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18 GIS Applications to the Basin-Scale Assessment of Soil Salinity and Salt Loading to Groundwater

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ABSTRACT

An overview is presented of previously published work by Corwin and his colleagues concerning the application of a geographic information system (GIS) to non-point source (NPS) pollutants in the vadose zone. Two different GIS-based approaches are described for the prediction of the area1 distribution of a NPS pollutant, specifically salinity, at a basin scale. The first approach couples a regression model of salinity development to a GIS of soil salinity development factors (i.e., permeability, leaching fraction, and groundwater electrical conductivity) for the Wellton-Mohawk Irrigation District near Yuma, AZ, during the study period 1968 to 1973. The regression model predicts the composite salinity of the root zone (i.e., top 60 cm.). Areas of low, medium, and high salinization potential are delineated for the entire 44 000 ha irrigation district. Measured salinity data verified that 86% of the predicted salinity categories were accurately predicted. The second approach loosely coupled the one-dimensional, transient-state solute transport model, TETrans, to the geographic information system ARC/INFO. Slightly less than 2400 ha of the Broadview Water District located on the west side of central California's San Joaquin Valley are being used as the test site to evaluate the integrated GIS/transport model during the study period 1991 to 1996. TETrans uses the GIS as a spatial database from which to draw its input data. Preliminary simulations are presented for the main growing season of 1991. Display maps show spatial distributions of soil salinity profiles to a depth of 1.2 m, irrigation efficiencies, drainage amounts, and salt loading to groundwater over the 2396 ha study area. These maps provide a visual tool for making irrigation management decisions to minimize the environmental impact of salinity on soil and groundwater. The first approach is best suited for areas where steady-state conditions are approximated, while the second approach can be used under transient-state conditions.

Limited surface water resources and continued contamination of surface water supplies, have increased the reliance upon groundwater to meet growing water demands from agricultural, industrial, and domestic consumers. Already, groundwater accounts for one-half of the drinking water and 40% of the irrigation water

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Application of GIS to the Modeling of Non-Point Source Pollutants in the Vadose Zone, SSSA Special Publication 48.

used in the USA. The degradation of soil and water resources by non-point source (NPS) pollutants, such as salinity, poses a tremendous threat because of the area1 extent of their contamination and the difficulty of effective remediation once soils and groundwater are contaminated.

Salinity within irrigated soils clearly limits productivity in vast areas of the USA and other parts of the world. In spite of the fact that salinity buildup on irrigated lands is responsible for the declining resource base for agriculture, the answers to a number of fundamental questions are still unknown. For instance, it is not known beyond speculated assessments what the area1 extent of the salt-affected soil is, where the location of contributory sources of salt loading to the groundwater are, to what degree agricultural productivity is being reduced by salinity, or whether the trend in soil salinity development is increasing or decreasing? Suitable regional-scale inventories of soil salinity do not exist, nor do practical techniques to monitor salinity or to assess the impacts of changes in management upon soil salinity and salt loading at a regional scale. The primary reason for the lack of answers to these questions stems from the area1 extent of the problem, and the spatially complex and dynamic nature of salinity in soil. The ability to locate sources of salt loading within irrigated landscapes and to model the migration and accumulation of salts in the vadose zone to obtain an estimation of their loading to the groundwater is an essential tool in combating the degradation of our groundwater. Groundwater quality affected by salinity depends on the spatially distributed properties that influence contaminant transport. The phenomenon of salt transport through the vadose zone is affected by the temporal variation in irrigation water quality, and the spatial variability of plant water uptake and of chemical and physical properties of soil. Coupling a geographic information system (GIS) to a deterministic model potentially offers a means of dealing with the complex spatial heterogeneity of soils which influence the intricate biological, chemical and physical processes of transient-state solute transport in the vadose zone.

Modeling the movement and accumulation of a NPS pollutant such as soil salinity is a spatial problem well suited for the integration of a deterministic model of solute transport with GIS. GIS serves as a spatial database to organize, manipulate, and display the complex spatial data used by a deteminisitic model to describe the regional-scale distribution of soil salinity and salt loading to groundwater. The coupling of the spatial data handling capabilities of GIS with a one-dimensional solute transport model offers the advantage of utilizing the full information content of the spatially distributed data to analyze solute movement on a field scale in three dimensions. As a visualization and analysis tool, GIS is capable of manipulating both spatially-referenced input and output parameters of the model.

The first applications of GIS to NPS pollution were for surface water resources in the mid 1980s (Hopkins & Clausen, 1985; Pelletier, 1985; Potter et al., 1986). These consisted of land evaluation and water quality models of runoff and soil erosion. The first application of GIS for assessing the impact of NPS pollutants in the vadose zone occurred in the late 1980s. Corwin et al. (1988, 1989), and Corwin and Rhoades (1988) first applied the use of GIS to delineate areas of accumulation of salinity in the vadose zone by coupling a GIS of the Wellton-Mohawk Irrigation District to a regression model of soil salinity development. For an in-depth review of GIS applications of deterministic models for regional-scale assessment of NPS pollutants in the vadose zone the reader is referred to Corwin (1996, this publication).

It is the objective of this chapter to review the work of Corwin and his colleagues regarding the development of practical methodologies for delineating area1 distributions of soil salinity and estimating salt-loading on irrigated agricultural land at a regional scale. Two approaches have been developed over the past 7 yr that use the spatial data handling and visualization capabilities of a GIS. One approach couples a regression model of salinity development to a GIS of soil salinization factors to model the accumulation of soil salinity in the root zone (top 60 cm) under steady-state conditions (Corwin et al., 1988, 1989; Corwin & Rhoades, 1988. This is referred to in this chapter as the *Steady-State GIS/Salinity Model. The* second approach integrates a one-dimensional solute transport model with a GIS of solute transport parameters to model the movement of salts through the vadose zone under transient-state conditions (Corwin et al., 1993a, b; Vaughan et al., 1993; Vaughan & Corwin, 1995). This approach is referred to as the *Transient-State GIS/Salinity Model.* Both approaches result in the capability of producing maps of soil salinity accumulation within the root zone.

METHODS AND MATERIALS

Steady-State GIS/Salinity Model

A regression model of salinity development was formulated upon commonly known cause-and-effect salinization factors (Corwin et al., 1988, 1989; Corwin & Rhoades, 1988). In arid climates, the development of soil salinity on irrigated lands can be conceptually related to several general factors: irrigation water quality, physical edaphology, groundwater characteristics and irrigation management. Figure 18-1 illustrates the interacting dynamics of these salinization factors.

The interaction of the factors illustrated in Fig. 18-1 causes the buildup of salts in the root zone. Evapotranspiration, which results in the selective removal of water by plant roots leaving behind any salts naturally present in the irrigation water, is the process primarily responsible for the accumulation of salt in the root zone. Under steady-state conditions with a net downward water flux, salt concentration will increase with depth through the root zone. All things being equal, irrigation water of poor quality (i.e., high salt concentration) results in higher soil salinity profiles. Edaphic factors such as soil permeability are potentially influential upon the accumulation of salt in soil due to the retarding effect upon water flow which reduces any leaching of salts. A shallow water table and high salinity groundwater also are likely to be influential in the development of soil salinity as a result of the increased potential for upward movement of salts (Ayers & Westcot, 1976; Shih, 1983). Figure 18-2a shows the relationship between the surface evaporation rate and depth to the groundwater, while Fig. 18-2b shows the accumulation of salt near the soil surface due to the upward movement of salts carried by water rising to meet the evaporative demand. As the depth to ground-

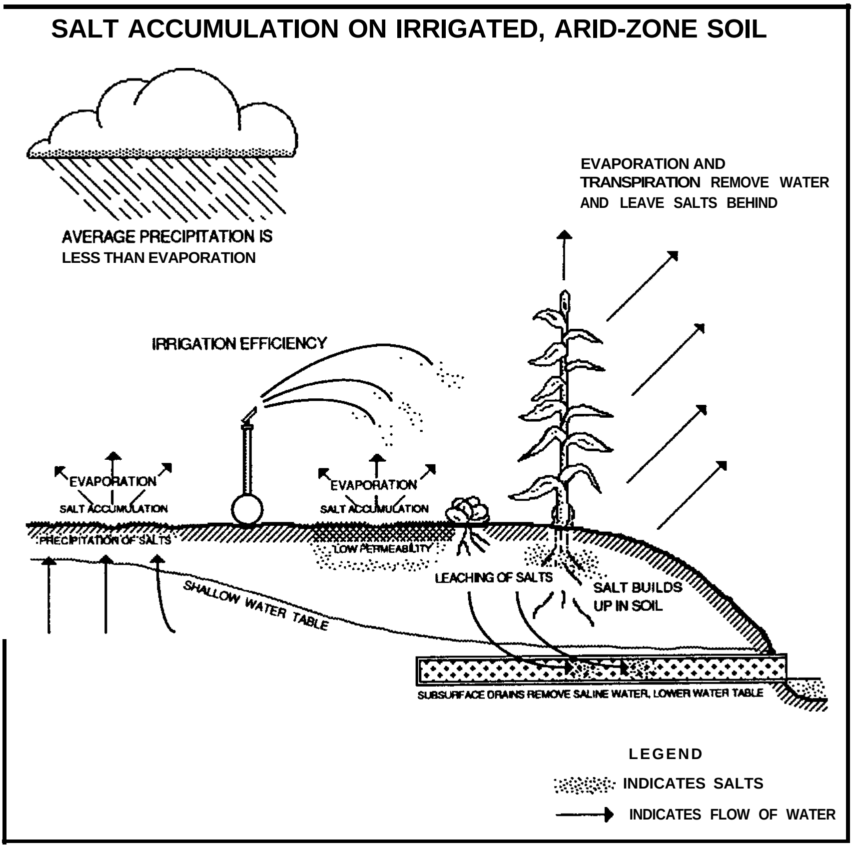

Fig. 18-1. Schematic illustrating the processes involved in the salinization of irrigated, agricultural lands.

water decreases, the soil surface evaporation rate increases and increased salt accumulates at the soil surface. Irrigation management practices determine the extent of leaching of salts from the soil profile. Because of the evapotranspiration process, repeated application of irrigation water to land results in the accumulation of salts within the root zone. To maintain agricultural productivity, these salts must be leached out of the crop root zone. The fraction of irrigation water, in excess of a crop's need, that is applied to a field and percolates below the root zone is called the leaching fraction. Leaching fraction is a common means by which irrigation management is measured and can be determined from the amount of irrigation water applied and the consumptive water use by a crop. As the leaching fraction increases, the salt concentration in the root zone decreases. Thus, it is possible to determine the area1 distribution and degree of salinity development over an irrigated landscape by coupling a GIS to a multiple linear regression model relating the interaction of four factors to salinity development in soil: (i) soil permeability, (ii) leaching fraction, (iii) depth to the groundwater, and (iv) groundwater quality.

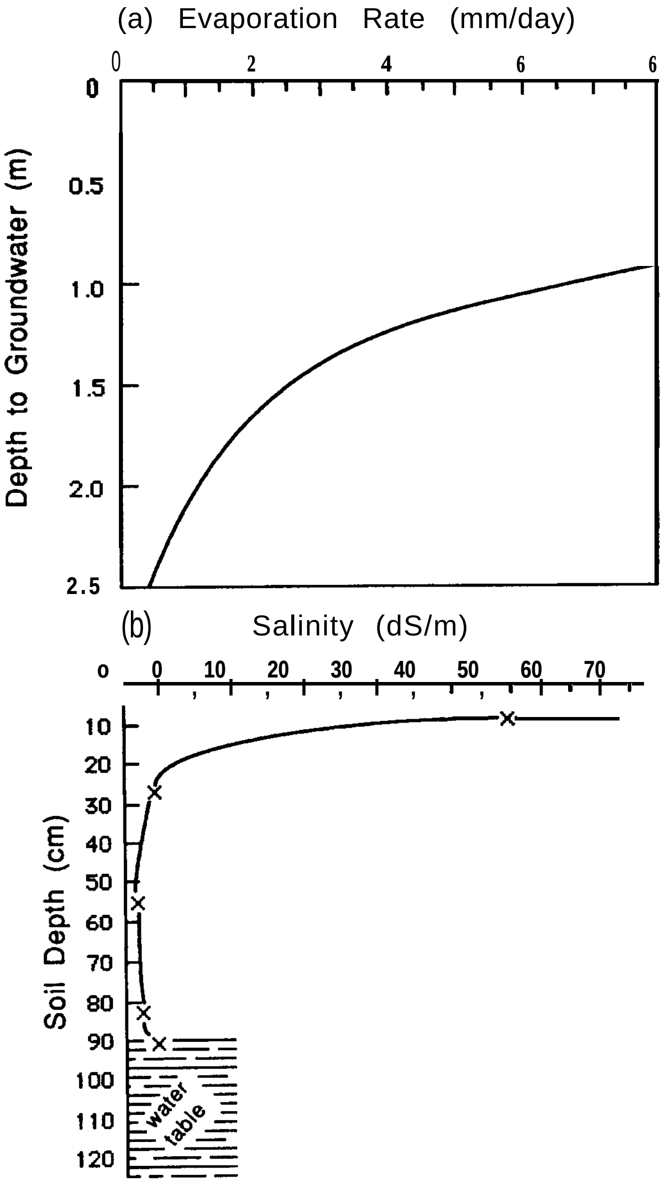

Fig. 18-2. (a) Soil surface evaporation rate as related to groundwater depth (data for Yandera loam soil from Talsma (1963) and (b) salinity accumulation at the soil surface due to shallow groundwater table (Ayers & Wescot, 1976).

The development of soil salinization potential maps from a multiple linear regression mode1 was divided into two procedural phases: (i) the organization and compilation of the GIS data layers, and (ii) the development and iteration of the salinization potential model. The first phase involved the development of a spa-

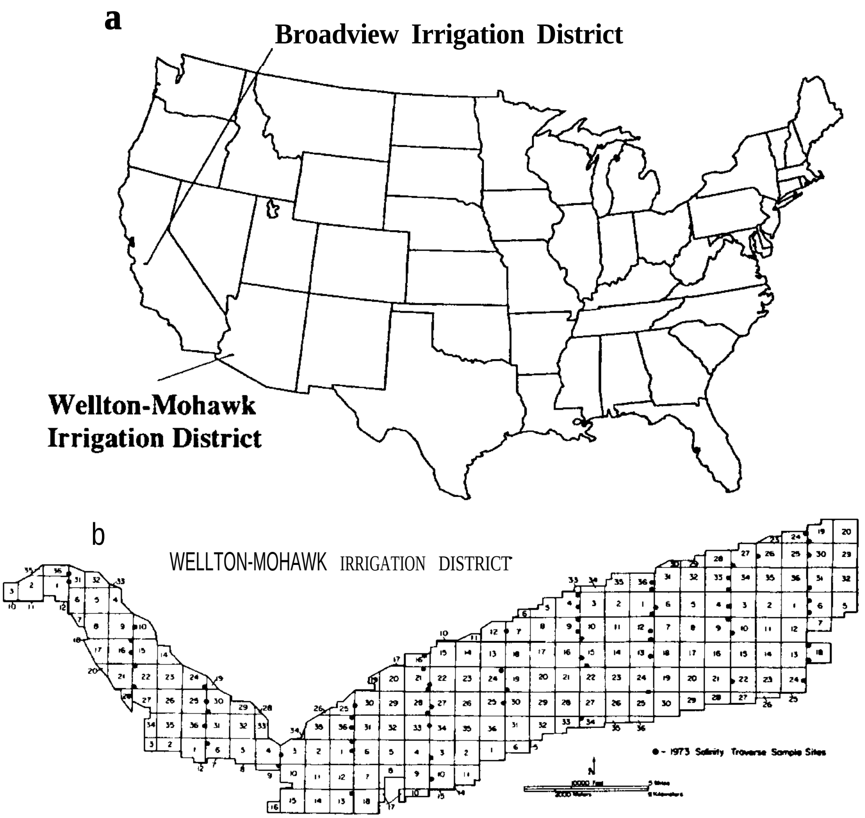

Fig. 18-3. (a) Location of the Wellton-Mohawk Irrigation District and the Broadview Water District within the continental USA and (b) Wellton-Mohawk Irrigation District study area showing the section lines and the salinity traverse sample sites.

tial database of georeferenced data for a study area. The selected study site was an area of approximately 170 square miles of the Wellton-Mohawk Irrigation District located outside Yuma, AZ, in the southwestern USA (see Fig. 18-3a and 18-b). The spatial database consisted of the four salinization factors: soil type with its associated soil permeability, depth to the groundwater and groundwater quality contour data, and leaching fraction data aggregated to Public Survey quarter section units. Contour maps of depth to groundwater, and groundwater quality were obtained from the Wellton-Mohawk Irrigation District. Each map was digitized by hand and associated attributed data were entered into the GIS for each map unit. Soil survey maps of the Wellton-Mohawk Irrigation District were obtained from the Soil Conservation Service. Similarly, these maps were digitized and associated soil permeability attribute data were entered into the GIS. Finally, crop history data was obtained from the Wellton-Mohawk Irrigation District including irrigation amounts, crops planted, and consumptive water use of each crop. From this data the leaching fraction was calculated for each quarter section. The quarter sections were digitized by hand and the associated leaching

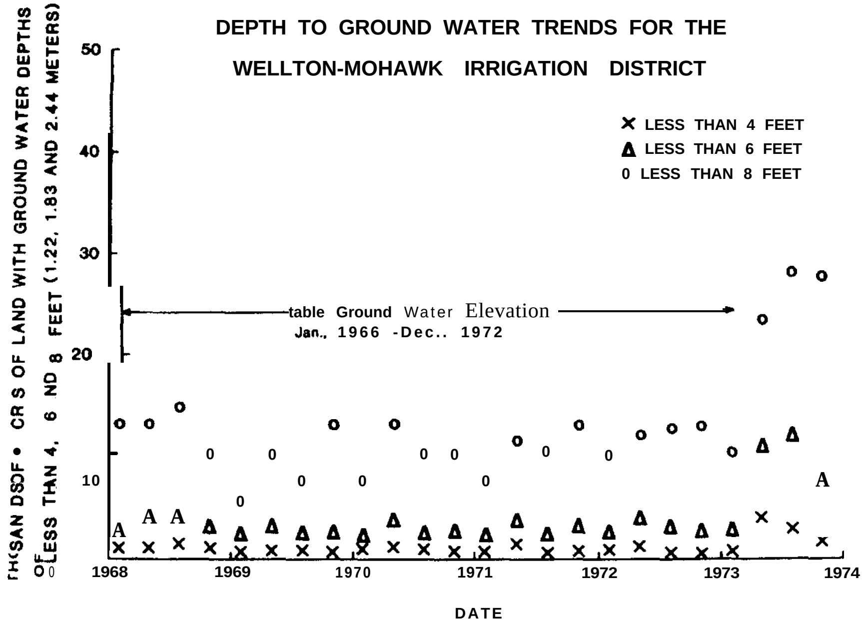

Fig. 18-4. Groundwater elevation trends in the Wellton-Mohawk Irrigation District from January 1968 to December 1973. (1 acre = 0.405 ha; 1 foot = 0.305 m).

fraction data entered into the GIS. Though pertinent to the development of soil salinity, irrigation water quality was ignored because it was assumed to be of uniform quality for the entire study area. This assumption was most likely valid because the source of the irrigation water was the same for all irrigated fields and the quality of the water was not temporally variable. Spatial data for the four salinization factors were compiled for the time period 1968 to 1973, a period in which no unusual perturbations (e.g., flooding) in the dynamics of the salinity development process for the study area had occurred as reflected by stable groundwater elevations (see Fig. 18- 4).

The second phase involved the formulation and testing of the salinization model followed by the iteration of the model to the georeferenced databank to produce a final map. In order to formulate and validate the salinization model, a salinity traverse data set of 66 sample sites (see Fig. 18-3b for the sample site locations) collected by the University of Arizona in 1973 was used as the ground-truth measure of soil salinity for the top 61 cm (24 inches) of soil. The data set of 66 observations was randomly split into two data sets: an estimation data set of 29 observations and a validation data set of 37 observations. The estimation data set was used to formulate a multiple linear regression model, and the validation data set was used to evaluate the regression model. Each salinization factor was weighted according to its significance in the overall salinization process. The weighted significance ascribed to each factor was determined using standard statistical methods (i.e., multiple linear regression) that correlate the geocoded variables to the ground-truth measurements of salinity. In other words, regression

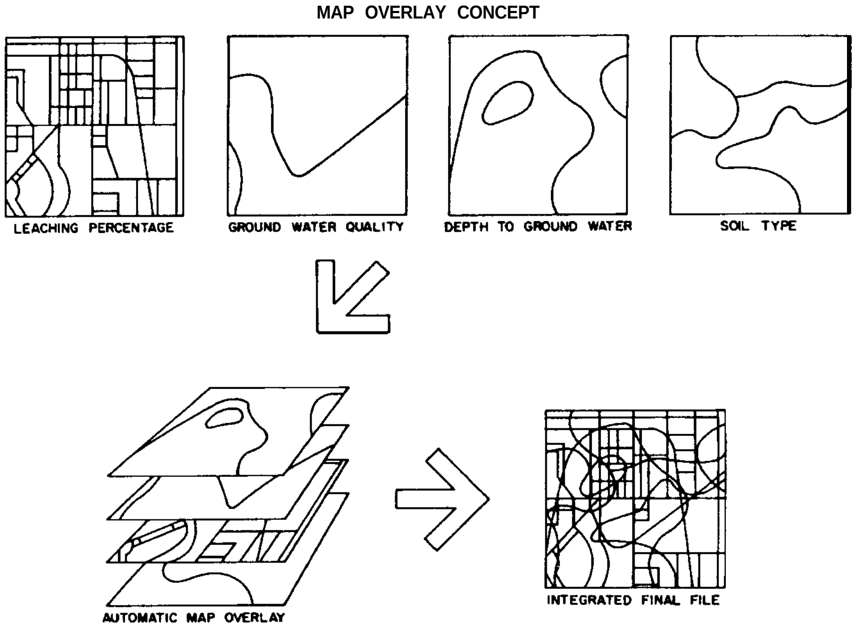

Fig. 18-5. Schematic of map overlaying of salinization factors.

coefficients of the salinization potential model were derived by using multiple linear regression to fit the four salinization parameters to the ground-truth soil profile salinity measurements (meq L^{-1}) comprising the estimation data set. To determine which of the four regressor variables were significant, a variable selection procedure was used which would provide a large coefficient of determination (R^2), a small estimation of error variance (s^2) and a model that is parsimonious. The regression model was applied to each delineated map unit generated from the map overlaying capability of the GIS, specifically ARC/INFO (see Fig. 18-5 for map overlay illustration). Applying the salinization potential model to the four salinization factor databases, the GIS computed map units that were subsequently assigned to one of three soil salinity categories as defined in the U.S. Salinity Laboratory's Handbook 60 (1954): low, medium, and high, corresponding to salt concentrations of less than 7.5 meq L^{-1} between 7.5 and 16.9 meq L^{-1} and greater than 16.9 meq L^{-1}), respectively. The maps were thereby a spatial expression of the salinity model. To evaluate the multiple linear regression model, salinities calculated from the model were compared with the measured salinities from the validation data set. A linear least squares analysis of the measured and predicted salinities was conducted to evaluate their 1:l correspondence. In addition, an evaluation of the correspondence of the calculated and the observed salinization category for each point of the validation data set was made.

Transient-State GIS/Salinity Model

The one-dimensional, functional transport model TETrans, introduced by Corwin and Waggoner (1990) and Corwin et al. (1991), was integrated into the

ARC/INFO geographic information system. TETrans was loosely coupled to ARC/INFO, implying that the GIS and model software were coupled sufficiently to allow the transfer of data and results; consequently, the GIS and modeling module did not share the same data structures. A detailed discussion of the coupling of TETrans to the GIS is provided in Vaughan and Corwin (1995).

A complete description of the theoretical development of TETrans is outlined in Corwin and Waggoner (1991) and Corwin et al. (1991). TETrans is a mass-balance, layer-equilibrium model that defines nonvolatile, solute transport as a sequence of events or processes: (i) infiltration and drainage to field capacity, (ii) instantaneous chemical equilibration for reactive solutes, (iii) water uptake by the plant root resulting from transpiration and evaporative losses from the soil surface, and (iv) instantaneous chemical reequilibration. Each process is assumed to occur in sequence as opposed to the collection of simultaneous processes that actually occur in nature. Furthermore, each sequence of events or processes occurs within each depth increment or layer of a finite collection of discrete depth increments. The physical and chemical processes that are accounted for in TETrans include fluid flow, preferential flow, adsorption, and evapotranspiration through plant root water uptake. From a knowledge of water inputs and losses, and of soil-solute chemical interactions, TETrans predicts the average concentration of reactive or nonreactive solutes through the vadose zone. The principal design philosophy behind TETrans was to develop a model around data which is commonly collected by irrigation districts or is present in existing soil databases. This design criteria would enable the model to be applied at a regional scale in the most cost-effective manner.

ARC/INFO was integrated with TETrans to provide spatial coverage to compute area1 distributions of soil salinity profiles and salt-loading to the groundwater over a selected geographic area. Both the computed results and all data required by TETrans are stored in the GIS database to permit spatial representation of any physical, chemical or biological variable.

Thirty-seven quarter sections (2396 ha) of the Broadview Water District located on the west side of central California's San Joaquin Valley were chosen as a test site (see Figs. l8-3a and 18-6). This provided sufficient variability and magnitude to test the methodology and the GIS/TETrans model, referred to as TETransgeo. A complete data set of spatially-referenced input parameters including irrigation data (i.e., irrigation dates, and the corresponding irrigation amounts and salt concentrations), crop data, (i.e., evapotranspiration amount between irrigation events; maximum root penetration depth of each crop; plant water uptake distribution of each crop; and the planting date, harvesting date and days to maturing of each crop), soil property data (i.e., thickness and bulk density of each soil horizon or layer) and initial conditions (i.e., initial water content and initial soil solution salt concentration for each soil layer) was assembled for the 1991 growing season (April to September) and entered into the GIS database.

In April and May of 1991, electromagnetic induction (EM) measurements of bulk soil electrical conductivity were taken at 64 locations (grid spacing of 0.16 km) within each of the 37 quarter sections (approximately 2350 total sites) of the Broadview Water District. April and May represent the time when nearly all of the crops in the study area were planted. From the roughly 2350 sites, a total

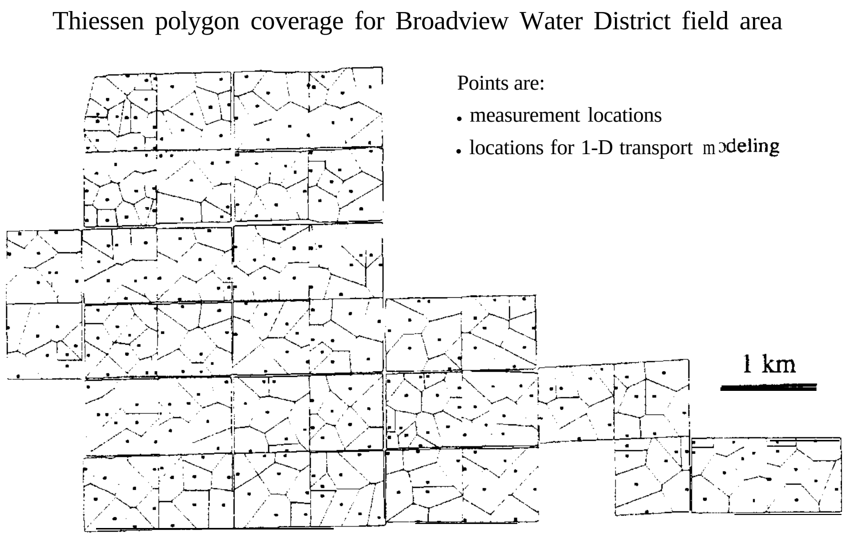

Fig. 18-6. Boundary lines of the 37 quarter sections of the Broadview Water District test site and the 285 soil sample sites. Thiessen polygons also are defined.

of 285 locations were statistically selected as representative soil sampling sites that represented approximately eight sample sites per quarter section (see Fig. 18-6 for sample locations). The statistical selection of the 285 soil sampling sites was based on the observed EM field pattern utilizing the technique of Lesch et al. (1992).

The initial conditions of water content and total salt concentration in the soil solution were established from the soil core samples taken at 0.30-m increments down to a depth of 1.2 m. A table was constructed from these measurements and stored in ARC/INFO format along with tables containing other relevant input data. Together these tables form a relational database for the Broadview Water District. The table of initial conditions contains records for the 285 locations. Each record included data for four depth increments: 0- to 0.3-, 0.3- to 0.6-, 0.6- to 0.9-, and 0.9- to 1.2-m. When the TETrans program was run, the initial conditions and other input data required for the calculation were obtained from these tables.

The boundary condition at the surface was established by the irrigation schedule for each quarter section. Irrigations generally occurred during a 2- to 3-day period. There were normally four to seven such periods during the summer growing season. The TETrans calculation requires that irrigation be characterized as specific events in which an amount of water is applied instanteously; therefore, the actual stored data representing the boundary conditions consists of irrigation event records containing the depth of water applied, the date applied, and the salt concentration of the irrigation water. The TDS (total dissolved solids) for each irrigation water was estimated from the electrical conductivity. Chemical analyses of the irrigation water were performed by the Soil Testing Laboratory at Colorado State University. Sampling was conducted at approximately 1-mo intervals.

The evapotranspiration (ET) was determined for each crop with CIMIS (California Irrigation Management Information System) data for the vicinity of the Broadview Water District.

Thiessen polygons were created from the 285 sample sites (see Fig. 18-6). The TETrans model was applied for each of the map units defined by the Thiessen polygons. Results of the TETrans simulations are presented for the main growing season of 1991. Preliminary display maps show calculated area1 distributions of irrigation efficiency (i.e., leaching fraction), drainage amounts and salt-loading to groundwater for the time period from April, 1991, to September 30, 1991. Future simulations will be conducted up to the project's expected termination date of 1996. In 1996 field measurements of salinity at the 285 locations will be measured for comparison with simulated results from the GIS/TETrans model.

RESULTS

Steady-State GE/Salinity Model

The best regression model of salinity development both in its goodness-of-fit to the estimation data set and in its ability to reliably predict the salinities of the validation data set consisted of three significant regressor variables: soil permeability (cm h^{-1}), leaching fraction and groundwater electrical conductivity (dS m^{-1}). As shown below, the functional form of the model indicated that the salinity (in meq L^{-1}) in the top 61 cm of the soil was inversely related to the soil permeability and the leaching fraction, and directly related to the electrical conductivity of the groundwater. The depth to the groundwater was determined to be an insignificant parameter due to the lack of a shallow water table:

$$\text{SALINITY (meq } L^{-1}) = 18.03 \times (\text{l/permeability}) - 0.40 \times (\text{l/leaching fraction}) + 1.32 \times (\text{groundwater electrical conductivity}) + 2.12 \qquad [1]$$

The R^2 for Eq. [1] was 0.86 showing a fairly high degree of fit. The estimator of error variance, s^2, was comparatively low, 2.59. Because the leaching fraction was not available for all quarter sections, a second regression equation (Eq. [2]) also was formulated. When leaching fraction data was not available, the permeability and groundwater electrical conductivity were the significant regressor variables formulating the model:

$$\text{SALINITY (meq } L^{-1}) = 23.16 \times (\text{l/permeability}) + 0.84 (\text{groundwater electrical conductivity}) + 1.26 \qquad [2]$$

The R^2 and s^2 for Eq. [2] were 0.60 and 10.64, respectively. The significant decrease in the R^2 and the increase in the s^2 when leaching fraction was removed as a regressor variable indicated that leaching fraction was particularly significant in the model.

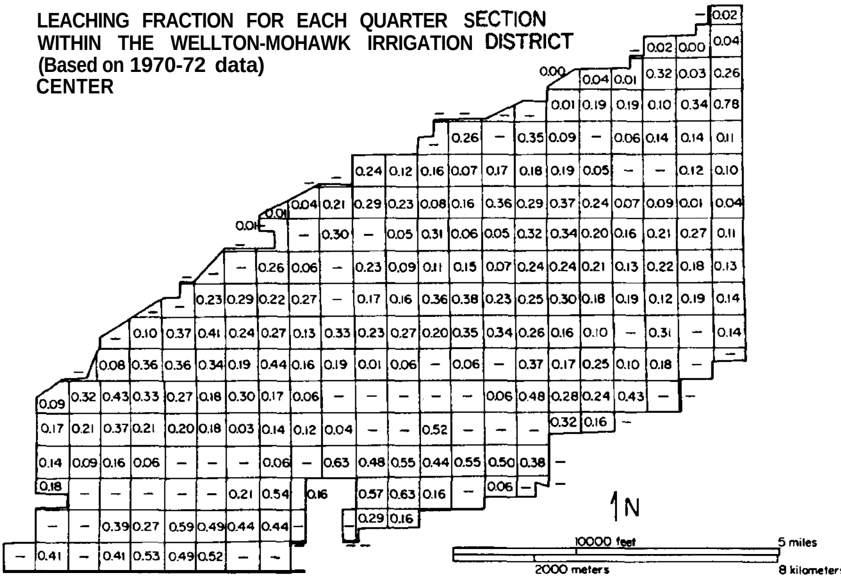

Fig. 18-7. Leaching fraction for each quarter section of the *center* portion of the Wellton-Mohawk study area.

Figures 18-7 to 18-10 show the spatial representation of the four salinization factors. For visualization detail purposes only the center portion of the Wellton-Mohawk is shown. The map of salinization potentials generated from the regression model (see Fig. 18-11) indicated general trends in salinity that were known to exist for the study area over the time period of interest, 1968 to 1973. The southern half of the irrigation district is a mesa on which low salinity existed. Generally speaking, the northern half was predominantly moderate in salinity with pockets of low and high salinities.

The ability of the model to correctly predict both the salinity category (low, medium, and high) and the actual measured soil salinity value was very good. Out of the 37 observations in the validation data set, the model was able to predict 86% of the categories correctly. Even more impressive was the close prediction of actual measured salinity values in the validation data set. A linear regression of predicted salinity values from the model and measured salinities resulted in a slope andy-intercept of 1.000 and -0.001, respectively, with an R^2 of 0.81. A plot of the residuals for the model showed an ideal residual plot with a random pattern around zero and no detectable trend. This fact further established the final formulation of the model as the most reliable.

Transient-State GIS/Salinity Model

Simulated results for the top 1.2 m of soil calculated for the time period of April 1991 to 30 September 1991, show the most significant change in salinity occurs in the top 0.3 m of the soil profile (compare Color Plates 18-l and 18-2). Noticeable salinity concentration increases occurred in the top 0.3 m at several

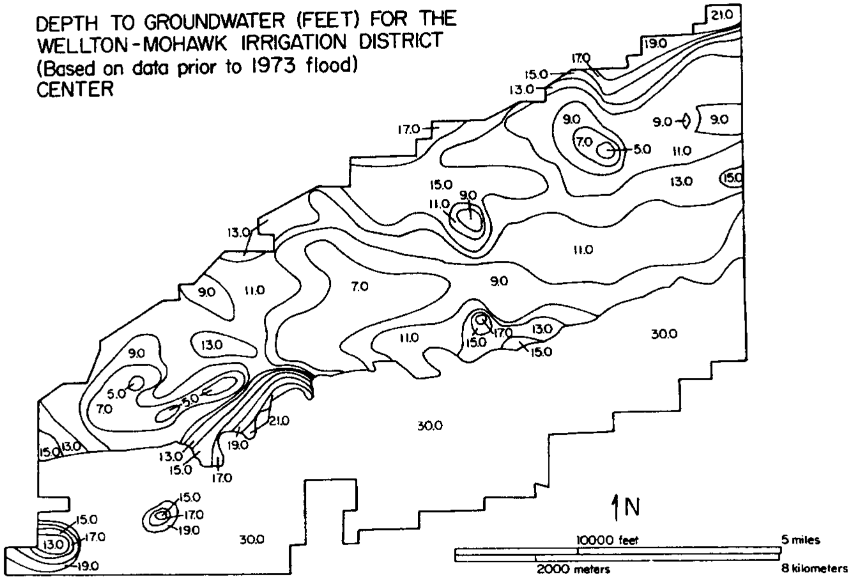

Fig. 18–8. Depth to groundwater contours for the center portion of the Wellton–Mohawk study area (1 foot = 0.305 m).

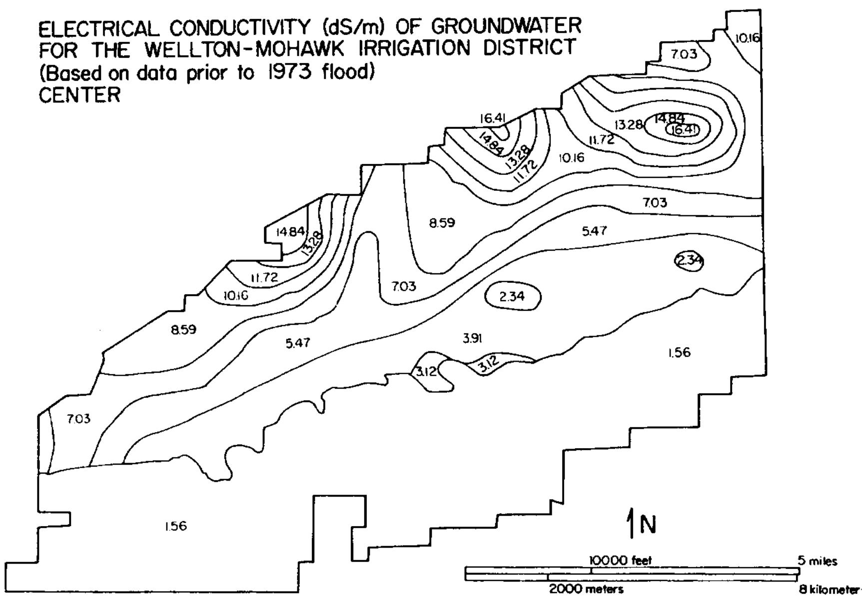

Fig. 18–9. Groundwater electrical conductivity contours of the center portion of the Wellton–Mohawk study area.

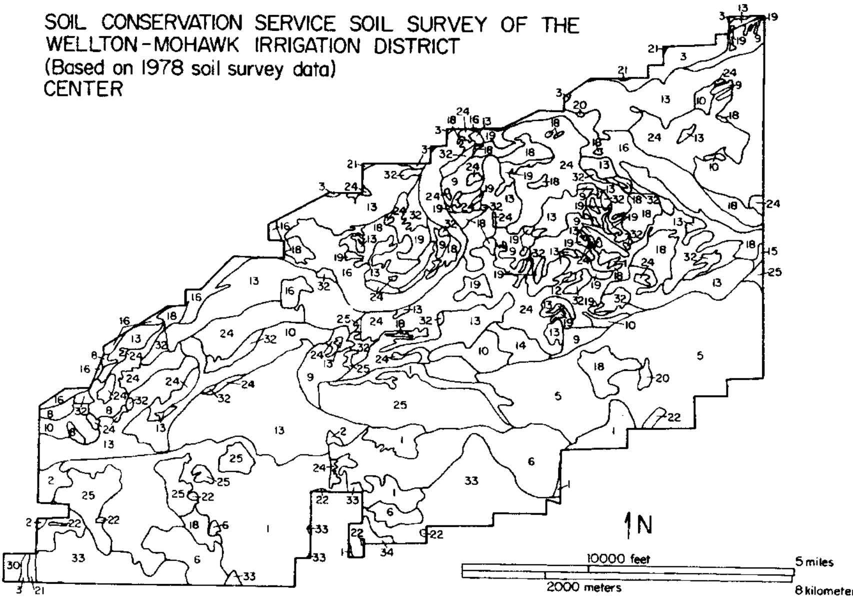

Fig. 18–10. Soil Conservation Service soil type map for the center portion of the Wellton–Mohawk study area. Each soil type corresponds to a defined permeability.

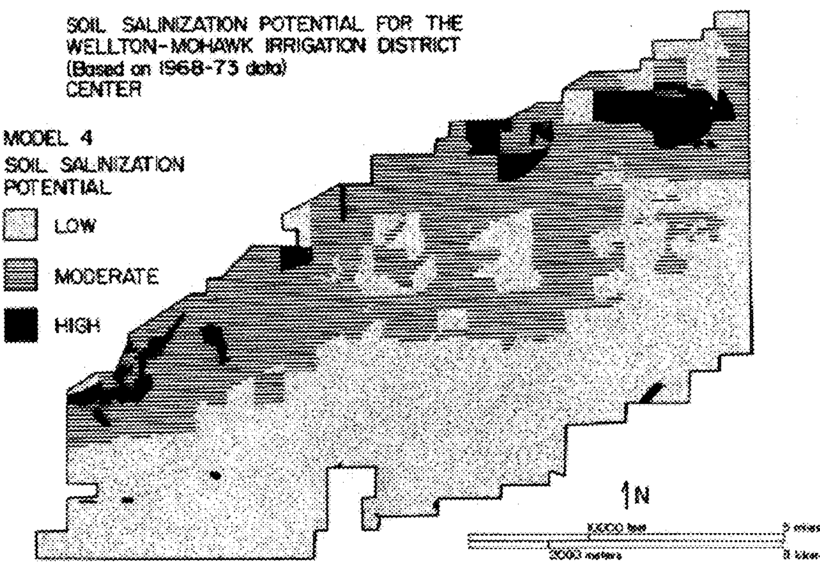

Fig. 18–11. Soil salinization potential map generated from the regression model of salinity development.

locations (see Color Plate 18-2). In every instance the salinity peaks are located on soil that had been left fallow. The peaks are most likely artifacts of the TETrans model and they point out one of the inherent weaknesses of the TETrans model. TETrans does not account for the upward movement of water; consequently, TETrans does not replenish the depleted water of the surface layer with moisture from lower in the profile. Without a calculation for upward water flow, the continuous removal of water by surface evaporation on fallow fields results in the depletion of water in the 0- to 0.3-m depth increment down to the residual water content (i.e., approximately the water content of air dried soil). The resultant calculated concentration of salts within the top layer is raised to an extremely high level. Even though the calculated upward movement of moisture to meet evaporative demand also would bring salt, it would not bring enough salt to approach the level of salinity calculated from the depletion of moisture in the top layer down to the residual water content; consequently, the salinity level calculated by TETrans for the surface layer of fallow areas is spuriously high.

Color Plate 38-3 shows the calculated leaching fractions for the preliminary 6-mo study period. An area totaling approximately twelve quarter sections had a calculated leaching fraction of less than 0.1. This area consisted of either fallow land or land which had a crop of seed alfalfa (see Color Plate 18-4). The application and/or precipitation of water in these areas totaled less than 0.1 m. The spatial distribution of the calculated amount of drainage beyond the root zone is shown in Color Plate 18-5. A composite area equal to greater than seventeen quarter sections had a drainage of less than 0.1 m.

Color Plate 18-6 shows an area1 distribution of the amount of salt that drained beyond the root zone and will ultimately enter the groundwater. Most of the study area shows very little salt loading because a significant portion of the land was fallow (no irrigation water was applied) for the preliminary 6-mo study period resulting in little drainage. Because little rainfall occurred in 1991, the fallow areas had no net calculated downward salt flux. In fact, evaporation exceeded rainfall during this time period. The greatest salt loading to the groundwater occurred in Section 3SE (i.e., the southeast quarter section of Section 3), Section 4NE, Section 8SE, and Section 15NE (see Color Plate 18-6). Not surprisingly, these areas are associated with high leaching fractions (i.e., in most cases leaching fractions ranging from 0.4 to 0.8; see Color Plate 18-3), and high soil salinity in the lower portion of the soil profile (see Color Plate 18-1, depths 0.6-0.9 m and 0.9-1.2 m). All four quarter sections were cropped with cotton (Gossypium *hirsutum* L.). An inventory of the extent of salt-affected soils for the Broadview Water District is shown in Color Plate l8-7.

DISCUSSION OF RESULTS AND CONCLUSIONS

Steady-State GE/Salinity Model

The regression model indicated by the magnitude of its coefficients that electrical conductivity of the groundwater and soil permeability were the dominating soil salinization factors in the Wellton-Mohawk Irrigation District over the period of study. Leaching fraction had only subtle effects. In spite of this fact, the model also showed that the greatest single increase in R^2 for a multivariate case occurred for the combination of leaching fraction and electrical conductivity of the groundwater. This suggests that salinity development within the soil profile was more a consequence of the leaching fraction with the groundwater electrical conductivity merely acting as a reflection of the leaching efficiency and the electrical conductivity of the irrigation water. Several other facts point to leaching fraction as the predominant mechanism of salinity development in this particular study. First, the correlation matrix for the model indicated an inverse correlationship (r = -0.71) between groundwater electrical conductivity and leaching fraction. The moderate negative correlation combined with the negative sign and the insignificant magnitude of the leaching fraction coefficient in Eq. [l] suggests the existence of multicollinearity. Second, depth to the groundwater was insignificant to the development of soil salinity. This was shown by the statistical insignificance of depth to groundwater as a regressor variable in the formulation of the regression model with the variable selection procedure. Figures 18-2 and 18-8 provide reaffirmation of this contention. Figure 18-8 shows that very few locations have a water table shallower than 1.5 m (5 ft); consequently, the influence of the depth to groundwater may not come into play. The evaporation rate at the soil surface, which is the driving force behind upward water flow on bare surfaces, quickly diminishes as the depth to groundwater exceeds 1.5 m (see Fig. 18-2). This would make the broad scale upward movement of salinity an unlikely mechanism for salinization in this study area. Third, leaching fraction was negatively correlated to soil salinity as would be expected if irrigation management was the dominating mechanism influencing soil salinity development. Though the results are inconclusive, the model points to irrigation management as the overall predominant mechanism for determining the development of salinity in the root zone for the study area and the time period of interest. Ostensibly, the high correlation of groundwater electrical conductivity to soil salinity development is actually a reflection of the irrigation efficiency and irrigation water salinity.

The obvious limitations to the use of regression models for characterizing soil salinity development or for quantifying any natural process for that matter are: (i) site specificity and (ii) most probably time specificity. Different locations will undoubtedly have different predominant mechanisms. Furthermore, any perturbations to cause the system to no longer be at steady state immediately negates the continued application of the model.

This approach has extremely limited application. Nevertheless, as long as steady state conditions remain in effect with the same mechanisms predominating, and as long as the inputs into the regression model are not outside the range of the estimation data set, then reliable predictions are possible. If nothing else, this approach provides a visualization of the area1 distribution of potential salinity development for inventory purposes which surpasses the spatial information provided by a map of point soil salinity measurements.

Transient-State GIS/Salinity Model

The justification for the role of the GIS in manipulating and displaying spatial data is profoundly revealed in the simulations presented in Color Plates 18-2, 18-3, 18-5, 18-6, and 18-7. These figures are the result of input data spatially defined by Thiessen polygons created around soil-core sample sites; quarter sections which defined irrigation map units and crop map units (i.e., evapotranspiration units); and a chloropleth map which defined soil types with their associated physical and chemcial properties. From the layers of geometrically-diverse georeferenced information the GIS permitted the display of simulated results as polygons (Color Plates 18-3, 18-5, 18-6, and 18-7) or as interpolated three-dimensional visualizations (Color Plate 18-2).

Quarter Sections 3SE, 4NE, 8SE, and 15NE (see Fig. 18-6) have high leaching fractions (see Color Plate l8-3), high drainages (see Color Plate l8-5), and high salt leaving the root zone (see Color Plate 18-6). Because these quarter sections were cropped with cotton (see Color Plate 18-4), which is a highly salt-tolerant crop, it is obvious that the salt-load could have been reduced by applying less irrigation water during the 6-mo preliminary study period. Irrigation amounts for Quarter Sections 3SE, 4NE, 8SE, and 15NE were OS-O.6 m, 0.3-0.4 m, 0.4-0.5 m, and 0.4-0.5 m, respectively. Reduced irrigation amounts would not have adversely affected crop production. A close look at the initial (April and May, 1991) and the simulated soil salinity profiles (30 Sept. 1991) for these quarter sections reveals that most of the salt that moved beyond the root zone came from the lower portion of the root zone (0.6-1.2 m). Even at a reduced irrigation application, the low initial salinity in the upper portion of the soil profile (O-0.6 m) at the time of planting would have permitted germination and maturation of the cotton. Though different factors may be responsible for the cause of the salt-loading, it becomes readily apparent from the displayed spatial information of salinity distributions how to manage various situations.

Color Plate 18-7 provides a useful inventory of salt-affected soil. If depth-averaged soil salinity for the top 1.2 m can be used as a measure of salt-affected soil, then approximately 40% of the 2400-ha study area would be defined as saline. An inventory of salt-affected soils is of value in assessing the extent of the impact of agricultural activities upon soil. Knowing the extent of the problem is the first step in determining whether or not there is a problem, and whether the problem is getting better or worse.

SUMMARY

The ability to show area1 distributions of soil salinity over time provides an essential tool for maintaining a sustainable agriculture by supplying the information needed to optimize food production while minimizing the use of finite natural resources such as water, and minimizing impacts upon the environment. Two different GIS-based approaches for assessing the impact of a non-point source pollutant (i.e., soil salinity) on soil and groundwater resources of agricultural lands have been presented that can be used under different conditions (i.e., steady state or transient state).

The ability to predict salt accumulation in soil from soil features and to visually display their area1 distribution provides an invaluable tool for agricultural management purposes. It can serve as a means of locating salinity monitoring

sites, to assist in formulating irrigation management practices, and to select crops. Area1 distributions of salt accumulation in the root zone indicate areas where close attention to crop selection and irrigation management should be paid to maximize crop yield. Soil salinization potential maps can serve as a guide for determining reclamation needs, or for deciding if cultivated lands should be brought into production or left untouched. Finally, an assessment of soil salinity can be made without labor-intensive field measurements of salinity by inventorying the extent of salt-affected soils as predicted from soil property relationships.

To minimize the environmental impact of salinity upon groundwater resources, a spatial knowledge of leaching efficiency and salt-loading is necessary. Area1 distributions of salt-loading to the groundwater define areas where the greatest attention must be given to reduce the downward flux of salt either through changes in irrigation management strategy or installation of drainage systems.

ACKNOWLEDGMENTS

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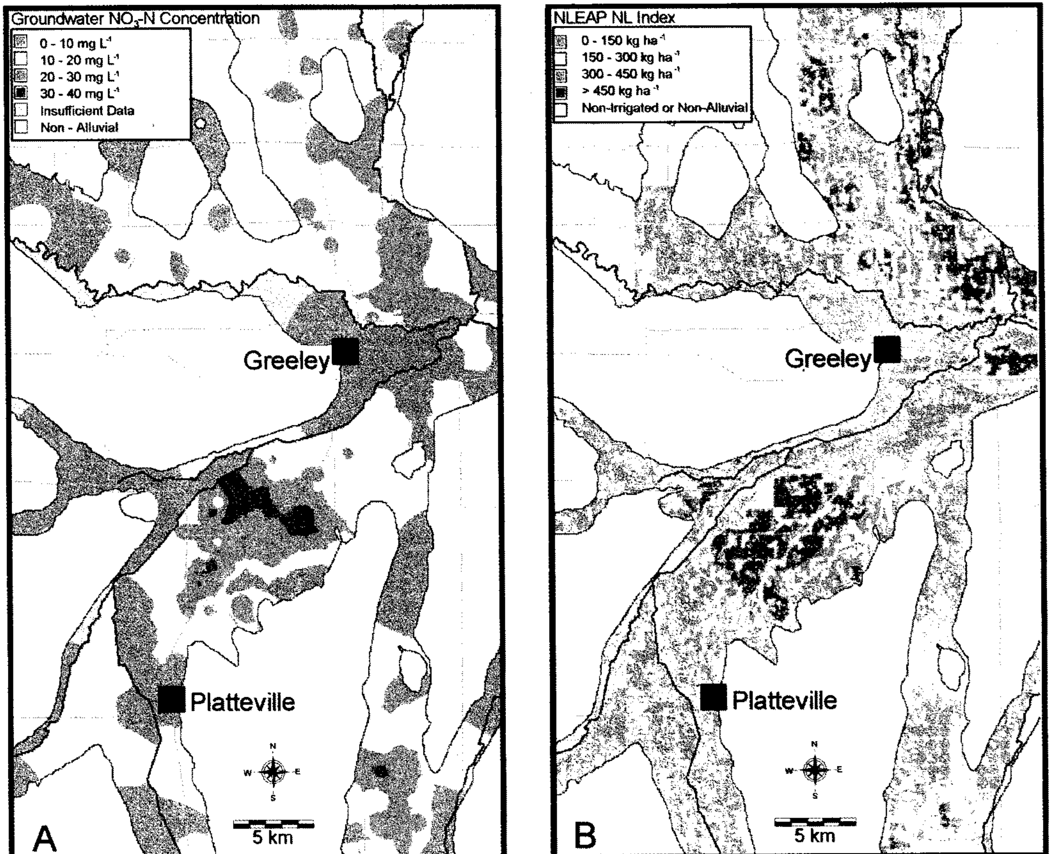
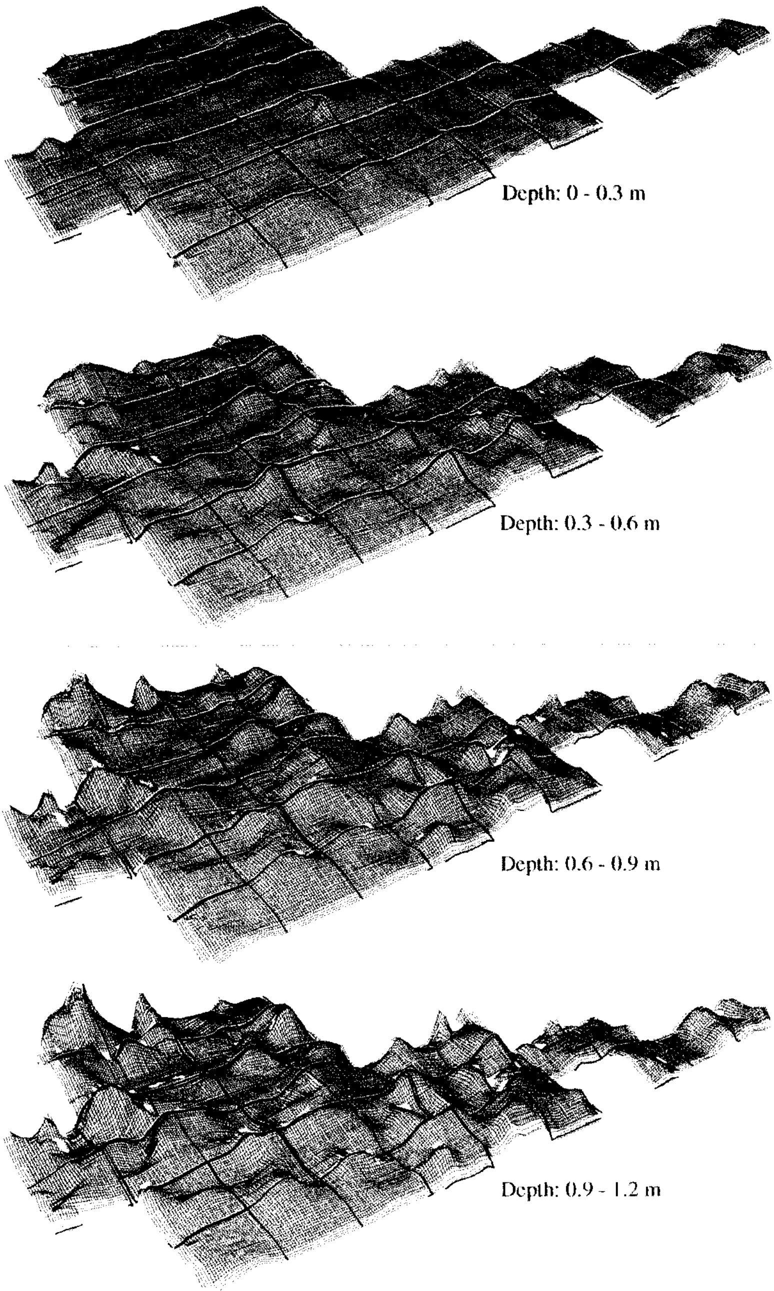


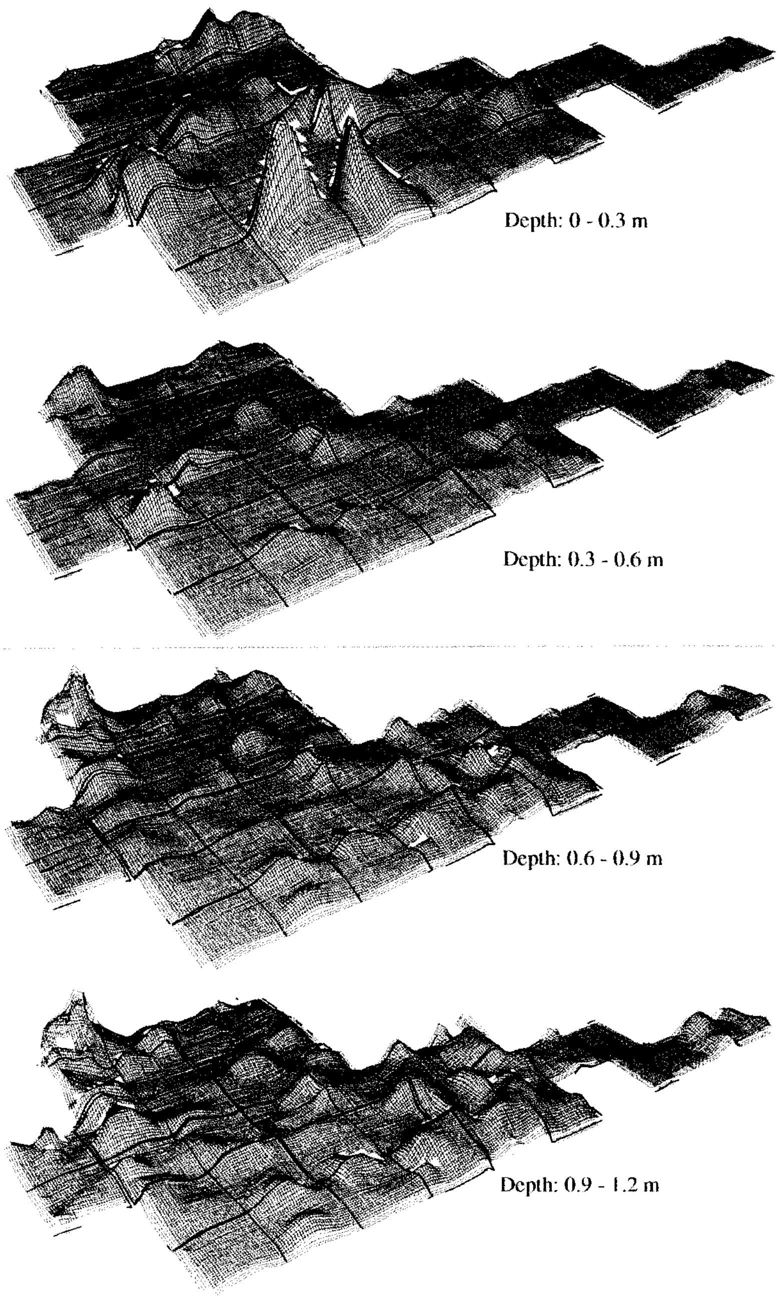
Color Plate 17–4 A. Interpolated groundwater NO_3–N concentrations and B. Nitrate Leaching and Economic Analysis Package (NLEAP) NL (Nitrate Leached) index for western portion of study area. Adapted from Shaffer et al. (1995).

Initial Condition, TDS in Soil Water, Samples Taken: 4/91 - 5/91

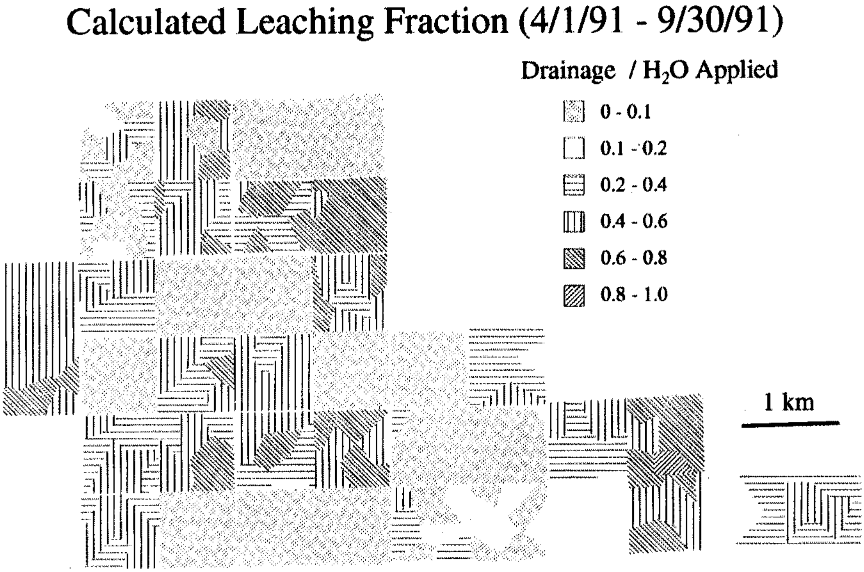


Color Plate 18–1. Spatial distribution of the measured initial soil salinity in TDS for the 0- to 0.3-, 0.3- to 0.6-, 0.6- to 0.9-, and 0.9- to 1.2-m depth increments of the Broadview Water District.

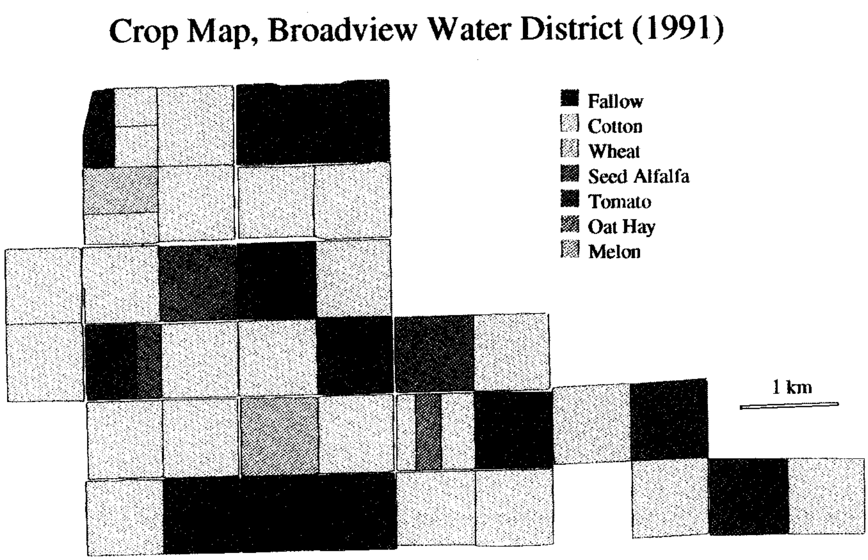
TDS in Soil Water Calculated for 9/30/1991



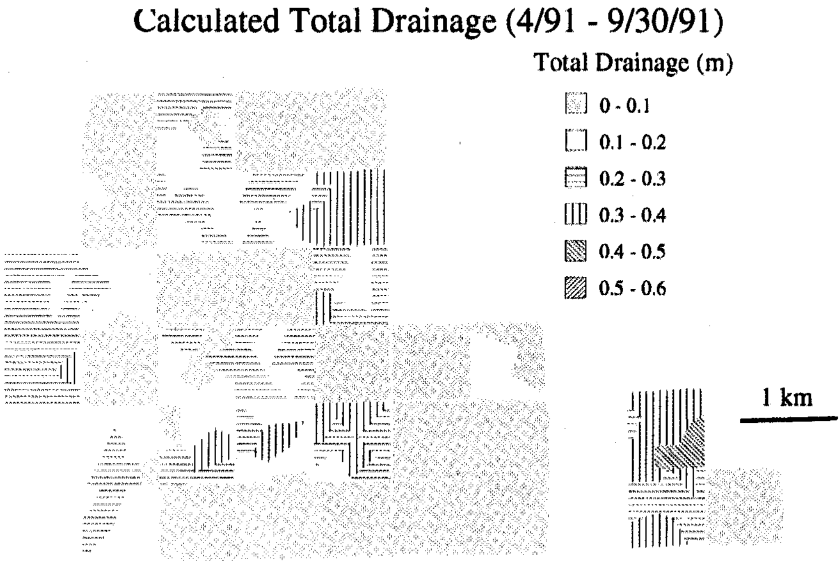
Color Plate 18–2. Spatial distribution of the calculated soil salinity in TDS for the 0- to 0.3-, 0.3- to 0.6-, 0.6- to 0.9-, and 0.9- to 1.2-m depth increments of the Broadview Water District up to 30 Sept. 1991.



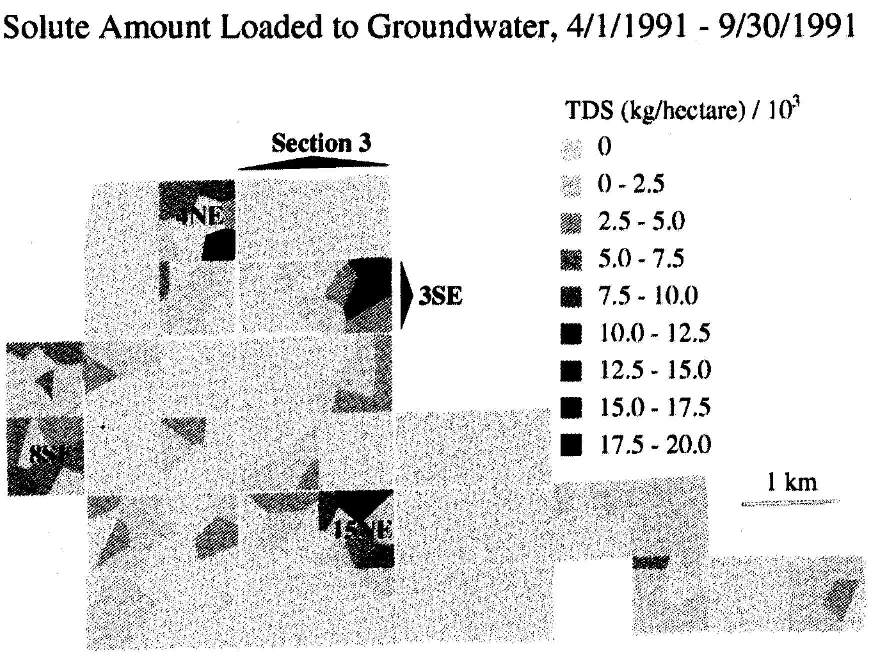
Color Plate 18–3. Areal distribution of the simulated leaching fractions for the preliminary 6-mo study period of the Broadview Water District test site.



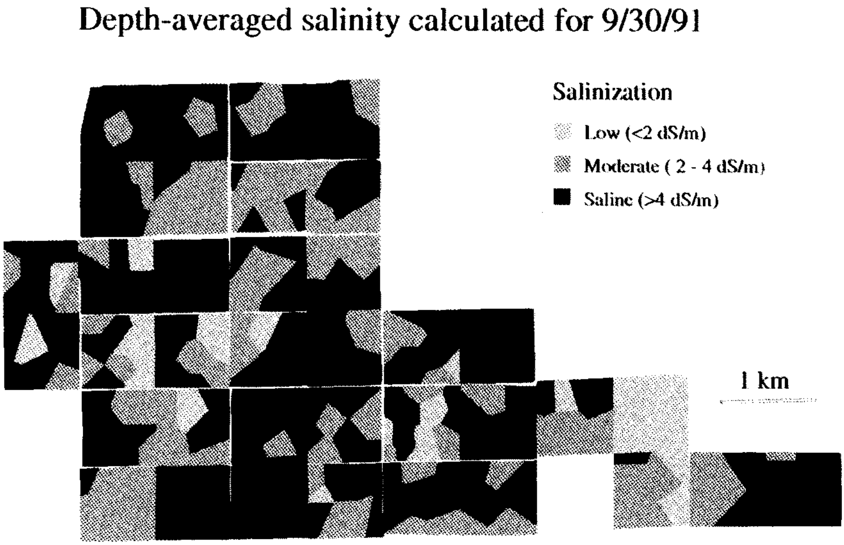
Color Plate 18–4. Crop map for the 1991 growing season (April to September 1991).



Color Plate 18–5. Areal distribution of the simulated amount of drainage beyond the root zone for the preliminary 6-mo study period of the Broadview Water District test site.



Color Plate 18–6. Areal distribution of the simulated amount of salt-loading to the groundwater for the preliminary 6-mo study period of the Broadview Water District test site. (3SE = southeast quarter section of Section 3; 4NE = northeast quarter section of Section 4; 8SE = southeast quarter section of Section 8; and 15NE = northeast quarter section of Section 15).



Color Plate 18–7. Areal distribution of the calculated depth-averaged soil salinity (top 1.2 m of soil) for the preliminary 6-mo study period of the Broadview Water District test site.