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The Use of Computer-Assisted Mapping Techniques to Delineate Potential Areas of Salinity Development in Soils

I. A Conceptual Introduction

D. L. Corwin, J. W. Werle, and J. D. Rhoades

II. Field Verification of the Threshold Model Approach

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ABSTRACT

I. A Conceptual Introduction

Several interacting factors are generally associated with the development of soil salinity on irrigated lands of the arid Southwest. Notable examples include physical edaphology (clay content and soil permeability), depth to the perched water table, salinity of the perched groundwater, and irrigation efficiency. By creating map overlays of these properties and noting the areas of intersection of specific levels or thresholds of these properties, areas can be delineated that demonstrate varying propensities for salt accumulation in the soil profile.

Utilizing an automated geographic information system (GIS), a conceptual approach to delineating areas with similar propensities for the development of soil salinity on irrigated arid-zone soils is presented. The computer mapping strategies provide an efficient and accurate means of organizing, compiling, analyzing, and displaying complex interrelated data bases that are associated with soil salinization. A map can easily be made from the data to aid in land and irrigation management decision making. The automated GIS operates on a microcomputer with enhanced graphics capabilities and requires only 32K of usable memory. The automated GIS is capable of performing mapping tasks generally reserved for larger and more expensive computer systems. The mapping system's polygonal spatial data base maximizes spatial accuracy and produces maps that are aesthetically pleasing and easy to interpret.

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The Use of Computer-Assisted Mapping Techniques to Delineate Potential Areas of Salinity Development in Soils[1]

I. A Conceptual Introduction

INTRODUCTION

COMPUTERS HAVE BECOME INDISPENSABLE TOOLS for storing, manipulating, retrieving, and displaying large quantities of diverse data. These qualities make the computer useful for processing the spatially associated data used to create maps (Fraser-Taylor 1980; Monmonier 1982; Nagy and Wagle 1979; Poiker 1982; Rhind 1977; Tomlinson, Calkins, and Marble 1976).

Computer-assisted mapping of geographically encoded data is used to compile and display data for diverse disciplines (Cadbury, Hawkes, and Readett 1971; Cliff and Ord 1981; Fraser-Taylor 1980; Hardy and Shelton 1970; Hawkes 1972; Knapp and Rider 1979; Salmen et al. 1977; Teicholz and Berry 1983; Tomlinson 1967). Cartographers, demographers, geologists, meteorologists, resource inventory specialists, city and regional planners, and various public service agencies are all common users of computer-assisted mapping (Cliff and Ord 1981; Dueker 1979; Sheehan 1979; Teicholz and Berry 1983). One application more specific to soil science is the use of computer-assisted map generation as a soil inventory tool (Burrough and Bie 1984; Giltrap 1983a,b; Moore, Cook, and Lynch 1981; J. D. Nichols 1975; Nichols and Bartelli 1972).

More than a quarter of a century ago, computer-assisted map generation was first developed as a means of creating maps from spatial data (i.e., from data associated with specific *x,y* coordinates). Over the years, computer-assisted map generation has developed from an electronic tool for creating maps into a sophisticated geographic information system (GIS) that can answer specific questions about the maps it stores (Cliff and Ord 1981; Monmonier 1982; Rhind 1977; Tomlinson 1984). The addition of the analysis capability, however, has required more complex data structures that can associate attribute information and positional data (Bouillé 1978; Peuquet 1984). With this associated attribute information, geographic information systems are now used extensively to produce maps that show the locations of natural resources. However, the ability to analyze tremendous amounts of data in relation to a set of established criteria gives computer-assisted mapping the potential for use by the soil scientist as a decision-making tool rather than a simple soil-inventory tool.

The development of soil salinity on irrigated lands of the arid Southwest can usually be related to three general factors: physical edaphology (specifically, clay content and permeability), groundwater characteristics (depth to the perched water table and salinity of the perched groundwater), and irrigation management practices (irrigation efficiency). Clay content and permeability are particularly influential in the development of soil salinity because they retard water flow. A shallow water table and high-salinity

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groundwater would increase the potential for upward movement of salts. Irrigation management practices, as reflected quantitatively by the leaching percentage, determine the extent of leaching of salts.

By coupling automated mapping techniques developed for polygonal mapping systems to a knowledge of the properties and conditions that lead to salinization in soils, it should be possible to predict areas where saline soils are likely to develop. The object of this paper is to introduce the concept of computer-assisted map generation as a tool for the assessment of salinization potential by demonstrating its ability to delineate areas of high potential salinization, based on hypothetical criteria. This is accomplished using a microcomputer-based automated GIS. Subsequent papers (Part II; Corwin, Sorensen, and Rhoades 1988) will test the validity of this mapping overlay approach as a semiquantitative assessment of salinization.

PROCEDURE AND COMPUTER TECHNIQUES

To test the automated GIS's ability to areally delineate the distribution of soil salinity potentials, a hypothetical irrigation basin was created. A soil survey map served as the hypothetical base map. The clay content and soil permeability were defined for each soil-type unit on the map (table 1). Hypothetical data bases were created for the depth to groundwater, groundwater salinity, and leaching percentage. The latter can be estimated from the amount of water applied to a crop and its consumptive water use. For each of the four overlays, individual map unit boundaries were created by manually digitizing a series of connecting-line segments that collectively formed a polygon, and assigning the polygon an attribute or value that represented the intensity or quality of that property. In the case of leaching percentage, the attributes were assigned for each field. For depth to the groundwater and groundwater quality, contour lines were drawn from well data. The area between two adjacent contour lines formed the polygonal map unit, and its attribute value was the average of the values of the adjacent contour lines.

Automated Mapping System

Using a 32K microcomputer with graphics capabilities, a variety of extended BASIC language programs were developed to process the automated mapping of the hypothetical data: SOILDIG, SOILEDIT, SOILSHADE, SOILPLOT, and POLYOVER.

The digitizing program, SOILDIG, used a bilinear transform to convert digitized tablet coordinates to a universal cartographic coordinate system such as Universal Transverse Mercator, latitude-longitude, or State Plane Coordinate System. An optional "rubber sheet" transform was also developed as an alternative. The latter transform was used for control points that were of questionable accuracy as indicated by error analysis. With the "rubber sheet" transform, the digitized points forming the polygons are converted to the appropriate cartographic coordinates using a weighting factor based on the closest control point. The weighting factor minimizes shifting to the least accurate control point.

A point-matching function was incorporated into SOILDIG to reduce the formation of "slivers," which result from the inaccurate digitizing of line segments shared by adjoining map units. Since topographic accuracy is essential to polygon overlay analysis

TABLE 1. HYPOTHETICAL SOIL TYPE AND THE ASSOCIATED PERCENTAGE OF CLAY AND SOIL PERMEABILITY

Soil-type map symbol	Clay	Permeability
	%	*cm/hr*
1	10.0	10.0
2	10.0	10.0
3	2.5	50.0
4	17.3	3.25
5	14.3	12.25
6	13.9	10.0
7	27.7	0.5
8	52.5	0.33
9	12.5	3.25
10	27.7	1.0
11	26.1	2.0
12	27.0	3.0
13	13.0	3.25
14	13.5	3.25
15	12.5	3.25
16	10.3	15.25
17	52.5	0.33
18	2.5	32.5
19	10.0	3.25
20	20.0	3.25
21	23.8	8.5
22	NA	NA
23	NA	NA
24	11.5	3.25
25	2.5	32.5
26	10.0	22.75
27	>40.0	0.33
28	2.5	30.75
29	6.6	28.25
30	15.0	10.0
31	18.5	15.0
32	7.5	10.0
33	13.8	10.0
34	12.7	14.25

and since overlaying is a key technique in the salinization model, point-matching is a vital feature. Before digitizing a map, the operator must specify the desired point-matching distance and locate each vertex of the intersecting line segments that form each polygon. Each fixed vertex is then digitized. When a point is digitized, the point-matching function scans all previously digitized points for a point of similar x,y values. If the cartographic coordinates of any previously digitized point fall within a preselected distance of the newly digitized point, those coordinates are assigned to the new point. This ensures that common vertices of adjoining polygons have identical coordinate values in spite of the limitations of the operator or the equipment. In this way the coordinate value of each vertex can be duplicated exactly no matter how many times it is used in contiguous polygons. Point-matching produces clean, topographically accurate maps where adjoining soil property map units are void of "slivers" having unknown or duplicate attributes.

A text entry facility within SOILDIG permitted the placement of text on the map by digitizing the starting point of the text. Text could also be adjusted for height and rotation. The text entry facility was used to enter the map title, the scale, and the legend, and to identify various geographic features.

An editing program, SOILEDIT, was created to add, change, or delete features that were inadvertently omitted or entered in the digitizing process. The editing program made it possible to shift the line segments of a digitized polygon interactively to any desired position, as well as to insert or delete points in order to add or delete line segments. Additional capabilities of the editing program expedited editing by allowing the operator additional means of manipulating the graphics. These features included coordinate window selection, "zooming," specific map redisplay, variable point-matching distance, and deletion of an entire map feature.

SOILSHADE, the attribute shading program, was designed to display up to 10 different soil properties or magnitudes of a specific soil property on a single map. Shading could be used as a graphic means of polygon overlay analysis by identifying areas that represented a certain minimum value of combined properties that are associated with salinity development in soil. When the shade patterns of the properties commonly associated with salinization were overlaid, the intersecting shaded areas delineated areas of varying salinization potential.

To add to the sophistication of the mapping system, an automated means of polygon overlay analysis was developed: POLYOVER. Polygon overlay analysis is a substantial computational task, since polygons are represented as the series of points where the sides intersect rather than as the closed areas that their sides surround. Determining whether a point falls within a polygon is a straightforward procedure, but to determine where a polygon crosses other polygons in several layers requires a good deal of computation. Basically, the polygon overlay analysis program determines the area of intersection of two or more overlaid polygons by creating a list of vertices common to the fields enclosed in the two polygons as well as creating a list of the points of intersection of the polygon sides. It then creates a polygon from these vertices, and checks it against a third intersecting overlaid polygon representing another property. This process is repeated for all relevant overlays.

SOILPLOT uses the plot files created from SOILDIG and the shade attribute files created from SOILSHADE to plot a finished map. The plot can be output to the computer terminal screen or to a hardcopy device such as a plotter. Curve smoothing was incorporated into SOILPLOT to smooth the straight line segments using a cubic spline function approximation. A window selection was also included to permit "zooming" into or out of an area of interest.

Structure of Stored Spatial Data

Figure 1 illustrates several typical contiguous map polygons where each polygon delineates an area of continuous data. The individual map units are represented as a series of connecting-line segments that closely approximate the curved and straight lines of the actual map units (compare figs. 1 and 2). The x,y coordinates of the points forming the connecting line segments make up a point list that defines each polygon.

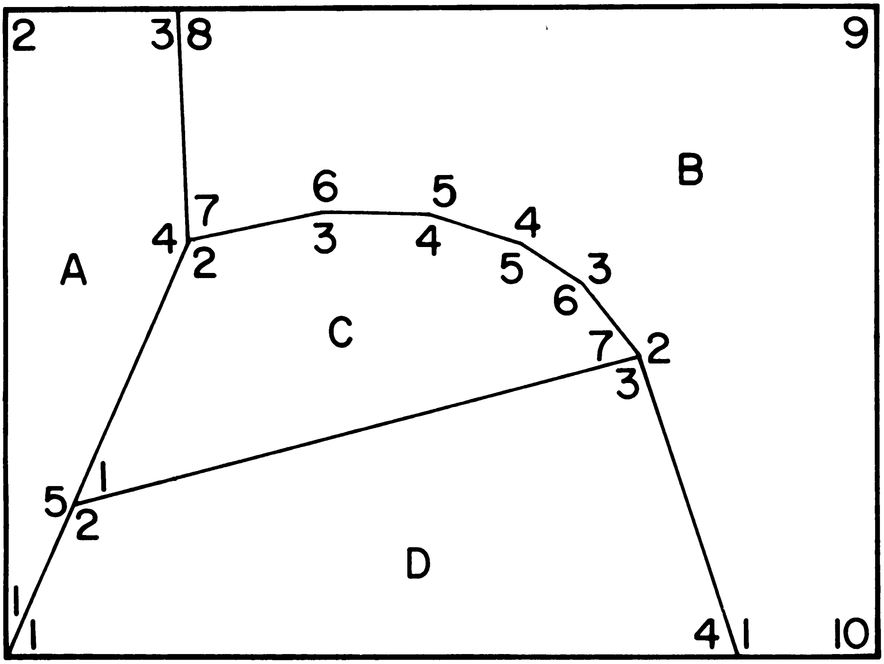

Fig. 1. Representative polygonal map with the vertices of each polygon encoded in a point list structure.

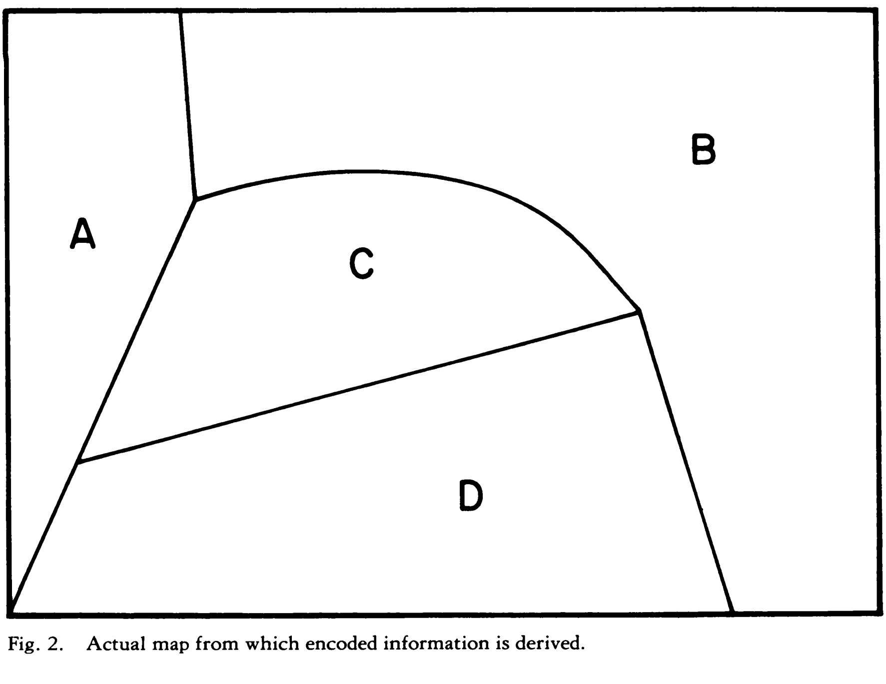

Fig. 2. Actual map from which encoded information is derived.

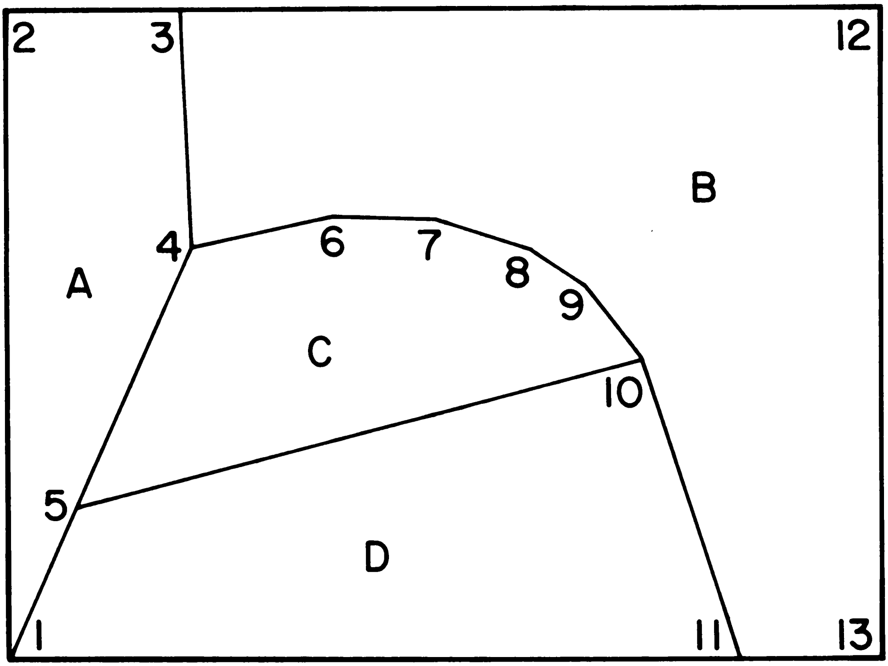

Fig. 3. Representative polygonal map with the vertices of each polygon encoded in a point dictionary structure.

The point lists of the four polygons in figure 1 are represented as

Polygon A = X_1Y_1, X_2Y_2, X_3Y_3, X_4Y_4, X_5Y_5

Polygon B = X_1Y_1, X_2Y_2, X_3Y_3, X_4Y_4, X_5Y_5, X_6Y_6, X_7Y_7, X_8Y_8, X_9Y_9, $X_{10}Y_{10}$

Polygon C = X_1Y_1, X_2Y_2, X_3Y_3, X_4Y_4, X_5Y_5, X_6Y_6, X_7Y_7

Polygon D = X_1Y_1, X_2Y_2, X_3Y_3, X_4Y_4

where X_n and Y_n represent the x,y coordinate values of point n for that particular polygon. Since several of the polygons share common points, it is more economical from a computer storage media point of view to convert the point list to what is known as a point dictionary structure (D. A. Nichols 1979). In a point dictionary structure each point is considered a single entity no matter how many different polygons share that point. Every point is assigned a unique index number and the polygons are defined as a sequence of index numbers referring to associated coordinate values. Figure 3 shows the exact same polygons as figure 1, but they are represented in a point dictionary structure. Assigning index numbers $i = 1,2,3,\ldots,13$ to the points so that

Point $i = X_iY_i$

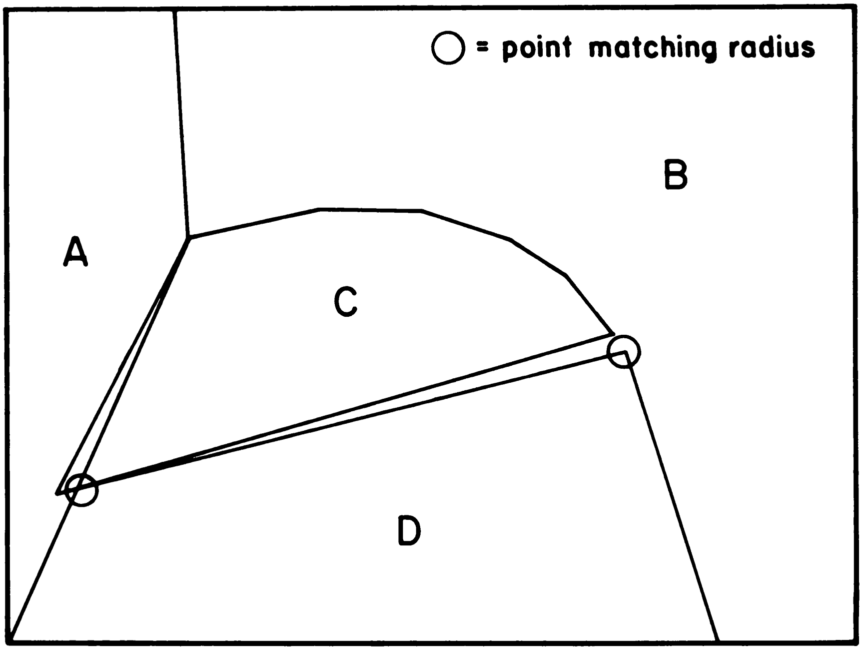

Fig. 4. Representative polygonal map showing the "slivers" that need to be removed by the editing process.

the polygons are designated as follows:

Polygon A = *1,2,3,4,5*
Polygon B = *11,10,9,8,7,6,4,3,12,13*
Polygon C = *5,4,6,7,8,9,10*
Polygon D = *1,5,10,11*

Even though the above information appears to be as great in volume as that of a point list structure, it actually requires significantly less space when stored in computer memory, especially when stored as character strings. Once the physical structure of a polygon is defined, it is assigned an attribute value. In essence, there is a three-level data structure: point index, point sequence, and polygon attribute.

Special Mapping Considerations

Figure 4 shows a representation of figure 1 before the plot files were edited to remove digitized errors. In this example "slivers" have resulted from inaccurately digitized vertices that fell beyond the limits of the preselected point-matching distance. The conspicuous "slivers" are easily edited out by manually shifting the vectors on a display screen using SOILEDIT. Figure 3 is the end result.

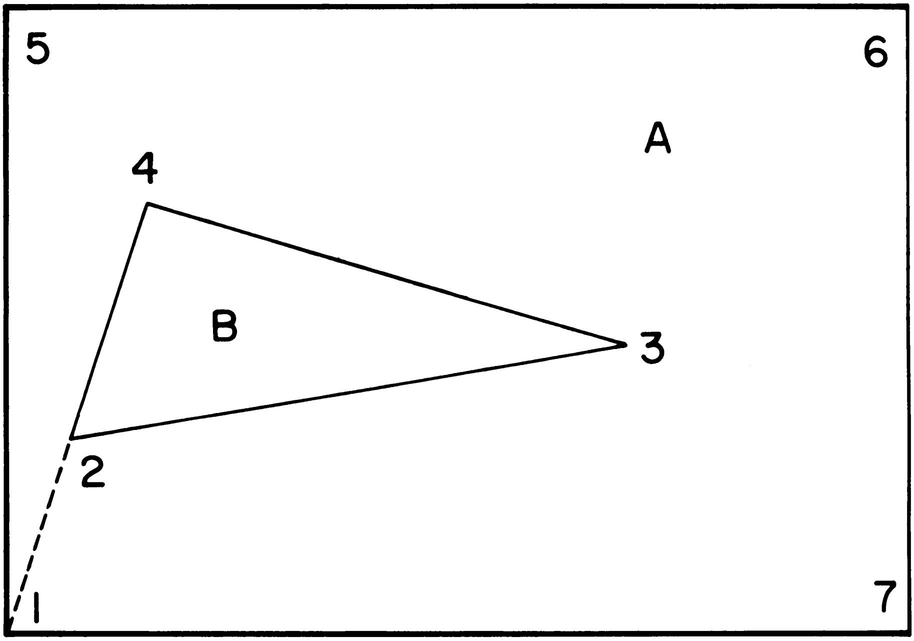

Fig. 5. Representative polygonal map showing an "island" encoding configuration.

Special consideration must be given to situations such as that in figure 5, where an "island" of continuous data exists. When a simple boundary line plot of the data is made, an island does not present any problem. But if shading, area calculations, or overlay analyses are to be performed, problems will occur unless the boundary line of the map unit surrounding the island also includes the island boundary. For example, if polygon A in figure 5 is represented in point structure as

Polygon A = 1,5,6,7

then the entire area within those points is considered. Rather, polygon A must be represented as

Polygon A = 1,2,3,4,2,1,5,6,7

in order to exclude the island, polygon B, within polygon A.

Modeling Salinization Factors

A simple quantitative "threshold model" approach was taken to determine the salinization potential level from a set of criteria. The levels of salinization potential (high, medium, and low) are based upon the presence of certain minimum levels (thresholds) of four attributes that tend to correlate well with salinity development. High potential salinization zones were defined as areas having all four of the following attributes:

1. Greater than 40 percent clay and a permeability of 0.5 cm/hr or less
2. Less than 1 m distance from the soil surface to the perched water table
3. Groundwater electrical conductivity greater than 4 dS/m
4. A leaching percentage of not more than 10 percent

For a moderate salinization potential, any three of the above four conditions must exist, while low salinization potential occurs when fewer than three of these conditions exist.

The threshold levels were based upon research that associated permeability, depth to groundwater, irrigation water quality, and leaching fraction either to salinity development or to factors related to salinity development, such as surface evaporation rates (Bohn, McNeal, and O'Connor 1979; Hillel 1971; Holmes 1971; Quirk 1971; Shih 1983; U.S. Salinity Laboratory 1954; Willis 1960).

DISCUSSION OF RESULTS

Hard copies of the actual maps generated on the computer screen demonstrate the map end product capability of the developed automated GIS (see figs. 6-13). Figure 6 is a plot of the hypothetical study area. The boundary line of the study area is illustrated along with a variety of geographic features. Crosshair markings and the associated cartographic coordinates provide an index to the absolute and relative locations of the map features.

The next four maps, figures 7-10, show overlays of the four factors that were selected as being closely associated with salinity development in arid soils. These four properties are not the sole factors associated with salinity development, but are generally major contributors. Nevertheless, the maps help to demonstrate the potential use of computer-assisted mapping as a means of reducing tremendous amounts of spatially distributed data into a more readily interpreted form. The clay percentage–soil permeability overlay map is actually a soil-type map developed by the USDA Soil Conservation Service (fig. 7). The soil-type map symbol is associated with a clay content and soil permeability as determined by the Soil Conservation Service survey (table 1). The overlay maps of depth to the perched groundwater (fig. 8) and electrical conductivity of the groundwater (fig. 9) are broken down into contour levels. The depth to the perched water table is delineated into areas of 0 to 1 m, 1 to 2 m, 2 to 3 m, and so forth. Groundwater quality is divided into electrical conductivities of 0 to 1 dS/m, 1 to 2 dS/m, 2 to 3 dS/m, and so forth. A leaching percentage is assigned to each cropped field. Figure 10 shows all of the cropped fields, and figure 11 shows an enlarged area of figure 10 with the associated leaching percentage of each field.

Figure 12 is a map of only those soil types meeting the threshold criteria for clay content (greater than 40%) and soil permeability (less than or equal to 0.5 cm/hr). Soil types with map symbols of 7, 8, and 17 meet these criteria (table 1). Similar plots can be made for each of the other three properties, and a final composite map can then be prepared (fig. 13a). Obviously, the composite map is not in an easily interpreted form; consequently, the polygon overlay analysis program was used to more clearly delineate and classify the intersecting overlay polygons according to their potential for salinization. The result is a map that clearly shows the areas of high salinization potential as based upon the established set of threshold criteria (fig. 13b).

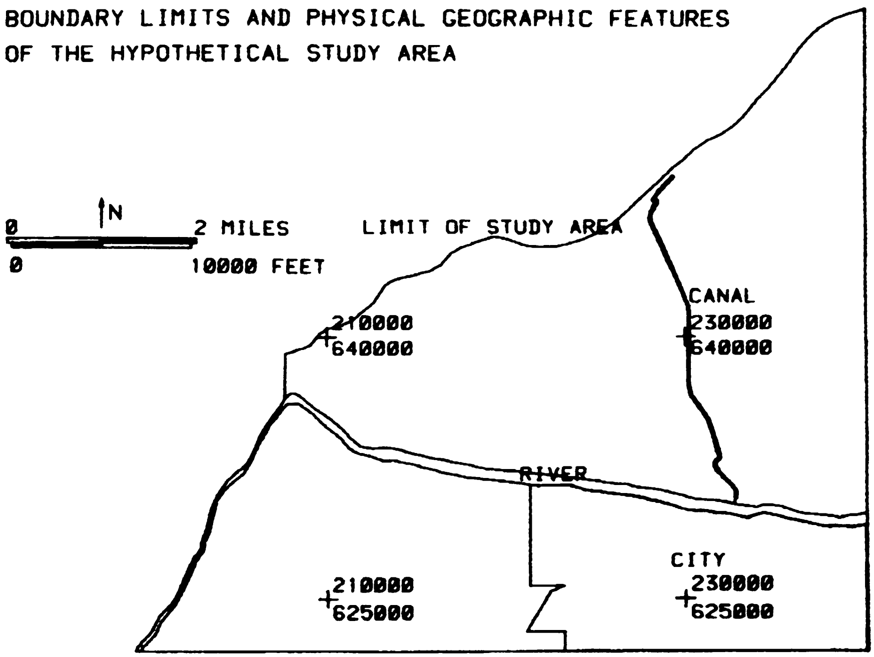

Fig. 6. Computer-generated map of the hypothetical study area showing physical geographic features, city limits, and study area boundary line.

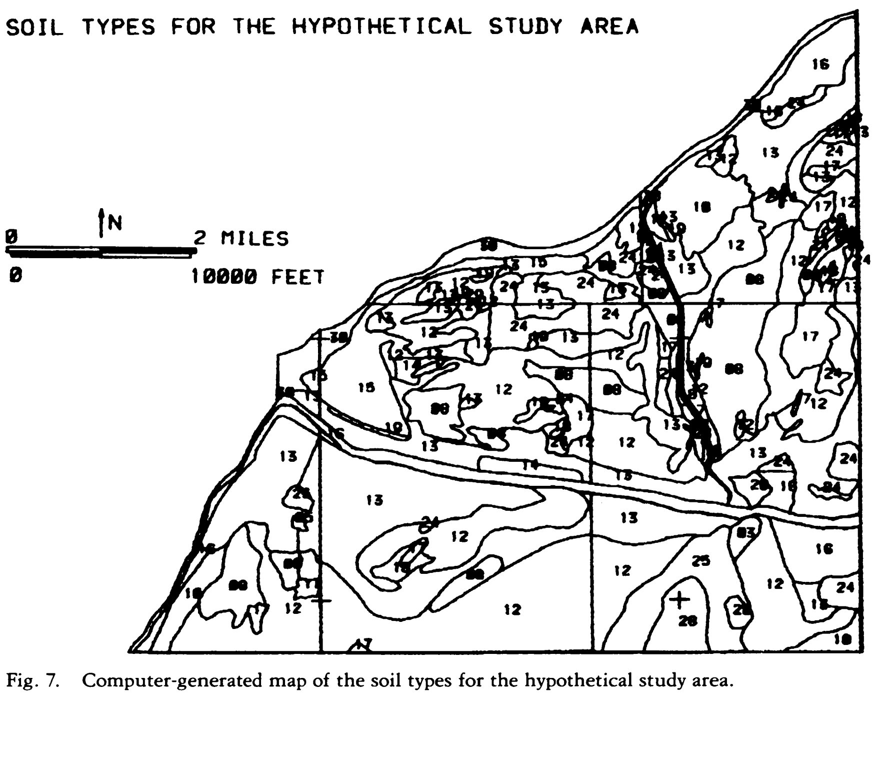

Fig. 7. Computer-generated map of the soil types for the hypothetical study area.

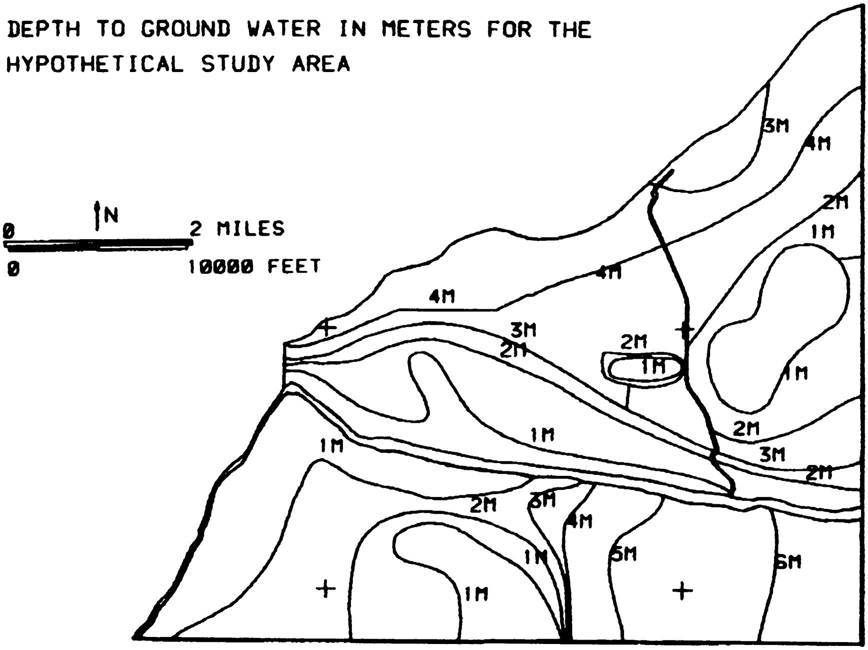

Fig. 8. Computer-generated map showing the depth to groundwater contours in meters (1 meter = 3.3 feet).

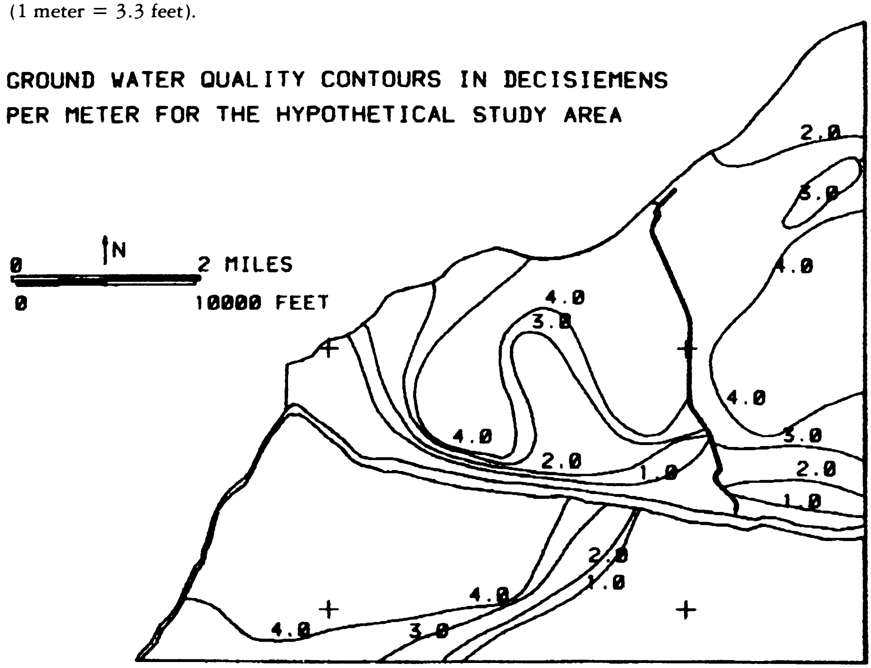

Fig. 9. Computer-generated map showing the groundwater salinity as measured by electrical conductivity in dS/m.

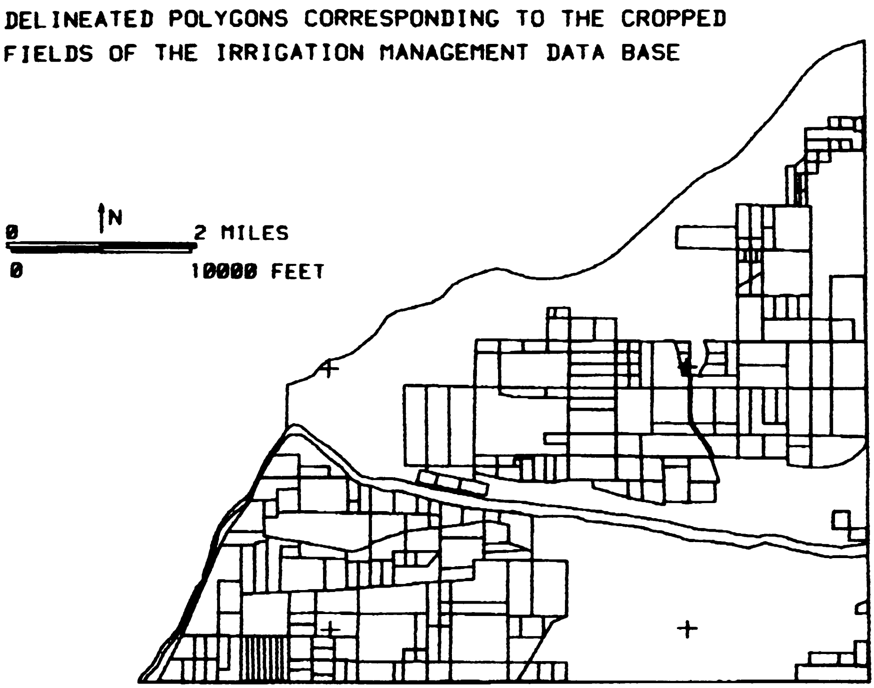

Fig. 10. Computer-generated map showing each cropped field comprising the irrigation management data base.

SUMMARY AND CONCLUSIONS

Computer-assisted mapping is a useful way to inventory natural resources or any other entity with a spatial association. This paper demonstrates the utility of the resource inventory capability of a computer-based GIS when used in combination with graphics display and overlay analysis programs to delineate areas of salinization potential. A cost-effective automated GIS requiring only 32K of usable memory was developed. Through subtle yet effective refinements, the automated GIS performed well when tested with a hypothetical database. The compact automated GIS provided a cost-effective means of creating salinization potential maps without the need for an advanced knowledge of automated cartography or specialized mapping workstation equipment.

In addition, this paper proposes that the potential of salinity development in soils can be assessed from certain existing quantifiable conditions. This approach does not presume to predict future salinity in soil, but is expected instead to point out areas of potential concern. From quantifiable attributes, areas of high salinization potential can be delineated by locating those areas where certain combinations of conditions exist at or above minimum levels or thresholds.

Heretofore, automated mapping techniques have not been combined with a salinization potential model to delineate areas of salinity development on irrigated soils. Ultimately, the utility of such an approach depends upon field verification studies. Such verification will be addressed in two subsequent papers (Part II; Corwin, Sorensen, and

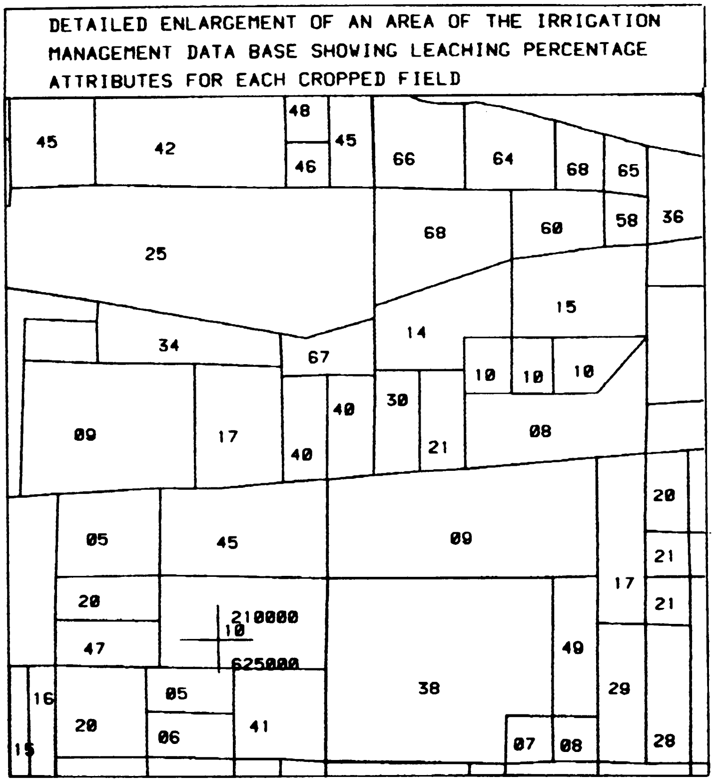

Fig. 11. Enlargement from figure 10 with the associated leaching percentage for each field.

Rhoades 1988). This paper, however, serves as a conceptual introduction to the mapping techniques used to delineate areas of salinization based on soil edaphology, irrigation management practices, and groundwater characteristics.

Though this project adds nothing significant to the existing knowledge of automated mapping, the salinization potential maps themselves are without precedent. The presented subtle innovations and improvements bring automated mapping technology to such a level of economic and technical sophistication that even the most modest irrigation management district can develop salinization potential maps. Such maps have definite practical value as irrigation management tools, especially for newly reclaimed lands that have no history of use. From a single composite overlay map, a rapid interpretation of several complex, interrelated spatially associated data bases can easily be made. Consequently, this system should be useful to anyone dealing with salinity problems, from a farm level all the way to a national level. By identifying areas of high salinization potential in newly developed agricultural lands, preventive irrigation and land use management practices can be used to avoid or mitigate the development of salinity problems. Crop selection decisions may also be based on a knowledge of the salinization potential of an area. Decisions regarding the location of salinitymonitoring sites and the intensity to which these sites are to be monitored can be based upon such data. At the present, there is no extensive accurate inventory of salinity in the arid Southwest. Decision makers in such government agencies as the Bureau of Reclamation and the Soil Conservation Service need this kind of information to formulate policies and to anticipate the extent and degree of future salinity problems.

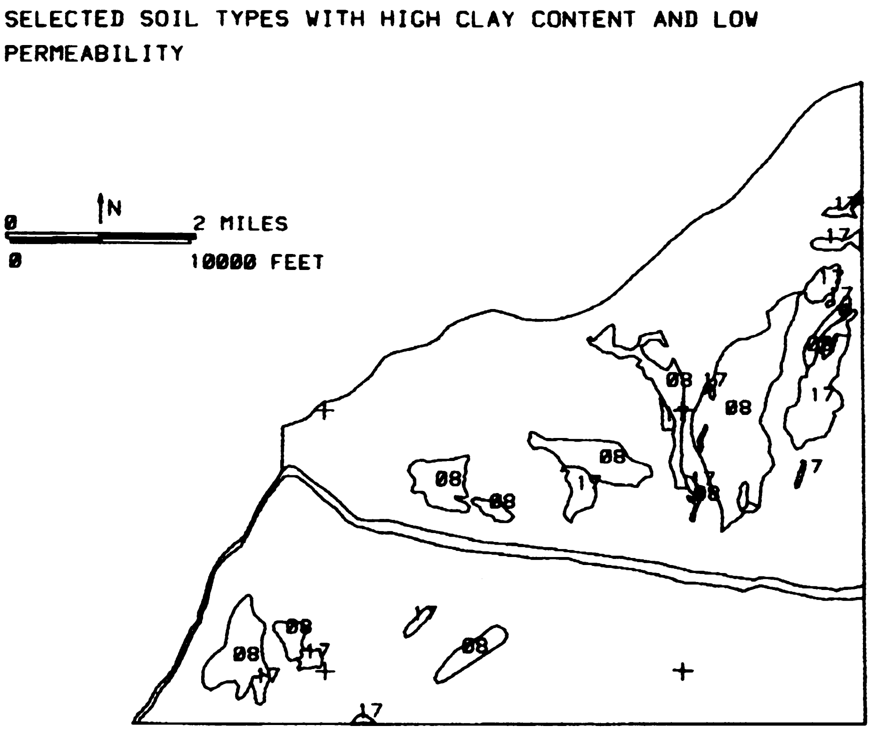

Fig. 12. Computer-generated map delineating only those soil types that meet the clay content (i.e., > 40%) and soil permeability (i.e., ≤ 0.5 cm/hr) thresholds.

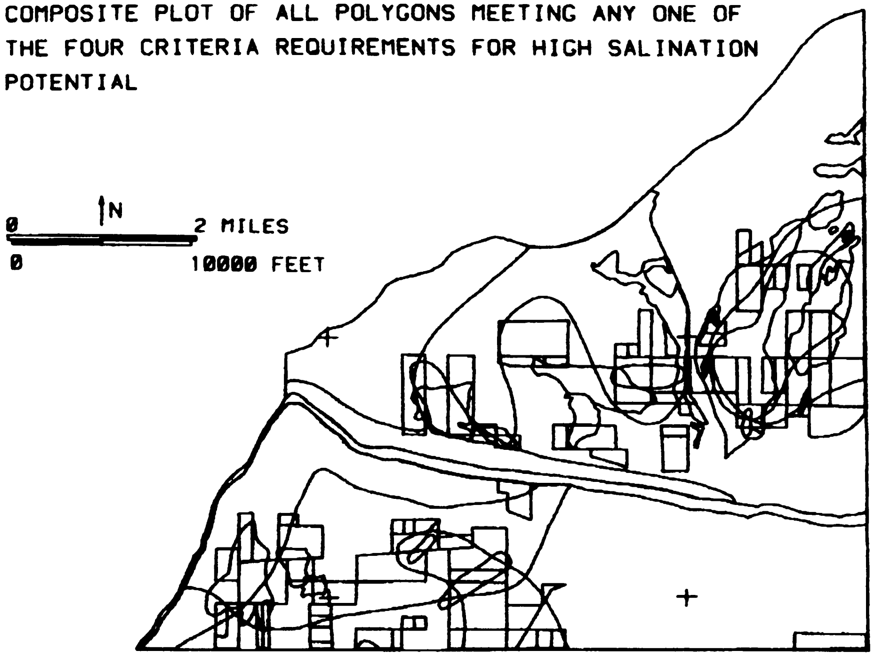

Fig. 13a. Composite map of figures 7, 8, 9, and 10 showing the areas meeting any one of the four established threshold criteria.

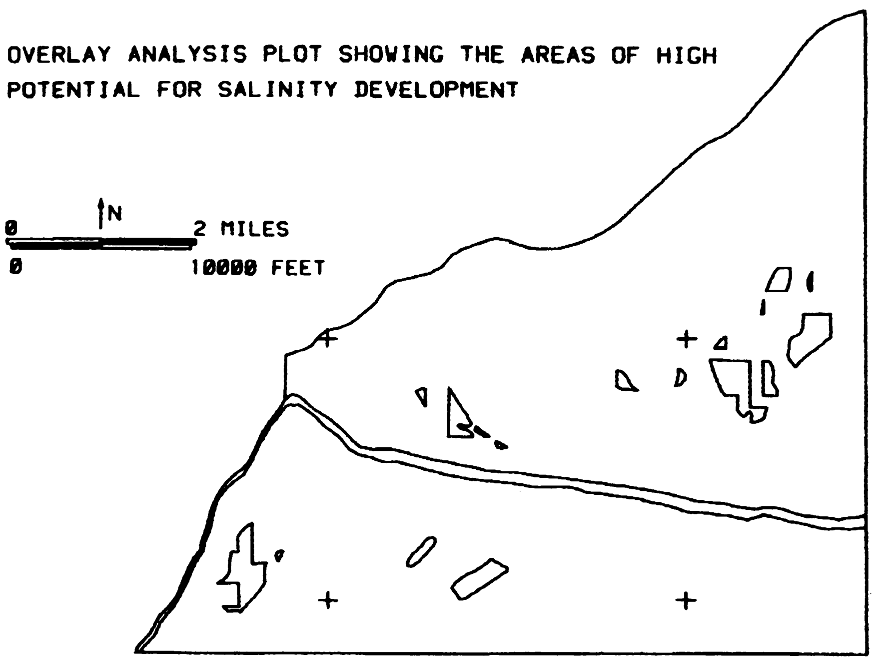

Fig. 13b. Composite map of figures 7, 8, 9, and 10 showing only those areas meeting all four threshold criteria, thereby constituting areas of high salinization potential.

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II. Field Verification of the Threshold Model Approach

A study area within the Wellton-Mohawk Irrigation District, which lies east of Yuma, Arizona, was used to verify the threshold model proposed in Part I. Verification results showed that the threshold model could not reliably predict salinization potential; consequently, a modified threshold model, Model 1, was formulated. Model 1 was capable of predicting nearly 60 percent of the salinization potentials correctly, a significant improvement over the original threshold model. Nevertheless, Model 1 fell short of being considered a reliable forecasting tool.

It is postulated that the interactions between the factors believed to give rise to salinity development at the study site were too complex to characterize with the simple threshold model approach. Rather, a means of weighting the significance of the individual factors in the overall salinization process may be necessary.

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