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Assessing irrigation/drainage/salinity management using spatially referenced salinity measurements

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Abstract

A unique technology-package for measuring the spatial distributions of salinity in irrigated soils and fields and for evaluating the appropriateness of some related irrigation-, drainage- and salinity control-management practices is described. This assessment technology is based on the use of: (1) geophysical–instrumental systems for intensively measuring bulk soil electrical conductivity and associated spatial coordinates; (2) statistical algorithms for site selection and salinity calibration; and (3) algorithms for data analysis and graphical display to facilitate interpretation. Results are presented to demonstrate some of the utility of the technology. Additionally, examples are given which show that much of the apparent chaos observed in the spatial pattern of soil salinity in irrigated fields is man-induced and related to such management practices as irrigation, drainage, and tillage. © 1997 Elsevier Science B.V.

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1. Introduction

Irrigated agriculture accounts for a substantial proportion of our food and fiber production. Yet, extensive areas of irrigated land have been and are increasingly becoming degraded by salinization and water-logging resulting from over-irrigation and other forms of poor agricultural management (Ghassemi et al., 1995). In some places, sustainability of irrigated agriculture is threatened by this degradation. At the same time, irrigated agriculture is also depleting and polluting water supplies in many places.

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Increased irrigation efficiency is being sought to conserve water, to reduce drainage, water-logging and secondary salinization, and to mitigate some of the water pollution associated with irrigated agriculture. Restrictions are increasingly being placed on the discharge of saline drainage water from irrigation projects. Concomitantly, the reuse of saline drainage water for irrigation is being increased. With less leaching and drainage discharge and greater use of saline water for irrigation, soil salinity may increase in some areas. Thus, a practical methodology is needed for the timely assessment of soil salinity in irrigated fields, for determining its causes and for evaluating the appropriateness of related management practices.

Traditionally, soil salinity has been assessed using soil samples and laboratory analyses. Additionally, the leaching requirement (L_r) and salt-balance-index (SBI) have been used to judge the appropriateness of irrigation and drainage systems and practices with respect to salinity control, water use efficiency and irrigation sustainability (U.S. Salinity Laboratory Staff, 1954). However, these approaches are either inadequate or impractical for these purposes. Soil salinity is too variable and transient to be appraised using the numbers of samples that can be practically processed using conventional soil sampling and laboratory analysis procedures. Furthermore, the conventional procedures do not provide sufficient detailed spatial information to adequately characterize salinity conditions and to determine its natural or management-related causes. The leaching requirement (L_r), which refers to the amount of leaching required to prevent excessive loss in crop yield caused by salinity buildup within the rootzone from the irrigation water, is a 'concept' which traditionally has been used to evaluate the appropriateness of irrigation and leaching management. The concept is based on assumptions of steady-state and of absolutely uniform conditions of irrigation, infiltration, leaching and evapotranspiration; none of which are achieved in most field situations which typically are dynamic and variable, both spatially and temporally. Furthermore, salt buildup in the rootzone resulting from the presence of shallow water tables is ignored in the traditional L_r calculation. Additionally, no practical way has existed to directly measure the degree of leaching being achieved in a field, much less in the various parts of it, as is required in order to determine its appropriateness.

The salt-balance-index, the net difference between the amount of salt added to an irrigation project and that removed in its drainage effluent, is another 'concept' that has traditionally been used to evaluate the appropriateness of leaching, irrigation and drainage practices. This approach is also inadequate for these purposes because it provides no information about the average level of soil salinity in the project, nor about the soil salinity level existing within any specific field of the project. The approach also fails because it does not even provide a realistic measure of trends in salinity within the rootzone, because salt from below the soil profile and of geologic origin is typically contained in the drainage water collected by the subsurface drain system (Kaddah and Rhoades, 1976). Additionally, the transit times involved in the drainage returns are so long (usually more than 25 yrs) that the index values are not reflective of current trends (Jury, 1975a,b). Nor can one deduce the extent of leaching being achieved in any field, nor of the irrigation uniformity and efficiency, nor anything about the extent of waterlogging and losses in crop yield, because the SBI measurements are impractical to make on the basis of individual fields.

Our opinion is that an appropriate assessment of the adequacy of irrigation, drainage, water-table and salinity control management practices can not be achieved using L_r and SBI concepts. On the other hand, it is possible to measure soil salinity levels within the rootzone regions of individual fields. From these levels and distributions, one can determine whether they are within acceptable limits for crop production. One can also infer whether leaching is adequate and uniform, or not, anywhere in a field, since salinity is a tracer of the net processes of infiltration, leaching, evapotranspiration and drainage. Thus, a more appropriate and practical approach for assessing the adequacy of salinity control is the acquisition of periodic, detailed information of soil salinity levels and distributions within the individual fields of the project. We refer to this approach as salinity assessment and envision its use to diagnose, inventory and monitor conditions of soil salinity, as well as to evaluate the appropriateness of leaching and drainage and to guide management practices. The same data can also be used for delineating the sources of salt-loading, as well as for mapping the distribution and extent of drainage problem areas, within both the project and individual fields.

Control of soil salinity, and also of salinity in drainage-receiving water resources, requires the following: (1) knowledge of the magnitude, extent and distribution of rootzone soil salinity in the individual fields of the irrigation project (a suitable inventory of conditions); (2) knowledge of the changes and trends of soil salinity over time and the ability to determine the impact of management changes upon these conditions (a suitable monitoring program); (3) ways to identify the existence of salinity problems and their causes, both natural and management-induced (a suitable means of detecting and diagnosing problems and identifying their causes); (4) a means to evaluate the appropriateness of on-going irrigation and drainage systems 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) an ability to determine the areas where excessive deep percolation is occurring, i.e., to identify where the water and salt loading is coming from (a suitable means of determining areal sources of pollution).

An assessment technology of the type described above begins with a practical methodology for measuring soil salinity in the field. This is complicated by the spatially variable and dynamic nature of soil salinity, which is caused by the effects and interactions of varying edaphic factors (soil permeability, water table depth, salinity of perched groundwater, topography, soil parent material, geohydrology), by 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, map and monitor a field's or a project's salinity condition with conventional soil sampling and laboratory-analysis procedures becomes prohibitive. A more rapid, field-measurement technology is needed. Additionally, this assessment technology should ascertain the spatial relations existing within extensive areal data sets. It should provide a systematic strategy for evaluating management effects and be able to statistically prove changes or differences in an area's salinity condition over time.

The salinity assessment system described herein measures soil salinity in detail at the field scale and provides the information needed to accomplish successful management. It consists of mobile instrumental techniques for rapidly measuring bulk soil electrical conductivity (EC_a) directly 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 large spatial databases, and appropriate spatial statistics to infer salinity distributions in rootzones and changes in salinity over space and time. The remainder of this text briefly describes this assessment technology and illustrates its utility for evaluating irrigation, drainage and tillage management and for locating areal sources of over-irrigation.

2. Assessment equipment and examples of use

Two kinds of mobile instrumental systems have been developed for measuring soil salinity at the field scale: one uses four-electrode units to measure EC_a; the other uses an electromagnetic induction sensor, either solely or together with four-electrode units, to measure EC_a.

2.1. The mobile four-electrode system

In this system (see Fig. 1), the electrodes are combined into the 'heels' of tillage shanks and mounted on a hydraulically controlled tool-bar attached to a tractor via a

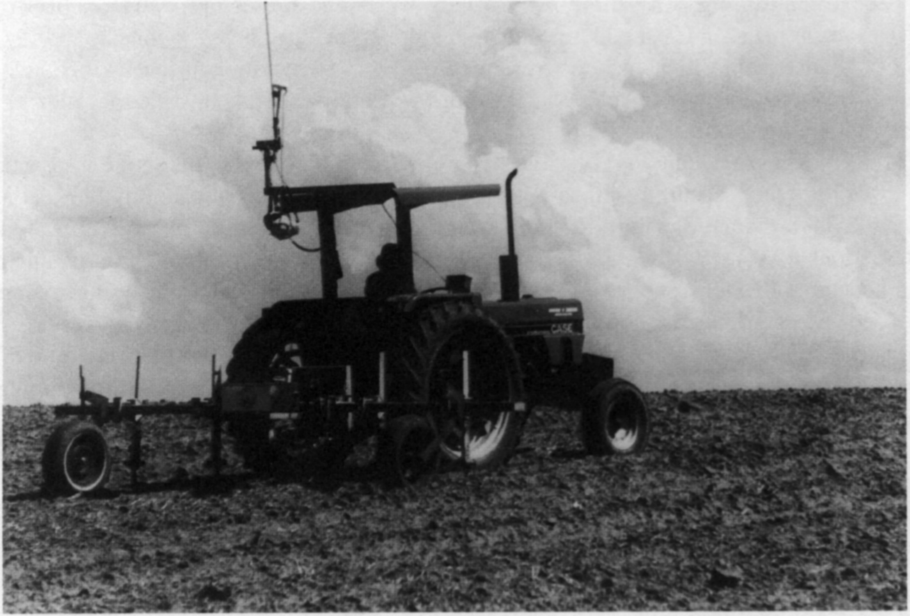

Fig. 1. Photograph of mobile, 'fixed-array' four-electrode system with GPS antenna mounted on the mast.

conventional three-point hitch. The distances between the electrodes are adjustable to accommodate different crop spacings. Typically, four row-spacings (about 3–4 m) are included in the measurement. The electrodes are drawn 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/s. A Global Positioning System (GPS) antenna is positioned above the electrodes and used along with a receiver to determine the spatial position of each sensor reading (the unit now being used is capable of real time accuracies of about 0.2 m). The EC_a and the GPS signals are sensed at adjustable frequencies (as often as every second) and logged into memory for later analysis of salinity/spatial relations. Thus, measurements of EC_a are made to a depth of up to 1.0 to 1.3 m ($\sim$ 4 row-spacings/3) about every 1 m or more, along the path of tractor travel. The four-electrode conductivity Martek meter used gives linear EC_a readings up to 15 dS/m. This corresponds to soil salinity values, as conventionally expressed in terms of the electrical conductivity of the extract of the saturated soil-paste (EC_e), of up to 45 to 100 dS/m, depending upon soil texture. The EC-meter, the GPS receiver, and their power supplies and data loggers are contained in the water-tight, stainless steel box mounted behind the tool-bar shown in Fig. 1. The tractor operator is provided with a remote monitor (not shown) displaying time, EC_a reading and logging status. The analysis of the spatial data is carried out at the side of the field in a mobile office equipped with a computer and with testing equipment for measuring the salinities (EC_e basis) of soil samples collected for purposes of sensor-calibration (explained later).

Example output data obtained with the above described mobile, four-electrode sensing system are presented in Fig. 2a, which shows EC_a readings collected every second (about every 1 m apart) as the tractor moved across a furrow irrigated, sugar beet field (Glenbar silty clay loam soil) in the Imperial Valley of California. Average rootzone soil salinities expressed in terms of EC_e, as predicted from the measured EC_a data along the transect and as measured in some 'calibration' samples, are shown in Fig. 2b. The theory and methods used to predict soil salinity from the sensor readings and limited calibration information, as well as 'fast', field methods for measuring EC_e, are described in detail elsewhere (Lesch et al., 1995a,b; Rhoades, 1992b, 1993; Rhoades et al., 1989a,b, 1990). As is shown here and in these earlier publications, the accuracy of these predictions is generally very good. The accuracies of the predictions are always quantitatively known from the statistical procedures used, though they are not shown here.

If irrigation application and infiltration were uniform across the field involved with Fig. 2, the value of EC_a (and EC_e) should be the same at each distance provided crop stand and soil type were also uniform. However in this case, the EC_a (and EC_e) values increased from the 'head' to the 'tail end' of the field; the coefficient of variability (CV) was 14.2% and the linear correlation coefficient (r) between EC_a and distance down the transect was 0.67. Thus, one may conclude from these rapidly ($\sim$ 6 min) obtained data that the field is not uniform with respect to one or more of the three possibilities. In this case, the crop was planted uniformly and the soil type was the same along the transect. Hence, the findings imply that irrigation application, or infiltration, was not uniform across this field, presumably due to reduced opportunity-time and infiltration of irrigation water with distance from the point of water delivery to the furrows. Another factor

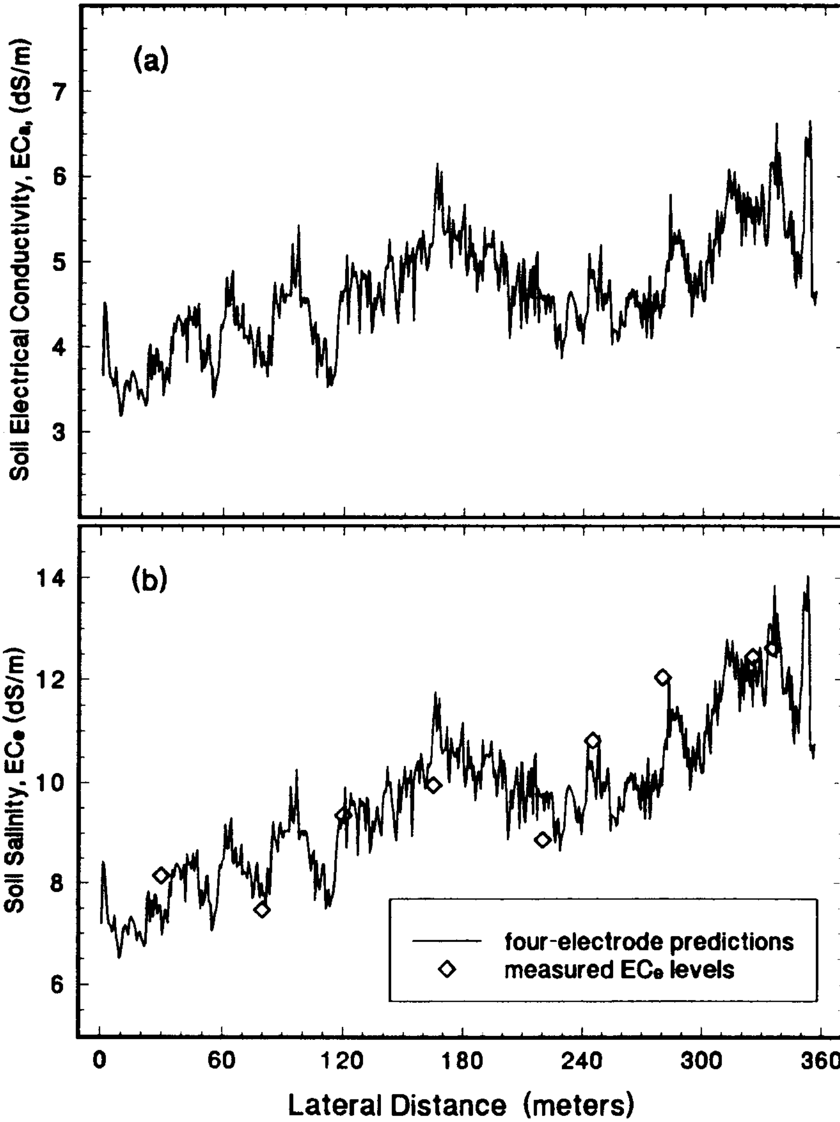

Fig. 2. Relation between (a) bulk soil electrical conductivity (EC_a) and (b) soil salinity (EC_e) and distance along a transect across a furrow-irrigated, sugar beet field (Glenbar silty clay loam soil) located in the Imperial Valley of California.

likely influencing the salinity distribution within this field is the lateral transport of salt that occurred in it as a consequence of the 'cracking' type of soil present in the field. This latter aspect is discussed elsewhere (Rhoades et al., 1997). This example illustrates how the spatial variation of average rootzone soil salinity can be used, assuming it is a tracer of the interactions of water infiltration, evapotranspiration, leaching and drainage,

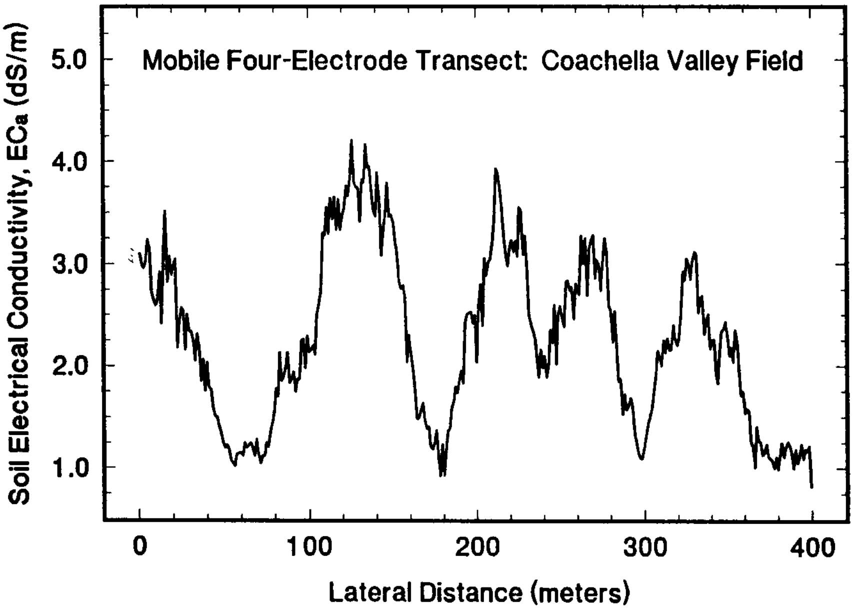

Fig. 3. Relation between bulk soil electrical conductivity (EC_a) and distance along a transect crossing subsurface tile-drains in field (silty clay loam soil) located in the Coachella Valley of California.

to evaluate irrigation uniformity in fields which are relatively uniform in soil type and cropping intensity.

An example of the marked effect that a subsurface drainage system can have on average rootzone salinity is provided in Fig. 3, in terms of EC_a. The corresponding values of EC_e (not shown) cycled between low values of about 2.5 dS/m to high values of about 25 dS/m. The CV and r values for this EC_a-distance traverse were 36.8% and −0.20, respectively. This example involved a field of silty loam soil in the Coachella Valley of California which had buried 'tile-lines' oriented perpendicular to the direction of the EC_a-traverse. In this field, soil salinity levels 'mimicked' the drainage system, with high values of EC_a (and EC_e) occurring in the soil located between tile-spacings and low values in the soil overlying them. These data suggest that most of the variability in average rootzone salinity across this field was caused by the effects of the drainage system. They also imply that the drainage system there was inadequate, given the circumstances of irrigation, soil type, geohydrology, etc. The distributions of salinity within the rootzone depth of such fields will be discussed later; they give further credence to the preceding conclusion.

The spatial pattern (average rootzone basis) of a neighboring field in the Coachella Valley determined using the above described equipment is shown in Fig. 4. The average profile EC_e value of 10–12 dS/m measured within the 0–1.2 m depth in much of this field is excessive for successful crop production. This observation itself is evidence of the inadequacy of the past irrigation and drainage management in the field. Assuming uniform irrigation and a leaching fraction of 0.05, the expected value of average

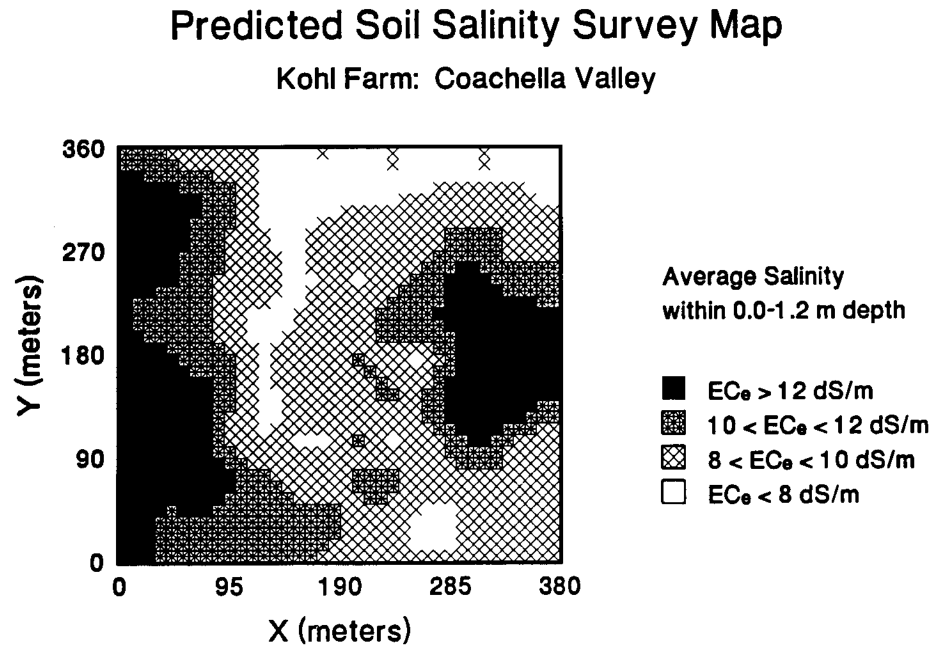

Fig. 4. Map of average rootzone (0–1.2 m) soil salinity (EC_e basis) in a tile-drained field (silty loam soil) located in the Coachella Valley of California.

rootzone salinity (as calculated using WATSUIT, Rhoades et al., 1992) would be about 2.1 dS/m under steady-state conditions of irrigation with the Colorado River water. Since the average soil-profile salinity in this field of silty–loam soil (non-cracking soil) exceeds 2.1 dS/m, one must conclude that the overall leaching fraction is negative either because of deficit-irrigation or because salt is being accumulated in the rootzone from the upflux of saline water from the water table. Since the information supplied by the irrigator showed that the applied water exceeded ET, the latter cause is deduced. The salinity distributions found within the profiles over much of this field are presented later; they also imply the cause is inadequate drainage.

2.2. *The combination, mobile electromagnetic-induction / four-electrode system*

This system involves a Geonics, 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 Fig. 5. The EM-38 mounting tube fastens to the vehicle by sliding over a short section of steel tubing. The 'EM-tube' is rotated, to enable the EM-38 readings to be made 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 to various heights above ground

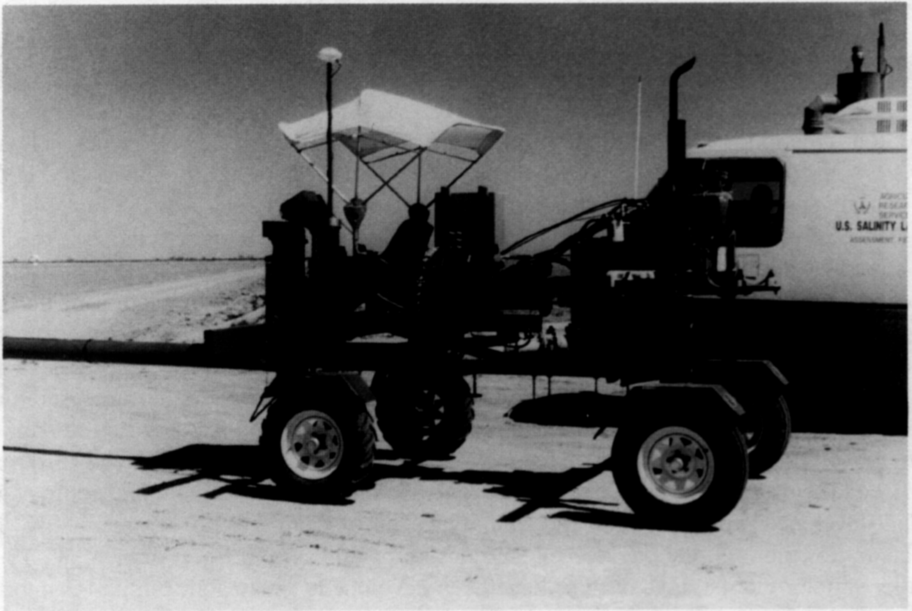

Fig. 5. Photograph of mobile salinity assessment vehicle with combined electromagnetic induction and four-electrode soil conductivity sensing systems.

and which also translates it 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 regions of the soil. 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 also to correspondingly measure EC_a at both 1-m and 2-m array spacings in both the furrow and seedbed. These changes in the height and orientation of the EM sensor, in the spacings of the electrodes and in their positioning in relation to the furrow and seedbed are undertaken in order to alter the depths and distributions of the EC_a 'sensing' in the soil and rootzone and, thus, to permit the determination of the salinity-distribution within the rootzone in two dimensions (Rhoades, 1993). In Fig. 5, the EM-sensor and the 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 the EM and four-electrode sensor measurements and for positioning the sensors over the furrow and seedbed in the case of the EM sensor and at various depths in the furrow and seedbed in the case of the four-electrode sensor. When the position-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 seedbed). The EM 'start' button then initiates the following automated sequence: (1) the EM_V reading is made and the reading is 'stored' in the data logger; (2) the EM-38 sensor is rotated to the horizontal position; (3) the EM_H reading is made and logged; 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 inserts the probes to the first depth limit, (2) EC_a is measured at the 1-m array spacing, (3) the 1-m reading is stored in the data logger, (4) the m/logger is switched to the 2-m array, (5) EC_a is read at the 2-m array spacing, (6) the 2-m reading is stored in the data logger, (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 delays for reading and logging operations. The mobile unit then moves to the next measurement site. All measurements at each site can be made in about 30–45 s. An earlier version of the above described equipment and some other examples of its utilization are discussed by Rhoades (1992a,b, 1994). A Cooperative Research and Development Act contract has been developed with AG Industrial Manufacturing of Lodi, CA to commercialize this system. For more on the engineering and design of this system, see Carter et al., 1993. Other simpler mobile, EM-systems have been developed to map soil salinity (Cannon et al., 1994).

With the combined EM/four-electrode equipment and limited calibration data, salinity distributions within the rootzone can be inferred. Example distributions are given in Fig. 6 for the furrow-irrigated and tile-drained field shown in Fig. 4. Relatively lower salinities occurred in this field in the soil overlying the tile-lines and higher salinities occurred in the soil located in between the tile lines. Additionally in this field,

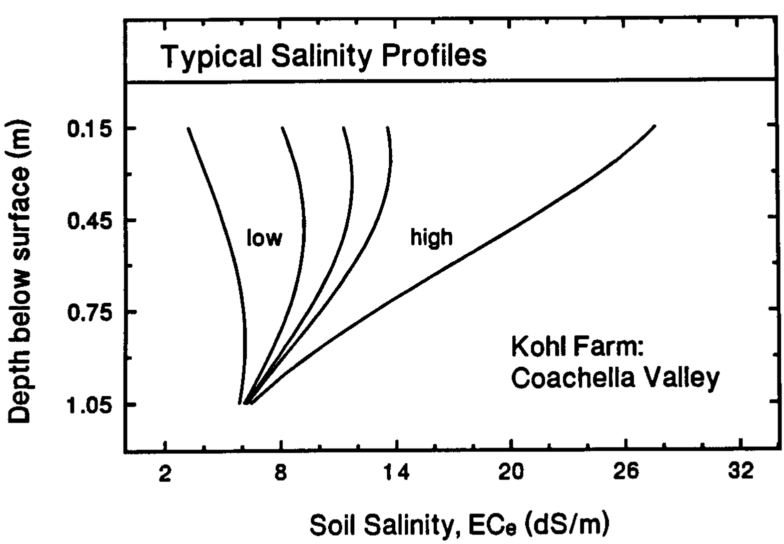

Fig. 6. Relation between salinity distribution and mean level of salinity in a tile-drained field (silty loam soil) located in the Coachella Valley of California.

as shown in Fig. 6, the distribution of salinity in the soil profile varied in relation to the mean level of salinity (which in turn varied in relation to the tile-line location). These distributions and relations imply, since the field was not deficit irrigated, that salinity is high in the areas of the field 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 (in the regions overlying the drain lines) where the net flux has been downward, that is where leaching has occurred. These data show that the salinity distribution(s) in the rootzone of an irrigated and tile-drained field can be used to infer the direction(s) of net water flux occurring in the different areas of the field and, hence, to assess the adequacy of the drainage system in interaction with the on-going irrigation management (the two are interrelated) existing there. In this case, the drainage system is concluded to be inadequate given the manner of irrigation, or geohydrologic situation, or both, existing in the field; since the level of salinity in the rootzone is excessive for normal crop production and the net flux of water is upward over too much of the field. A more quantitative discussion of how the distribution of salinity within the soil profile can be used to infer leaching/drainage adequacy is given later.

The salinity distributions in the upper part of the rootzone (0–0.5 m) of the same Coachella Valley field involved in Figs. 4 and 6 are portrayed in Fig. 7. These data indicate that the salinity levels and patterns within the seedbed of much of this field are

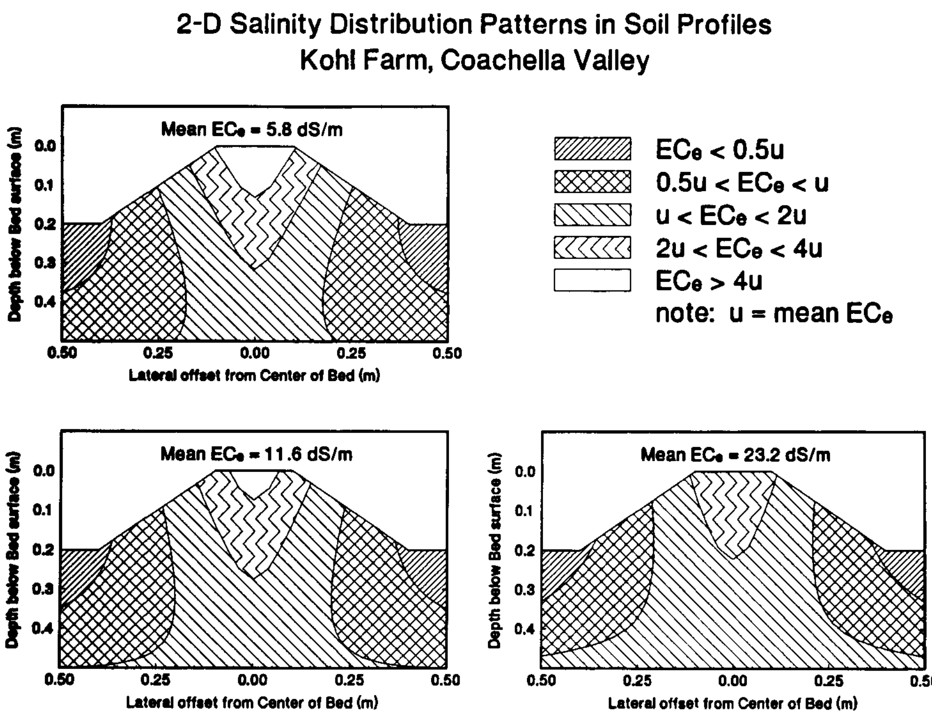

Fig. 7. Two-dimensional distributions of salinity in the upper half-meter of the soil profiles of a field located in the Coachella Valley of California, as influenced by mean (0–0.5 m) salinity level.

Table 1
Percent area of Borba-farm field with soil salinities (EC_e basis)within various ranges

Soil salinity (dS/m)	Soil depth (m)				
	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2	0–1.2
0–2	14	44	17	15	3
2–4	41	32	34	31	49
4–8	36	17	22	25	29
8–16	9	6	16	17	16
> 16	0	1	10	11	2

Table 2
Percent area of furrow-irrigated, Borba-farm field by different soil salinity (EC_e basis)—depth profile types

Profile ratio	Profile type	% Area
> 0.75	very negative leaching	5
0.50–0.75	negative leaching	23
0.35–0.50	excess leaching	17
0.20–0.35	normal leaching	35
< 0.20	low leaching	20

not only excessively high but also are related to the mean profile salinity levels, which in turn are related to the drainage pattern. These data further indicate that the drainage system in this field is inadequate. The salinity distributions in this silty–loam soil are clearly two-dimensional, as would traditionally be expected under conditions of furrow irrigation. These results are in contrast to the one-dimensional profiles observed in clay textured, 'cracking' Imperial Valley soils. The data and reasons for this difference are given elsewhere (Rhoades et al., 1997).

Salinity 'distribution' data obtained with the 'combination sensor system' in two other fields (both near each other in the San Joaquin Valley of California) are given in Tables 1–3 to further illustrate how information about the levels and distributions of salinity within the rootzone obtained with this equipment can be used to evaluate the adequacies of salinity control and irrigation and drainage management. The percentages of the Borba-farm field having levels of salinities with certain ranges are given in Table 1. By reference to salt-tolerant tables, one can estimate how much yield loss caused by

Table 3
Percent area of sprinkler-irrigated, field by different soil salinity (EC_e basis)—depth profile types

Profile ratio	Profile type	% area
> 0.75	very negative leaching	0
0.50–0.75	negative leaching	3
0.35–0.50	excessive leaching	13
0.20–0.35	normal leaching	71
< 0.20	low leaching	13

such salinity conditions would result for any given crop. For example, assuming the crop is alfalfa (which has a threshold EC_e value of 2.0 dS/m and rate of yield loss of 13% for each unit of EC_e in excess of 2.0; Maas, 1990) and its effective depth of rooting is 1.2 m, one would estimate the relative yield loss due to salinity to be as follows by percentages of the Borba field: 0% loss in 3% of the field, 14.6% loss in 49% of the field, 44% loss in 29% of the field, and 100% loss in 18% of the field. Thus, on a whole field basis, the expected salinity induced loss in relative alfalfa yield would be 38%. The economic significance of this yield loss in turn can be calculated given other cost information and used to evaluate the economic impact of salinity on the profit-line of the operation of this field and also to evaluate the affordability of improving the management to eliminate the salinity-induced yield losses.

As explained earlier, the information of salinity by depth and location in the soil profiles of irrigated fields acquired by the 'combination system' can also be used to assess the adequacy of the past leaching and drainage practices. For example, where salinity is high in the near-surface soil of non-deficit irrigated fields and decreases with depth in the profile, the net flux of water (and salt) can be inferred as having been upward. This is reflective of inadequate drainage. Where salinity increases with depth in the profile, the net flux of water and salt can be inferred as having been downward. When salinity is low and relatively uniform with depth, leaching can be inferred as having been excessive, probably contributing to water-logging elsewhere. As shown previously (Table 29 in Rhoades et al., 1992), an approximate relationship can be established between steady-state leaching fraction (L) and the ratio: EC_e in the top-half of the rootzone/the sum of EC_e throughout the profile. This relationship (see Fig. 8) between L and the latter ratio (salinity profile ratio, P) is: $L = 0.01843\ (e^{8.0P})$. Thus,

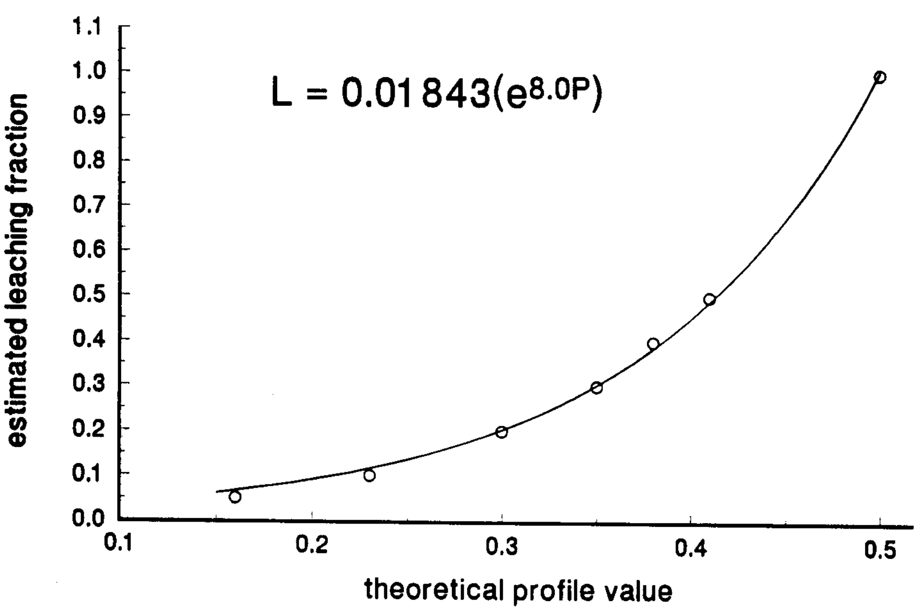

Fig. 8. Relationship between the salinity profile value and leaching fraction.

one can infer the approximate degree of leaching from the salinity profile ratio, which, in turn, can be determined from the data acquired with the 'combination system'. As an example, the percentages of a furrow-irrigated cotton field in the San Joaquin Valley of California are given in Table 2 by classes of profile values. Inverted salinity profiles (values > 0.50) occurred in 28% of this field. Such profiles are indicative of the net upward flux of water for the reasons previously given. We speculate, knowing that the irrigator applied water in excess of ET in this field, that excessive deep percolation occurred in the pre-season and early-season irrigations, causing a 'mounded, perched' water table which was the source of the water and salt that subsequently 'subbed' back up into the rootzone. Profiles with salinity distributions indicative of excessive leaching without causing mounding and the subsequent upflux (L values of greater than 0.3; salinity profile values of 0.35–0.50) occurred in 17% of the field, and profiles with salinity distributions indicative of normal leaching (L values of less than 0.3; salinity profile values < 0.35; salinity increasing with depth) occurred in only 55% of the field. Such data indicate that the leaching/drainage management is inadequate over much of the field. The analogous percentages obtained in a nearby San Joaquin Valley field (this one sprinkler irrigated) are given in Table 3. While both fields were of the same soil type (SiCL) and water table depth (~ 1.5 m), quite different results were obtained. Hardly any of the sprinkler-irrigated field had inverted (upward-flux) profiles; the desired normal leaching profiles were evident over 84% of the field. These examples show the improved irrigation, drainage and salinity management that can result from the use of the more efficient and uniform method of sprinkler irrigation compared to furrow-irrigation. These data further illustrate the utility of the assessment system and of detailed spatial information of soil salinity and its distribution through the rootzone to evaluate the adequacy and effectiveness of irrigation and drainage systems and practices. Maps of the areas with excessive leaching or of inadequate drainage can easily be prepared from these data to display the areal extent and locations of these areas. It may be possible to further quantify the degree of leaching in such areas from knowledge of salinity distributions and patterns, provided drainage is adequate, using salt balance approaches and additional spatial data of water applications and evapotranspiration, as suggested shown elsewhere (Rhoades, 1980, 1981; Slavich and Yang, 1990; Dowling et al., 1991), but more research is needed in this regard.

Besides irrigation and drainage, tillage and tractor traffic-patterns have been observed in some of our intensive, spatially referenced data sets to significantly affect soil salinity levels and distributions in fields. Tractors typically move through the fields in a systematic way, as dictated by the invoked practices of seedbed/furrow preparation, cultivation and tillage. As a result, tractor weight is repeatedly exerted in some furrows, but not in others, leading to cyclic patterns of compaction among some sequential sets of neighboring furrows. Similarly, tillage and cultivation operations are often implemented using equipment with guide/depth wheels which similarly lead to other analogous definable 'traffic' patterns. As a result, some furrows can become more compacted than others leading to reduced water-intake rates and to relatively increased lateral water flow rates and, hence, to higher salinity levels in both the associated furrows and beds. Systematic, cyclic differences observed in the salinity patterns of some irrigated fields surveyed with the 'combination' equipment were found to 'mimic' the traffic patterns undertaken with the tillage equipment. An example is shown in Fig. 9, in which the EC_a readings obtained in a succession of neighboring furrows are presented. The furrows in which the tractor tires travelled are indicated by an inverted triangle. The EC_a values associated with the spline fit (the plot of the 'running average' of neighboring values) of the readings are indicated by the dotted line. The differences between the individual EC_a values for each furrow and its spline-fitted value are presented in Fig. 9b. These data show that EC_a is substantially higher in each furrow the tractor tires travelled compared to its neighboring furrows. They also show that EC_a is substantially lower in each furrow that is 'sandwiched' between 'travelled' furrows. The other furrows have EC_a values that are only slightly higher, or lower, than its neighbors, as would be expected if

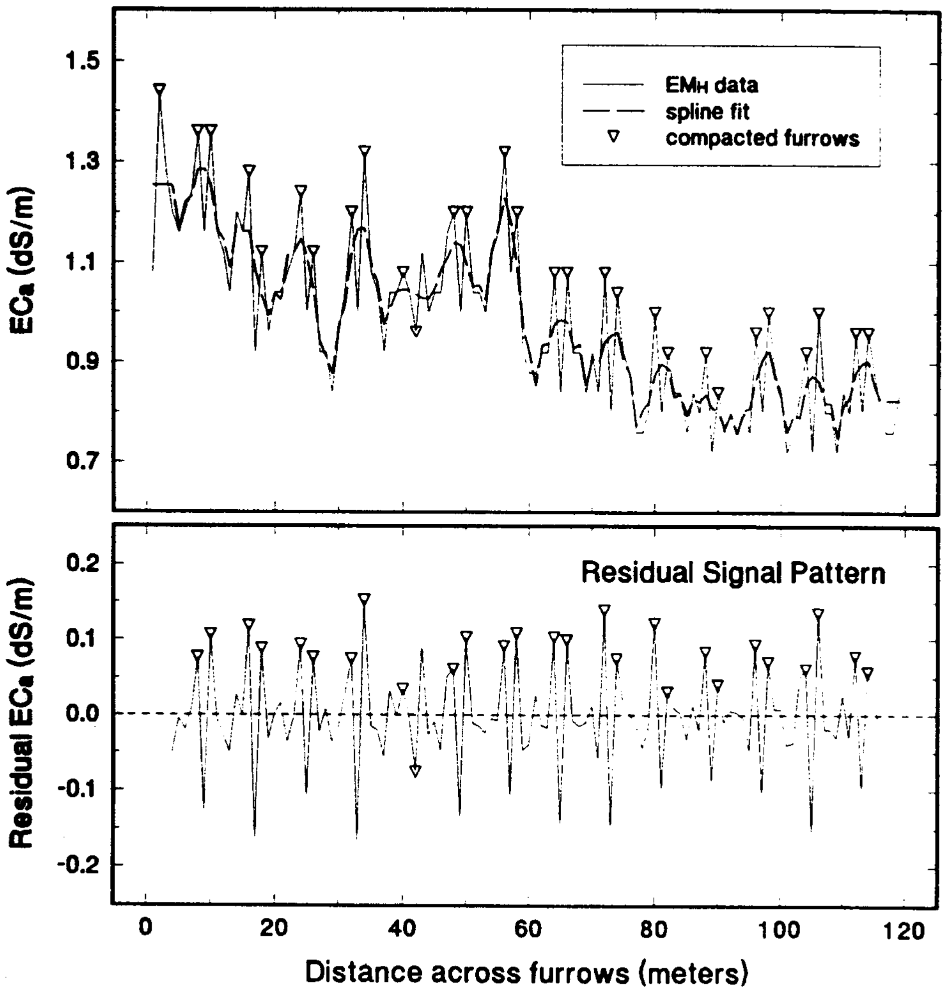

Fig. 9. Cyclic pattern of soil electrical conductivity across a succession of furrows, some trafficked by a tractor and some not.

there was no cyclic pattern or significant difference between them (that is, if all the furrows were essentially the same in their degree of compaction). The observed salinity pattern across this succession of furrows was clearly cyclic in nature and related to the tractor traffic pattern that had been followed in the field. In some fields displaying this phenomenon, the EC_e values in adjacent beds of furrow-irrigated fields have differed from their neighbors by as much as 4 dS/m, or more. Analogous cyclic patterns of soil salinity have been observed in other 'surveyed' fields that were caused by deep chiselling actions of subsurface tillage operations. In this case, the data obtained led to the inference that water had infiltrated and flowed preferentially in the tillage 'slits' and then flowed horizontally out into the adjacent soil causing salinity to be lower in the vicinity of the 'slit' compared to the inter-slit soil areas (data not shown). In one 'surveyed' field which had been 'ripped' to 0.5 m with chisels, markedly abrupt cyclic patterns of EC_a were observed that mimicked the tillage pattern. An excavation and detailed examination of the soil profile was made at the cyclic locations where the abrupt changes in EC_a were measured. This examination revealed (once the topsoil was removed) the presence of deep narrow trenches, or cracks, approximately 2.5 cm wide in the soil underlying the 'disced' topsoil. An interesting feature of these 'cracks' was that they were full of dry aggregates of *surface soil* that had fallen down into them. Hence, such 'cracks' not only provide preferential paths for water flow, but as well provide a means for soil particles and associated organic matter to 'fall' to deeper depths in the soil profile and thus a means by which certain pesticides and other relatively immobile chemicals may translocate in soils that is not accounted for in classical solute transport theory. This observation would not have been made without the use of our detailed spatial measurement system.

3. Salinity conversion and mapping theory / software

Several of the examples given above to show the utility of the assessment equipment involved results expressed in terms of soil salinity, as conventionally determined using soil samples and laboratory procedures. The most effective use of the mobile sensor-systems described above requires a rapid, accurate method for converting EC_a measurements to EC_e values. The various ways that EC_a may be measured and that EC_e may be determined from EC_a are reviewed by Rhoades (1993). EC_e can be predicted from EC_a with sufficient accuracy for the practical needs of salinity assessment using knowledge, or reasonably accurate estimates, of the clay and water contents existing in the soil profile at each EC_a measurement site (Rhoades et al., 1989b, 1990). While this method is suitable when EC_a measurements are made by hand-held equipment, it is impractical for the large numbers of sites sampled with the mobile assessment systems. For this reason, we developed a practical methodology to estimate soil salinity from extensive EC_a survey data, using limited calibration data of EC_e, various surface-trend parameters and multiple linear regression (MLR; Lesch et al., 1992). These 'MLR' techniques were shown to be theoretically equivalent to geostatistical, cokriging techniques, but to be more cost-effective and practical, (Lesch et al., 1995a,b). The MLR technique is an appropriate method when the 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 and/or four-electrode instrument readings are acquired across a field using a systematic survey scheme, the density of which varies with need and variability. A limited number of soil samples (typically about 8–12) 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; Rhoades, 1996). A MLR equation, of the type shown in Eq. (1), is subsequently established with the co-located data and tested for residual spatial autocorrelation:

$$\log(EC_e) = \alpha_0 + \alpha_1[\log(EM_H)] + \alpha_2[\log(EM_H) - \log(EM_V)]. \quad (1)$$

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 four-electrode data, as well as location coordinates, into the MLR equation. The uncertainty in the predictions of salinity are provided along with the predicted values. This methodology is explained in more detail elsewhere (Lesch et al., 1992, 1995a) and is contained within a software package that we developed to facilitate the implementation of the salinity assessment technology described herein and in the presentation and interpretation of the data (Lesch et al., 1995c).

An important requisite of the MLR approach is that the locations of the soil salinity calibration sites must be spatially representative of the entire survey area. This requisite was satisfied by implementing a newly developed spatial sampling procedure (Lesch et al., 1995b). 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., 1995a,b). The procedures are also given in the salinity assessment software package of Lesch et al. (1995c). Additionally, we have developed other software to process the mobile, four-electrode transect data for the purposes of plotting transect 'profiles', evaluating irrigation variability and producing salinity maps. The user manual for this software is presently in preparation.

A statistical test based on the above described MLR procedure/theory has also been developed and demonstrated to be suitable for monitoring changes in soil salinity over time, but will not be described in this paper for lack of space. A description of this methodology, as well as an example of its use for monitoring soil salinity, is given by Lesch et al. (1997).

4. Summary and conclusions

This paper describes an integrated package of instrumental systems and data-processing methodology for intensively measuring EC_a and x, y coordinates and for determining detailed spatial patterns of salinity within soil profiles and fields (for inventorying and monitoring soil salinity). It also presents examples of its utility for evaluating the appropriateness of the irrigation, drainage and tillage management practices (including determining the areal sources of irrigation-pollution) of which salinity is an indicator. The technology package described is unique and represents a breakthrough in our ability to rapidly and accurately assess soil salinity in irrigated lands.

Results presented in this paper show that much of the apparent chaos in the spatial pattern of soil salinity in irrigated fields is man-induced and related to the interacting irrigation, drainage, and tillage management practices. As our examples show, the particular edaphic and management practices causing the salinity patterns in individual fields can often be ascertained using the described integrated salinity assessment technology and procedures. Since salinity is a tracer of water flow, the instrumental systems and associated data analysis technology may have a much broader application than just salinity assessment. For example, the technology could potentially be used to identify or define the underlying rootzone and field-scale processes affecting the transport of individual solutes (i.e., nitrates or pesticides) in irrigated fields and to assess irrigation uniformity and degree of leaching.

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