EFFECTS OF INTERMITTENT PONDING ON SALT REDISTRIBUTION THROUGH A SALINE-SODIC CLAY SOIL

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Contribution nos. R-360 of the Saskatchewan Institute of Pedology, and 83-07 of the Land Resource Research Institute; received 26 Nov. 1984, accepted 15 Mar. 1985


The effects of intermittent ponding on salt movement through a saline-sodic clay soil were investigated by adding varying total amounts of water (16 and 32 cm) at different irrigation intervals (5, 10 and 20 days). The soil columns were subjected to a potential evaporation rate of 0.48 cm/day. The application of water resulted in the formation of a desalinized zone underlain by a salt accumulation zone. The highest salt concentrations coincided with the wetting front. Salt leaching was more efficient with large and less frequent applications. A modified Versatile Soil Moisture Budget, which incorporated soluble salt mixing concepts as advanced by Burns (1974) showed satisfactory agreement between measured and predicted salt redistribution profiles. Discrepancies, which occurred toward the end of the experiment, were believed to be related to the assumption that salt diffusion could be neglected.

INTRODUCTION

Leaching, to obtain a favorable distribution of soluble salts in the profile, is an important aspect of the utilization of salt-affected soils. Early reclamation practices which aim at the complete removal of salts from the profile by leaching and subsurface drainage are usually not feasible for heavy clay, montmorillonitic soils because of their low hydraulic conductivity. Intermittent application of water has been proposed as an efficient method for the leaching of inherent saline soils and for establishing an overall favorable salt distribution within the profile (Wilson et al. 1961; Oster et al. 1972; Carter and Robbins 1978), although Abrol and Bhumbia (1973) found that intermittent ponding had no particular advantage over continuous ponding.

Previous research has suggested that leaching is more water-efficient when the soil is maintained unsaturated and when flow rates are relatively small (Biggar and Nielsen 1967; Bresler and Hanks 1969; Kirda et al. 1974). As a result irrigation water for the leaching of initially saline soil is utilized most efficiently when applied by sprinkler or trickle systems, as opposed to flooding or ponding. Yet the latter form of application is often only economically feasible one in the arid and semi-arid regions of Sudan. The two factors which must be considered simultaneously in reclaiming saline areas with limited irrigation-water resources, (i) the total quantity of water available and (ii) the frequency at which this water should be applied, have attracted little attention.

In the field the intermittent conditions of infiltration and evaporation lead to very complex situations for the coupled translocation of water and salts. Suggestions have been made (King and Hanks 1973; Bresler et al. 1982) that the modelling of water and salt movement could aid appropriate water management techniques. Mathematical models based on mass balance equations, phenomenological equations (Darcy's and Fick's law) and expressions describing physical, chemical and biological relationships have been developed (Bresler 1973; Hillel et al. 1976; Segol 1977; Jury et al. 1978; Van Genuchten 1980). Most give reasonable predictions of the redistribution of salts but they require a detailed knowledge of soil water characteristics (water retention and hydraulic conductivity functions) and salt transfer characteristics (hydrodynamic dispersion function). These data are generally not available, because they are time consuming and expensive to obtain. Model functions are also frequently adjusted and optimized (Cameron et al. 1978) in order to obtain good results. Combinations of soil water budget and simple soluble salt mixing models formulated by Bresler (1967), Terkeltoub and Babcock (1971) and Burns (1974) do not suffer from these disadvantages, but only the one developed by Burns (1974) takes the redistribution of salts under evaporative conditions into account, provided that the evapotranspiration data are fed into the model. This latter qualification restricts the predictive capability of the model to those cases where evapotranspiration has been measured or estimated separately.

The purpose of this study was to investigate the effect of frequency and total quantity of water applied under intermittent ponding conditions upon salt redistribution in a saline-sodic soil. While the results of such a study serve as a general guide for reclaiming saline soils, they are not directly applicable to field conditions in Sudan. In order to bridge this gap between the laboratory experiment and the field situation, a second objective was to incorporate the soluble salt mixing concepts of Burns (1974) into the Versatile Soil Moisture Budget (VSMB) of Baier et al. (1979). This simple modelling approach was selected because it does not require a detailed knowledge of soil water and salt transfer characteristics or of differential equations and numerical analysis techniques. Moreover, the VSMB procedure has successfully simulated soil water contents under semi-arid conditions (Baier 1972; De Jong and MacDonald 1975; Van Schaik et al. 1976). In a previous paper Mustafa et al. (1983) used the VSMB successfully to predict the infiltration and actual evaporation of the soil columns considered here. The correspondence between the measured and estimated values compared favorably with the results achieved using a diffusion-based model. The present paper will deal with salt redistribution associated with water infiltration and evaporation.

MATERIALS AND METHODS

Salt Redistribution Experiments

A detailed description of the experiment was given in a previous paper where the infiltration and evaporation of the water
TABLE 1. SOME PHYSICAL AND CHEMICAL PROPERTIES OF THE SOIL USED

<table>
<thead>
<tr>
<th>Particle-size distribution</th>
<th>Organic matter (%)</th>
<th>pH paste</th>
<th>EC₆</th>
<th>CEC (meq·100g⁻¹)</th>
<th>SAR‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (%)</td>
<td>10.37</td>
<td>3.08</td>
<td>7.9</td>
<td>14.9</td>
<td>16.7</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>32.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay (%)</td>
<td>57.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EC₆ = electrical conductivity of the saturation extract.

SAR = sodium absorption ratio = Na⁺/((Ca²⁺ + Mg²⁺)/2)₁/₂, where all concentrations are expressed in meq/1.

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Figure 1. Profile distribution of electrical conductivity of the soil solution extract at the end of the experiment.

The soil columns were placed on the floor of a growth room with temperature and relative humidity controlled at 20°C and 45%, respectively. Potential evaporation from a free water surface in the growth room was measured to be 0.48 cm·day⁻¹.

Soil columns were irrigated with deionized water at 5-, 10- or 20-day intervals. Applications of 1, 2, 4 or 8 cm were used to give the treatment total water quantities of 16 or 32 cm, representing equivalent daily rates of 0.2 and 0.4 cm (Table II). The amount of water added to a column was directly proportional to the length of the interval between applications. The water application and sampling schedule was delayed at day 40 by 2 days; i.e. day 40 activities were not done until day 42. Calculations, to be described in the next section, took into account that this one interval was longer than the others.

After 20, 40 and 60 days from the start of the experiment, one column from each of the high rate application treatments was selected and sectioned into 2-, 3- or 5-cm increments, the shorter segments taken where steeper water content gradients existed. The soil moisture distribution was measured gravimetrically for each column using half the soil from each section. The remaining soil of each section was air-dried, crushed and passed through a 0.2-

cm sieve and saved for salt analysis. The remaining columns were sectioned after 80 days, the end of the experiment.

The electrical conductivity of the saturation extracts of soil samples from each section was measured using a conductivity bridge. Percent saturation of each sample was recorded. Soluble and extractable Ca²⁺, Mg²⁺, Na⁺ and K⁺ were determined using atomic absorption techniques.

Modelling

The essential features of the VSMB, as employed in the present study, were described previously (Mustafa et al. 1983). In that study, the soil column was subdivided into six ‘standard’ sections of, respectively, 3.0, 4.5, 7.5, 15.0, 15.0 and 15.0 cm thickness. In the VSMB, it is assumed that the water infiltrating into the soil recharges the moisture content in the top section to its field capacity value. The remaining water then infiltrates into the next section and so forth, until all the water has been distributed in the column. The use of relatively large section sizes of 15.0 cm in the lower part of the column may invalidate the assumption, used in the Burn’s (1974) model, that complete convective mixing of dissolved salts occurs in each section. In order to alleviate problems concerning this assumption, the column was subdivided into 20 equal sections of 3.0 cm thickness, each with an available water-holding capacity of 1.13 cm (total available water-holding capacity was estimated to be 22.6 cm).

In the VSMB, the movement of water to the surface due to capillary rise during evaporation is accounted for by using empirical parameters called ‘k’ coefficients. These coefficients, which were determined from field observations (Baier and Robertson 1966), partition the water loss due to evaporation among the sections. The ‘k’ coefficients decrease rapidly with depth, especially when there are no roots extracting water. The reduction of potential water loss to actual water loss from each section is a function of the available water in the section and the characteristics of the soil (Mustafa et al. 1983). Therefore, increasing the number of sections in the profile necessitated the adaptation of 20 ‘k’ coefficients for bare soil evaporation in such a way that the same water extraction and evaporation pattern would be obtained as if the six recom-
mended coefficients for bare soil were used. This was accomplished by dividing each of the six bare soil coefficients by the number of the smaller sections which fell within the corresponding larger one. Whenever one of the new 3-cm sections would overlap the boundary between two standard ones, linear interpolation was used to compute the appropriate coefficient for that section.

On those days when water was applied, the downward flux of water at the boundary between two sections was calculated as the difference between the amount of water applied at the surface and the fraction of the applied water which was retained in all sections on that day above the boundary under consideration. The downward flux was set to zero when no water was applied. The upward flux of water at the boundary between two sections, on every day, was computed as the cumulative amount of water withdrawn from all sections lying below the boundary of interest. Thus the upward flux at the soil surface was calculated to equal the daily actual evaporation. The net downward or upward flux of water was the difference between the two fluxes described above.

The concepts of complete soluble salt mixing and movement as developed by Burns (1974) were incorporated into the VSMB. All the water added to the soil surface \((X_t)\) infiltrated the first section and mixed completely with the water that was present in this section \((M_t)\). No exchange or precipitation of salts was thought to occur and the added water was assumed to mix completely with that originally present. Any water in excess of field capacity in the first section \((W_t)\) would then move down to the next section leaching a quantity of salts equal to

\[ T = A_1 \cdot R_p \]

where \(A_1\) is the salt content in the first section and \(R_p\) is the fraction of water that was held only temporarily in the upper section, i.e. \(W_t/(X_t + M_t)\). The salt remaining in section 1 was determined by subtracting the leached quantity of salt \((T)\). The new salt content of section 2 was evaluated by adding \(T\) to that already present. The calculations were continued for each section until downward percolation ceased.

Evaporation of water from the first (top) section to the atmosphere did not cause any loss of salt, but the upward transport of water from the lower sections caused dissolved salts to move towards the surface. The fraction of water lost through upward movement from the second to the first section, \(R_c\), equaled the volume transported upward between the two sections, divided by the water content of the lower section. Since each section was assumed to be at equilibrium before any losses occur, \(R_c\) also represented the fraction of dissolved salts which were transferred. The actual quantity of salts lost from the second section was then the product

\[ A_2 \cdot R_c \]

where \(A_2\) is the quantity of salts originally present in the lower (second) section. The salts remaining in this section were calculated by difference, while the transported salt was added to that present in the first section. These calculations were then repeated for each section in turn down the column.

The salt content of each section was converted to electrical conductivity units by using the mean measured saturation percentage and by assuming that the concentration of salts in the water was directly related to electrical conductivity (1 dS m\(^{-1}\) = 640 ppm (King and Hanks 1973)).

### RESULTS AND DISCUSSIONS

**Electrical Conductivity Redistribution**

The effects of the two quantities of water and the three intervals between water applications on the electrical conductivity of the saturation extracts \((E_{c})\) of the soil columns studied are illustrated in Fig. 1. Compared with the initial uniform soil salinity \((14.9 \text{ dS m}^{-1})\), the final \(E_{c}\) distribution profiles generally exhibited a leached upper zone underlain by a salt accumulation zone. Irrespective of the number of wetting and drying cycles the maximum salt concentrations were found at the wetting front (the latter data were reported previously by Mustafa et al. (1983)). Our observed salt distribution pattern was similar to the findings of Kirda et al. (1974) and Ghanem et al. (1975) which they obtained for different initial and boundary conditions. It was not possible to achieve good sectioning of the dry soil below the wetting front and it was assumed that the water content and \(E_{c}\) remained unchanged below it. Surface crusts of high \(E_{c}\) values were formed at the low application rate with water application intervals of 5 and 10 days (treatments \(Q_{t10}\) and \(Q_{t10}\))

The leached depth \((Z_t)\), defined as the soil depth at which \(E_{c}\) was equal to the initial value \((14.9 \text{ dS m}^{-1})\) is reported in Table III. For treatments \(Q_{t10}\) and \(Q_{t10}\) the concept of \(Z_t\) was not applicable.
because salt concentrations in excess of the initial value were measured both near the surface and at depths ranging from 10 to 12 cm (Fig. 1). For a given total quantity of water available for irrigation, the depth of salt leaching was related directly to the frequency of water applications. For example, with a total application of 32 cm, $Z_L$ increased by 61 and 108%, respectively, for the 10- and 20-day intervals compared with the 5-day interval. Furthermore, for a given interval between applications, the depth of salt leaching increased with an increase in the total quantity of irrigation water. For intervals of 5, 10 or 20 days, $Z_L$ increased by about 150, 230 and 265%, respectively, due to the application of 32 cm over that of 8 cm of water at an equivalent rate of 0.4 cm·day$^{-1}$. The application of 16 cm at an equivalent daily rate of 0.4 instead of 0.2 cm at an irrigation interval of 20 days increased $Z_L$ by about 58%.

While it is important to maximize the depth of salt leaching for establishing an overall favorable salt distribution in the profile, it is also desirable to leach the soil in the most efficient manner, particularly in areas of limited water supply. Water efficiency of salt leaching (Table III) was defined as the increase in $Z_L$ per centimetre of net water applied. The latter quantity was calculated as the accumulated amount of water applied minus accumulated actual evaporation (reported by Mustafa et al. (1983)). Maximum water efficiency (3.4) was obtained when 16 cm of water was applied at an equivalent rate of 0.2 cm·day$^{-1}$ at 20-day intervals (treatment Q$_{120}$). This efficiency dropped by about 29% when the equivalent application rate was 0.4 cm·day$^{-1}$ (Q$_{240}$). With a total application of 32 cm the water efficiency increased by 33 and 38%, respectively, for the 10- and 20-day intervals compared with the 5-day interval.

The results suggested that salt leaching and water efficiency of leaching increased with deep and less frequent applications compared with shallow and more frequent ones. These findings could be related to the effects of treatments on the soil moisture redistribution profiles; Mustafa et al. (1983) showed that after the initial stage of the experiment, water added at low frequencies and in large amounts infiltrated more deeply and redistributed more deeply, resulting in less evaporation. Consequently, dissolved salts would leach deeper with decreasing application frequencies and increasing amounts of water added.

**Model Predictions**

The 6-zone and the 20-zone VSMB gave essentially the same water balance results; differences in cumulative evaporation with these two budgets were within 3%. The predicted soil water distribution profiles were also similar (see Fig. 2), but the 20-zone model gave a better representation of the measured wetting front.
which was necessary to locate regions of salt accumulation. The small discrepancies (between the two models) which did occur were attributed to rounding-off errors in the available water-holding capacities and the "k" coefficients of the zones. Dividing the soil into smaller sections should reduce the discretization error and provide a more accurate representation of the continuous soil column.

The EC<sub>s</sub> distribution profiles predicted by the 20-zone model were of similar shape and magnitude as the measured ones throughout the experiment (Figs. 3, 4 and 5). A leached upper zone was underlain by a salt accumulation zone, and the maximum salt concentrations were predicted to occur near the wetting front. Some salt surface crust was predicted at the end of the experiment for all treatments in contrast to measured values.

Good agreement between predicted and measured salt redistribution profiles was obtained during the first half of the experiment (see for example days 20 and 42). During the last half of the experiment, however, the predicted EC<sub>s</sub> in the upper part of the columns were lower than the measured ones, whereas the reverse was true in the lower part of the columns. Part of this discrepancy might be explained by the fact that salt redistribution within the profile was assumed to result solely from mass flow while diffusion was ignored. Although salt diffusion coefficients are generally small, it is conceivable that over longer periods the high salt concentration gradients across the wetting zone caused salt to diffuse back toward the upper part of the columns. This would decrease concentrations in the wetting front portion of the columns and increase concentrations in the upper part of the columns.

**CONCLUSION**

The application of water to a uniform saline-sodic soil column resulted in the formation of a desalinized zone underlain by a salt accumulation zone. For a given total application of water, greater leaching of salt and more efficient use of water was accomplished when the water was applied in larger amounts per application (i.e. at increased intervals). The peak salt concentrations coincided with the wetting front.

The soluble salt mixing concepts of Burns (1974) were successfully incorporated into the VSMB of Baier et al. (1979). The predicted EC<sub>s</sub> redistribution profiles compared well with the measured ones during the first half of the experiment. The discrepancies which occurred toward the end of the experiment were thought to be related to the assumption that salt diffusion was negligible. The results suggest that this empirical simulation model has considerable potential for assessing the feasibility and predicting the proper water management practice for reclaiming salt-affected heavy clay soils for irrigated agriculture. Clearly more elaborate field investigations are required to establish the range of applicability of this model and to con-
firm the relevance of the laboratory results to field conditions.

ACKNOWLEDGEMENTS
We wish to express our gratitude to Professor E. de Jong (Saskatoon) for valuable discussion during the planning stage of this research. One of us (M.A.M.) gratefully acknowledges the International Development Research Centre for the Research Associate Award, without which this research would not have been possible.

REFERENCES