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Salt Distributions in Cracking Soils and Salt Pickup by Runoff Waters

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Abstract: Detailed measurements were made of the levels and distributions of salts present in representative soil profiles and fields and associated tailwaters in the Imperial Valley of California. The findings showed that the potential salinity-pickup hazard may be greater in this valley that is dominated by cracking soils than classical theory would predict. Salts that would otherwise be "isolated" in seedbeds or leached downward during irrigations are more "exposed to" and "picked up by" the runoff water than previously recognized as a result of the flow of the irrigation water throughout the beds and horizontally in the topsoil via the extensive network of cracks and fractures that form in the cracking soils. As a result, the pattern of salinity within the beds of such soils is one-dimensional, rather than the expected, classical two-dimensional pattern. Salt content in the tailwater associated with cracking soils was higher and sustained over longer periods of time than in the case of noncracking soils.

INTRODUCTION

Water is a valuable and scarce resource in arid and semiarid regions where a high percentage is used for irrigation. Runoff of irrigation water ("tailwater") is a common phenomenon from fields irrigated by gravity-flow surface systems. The minimization and the utilization of tailwater is a requisite to the efficient use of water resources for such systems.

Positive utilization of tailwater could include: reuse for irrigation (for the same or other fields), return to surface streams, the creation of wetlands, etc. In the Imperial Valley of California, tailwater drainwater is comingled with the subsurface drainwater and discharged to the Salton Sea. Although some runoff to the sea may be considered beneficial to the maintenance of a suitable elevation and salinity of the sea, excessive runoff in the past has contributed to a rising sea level with negative consequences to surrounding agricultural land and recreational facilities.

One means of reducing runoff to the sea is to install tailwater recovery systems, whereby the water is recirculated on the same field or farm. Generally the value of the "conserved water" will not justify the costs of the recovery system unless fees are imposed against excessive discharges. Because the economic value of water is higher for urban use, and water supplies in California are limited, there is opportunity for a mutually beneficial cooperative agreement between agricultural and urban sectors in this regard. The urban sector can pay for the tailwater recovery system in return for receiving water in an amount equivalent to that conserved.

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Such an arrangement has been considered for implementation in the Imperial Valley. However, salinity is an old nemesis there and the farmers are concerned that salinity levels will increase unduly in their soils through the recycling of tailwater for irrigation. The source of water for irrigation is the Colorado River, which has an electrical conductivity (EC) of about 1.3 dS/m. Prevalent "textbook logic" would lead to the conclusion that salt pickup via tailwater flow should be negligible because the "leading edge" of the water that flows over the soil is thought to infiltrate into the soil and to "carry" the readily soluble salt with it. The salt in the soil is not expected to diffuse upward significantly when the water is percolating downward. With this prevalent view of the transport processes, one would not expect to find a significant increase in the salinity of the tailwater compared to the irrigation water other than that which might be derived from the dissolution of suspended sediment gained through furrow erosion. Such were the conclusion and findings of the study of Reeve et al. (1955) into the potential to reclaim saline soils in the Coachella Valley of California by "flushing."

However, one can envision situations where salt could be accumulated in the seedbed region of the soil through convective and capillary flow during early season periods and subsequently exposed to surface flows and redissolved in them when the "integrity" of the bed fails due to soil cracking and fracturing and when the infiltration rate of the furrows is diminished later in the irrigation season as the result of sedimentation and crusting. Most theory and research about salinity transport has been directed to vertical leaching of salts and little attention has been given to the lateral transfer of salts in surface runoff, especially regarding soils of various shrink-swell capacities. In any case, some Imperial Valley farmers were concerned about the possibility of excessive salinity buildup in their soils from recycling of tailwater. For these reasons, this study was undertaken. It was carried out in a set of commercial fields in Imperial Valley selected by local staff of the Imperial Irrigation District to be representative of major soil types, including those with varying shrink swell properties, though much of the area consists of soils that crack considerably upon drying. It was postulated that the dynamic salt transport would be significantly different on soils that have high shrink-swell properties from those without these properties. The study had two goals. One was to measure salinity in the soil and runoff water to obtain evidence of the extent of and the potential for salt pickup in tailwater and of the influence of soil properties in this regard. The other was to obtain information on the dynamics of salt transport in cracking and noncracking soils so that the feasibility of tailwater recycling could be assessed more reliably.

EXPERIMENTAL PROCEDURES

Nine fields were selected to include a representative set of soil and crop types for the Imperial Valley. The crops selected for investigation were sugar beets (flat beds; furrow-irrigated), border-irrigated alfalfa (no beds), and furrow-irrigated alfalfa (flat beds). For each cropping system, three fields were selected to vary shrink-swell characteristics and to evaluate their effects; one with clay textured soils, one with sandy soils, and one of intermediate texture. The soil classifications for each of the investigated fields are presented in Table 1. The terms "heavy," "medium," and "light" refer to the relative clay content and the expected degree of cracking. Thus, the soil identified as being heavy is one that exhibits high shrink-swell properties, whereas the light soil exhibits relatively little shrink-swell behavior. By employing these nine fields, the effects of beds could also be evaluated along with variation in the soils' shrink-swell properties. The irrigation and other management of these fields were routinely carried out by the farmers. We only monitored the salinity conditions of the soils and tailwaters. A bromide tracer study was conducted on two of the fields and the details of that study are reported elsewhere (Shouse et al. 1997).

Surface water samples were collected during two to five irrigations of one cropping season at the head of each field and at points one-fourth, one-half, three-fourths, and the end of the field. At each sampling point, except the head of the field, water samples were collected when the leading edge (LE) of the water reached the point and then at 5, 15, and 30 min after the leading edge had passed the point. The EC of all samples was measured using a standard, temperature-compensating conductivity meter as an index of the water salinity.

Soil salinity conditions in the soil profiles and beds from the head to tail ends of the nine fields were established using the instrumental methodology and mobilized systems of Rhoades and colleagues (Rhoades 1992, 1993, unpublished paper 1994). Measurements of soil electrical conductivity were obtained along a six-row-wide traverse in each furrow-irrigated field about every meter using a tractor-mounted, mobile, four-electrode system. These measurements were made for two such transects separated by 8 m in the furrow-irrigated alfalfa fields. Only one transect was made in the sugar beet fields. Analogous measurements were not made in the border-irrigated alfalfa fields to avoid damaging the crop. These data were acquired to determine the trend of average root zone salinity in relation to distance along the path of irrigation. Additional measurements of electrical conductivity were made in the furrow-irrigated fields at sites every 5–10 m along the transects with a mobile, combination electromagnetic-induction/four-electrode system and, in the border-irrigated fields, using hand-held sensors. Exact site spacing varied depending on transect length.

Soil samples were acquired at nine sites in each field. These data, together with the analyses of the soil samples, were acquired to determine the distribution of salinity within various two-dimensional regions of the seedbed and throughout the rootzone to a depth of 1.2 m. Soil salinities were determined for the samples using the laboratory paste procedure of Rhoades et al. (1989). In the six furrow-irrigated fields, three "soil cores" were acquired at each sampling site; one core was centered on the bed, one was centered on the furrow, and one was centered intermediately between the other two. Within the three border-irrigated fields only one "core" was acquired at each sampling site. In all cores, soil samples were obtained from the following depth increments: 0–15, 15–30, 30–45, 45–60, 60–90, and 90–120 cm. This produced 162 soil samples from the furrow-irrigated fields and 54 soil samples from the border-irrigated fields. The soil samples were used as "ground truth" to calibrate the instrumental sensors individually for each field condition using the spatial regression modeling techniques of Lesch et al. (1992, 1995a, 1995b). A user-friendly software package is available in this regard and additionally for portraying the results in maps and various other graphical forms (Lesch et al. 1995c).

TABLE 1. Description of Fields and Soils Used in Study

Crop (1)	Degree of cracking[a] (2)	Soil type and classification (3)
alfalfa (furrow-irrigated)	heavy	Imperial silty clay; fine, montmorillonitic (calcareous), hyperthermic vertic torrifluvents
	medium	Glenbar clay loam; fine-silty, montmorillonitic (calcareous), hyperthermic vertic torrifluvents
	light	Holtville silty clay loam; clayey over loamy, montmorillonitic (calcareous), hyperthermic vertic torrifluvents
alfalfa (border-irrigated)	heavy	Imperial-Glenbar silty clay loam
	medium	Vint loamy very fine sand loam; coarse-loamy over clayey, mixed (calcareous), hyperthermic typic torrifluvents
	light	Meoland very fine sandy loam; coarse-loamy over clayey, mixed (calcareous), hyperthermic typic torrifluvents
sugar beets (furrow-irrigated)	heavy	Imperial-Glenbar silty clay loam/Imperial clay
	medium	Imperil-Glenbar silty clay loam/Imperial silty clay
	light	Rositas fine sand; mixed, hyperthermic typic torripsamments

[a]Based on shrink-swell potential ratings provided in the classification of the soils of the Imperial Valley (Zimmerman 1981).

RESULTS AND ANALYSIS

Soil Measurements

For eight of the nine fields studied, high correspondence was observed between measured and sensor-predicted salinity values (r^2 levels of 0.84–0.98). These results (not given) suggest that the salinity distributions obtained with the sensor-measurement/regression methodology employed reflected the true nature of the salinity levels, patterns, and distributions across each survey-transect and that the data basis for the interpretations that follow is reliable. The exception was the furrow-irrigated field of medium soil texture, for which the sensor and ground truth data did not correlate well, possibly due to complex changes in soil type within the profile and across the field or, more likely, an instrument glitch that occurred in that field—one that required repairs and that caused delay and confusion about the data at the time. Since no attempt was made to repeat the measurements in this field, these results will not be reported.

The average rootzone soil salinity (expressed in terms of the electrical conductivity of the saturation-paste extract, EC_e) distribution from the head (left side of figure) to the tail (right side of figure), hereafter referred to as "across the field," of the light textured, furrow-irrigated sugarbeet field is presented in Fig. 1. Though the salinity is somewhat higher in the upper one-third of the field, it is relatively low and uniform across the field. The EC_e values ranged from about 1.3 to 2.0 dS/m. These data suggest that considerable leaching occurred relatively uniformly across the field to produce low levels of soil salinity. The ratio of EC_e/EC_{iw} for this field is equivalent to a leaching fraction of about 0.25–0.30, assuming steady-state conditions and an irrigation water electrical conductivity value, EC_{iw}, of 1.3 dS/m for Colorado River water (Rhoades et al. 1992).

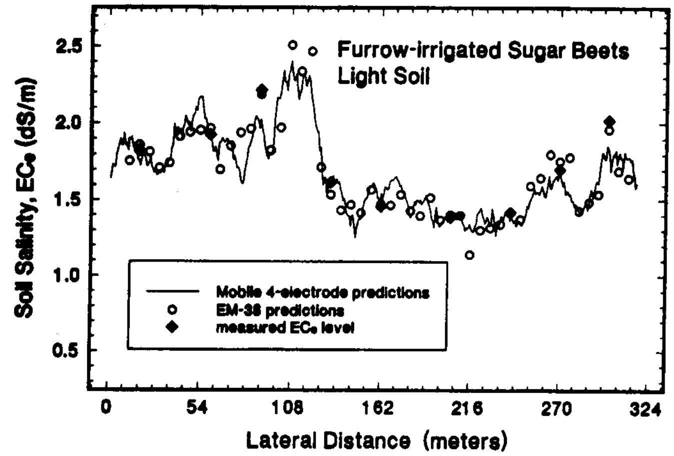

FIG. 1. Relation between Soil Salinity and Distance along Traverse Made across Furrow-Irrigated Sugar Beet Field with Light-Textured Soil

The cross-sectional distribution of salinity within the bed-furrow region of the soil of the furrow-irrigated, light textured sugar beet field is depicted in Fig. 2. This distribution is the classical one depicted in text books wherein soil salinity is lowest beneath the furrow and increases symmetrically towards the center of the bed and with depth. Such a distribution is expected from the flow of irrigation water out of the furrow into the center of the bed, the accumulation of salt in the top of the bed through leaching and evaporation processes, and the increase in salinity with depth through the interactions of leaching and water use by crop transpiration. The salinity level within the bed of this field is low and should not limit seedling establishment of any crop, even salt-sensitive ones (Maas 1990).

The level of average soil salinity increased from the head to the tail of the medium textured sugar beet field (see Fig. 3). The level of salinity in this field is higher than that observed in the analogous light textured field. The EC_e values ranged from about 7 to 12 dS/m; the corresponding leaching fraction would be less than 0.1. The average cross-sectional pattern of salinity in this field is shown in Fig. 4. The salinity distribution across the bed in this soil deviates from the classical distribution. While there is some salinity buildup in the edges of the bed, there is relatively little accumulation of salts in the center of the bed compared to the analogous light textured soil; rather the pattern is indicative of a vertically increasing distribution (one-dimensional pattern).

As the mean salinity of the soil profile increased across the field (Fig. 3), there also occurred a deterministic redistribution of salinity within the specific depths of the profile. The relative shifts observed in this regard are shown in Fig. 5 in terms of the relative change in salinity per every 100 m of distance across this field traverse, as referenced to the mean distribution for the traverse. These results show that while the average salinity in the profile increased across the field, the salinity in the top 0.5-m depth increased relatively more rapidly and that below 0.5 m increased more slowly with respect to the mean profile of the entire traverse. These results imply that as the

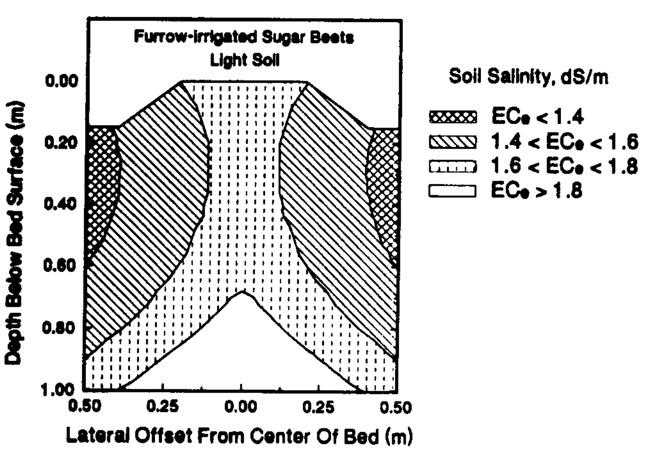

FIG. 2. Average Two-Dimensional Distribution of Salinity within Furrow/Bed Environment of Traverse Made across Furrow-Irrigated, Sugar Beet Field with Light-Textured Soil

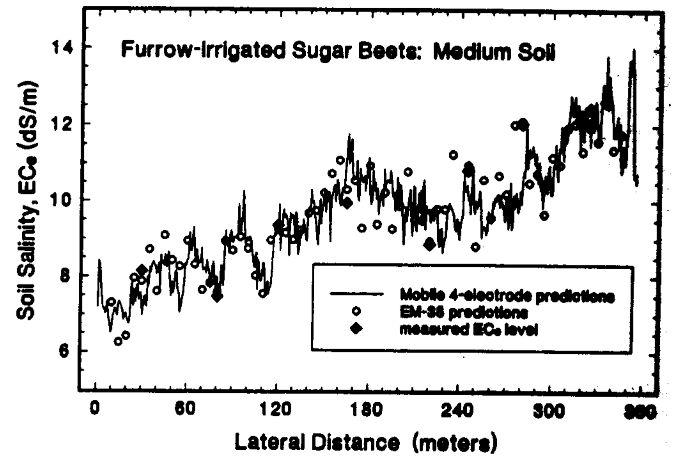

FIG. 3. Relation between Soil Salinity and Distance along Traverse Made across Furrow-Irrigated, Sugar Beet Field with Medium-Textured Soil

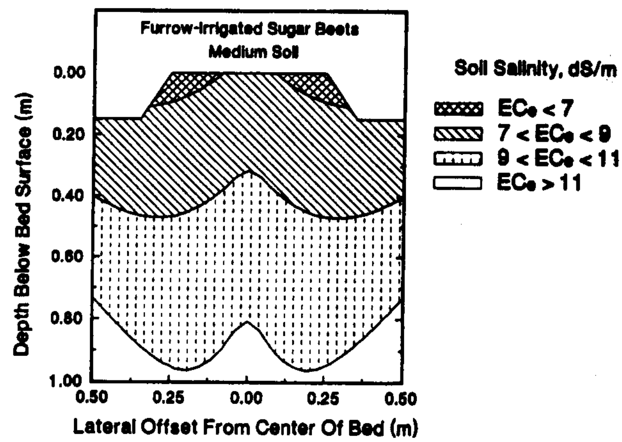

FIG. 4. Average Two-Dimensional Distribution of Salinity within Furrow/Bed Environment of Traverse Made across Furrow-Irrigated, Sugar Beet Field with Medium-Textured Soil

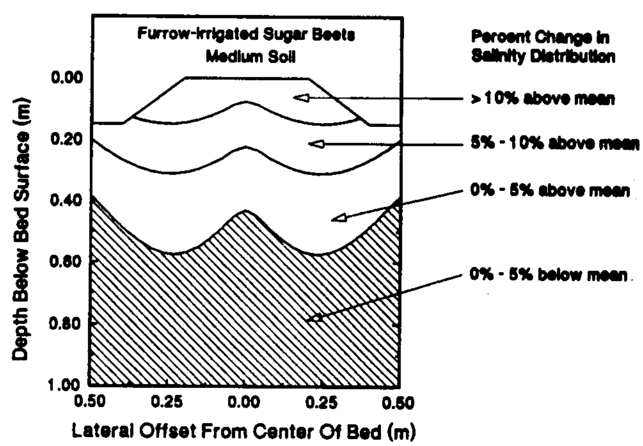

FIG. 5. Relative Changes (Percentage Basis) in Distribution of Salinity, with Reference to Mean Profile, within Soil Profiles Every 100 m along Traverse Made across Furrow-Irrigated, Sugar Beet Field with Medium-Textured Soil

mean salinity increased, relatively more of the salts tended to be concentrated near the soil surface compared to greater depths in the profile. Thus a lateral translation of salts from the head to the tail end of the field appears to have occurred in this medium textured sugar beet field.

Results analogous to that depicted for the medium-textured field in Figs. 3–5 are shown in Figs. 6–8 for the analogous, heavy textured sugar beet field. The mean profile salinity for this field was relatively uniform through the first 350 m; thereafter it decreased and then steadily increased to the tail end of the traverse (Fig. 6). This field had previously been irrigated as two separate fields of about 400 m each in length. Only in the last few years had the separation been eliminated and the field irrigated as one entity 800 m in length. Thus the observed salinity pattern is still indicative of the previous management/field situation. The level of mean salinity is a bit higher in this field than it was in the analogous, medium textured sugar beet field. The EC_e values ranged from about 9–15, indicating a leaching fraction of less than 0.1. The average cross-sectional pattern of salinity observed in this field traverse (Fig. 7) shows that it is, unlike the classical one, entirely one-dimensional and without the appearance of any furrow/bed influence. The level of salinity found in the average bed of the heavy textured sugar beet field would be too high for good stand establishment, as well as too high for good crop growth, of many crops other than salt-tolerant ones. As was the case with the medium textured sugar beet field, the soil salinity tended to redistribute upwards (within the profile) from the head to the tail of the analogous, heavy textured field (Fig. 8).

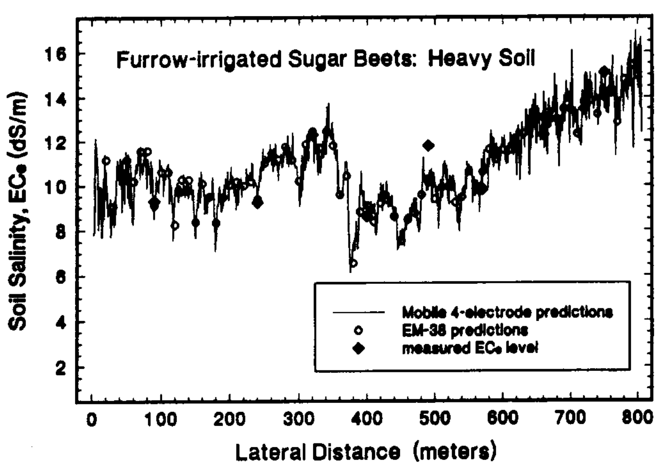

FIG. 6. Relation between Soil Salinity and Distance along Traverse Made across Furrow-Irrigated, Sugar Beet Field with Heavy-Textured Soil

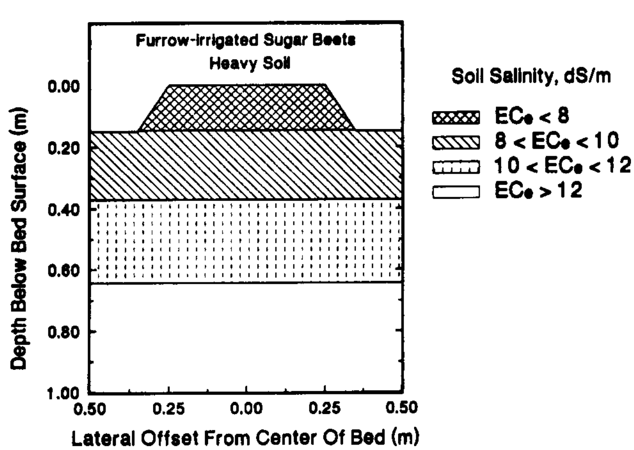

FIG. 7. Average Two-Dimensional Distribution of Salinity within Furrow/Bed Environment of Traverse Made across Furrow-Irrigated, Sugar Beet Field with Heavy-Textured Soil

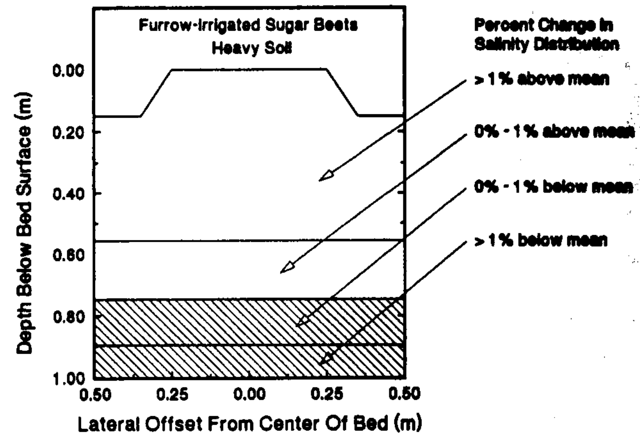

FIG. 8. Relative Changes (Percentage Basis) in Distribution of Salinity, with Reference to Mean Profile, within Soil Profiles Every 100 m along Traverse Made across Furrow-Irrigated, Sugar Beet Field with Heavy-Textured Soil

In summary, these data show that soil type markedly affects salinity levels and distributions within the soil profiles of furrow-irrigated sugar beet fields of the Imperial Valley in a very deterministic way. Salinity was relatively low and uniform across fields of light textured soils, suggesting considerable leaching throughout these fields. The salinity accumulation patterns observed within the bed/furrow environment of these fields was of the classical type, with salts increasing towards the center and top of the bed. Average salinity was much higher in analogous, medium textured fields and it was the highest in heavy textured fields. For these types of soils, mean salinity increased towards the tail of the field with a concurrent trend toward redistribution of salt from the lower part of the profile to the top part with distance across the field. The salinity accumulation pattern within the beds of these fields was not of the classical type; rather the pattern was one-dimensional with salinity increasing uniformly with depth beneath both the furrow and bed.

The mean levels of salinity in the soil profiles across the border-flooded, light textured alfalfa field ranged between about 1.0 and 2.5 dS/m, those of the analogous, medium textured field ranged between 2.5 and 5.0 dS/m, and those of the heavy-textured field ranged between 5.0 and 13.0 dS/m. The trend of mean salinity in the soil profile observed across the latter field is shown in Fig. 9. The increase in salinity from the head to the tail observed in this field, like that observed in the other fields with medium and heavy textured soils, re-

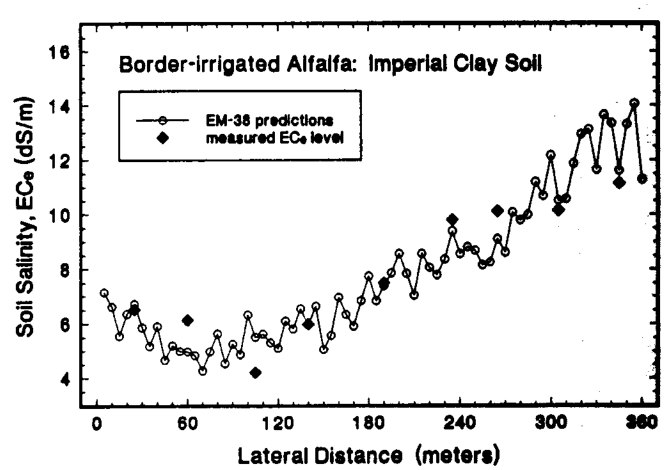

FIG. 9. Relation between Soil Salinity and Distance along Traverse Made across Border-Irrigated, Alfalfa Field with Heavy-Textured Soil

flects the interaction of nonuniformity of water infiltration and leaching and the lateral transport across the field of salts picked up from shallow soil depths. If the field was uniform in soil properties, was irrigated uniformly throughout, and lateral transport did not occur, the mean salinity should be uniform across the field. The areas between the curve shown in Fig. 9, with respect to a straight line set at a value equal to the mean for the entire traverse, provides a measure of the nonuniformity of irrigation/leaching/transport across the field. From such evaluations, we concluded that infiltration uniformity was poor for all of the medium and heavy textured fields studied in the Imperial Valley.

The same trend of relative salinity increasing towards the top of the profile with distance from the head to the tail of the field previously described for the medium and heavy textured, sugar beet fields was also observed in the analogous alfalfa fields. While no bed/furrow patterns existed in the border-flooded alfalfa fields, they did in the furrow-irrigated alfalfa fields, and these patterns were essentially the same as those previously described for the sugar beet fields. These data, as well as the rest of the results obtained in the other five alfalfa fields studied, are not presented since their patterns and trends are similar to the data already presented.

TABLE 2. Differences in Irrigation Water Salinity (dS/m) from Head to Tail of Run

Date (1)	LE[a] (2)	LE + 5[a] (3)	LE + 15[a] (4)	LE + 30[a] (5)
(*a*) Sugar beets				
Light soil				
3/8	0.12	0.09	0.08	0.09
4/8	0.18	0.18	0.17	0.16
11/23	0.12	0.07	0.08	0.07
Medium soil				
2/17	0.42	0.34	0.25	0.23
5/12	0.54	0.30	0.27	0.25
9/14	0.95	0.21	0.13	0.09
Heavy soil				
2/24	0.91	0.93	0.91	0.86
11/5	1.37	0.56	0.52	0.50
(*b*) Alfalfa—border irrigated				
Light soil				
3/22	0.41	0.20	0.22	0.20
7/13	0.48	0.22	0.05	0.05
8/20	0.41	0.18	0.11	0.10
Medium soil				
3/11	0.33	0.01	−0.04	−0.05
Heavy soil				
3/17	0.18	0.11	0.08	0.03
7/10	2.73	0.98	0.86	0.48
8/17	1.31	0.78	0.51	0.40
(*c*) Alfalfa—furrow irrigated				
Light soil				
3/10	0.12	0.10	0.08	0.08
7/14	0.40	0.20	0.15	0.10
8/20	0.33	0.19	0.07	0.07
9/20	0.40	0.21	0.14	0.11
10/20	0.95	0.09	0.05	0.01
Medium soil				
3/11	0.27	0.19	0.17	0.16
7/14	0.40	0.14	0.11	0.10
8/20	0.29	0.13	0.10	0.10
9/20	0.27	0.12	0.09	0.09
10/20	0.31	0.14	0.11	0.10
Heavy soil				
7/23	0.87	0.23	0.21	0.19
8/15	1.78	0.87	0.73	0.70

[a]LE is leading edge and + indicates minutes following passage of the leading edge.

Water Measurements

Water sample data from the tail end of each field are shown in Table 2. These data are given in terms of the increases in electrical conductivity observed in the tailwaters, with respect to the applied irrigation water, in the LE and at 5, 15, and 30 min after the runoff had reached the end of the field.

The EC of the LE of the tailwater was always higher than that of the irrigation water and the amount of the increase was, in general, substantially more in the case of the heavier textured soils. For the latter soils, the EC of the LE of the tailwater was double or more that of the irrigation water. The analogous increase for the medium textured soils was usually intermediate between that of the light and heavy textured soils and was somewhat more variable in this behavior. The EC of the tailwater collected 5 min after the passage of the LE was typically substantially lower than that observed in the LE and was relatively constant or slowly decreasing thereafter. For example, on July 10 the EC of the initial runoff from a heavy textured soil, border-flooded alfalfa field was 2.73 dS/m higher than the water applied to the field. Although the EC of the subsequent runoff decreased with time, the increase in EC of the tailwater compared to the irrigation water was 0.98, 0.86, and 0.48 dS/m after 5, 15, and 30 min of runoff, respectively. For the heavy textured soils, the relative increase in the EC of the tailwater from the furrow-irrigated fields was often still very high (~0.5 dS/m or greater) after 30 min of continuous runoff.

The amount of salt pickup in the tailwater tended to increase over the irrigation season, especially in the case of the heavy textured soils and the border-irrigated alfalfa field. For the latter soil/field, very little pickup occurred in the March irrigation, whereas very high increases in EC were observed in the July and August irrigations. We speculate that these differences in seasonal effect are caused by the drier and more cracked conditions of the soil existing during the summer period.

CONCLUSIONS

Salinity conditions observed in the selected irrigated fields and associated tailwaters of the Imperial Valley were consistently related to soil type, as were the spatial trends of soil salinity within and across the fields. Salinity increases observed across the fields with heavy textured soils show that irrigation/leaching is markedly nonuniform across such fields, possibly reflecting the major attempt in the Imperial Valley in the recent past decade to reduce irrigation runoff, as well as the phenomenon of lateral solute transport. The magnitude of the salinity levels observed in the medium and heavy textured soils, especially in the lower sections of the selected fields, would be expected to result in substantial losses in alfalfa yield and in significant losses in the yields of sugar beets and other such relatively salt-tolerant crops. The excessive levels of salinity in the lower sections of the fields with heavy textured soils indicate insufficient water application/leaching is being achieved in these areas/fields with prevalent management practices to achieve optimum crop production.

The concentration of salt in the irrigation water increased as it flowed across the field. The increase, however, was much greater for the heavy textured soils, which exhibit large cracks and fractures. We conclude that substantial amounts of salt can be picked up by such lateral flowing water from highly cracking soils and discharged in the tailwater, though the actual amounts could not be quantified in this study since the runoff volumes were not determined. This inference is supported by the very large increases observed in the tailwater ECs, as compared to the EC of the applied water. Increases in EC of 0.5 dS/m or more were almost always observed in the tailwaters emanating from heavy textured soils. Such increases in EC cannot be explained by evaporation of the water as it flows across the field.

The average profile salinities of the heavy textured Imperial Valley soils were always considerably higher in the tail end portions of the fields compared to the upper sections, and the salinity levels were proportionally higher in the shallow soil depths in the tail end of the fields compared to the upper end. While absolute levels of salinity were always higher in the heavy textured soils compared to the light textured soils, accumulations of salt were not found within the beds of the former furrow-irrigated soils as they were in the analogous light textured ones. These data imply that, as the result of cracking, the salts that otherwise would be expected to accumulate in the beds have been removed as the irrigation has flowed through the beds via the network of fractures and cracks that form during the drying of such heavy textured soils between irrigation events. Whereas classical two-dimensional distributions of salinity were observed in the furrow/bed environment of the light textured soils, only one-dimensional patterns were observed for the heavy textured soils. The fact that salinity increased more rapidly in the upper part of the soil profile compared to the lower sections of the fields of heavy textured soils suggests that significant horizontal salt transport occurred from the head to the tail of such fields.

Thus prevalent concepts of salt movement and leaching described in typical textbooks do not apply to highly cracking soils—certainly not those that dominate the Imperial Valley of California. Similar heavy textured swelling/cracking soils are found in the many other irrigated lands of the world, such as the Nile Delta of Egypt. The leaching patterns of such soils are dictated by the dynamic flow of water in the network of cracks that exist within and throughout the beds. The water that "drops" into the cracks moves horizontally at the bottom of the cracks, gradually filling up to the surface. This process, over time, causes a horizontal and upward transport of salt across the field. The salinity assessment technology of Rhoades and colleagues used in this study is well suited to establishing the levels and patterns of soil salinity within soil profiles and fields and to the evaluation of the adequacy/suitability of irrigation/drainage management of fields with respect to salinity control and to the evaluation of irrigation uniformity. A complementary bromide tracer study undertaken along with this study confirms these conclusions and is reported elsewhere (Shouse et al. 1997).

APPENDIX. REFERENCES

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