1480

Proc. Intl. Symp. on Development of Basic Technology for Sustainable Agriculture under Saline Conditions
December 12, 1996, ALRC. Tottori Univ., JAPAN

New Assessment Technology for the Diagnosis & Control of Salinity in Irrigated Lands

J. D. Rhoades

U. S. Salinity Laboratory, USDA-ARS, Riverside, Calif., USA

Abstract

A practical methodology for appraising soil salinity and assessing the adequacy and appropriateness of irrigation, drainage and salinity-control systems and practices is described. This methodology is based upon the use of geophysical-instrumental systems for intensively measuring bulk soil electrical conductivity within irrigated fields/rootzones and associated spatial coordinates, algorithms for multi-linear regression data analysis and sensor calibration, and methods for selecting measurement-sites and obtaining salinity ground-truth. The technology package is unique and represents a breakthrough in our ability to rapidly and accurately assess soil salinity in irrigated lands. Results are presented to demonstrate the utility of the technology along with evidence supporting the conclusion that much of the apparent chaos observed in the spatial pattern of soil salinity in irrigated fields is man-induced and explainable in terms of deterministic processes caused by such management practices as irrigation, drainage, cultivation and tillage.

Key Words: salinity, irrigation, management, land degradation

I. Introduction

The achievement of efficient irrigation and effective salinity control requires periodic information of soil salinity levels and distributions within the crop rootzones and fields of the project, in order to diagnose and inventory conditions of soil salinity, to assess the adequacy of leaching and drainage and to guide management decisions. In addition, practical procedures are needed for delineating the sources of salt-loading and for mapping the distribution and extent of drainage problem areas. More specifically, the proper management of soil and water salinity requires: 1) an adequate knowledge of the level, extent, magnitude and distribution of rootzone soil salinity in the fields of the irrigation project (a suitable inventory of conditions); 2) the ability to be able to detect changes and trends in the status of soil salinity over time and the ability to determine the impact of management changes upon the conditions (a suitable monitoring program); 3) the ability to identify salinity problems and the underlying inherent causes of the observed conditions, both natural and management-induced (a suitable means of detecting & diagnosing problems and their causes); 4) a means to evaluate the adequacy and effectiveness of on-going irrigation and drainage systems, operations and practices with respect to controlling soil salinity, conserving water and protecting water quality from excessive salinization (a suitable means of evaluating management practices), and 5) the ability to determine the areas in fields and in irrigation projects where excessive deep percolation is occurring, i.e., where the water- and salt-loading to the underlying groundwater is coming from (a suitable means of determining areal sources of pollution). I refer to the above set of measurement-related techniques and methods and the means of evaluation, as “salinity assessment”.

The achievement of an assessment technology such as the above begins with a practical methodology for measuring soil salinity in the field, which is complicated by its spatially variable and dynamic nature caused by the effects and interactions of varying edaphic factors (soil permeability, water table depth, salinity of perched groundwater, topography, soil parent material, geohyrology), management induced processes (irrigation, drainage, tillage, cropping practices), as well as by climate-related factors (rainfall, amount and distribution, temperature, relative humidity, wind). When the need for repeated measurements and extensive sampling requirements are met, the expenditure of time and effort to characterize and map a project’s salinity condition with conventional soil sampling and laboratory-analysis procedures becomes prohibitive. A more rapid, field-measurement technology is needed. Also needed is a practical to establish the spatial location of the salinity-measurement sites involved with the required large intensive and extensive data sets. Additionally, the methodology should provide a systematic strategy for evaluating management effects, as well as a means to statistically-prove changes or differences in an areas salinity condition over time.

I have undertaken the development of such a technology over a period of many years and, with the assistance of my colleagues, have essentially completed the task. It is an integrated system comprised of rapid, mobile instrumental techniques for measuring bulk soil electrical conductivity (EC_a) in the field as a function of spatial position on the landscape, procedures and software for inferring salinity from EC_a, computer-assisted mapping techniques capable of associating and analyzing spatial databases, and appropriate spatial statistics to infer salinity distributions in rootzones and trends/changes over space and time. The remainder of this text briefly describes this system with emphasis on the measurement component of it. Additionally, some examples are given to illustrate some of the applications and utility of the developed assessment technology.

II. Assessment Equipment

Two alternative kinds of mobilized, instrumental systems have been developed for purposes of field salinity measurement: one is based solely on the use of four-electrode units to measure EC_a; the other uses an electromagnetic induction sensor, either solely or together with four electrode units.

The Mobile Four-electrode Sensing In this system (see Figure l), the electrodes are combined into the "heels" of tillage shanks which, in turn, are mounted on a hydraulically controlled tool-bar attached to a tractor via a conventional three-point hitch. Soil electrical conductivity is measured "on-the-go" as the electrodes are pulled through the soil at a depth of about 10 cm as the tractor moves across the field at a speed of 1.0 to 2.5 m/sec. A Global Positioning System (GPS) antenna is positioned above the tractor cab and used with the onboard receiver to determine the spatial position of each sensor reading (the GPS unit now being used provides real time accuracies of less than one-half meter).

Figure 1. Photograph of mobile. "fixed-array" four-electrode system with GPS antenna mounted on the mast.

The EC_a and the GPS signals are sensed at adjustable frequencies (typically every second) and logged into memory for later analysis of salinity condition and spatial relations. The four-electrode conductivity meter (the Martek meter[1] used gives linear EC_a readings up to 15 dS/m, correspondingly to EC_e readings of up to 45 to 100 dS/m depending upon soil texture), the GPS receiver, their respective power supplies and their data loggers are contained in the water-tight, stainless steel box mounted behind the tool-bar shown in figure 1. The tractor operator is provided with a remote monitor (not shown) displaying time, EC_a reading and logging status. Analysis of the extensive sensor data and of a small set of soil samples for salinity (undertaken for purposes of calibration and "ground-truthing") is carried out at the side of the field in a mobile office equipped with a computer work station and analytical facilities. The latter analysis is discussed in more detail later.

Example output data obtained with the mobile, four-electrode sensing system are presented in Figure 2, which shows EC_a readings collected every second (about every 1 m apart) as the tractor moved across a furrow irrigated, tile-drained alfalfa field (clay-textured soil) in the Imperial Valley of California. The "minimum" in

1 Reference to specific products is made for identification purposes and does not imply endorsement by the United States Government.

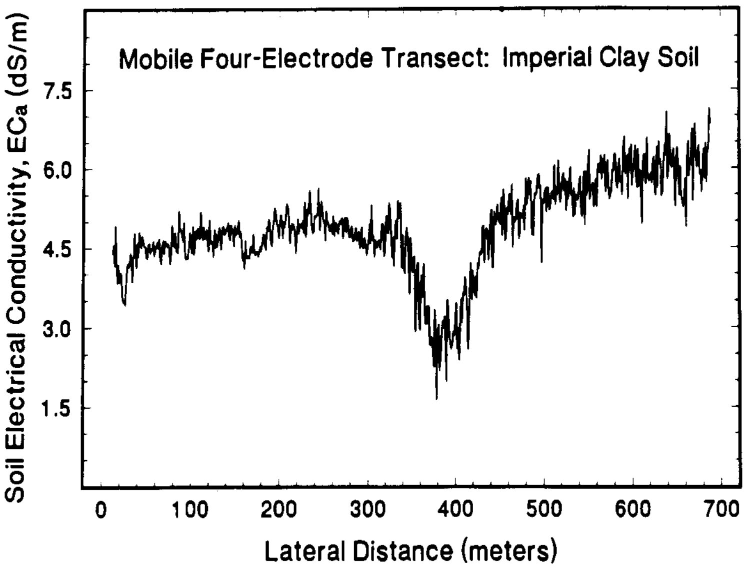
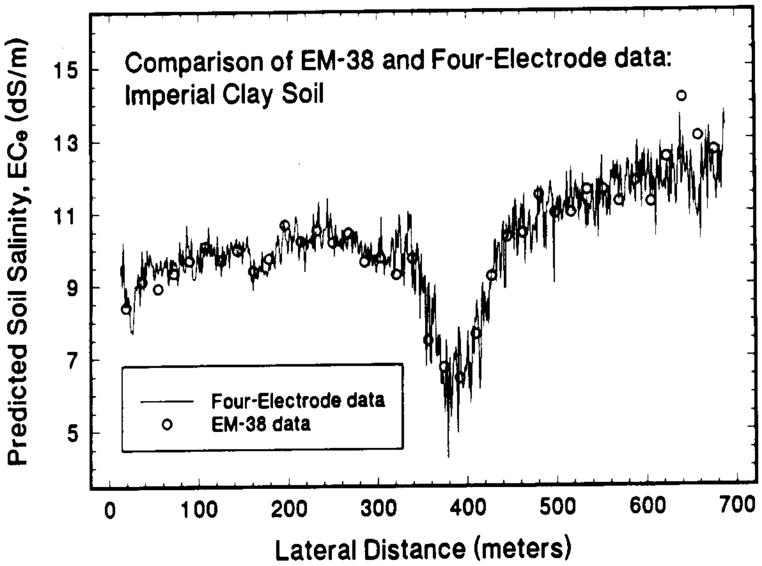


Figure 2. (Top) Relation between bulk soil electrical conductivity (EC_a) and distance along a transect across a furrow-irrigated, tile-drained alfalfa field (Imperial clay soil) located in the Imperial Valley of California.

the EC_a readings occurring at a distance of about 380 meters from the irrigation-intake end of the field corresponds to the position of a suite of subsurface drains. Otherwise, the ECa values increased toward the "tail end" of the field, presumably due to reduced application and infiltration of irrigation water with distance from the point of water delivery to the furrows. Average

Figure 3. (Center) Correspondence between soil salinity predictions (EC_e basis) based on bulk soil electrical conductivity measurements obtained by mobile, electromagnetic induction (EMH) and four-electrode systems along a transect across a furrow-irrigated, tile-drained alfalfa field (Imperial clay soil) located in the Imperial Valley of California.

rootzone soil salinities on a laboratory, soil sample-saturated extract basis (EC_e), as predicted from the measured EC_a values along the transect, are shown in Figure 3. Also shown are salinities predicted from the EM-sensor system to be discussed later. This figure shows that agreement between



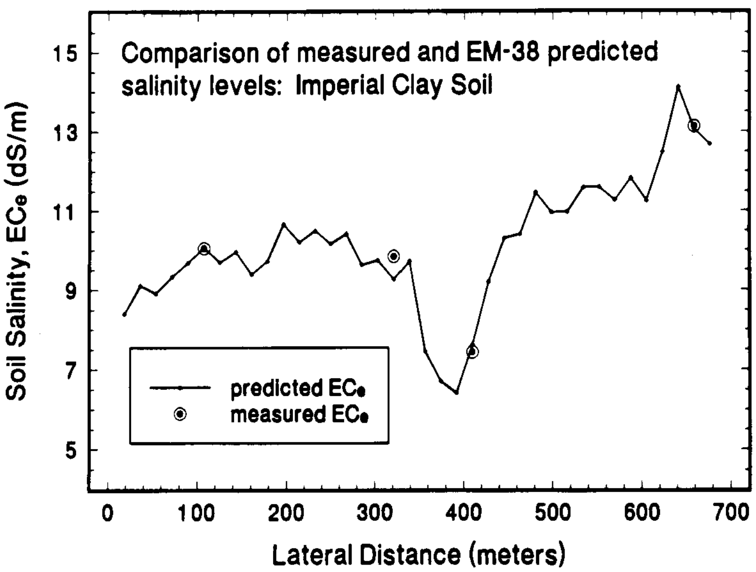


Figure 4. (Bottom) Correspondence between measured soil salinity and that predicted from electromagnetic induction in relation to the transect displayed in Figure 3.

the two methods of measurement is quite good. The accuracies of both methods of salinity prediction are also generally excellent, as may be inferred from the data presented in Figures 3 and 4. An example of a field with a much greater increase in "tail end" salinity is given in Figure 5; other examples were previously presented (Rhoades, 1992). An example of the marked effect that a subsurface drainage system can have on average rootzone salinity is given in Figure 6, in terms of EC_a. This example

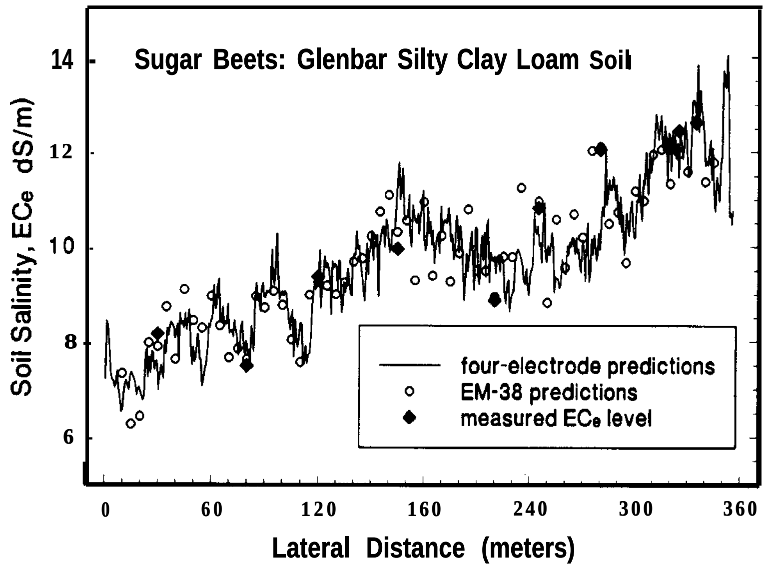


Figure 5. Correspondence between measured soil salinity and that predicted by electromagnetic induction and four-electrode data along a transect across a furrow-irrigated sugar beet field located in the Imperial Valley of California.

involves a field of silty loam soil in the Coachella Valley of California which has a subsurface drainage system. The figure shows that soil salinity levels "mimicked" the drainage system, with high values of EC_a measured in the soil located between drain-spacings and low values in the soil overlying them. The corresponding range in EC_e values was 2 to 25 dS/m. Taken together, Figures 2, 5 and 6 imply that much of the variability in average rootzone salinity observed across the studied fields is caused by the interactive, effects of the drainage and irrigation systems. The distributions of salinity observed within the rootzones of representative irrigated/drained fields will be discussed later.

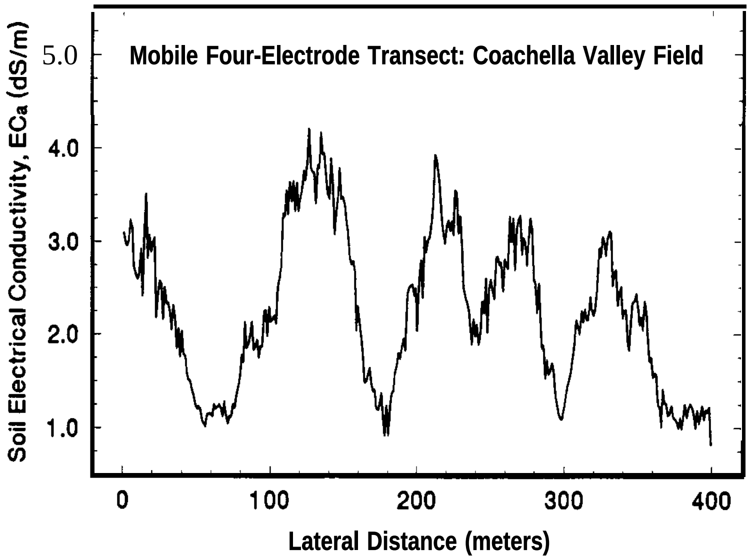


Figure 6. Relation between bulk soil electrical conductivity (EC_a) and distance along a transect crossing tile-drains in a field (silty clay loam soil) located in the Coachella Valley of California.

The Combination. Mobile Electromagnetic-Induction/Four-Electrode Sensing System: This system involves a Geonics[1], EM-38 instrument mounted in front of the transport vehicle (a modified spot-spray tractor) within a vinyl ester pipe, as well as two-sets of four-electrode arrays (having 1- and 2-m spacings between current-electrodes, respectively) mounted underneath the vehicle, as shown in Figure 7. The EM-38 mounting tube fastens to the vehicle by sliding over a short section of steel tubing. The EM-38 is secured within the vinyl ester tube by means of slotted hardwood bulkheads. All hardware within the tube is non-metallic. The tube may be removed and placed in a cradle at the back of the vehicle for long-distance travel. The "EM-tube" can be rotated.

Figure 7. Photograph of mobile salinity assessment vehicle with combined electromagnetic induction and four-electrode soil conductivity sensing systems.

to enable the EM-38 readings to be made with the magnet-coils oriented in both horizontal (EM_H) or vertical (EM_V) configurations. by means of a small gearhead DC motor and belt which operates via a non-slip cable applied to the tube. The tube and "rotator" are mounted on a hydraulic apparatus which elevates the EM-38 sensor sequentially to various heights above ground and translates it sequentially in the horizontal direction. so as to allow both EM_H and EM_V measurements to be made sequentially at various heights above both the furrow and seedbed. These changes in the height and orientation of the EM sensor are undertaken in order to alter the depth and distribution of the EM signal in the soil and. thus. to permit the determination of the salinity-distribution in the rootzone in two dimensions. The four-electrode arrays are mounted on a hydraulically operated scissor-action mechanism which includes a sensor and control mechanism to insert the probes sequentially to selected depths in the soil and to correspondingly measure EC_a at both l-m and 2-m array spacings in both the furrow and seed bed. In Fig. 6. the EM-sensor and four-electrode arrays are both in the "up". or "travel". position.

An automated control system was developed to carry out the sequence of 52 operations involved in the full range of possible sequential "EM-38 and four-electrode" measurements. The control system is based upon switches and relay logic with auxiliary electronic timing. The control system is operated via an interface control panel with enable-buttons for activating EM and four-electrode sensor measurements and a selection switch for positioning the sensors over (and at various heights above for the EM sensor) the furrow and seed-bed. When the EM button is enabled. the EM sensor is rotated to the vertical (EM_V) configuration and the carriage moves both the EM and four-electrode sensors to the selected position (e.g.. above the furrow or seed-bed). The EM "start" button then initiates the following automated sequence: 1) the EM_V reading is made and a selectable delay (usually 1 .5 sec) is provided for data logging, 2) the EM-38 sensor is rotated to the horizontal position: 3) the EM_H reading is made and logged after the selected delay interval, and 4) the EM-38 sensor is rotated back to the vertical position. This sequence is repeated for each Y-Z position selected. Depressing the four-electrode "start" button initiates the following automated sequence: 1) the scissors apparatus probes to the first depth limit. 2) EC_a is measured at the l-m array spacing. 3) a delay is provided for data logging at the l-m spacing. 4) the meter/logger is switched to the 2-m array, 5) EC_a is read after a delay at the 2-m array spacing. 6) a delay is provided for data logging at the 2-m spacing. 7) the probes are inserted to the next depth limit (up to 5-depths are possible). and 8) steps 2-6 are repeated. After completion of the last logging, the scissors apparatus lifts the electrodes from the soil and stores them in the travel position. A small printed circuit board provides the necessary time delay functions. The mobile unit then moves to the next measurement site (stop). All measurements at each site can be made in about 30-45 seconds. A Cooperative Research and Development Act contract has been developed with AG Industrial Manufacturing Inc. 1 of Lodi, California to commercialize this system. For more on the engineering and design of this system. see Carter, et. al. 1993.

Some example results obtained with the combined EM-38/four-electrode system were shown in Figures 3. 4 & 5: others follow. With this equipment. salinity distributions within the rootzone can be inferred. To illustrate. the average two-dimensional pattern of salinity in the soil profiles of the transect of Figure 2 are shown in Figure 8. This figure shows that salinity in the center of the seed-bed of the fine-textured soil is not as high as might be expected. A likely reason for this is the presence of an extensive network of cracks and fractures within

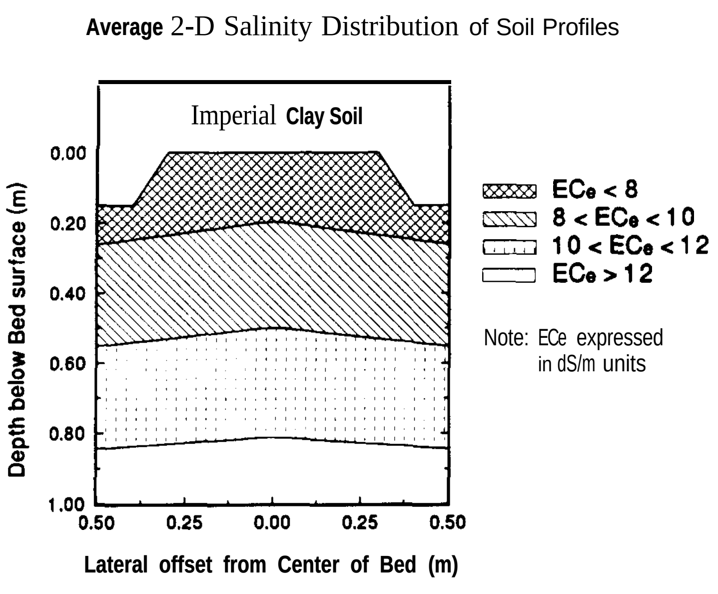
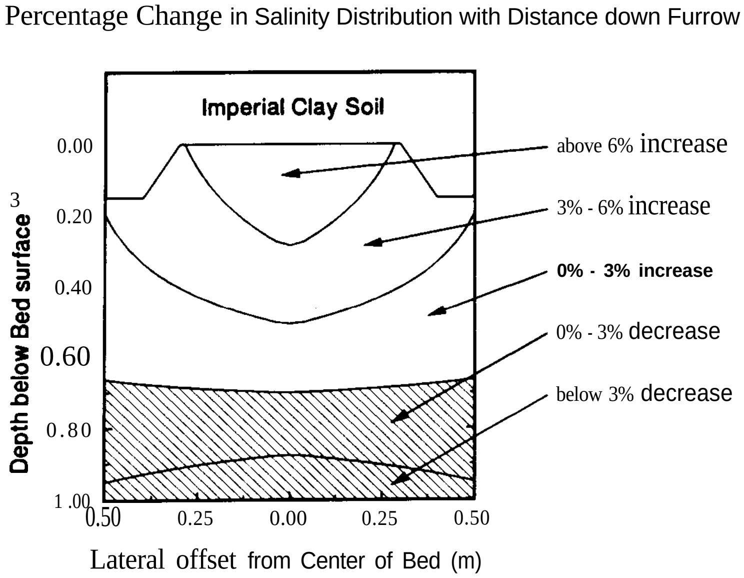


Figure 8. Average two-dimensional distribution of salinity in the soil profiles along a transect across a furrow-irrigated. tile-drained alfalfa field (Imperial clay soil) located in the Imperial Valley of California.

Figure 9. Relative changes (percentage basis) in distribution of salinity. with reference to the mean profile. within soil profiles every 100 meters along the traverse made across the furrow-irrigated. alfalfa field (imperial clay soil) located in the Imperial Valley of California.



the bed which allowed water movement through it, especially in the later stages of the irrigation season. This "inter-flow" likely leached out salts which otherwise would have accumulated by capillarity and upward flow in the bed, if it was completely isolated from the furrows. The patterns of salinity within the soil profiles were very similar at various points along the transect; however, in relation to the average profile shape, salinity increased in the upper part of the profile and decreased in the lower part of the profile withdistance towards the down gradient end of the furrow-irrigated field (see Figure 9). The data in Figures 8 and 9 show that the pattern of salinity within the bed and throughout the soil profile varied systematicallyin this field in

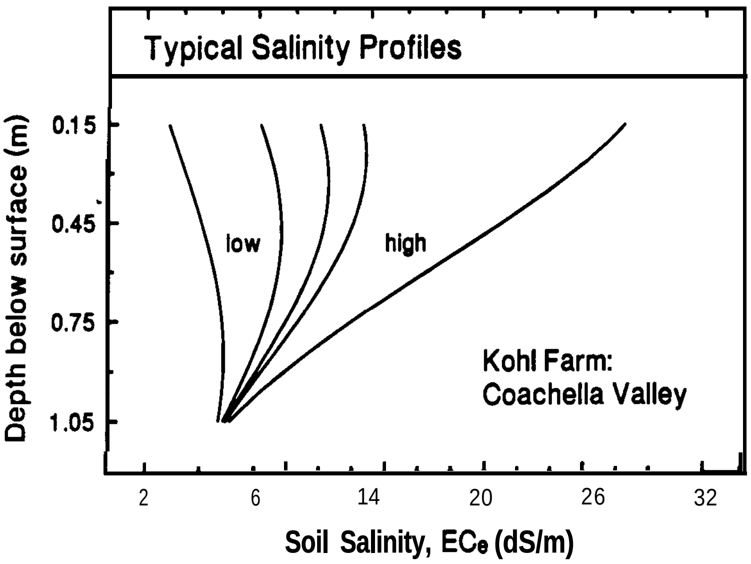
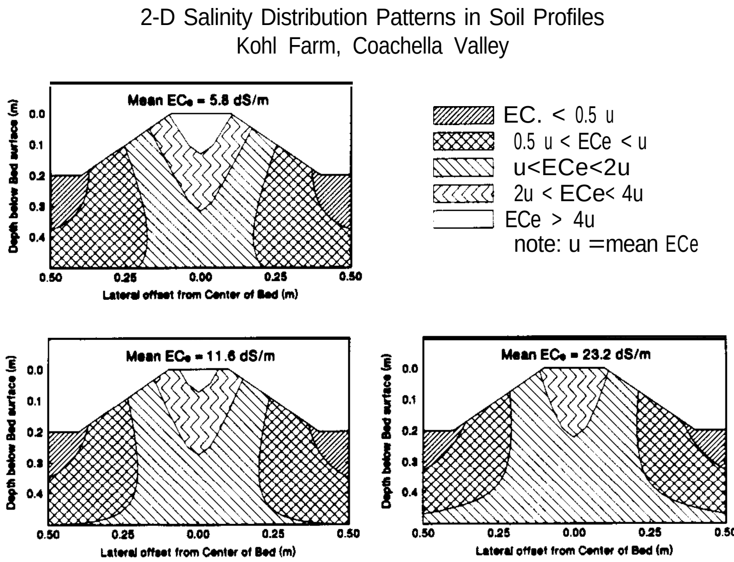


Figure 10. Relation between salinity distribution and mean level of salinity in a tile-dramrd field (silty loam soil) located in the Coachella Valley of California.

response to the imposed irrigation system.

Salinity distribution in the rootzone can also be affected by the drainage system; this was observed in the Coachella Valley field previously discussed and in others. In such fields. lower salinities occurred in the soil overlying the tile-lines and higher salinities occurred in the soil located in between the tile lines. Additionally. as shown in Figure 10, the distribution of

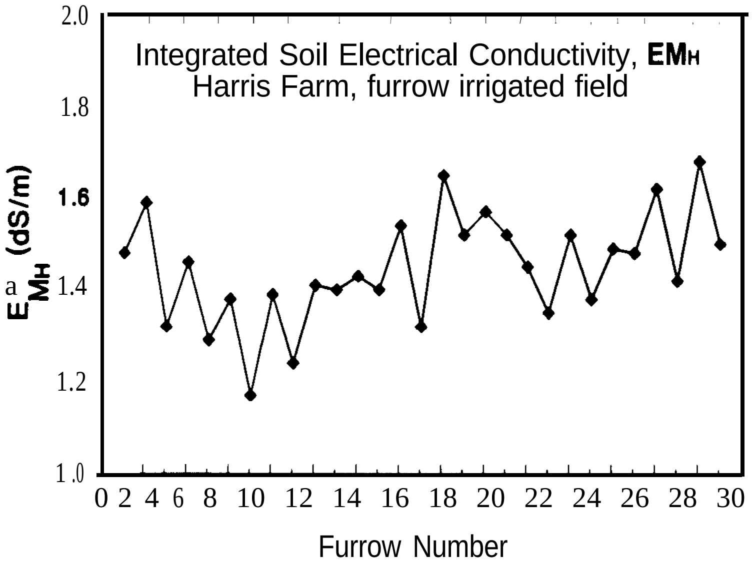
Figure 11. (Top) Two-dimensional distributions of salinity in the upper half-meter of the soil profiles of a field located in the Coachella Valley of California. as influenced by mean (O-0.5 m) salinity level.



salinity in the soil profile varied with the mean level of salinity. These distributions imply that salinity is high in areas where the net flux of water has been upward in the field (in the region of the field located in between the drain lines) and is low in the areas where the flux has been downward, IE.. where leaching has occurred in the soil overlying the tile lines. Figure 11 portrays the salinity distribution in the upper part of the rootzone (0-0.5 m) of a Coachella Valley field. These data indicate that the salinity levels and patterns within the seed bed of this field are also related to the mean profile salinity levels, which in turn are related to the drainage pattern. As shown in Figure 10, the salinity distributions in this silty-loam soil are clearly two-dimensional in contrast to the one-dimensional profiles observed for the clay textured Imperial Valley soil (Figure 8). This difference in salinity distribution is thought to be due to differences in the cracking properties of the two soils. Taken together, all these data (Figs. 6, 10 & 11) indicate that the drainage system in this field is inadequate given the manner of irrigation. or geohydrologic situation, or both, existing there.

Besides irrigation and drainage, another man-induced factor, which "emerged' from the intensive, spatially referenced data obtained with these salinity assessment systems, is that of tillage. Systematic differences in salinity patterns of some surveyed, irrigated fields were found to "mimic" the traffic patterns undertaken with the farm equipment. Figure 12 is an example of the cyclic-symmetry in EC_a values observed among neighboring furrows which are trafficked/compacted differentially as a result of tractor movement and related operations. Tractors typically move through the fields in a systematic way, as dictated by the invoked practices of seed-bed/furrow preparation, cultivation and tillage. As a result. tractor weight is exerted in some furrows, but not in others, leading to uneven compaction among neighboring furrows. Similarly, tillage and cultivation operations are often implemented using equipment with guide/depth wheels which similarly lead to other analogous definable patterns. As a result, some furrows are more compacted than others leading to reduced water-intake rates and to relatively increased lateral water flow and, hence, higher salinity levels in both the associated furrows and beds of trafficked areas compared to non-trafficked areas. Other salinity data supporting this conclusion are given elsewhere (Rhoades, 1994).

Figure 12. Cyclic pattern of electromagnetic induction readings of depth-integrated. soil electrical conductivity across a set of neighboring furrow in an irrigated field in the San Joaquin Valley of California.



While the above described "compaction" patterns were determined from EM-38 readings, analogous "tillage" patterns (data not shown) have been observed in some of our mobile, four-electrode data. For example, markedly abrupt cyclic patterns of EC_a were observed in a field which had been "ripped" to 0.5 m with chisels. Excavation and detailed examination of the cyclic locations where abrupt changes in EC_a were measured revealed the presence of deep narrow trenches, or cracks, in the soil approximately 2.5 cm wide. An interesting feature of these "cracks" was that they were full of dry aggregates of surface soil that had fallen down into them. Such "cracks" not only provide preferential paths for water flow, but as well a means for soil particle translocation to deeper depths in the soil profile and a process by which certain pesticides and other solutes may move in soils that is not accounted for in classical solute transport theory.

III. Salinity Calibration and Mapping Theory/Software

Most effective use of the mobile sensor-systems described above requires a rapid, accurate method for converting EC_a measurements to EC_e values. We previously showed (Rhoades et al., 1989b, 1990) that EC_e can be determined from EC_a with sufficient accuracy for practical assessment using knowledge, or reasonably accurate estimates. of the clay and water contents in the soil profile at each EC_a measurement site. While this method is suitable when EC_a measurements are made by hand, it is impractical for processing the large amounts of data generated with the mobile measurement systems. For this reason we developed a practical methodology based on multiple linear regression (MLR) to estimate soil salinity from extensive EC_a survey data. limited ground-truth data of EC_e, and trend surface parameters. MLR techniques were shown to be theoretically equivalent to geostatistical, cokriging techniques, but to be more cost-effective and practical. (Lesch et al. 1993a.b). The MLR technique is an appropriate method when a sufficiently fine grid of secondary data can be acquired quickly and cheaply and where a strong correlation exists between the primary and secondary variables. This last requisite involving correlations between EC_e and EC_a was previously validated by Rhoades et al.. (1989b, 1990). With the assessment system described herein. a series of easily obtained EM, or four-electrode. or both, instrument readings are acquired across a field using a relatively dense. systematic survey scheme. A limited number of soil samples are then acquired from a specially selected. subset of measurement-sites (as explained below) and measured for salinity (the rapid field method of Rhoades et al, 1989a is most practical for this purpose). An MLR equation is subsequently established with the co-located data and tested for residual spatial autocorrelation. If the residuals are independent (or reasonably so), the MLR approach is deemed adequate for salinity assessment involving the prediction, mapping, and monitoring of soil salinity. Kriging for interpolation purpose is used to predict salinity at sites where no secondary information (i.e. EC_a measurements) exists. The accuracy of the salinity predictions can be increased by incorporating the EM-38 and four-electrode data. as well as location coordinates. into the MLR equation. Several of the examples given earlier to show the utility of the assessment equipment involved results which had been converted to soil salinity. expressed in terms of EC_e. using these methods.

An important requisite of the MLR approach is that the locations and the soil samples used for calibration purposes must be spatially representative of the entire survey area. This requisite was satisfied by implementing a newly developed spatial sampling algorithm. The calibration site selection algorithm developed ensures that linear, quadratic and interaction terms in the MLR model can be accurately estimated. The algorithm also provides decision rules for selecting the final MLR model variables. Theory and tests of appropriateness of both the MLR approach and the calibration sampling/siting algorithm are described in detail elsewhere (Lesch et al. 1993a.b). Software for this approach is available from the U. S. Salinity Laboratory (Lesch, et. al.. 1995). Additionally. other software has been developed to process the mobile. four-electrode transect data for the purposes of plotting transect "profiles". evaluating management effects and producing salinity maps.

An example soil salinity map produced using the above procedures and software is shown in Figure 13. which shows the spatial pattern (average rootzone basis) one of the Coachella Valley fields previously discussed. The

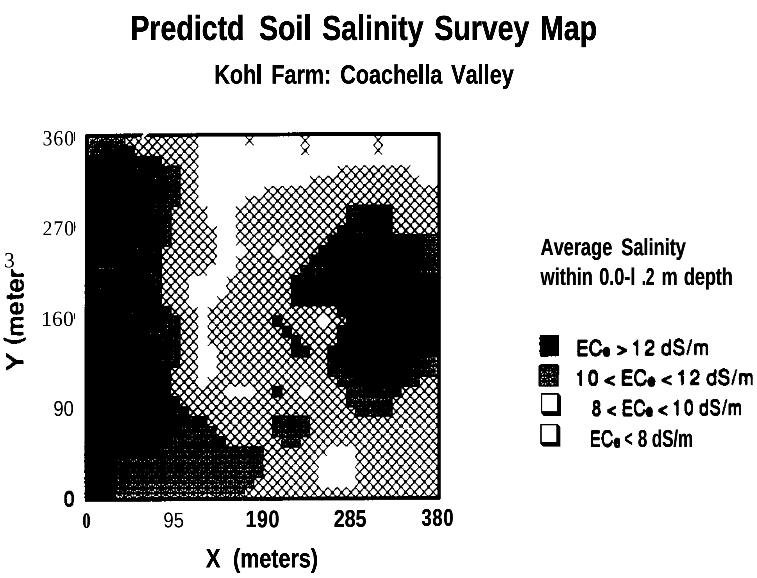


Figure 13. Map of average rootzone (0-1.2 m) soil salinity (EC_e basis) in a tile-drained field (silty loam soil) located in the Coachella Valley of California.

median EC_e value of 10-12 dS/m measured within the O-l m depth in this field is excessive for most crop production. Additionally, the type of salinity distribution found within the profile, as previously discussed, implies that the direction of net water within the rootzone varies across the field depending upon the invoked patterns of irrigation and drainage. The net-flow direction is upward over much of the field implying inadequate irrigation and drainage systems and related management.

IV. Conclusions

Results presented in this paper indicate that much of the apparent chaos in the spatial pattern of soil salinity in irrigated fields is man-induced and can be explained in terms of deterministic processes caused by such management practices as irrigation, drainage. cultivation and tillage. The edaphic and management practices causing the salinity patterns can often be ascertained using the described, integrated salinity assessment approach and procedures. The system offers a unique technology for accurately and rapidly mapping and monitoring salinity-distributions in the field as well as for determining the causes of salinity, the diffuse sources of salt-loading from irrigated lands and for evaluating the effectiveness (possibly efficiency) of irrigation/drainage management practices. Since salinity is a tracer of water flow, the instrumental systems and associated data analysis may have a much broader application than just salinity assessment. For example, the methodology could potentially be used to explain or define the underlying processes affecting the transport of individual solutes (i.e. nitrates or pesticides) in irrigated fields and to assess irrigation uniformity and degree of leaching.

V. References

Carter, Lyle M., J. D. Rhoades and J. H. Chesson. 1993. Mechanization of soil salinity assessment for mapping. Paper presented at 1993 Water Meeting of American Society of Agricultural Engineering, Chicago, Illinois, Dec. 12-17, 1993.

Kaddah, M. T. And J. D. Rhoades. 1976. Salt and water balance in Imperial Valley, California. Soil Sci. Soc. Am. J. 40:93-100.

Lesch, Scott M., D. J. Strauss and J. D. Rhoades. 1995. Spatial prediction of soil salinity using electromagnetic induction techniques. I. Statistical prediction models: A comparison of multiple linear regression and cokriging. Water Resour. Res. 31:373-386.

Lesch, Scott M., D. J. Strauss and J. D. Rhoades. 1993. Spatial prediction of soil salinity using electromagnetic induction techniques. II. An efficient spatial sampling algorithm suitable for MLR model identification and estimation. Water Resour. Res. 31:387-398.

Lesch, Scott M., J. D. Rhoades, D. J. Strauss, K. Lin and M. A. A. Co. 1995. The ESAP user manual and tutorial guide. Version 1.0, U. S. Salinity Laboratory Research Report # 138, 108 pp.

Rhoades, J. D. 1992. Recent advances in the methodology for measuring and mapping soil salinity. Proc. Int'l Symp. on Strategies for Utilizing Salt Affected Lands, Bangkok, Thailand, Feb. 17-25, 1992. pp. 39-58.

Rhoades, J. D. 1994. Soil salinity assessment: Recent advances and findings. Proc. ISSS Sub-Commission Salt-Affected Soils Conference, Acapulco, Mexico, July 10-126, 1994. (In press).

Rhoades, J. D., N. A. Manteghi, P. J. Shouse, and W. J. Alves. 1989. Estimating soil salinity from saturated soil-paste electrical conductivity. Soil Sci. Soc. Am. J. 53(2):428-433.

Rhoades, J. D., N. A. Manteghi, P. J. Shouse, and W. J. Alves. 1989. Soil electrical conductivity and soil salinity: New formulations and calibrations. Soil Sci. Soc. Am. J. 53 (2):433-439.

Rhoades, J. D., P. J. Shouse, W. J. Alves, N. A. Manteghi and S. M. Lesch. 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. Soil Sci. Soc. Am. J. 54(1):46-54.