.g. Frissel, Poelstra & Reiniger, 1970; Rose & Passioura, 1971; Amoozegar-Fard, Warrick & Fuller, 1983). Using experimental data, we estimated D and K by a least-squares minimization technique. Values of D thus obtained were 75 and 270 cm²/day for intermittent and continuous ponding, respectively. The corresponding values of K were 0·5 and 1·2 m-equiv/day. We preferred this technique because others are time consuming and rather complicated.

RESULTS AND DISCUSSION

Treatment effects

The amount of variation (expressed as c.v.) between replicates ranged between 1·4 and 8·2 % for salt content and 1·1 and 6·3 % for water content for different treatments. For clarity, effectiveness of different treatments on leaching behaviour was examined by comparing the best fit leaching (desalinization) curves obtained by regression between C/C_0 and dw/ds. These curves are shown in Figs 1 and 2. Their regression equations with other statistical parameters appear in Table 2. Figure 1 also includes data points. Here, dw is the total amount of leaching (drainage) water at successive samplings and ds is the depth of soil. C and C_0 are as defined earlier (equations 2 and 3). It is seen from Table 2 that the same equation fits the data

reasonably well for all depths for a given treatment ($r = 0·84-0·93$). A summary of statistical analysis of the data comparing different treatments is given in Table 3. For a still better comparison of treatment effects, C/C_0, calculated from regression equations of Table 2 at a given pore volume, p, is plotted against plot size in Fig. 3. Here, p is given by $(dw/ds)/\theta_{fc}$.

Figure 1(a) compares leaching curves for plots S_1, S_2 and S_3 under continuous ponding (CP). It is seen that there was little effect of plot size on leaching behaviour of the experimental soil under this mode of water application. Leaching efficiency $(1 - C/C_0)$ slightly decreased as plot size increased. This is further evident from Fig. 3. Table 3 (lines 1–3) shows that mean C/C_0 values for these treatments do not differ significantly from one another. The ineffectiveness of plot size under CP may be attributed to the continuous water standing on the soil surface. As a result of this, possible spatial variation in infiltration rate due to micro-relief effect in larger plots might have been minimum.

Figure 1(b) compares leaching curves for plots of different size under intermittent ponding (IP). It is seen that there was considerable difference between any two of the three leaching curves. Figure 3 further elucidates this fact. The leaching efficiency decreased sharply as plot size increased. The rate of this decrease might become zero with further increase in plot size (> 36 m²). The means
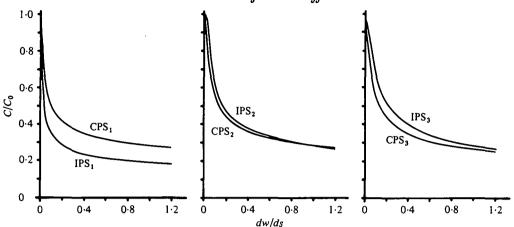
Fig 2. Leaching curves showing effect of modes of water application (CP, continuous ponding; IP, intermittent ponding) in plots of different sizes (S_1, 2×2 m; S_2, 4×4 m; S_3, 6×6 m)

Table 2. *Best fit desalinization curves for different treatments*

Treatment*	Regression equation	Standard error of		Correlation coefficient
		Slope	Intercept	
CPS_1	$C/C_0 = 0.095 + 0.190 \ (dw/ds)^{-0.333}$	0.029	0.054	0.84
CPS_2	$C/C_0 = 0.064 + 0.216 \ (dw/ds)^{-0.333}$	0.030	0.056	0.87
CPS_3	$C/C_0 = 0.019 + 0.246 \ (dw/ds)^{-0.333}$	0.036	0.068	0.84
IPS_1	$C/C_0 = 0.051 + 0.141 \ (dw/ds)^{-0.333}$	0.019	0.032	0.88
IPS_2	$C/C_0 = 0.009 + 0.263 \ (dw/ds)^{-0.333}$	0.035	0.062	0.86
IPS_3	$C/C_0 = -0.053 + 0.335 \ (dw/ds)^{-0.333}$	0.031	0.054	0.92
$CPS_{3(cal)}$	$C/C_0 = -0.050 + 0.277 \ (dw/ds)^{-0.333}$	0.032	0.059	0.91
$IPS_{3(cal)}$	$C/C_0 = -0.071 + 0.324 \ (dw/ds)^{-0.333}$	0.031	0.053	0.93

* CP, continuous ponding; IP, intermittent ponding; S_1, 2×2 m plot; S_2, 4×4 m plot; S_3, 6×6 m plot.

of any two curves differed significantly from each other (Table 3, lines 4–6). The possible reason for obtaining significantly lower leaching efficiency in larger plots (S_2 and S_3) may be that in these plots there might have been a relatively larger effect of micro-relief on infiltration of intermittently applied water. After the addition of each increment of 5 cm water on alternate days, the water was concentrated in localized small depressions randomly distributed in these plots. This was because perfect levelling of them was not feasible. On the other hand, in small plots (S_1), more or less perfect levelling was attained. As one would expect, uniformly distributed irrigation would ultimately be more effective in leaching salts than would be non-uniformly distributed irrigation, all other conditions remaining equal. Recently, Bresler *et al.* (1982) have presented quantitative estimations of salt leaching in large fields under uniformly and non-uniformly distributed irrigation. For example, they estimated that for spatially uniform recharge rate, leaching to a desired level in a fictitious homo-geneous soil would be completed only 80 h after the commencement of irrigation. For the case with an abnormally high coefficient of variation for the recharge resulting from non-uniformly distributed irrigation, only 24% of the total area of the field was leached after 100 h.

Curves in Fig. 2 show a comparison of the effects of modes of water application. This Figure and Table 3 (lines 7–9) show that leaching efficiency was significantly higher in S_1, insignificantly lower in S_2 and significantly lower in S_3 plots with intermittent than with continuous ponding. Figure 3 shows these differences more clearly. As mentioned earlier, several previous workers also obtained more efficient salt leaching with intermittent than with continuous ponding in soil columns (e.g. Dahiya & Abrol, 1974; Kirda *et al.* 1974; Dahiya, Singh, Singh & Hajrasuliha, 1980) and 2×2 m field plots (e.g. Dahiya *et al.* 1981, 1982). They argued that leaching intermittently to allow more time for movement of water through the small pores will improve the leaching efficiency in the soils. Also,

Table 3. *Statistical analysis of desalinization data*
(C/C₀) for comparison of treatment effects

Pairs*	Mean difference	Standard deviation of mean difference	$t_{(cal)}$†
CPS_1/CPS_2	−0·017	0·022	0·77
CPS_1/CPS_3	−0·017	0·026	0·65
CPS_2/CPS_3	−0·004	0·008	0·50
IPS_1/IPS_2	−0·145	0·027	5·37
IPS_1/IPS_3	−0·185	0·040	4·63
IPS_2/IPS_3	−0·055	0·023	2·40
CPS_1/IPS_1	0·128	0·021	6·10
CPS_2/IPS_2	0·003	0·015	0·20
CPS_3/IPS_3	−0·059	0·023	2·57
$CPS_3/CPS_{3(cal)}$	0·020	0·031	0·65
$IPS_3/IPS_{3(cal)}$	0·039	0·036	1·08

* Number of pairs = 20.

† $t_{0·05}$ = 2·09 at 19 degrees of freedom.

intermittent leaching may give time for solutes to diffuse from the less mobile to the mobile water in between successive applications of water. On the other hand, since the intermittently applied water was not uniformly distributed over the soil surface in the larger plots (S_2 and S_3), the leaching efficiency was lower in these plots with intermittent than with continuous ponding.

These results suggest that under practical situations in which reclamation is carried out in large plots, the practice of leaching salts with intermittent ponding would be less effective. Such a practice would require more labour and time than single continuous application of water. Thus, leaching of salts down into the soil with a single heavy irrigation would be more desirable.

Nature of soil solution displacement

Further examination of Fig. 3 indicates that in 2 × 2 m (S_1) plots under IP, salt leaching from the soil profile at one pore volume was (1−0·26) 100 = 74%, i.e. $(1−C/C_0)$ 100. Some recent studies, conducted in this part of India, showed that one pore volume of water displaced 80–94% of the salts from the soil profile in 2 × 2 m plots (Dahiya *et al.* 1981, 1982) and small infiltrometers (Leffelaar & Sharma, 1977; Khosla *et al.* 1979; Dahiya *et al.* 1983). Under ideal piston flow conditions, the resident soil solution would be displaced, or pushed, by the leaching water right in front of it, i.e. at one pore volume 100% salt removal would occur. Removal of 74–94% of salts at one pore volume in these studies indicated that a piston-like displacement of soil solution occurred. This behaviour has also been reported by Smiles *et al.* (1978, 1981), Dahiya, Singh, Richter & Singh (1984) and many
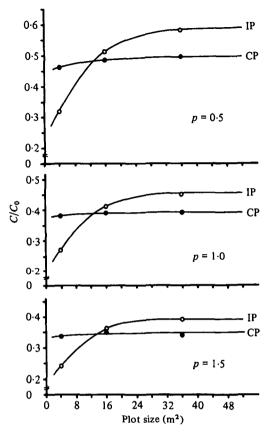

Fig. 3. Values of C/C_0 at a given pore volume (p) plotted against plot size. CP, continuous ponding; IP, intermittent ponding.

others in laboratory columns containing non-aggregated soils, as the case in the present study.

In other plots, salt removal at one pore volume varied from 55 to 62% (Fig. 3). This indicated that, in general, as plot size increased, salt displacement tended to deviate from piston-like flow. This means that there was not as complete leaching in these plots as in 2 × 2 m plots under IP. These results and those obtained in field studies by other workers (e.g. Talsma, 1967; Wild & Babiker, 1976; Addiscott, 1977) show that, in general, a piston-like displacement of soil solution would not occur in practical situations.

Comparison with model predictions

We have seen from Fig. 3 that the effect of plot size on leaching might beome insignificant irrespective of mode of water application when the plot size becomes greater than 6 × 6 m. Thus, this plot size may be considered as the minimum plot size for the experimental soil for practical purposes.
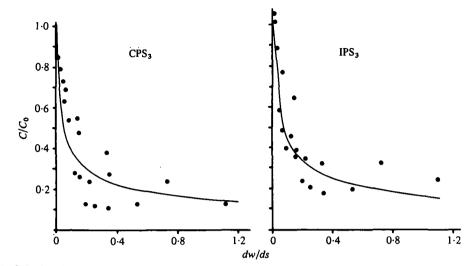
Fig. 4. Calculated (solid lines) and observed (points) leaching data for S_3 plots (6×6 m) under continuous (CP) and intermittent (IP) ponding.

Hence, leaching curves only for CPS_3 and IPS_3 plots were compared with predicted ones. Figure 4 shows this comparison. The predicted curve passed fairly well through the experimental points. Thus, the agreement was good through the whole range of desalinization. Statistically, the predicted and experimental data did not differ significantly from each other as can be seen from Table 3 (lines 10 and 11). In the final stages of leaching, the simulation showed slightly higher leaching efficiency than did the experimental data (compare regression equations CPS_3 and CPS_{3cal}. and IPS_3 and IPS_{3cal} for high values of dw/ds). This lack of agreement may partly be attributed to the incomplete leaching as a result of a dead-end-pore effect as suggested by Dahiya & Abrol (1973) and Dahiya, Abrol & Hajrasuliha (1980). According to them, the flow in unsaturated state produces a configuration of water distribution in a manner that there are certain localized volumes of stagnant water which are connected to the main stream through very thin films or narrow channels in which the transverse hydrodynamic dispersion is reduced considerably. Whereas in the theoretical model, mixing of the solutions (one added and the other already present)

has been envisaged, there would always be partial mixing of the solutions due to the presence of the so-called dead or blocked pores. This would, evidently, give rise to higher experimental values than expected on the basis of complete mixing.

Since the agreement between the simulated and observed data is good, it is evident that a good prediction can be made using the model for practical situations. More comprehensive models are available for predictive purposes. However, owing to the complicated nature of such models, practical application is often difficult. The present model is much simpler to apply than others.

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