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# A method of modeling vertical fluid flow and solute transport in a GIS context

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**Abstract**

An irrigated agricultural area of 2350 ha in the San Joaquin Valley of California was used for assessing regional-scale vertical flow and solute transport. The study area was sufficiently large to show variability in salt-loading to the groundwater due to cropping and irrigation efficiency. A geographic information system (GIS) was used to store and manipulate a variety of data required for vertical transport modeling of water flow in the field area. Measured data included crop and irrigation schedules, daily evapotranspiration, soil type maps, and field sampling for determination of physical properties such as the saturation percentage and the gravimetric water content. A data classification scheme was developed consisting of four basic types of variables: ( 1) local variables for point data; (2) spatial variables for data having a constant value within a restricted domain such as an individual quarter-section; (3) derived variables being those selected based on a discrete value of another parameter (e.g. maximum root depth depends on the discrete variable, crop type), and (4) regional variables exhibiting a constant value over the entire study area. Each specific variable was classified utilizing the classification scheme and a relational database was created for all the data. From the data included in this database, calculations of fluid and solute transport were made at selected locations by a capacity-based, one-dimensional transport model. The results of a calculation were incorporated into the database for further manipulation and representation. A sample calculation was run for 3 15 locations within the field area to determine the spatial variation of salt-loading to the groundwater.

## 1. Introduction

Reduction in the quality of irrigated agricultural lands is occurring in many countries due to increasing salinization and waterlogging of soils. Damage due to these problems can be ameliorated by cropping and irrigation management strategies. The development of irrigation strategies continues to be a motivating factor for investigations of the physical and chemical responses of soils to irrigation, these studies have been carried out from both theoretical and experimental standpoints. A long history of theoretical work and computa-

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tional modeling has provided an understanding of the relevant physical characteristics of soils for fluid flow and chemical transport (some review papers: Molz, 198 1; Addiscott and Wagenet, 1985; Van Genuchten and Jury, 1987). Experimental studies have utilized lysimeters to measure vertical water and solute flux (Gardner, 1964; Belmans et al., 1979; Corwin et al., 1991, 1992). Field-scale simulation studies calculated solute flux in geographic areas using available databases (Breeuwsma et al., 1986; Petach et al., 1991). The lysimeter studies are useful for characterizing, in detail, the response of cropped soils to irrigations. However, these studies, carried out under carefully controlled conditions in a relatively small container, cannot adequately represent the variety of conditions and responses obtained in the field. Field studies can evaluate the large-scale variability, but are much more difficult to control and more time is required to obtain a far less comprehensive data set for each measurement location. One fundamental difficulty with field-scale studies is the organization and representation of the large quantities of data being generated. Over the past 20 years a database technology called geographic information systems (GIS) has been developed to handle spatial data (Burrough, 1986; Petach et al., 1991) . The intent of this paper is to describe a GIS database for irrigated fields and the incorporation of a water flow/solute transport model into the GIS framework. ARC/INFO' was the GIS system utilized for the work discussed here. However, the methodology presented should be applicable to any GIS package that interfaces with a relational database program.

The objective of a water flow/solute transport model is the calculation of the redistribution of water and solutes given a set of initial conditions and time-dependent boundary conditions. Numerous transport models created for modeling flow in the unsaturated zone have been reviewed in the following papers: Addiscott and Wagenet (1985), Nielsen et al. ( 1986)) Van Genuchten and Jury ( 1987) and Engesgaard and Christensen ( 1988). Many of the models that have been used are deterministic and involve numerical solution of the Richards equation. These numerical models require knowledge of water retention curves (h-0) and the hydraulic conductivity versus head (K-h) relation. For most soils these relations are not available. Thus, the accuracy of simulations utilizing the Richards equation, in the context of regional flow modeling, are limited, in part, by the accuracy of assumptions made with respect to these relationships. In one field study the h-0 and K-h curves were measured for 9 major soil horizons for a small region of 125 ha in the eastern part of the Netherlands (Wosten et al., 1985). A map of soil physical properties was created containing 18 different units based on the measured physical properties and on textural analysis. The simulation model, SWATRE (Belmans et al., 1983)) was then used to calculate evapotranspiration for one pedon in the area from soil physical properties. The simulation was successful, but the study illustrates the significant effort involved in obtaining water retention and K-h curves even for a small geographic area. A functional transport model, described in detail in the procedure section, was developed to provide a rough calculation of water flow and solute transport for a less complete data set (Corwin et al., 199 1)

## 2. Database development and integration with GIS

A GIS database can be divided into a data set of geographically-referenced variables such as soil type that relate, specifically, to geography and a separate data set consisting of

[1]The use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Department of Agriculture.

variables that are independent of location. The database generated for the field area discussed here has over 50 variables of both types. Organization of these variables within the database is important to: (1) maximize accessibility of the data, (2) minimize the amount of data duplication, and (3) establish a hierarchy of variables. These goals were achieved by constructing a variable classification scheme having 4 categories:

(1) Local variables: Variables of this type have values established for specific geographic locations (points). The locations of these points may be determined by statistical methods, they may lie on a grid or they may be determined by external factors such as sampling convenience.

(2) Spatial variables: Variables of this type are constant within a defined spatial domain. The distinction between spatial data and local data depends on the sample spacing for the local data. For example, a variable may be known to be single-valued within a domain, but if the domain size is smaller than the point spacing for the local data representation of the variable then classification as local data is appropriate. Spatial variables are represented by polygons in this study.

(3) Derived variables: Derived variables have values that depend on the discrete value of some other variable. For example, the variable representing the crop identification number is an integer which serves as an index to the derived variable, maximum plant root depth. Derived variables generally occur in sets such as the set of variables that describe crop properties.

(4) Regional parameters: Every environmental study must restrict itself to some geographic area. Regional parameters are those quantities which can be considered constant over the entire area. Such parameters may be either simple constants or they may be time-dependent functions.

The field area consists of 2350 ha in the Broadview Water District located in the San Joaquin Valley west of Fresno, California (Fig. 1) . This area is divided into 1 mile (1.609 km) squares, called sections, which are subdivided into 4 square quarter-sections (64.8 ha). The GIS database constructed for this field area includes both regional, spatial and local data. As the first step in the construction of a database for the Broadview Water District field area, significant variables for flow modeling in variably-saturated conditions were classified according to the variable classification scheme outlined above. Table 1 summarizes use of the classification scheme for the Broadview Water District data. A list of the various kinds of data appears in the left column. The center column indicates whether data of each kind are spatially variable and, therefore, exist in a geographic context. The right column identifies the related variables of the TETrans transport mode1 which is discussed in more detail later. Derived variables can be stored in thematic tables (for example, a table of soil physical properties with records identified by a soil type ID number). Substantial savings of computer memory may be achieved by classifying as many variables as possible as either derived variables or regional parameters. The greatest benefit of classification, however, is the improved accessibility of the data obtained by dividing the large data set into smaller, thematic tables.

Further classification of parameters involves the distinction between spatial and local variables. An example of spatial data is soil type as defined on a soil map. The physical properties of soils needed for flow modeling are derived variables which take on different values depending on the spatial variable, soil type. However, not all the soil properties

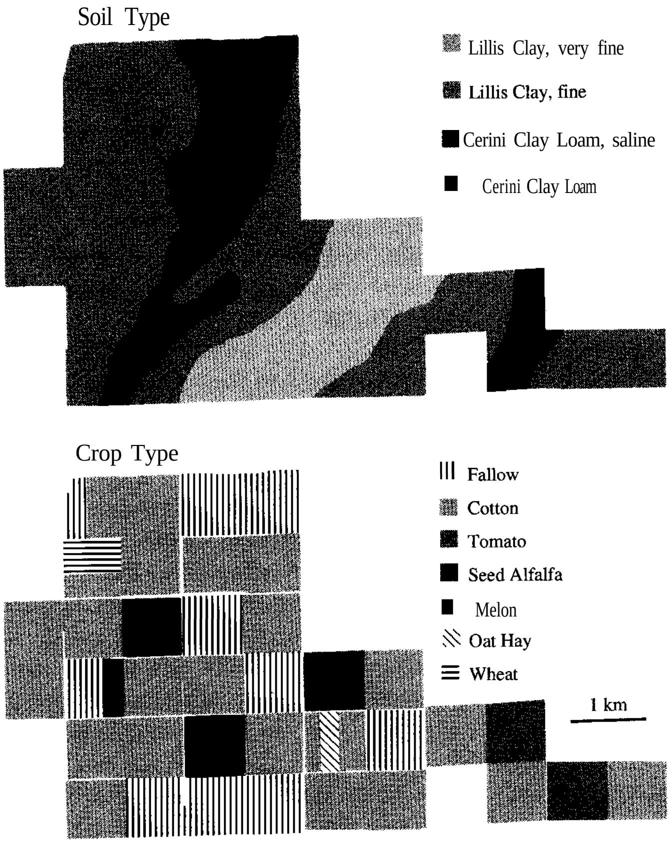


Fig. 1. Soil and crop type maps of the Broadview Water District study area. The soil map is based on digitization of a soil map drawn on an aerial photo that was obtained from the Soil Conservation Service (the map is shown for the purpose of illustration of the techniques described in the paper only, it is not an official map), The crop map covers the period from 4/91 to 9/91. Both maps are referenced to a transportation layer obtained as DLG (Digital Line Graph) data from the US Geological Survey.

required for the flow modeling can be obtained in this way. For certain variables, notably the initial value of percent water, measurements were made at specific locations within the field area. The initial percent water is, therefore, a local variable because it has a unique, depth-dependent set of values for a single geographic location. Finally, there are regional properties such as reference crop evapotranspiration (Jensen et al., 1990) which is constant over the entire study area for a particular day.

After all variables were classified, a database structure (Fig. 2) was established to provide easy access to all variables for purposes of calculation and representation while minimizing duplication. The database consists of two entirely separate structures (Fig. 2). Regional and derived variables that are completely independent of location are allocated to one structure labelled “Regional Data” while the remaining, location-dependent variables are allocated to the structure labelled “Quarter-section Data”. Examples of location-dependent variables include: soil attributes determined by soil type; irrigation data that are specific to

Table 1
Various data relevant to modeling of vertical water and solute transport in the Broadview Water District. Some data have associated geographic coordinates (points or boundaries of areas) other data are location-independent (e.g. evapotranspiration data)

| Classification of Data | | |
|---|---|---|
| Data gathered | Geographic data | TETrans parameters |
| Soil type Maps (source: SCS) | Boundaries of soil types | Inferred field capacity, minimum water content |
| GPS outline of fields, survey conducted by USSL staff | Actual boundaries of crop-growing areas | |
| Field measurements of EC, electromagnetic response | Point locations | Initial conditions: TDS |
| Cores, soil water chemistry and gravimetric %water | Point locations | Initial conditions: TDS, % water |
| DLG Data, transportation (source: USGS) | Reference for quarter-section boundaries obtained by GPS | |
| Irrigation schedules byquarter-section. irrigation water chemistry, (Broadview Water District data) | | Boundary conditions: amounts of water applied, dates, water chemistry |
| Crop Maps | Utilize boundaries of crop-growing areas (GPS) | Crop name |
| Maximum root depth, root water uptake distribution, other crop-specific data | | Crop parameters: maximum root depth, etc. |
| ETo Data, evapotranspiration for crops (source: CIMIS) | | Reference crop evapotranspiration, crop coefficients |

GPS: Global Positioning System, DLG: Digital Line Graph, TDS: Total Dissolved Solids, CIMIS: California Irrigation Management Information System.

each quarter-section; and variables measured at point locations. A detailed discussion of specific variables used in the model is given in Section 3.

Fig. 2 shows both the classification of data into tables and, using lines connecting various boxes, the linkage through which a particular table can be accessed from other tables. For example, from a table listing quarter-sections one can access tables of individual locations within those quarter-sections. Likewise, from these location tables one can access tables of physical and chemical variables. Access is implemented through the use of a relate which is a connection between individual records in different tables that share a common identification number. Often, relates are used to create virtual tables (views) that combine specific items from several different actual tables. For example, the location list is a point attribute table containing geographic coordinates of the point locations and location ID integers. A relate linking locations from the location list with records stored in a separate INFO table provides simultaneous access to geographic information and calculated values of the percent water after a run of the model. Using the relate to access the separate table facilitates preparation of a map representing this calculated result.

Representation of data in map form and the existence of facilities for graphical interaction between the user and the data distinguish a GIS from a conventional database. For the GIS application discussed here, data representation in map form is problematic because the data

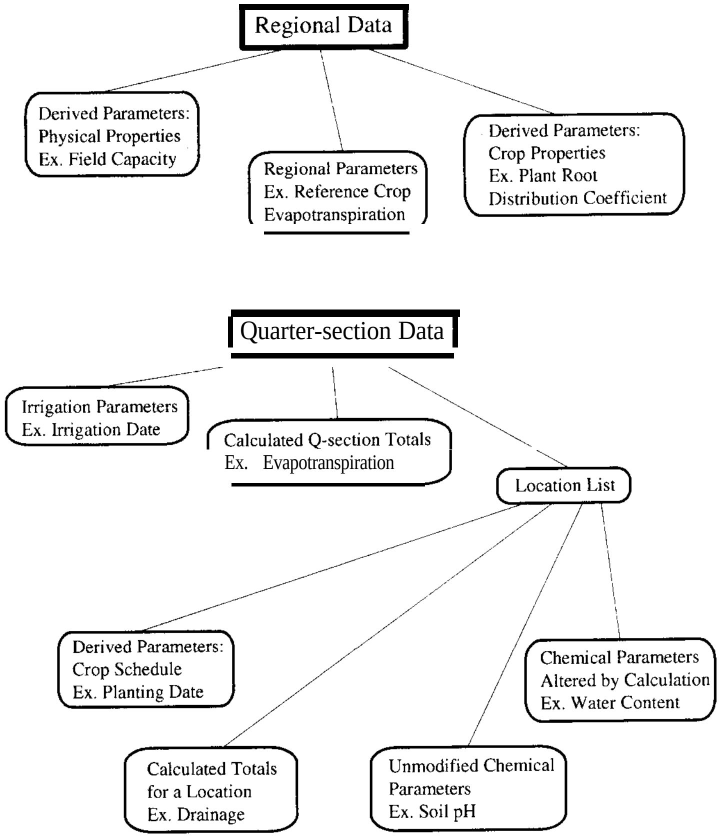


Fig. 2. Structuring of data in the GIS database closely resembles data structures in the external TETransgeo program, The main division occurs between data obtained for specific sites or areas (quarter-section data) and data that are independent of location (regional data). Diagram illustrates the hierarchy of data under each major type.

include both depth and time dependence. Several techniques for data representation utilizing three-dimensional graphical constructs such as wire mesh diagrams (Vieux, 199 1)) fence diagrams (Van Driel, 1989) and hollow block models (Smith and Paradis, 1989) are available but production of these graphics is complicated and a time-dependent application would still require a sequence of images. Representation of spatial data in the current work utilizes shaded maps for spatial variability and line graphs for time-dependence of spatially-averaged properties. An example of a type of map that has been prepared is a map representing a calculated result at a point location. Because the sampling locations in the Broadview Water District are not uniformly spaced (Fig. 3)) data values and calculated results were interpolated from the existing point locations onto a uniform grid and shaded using a gray scale (Fig. 4). The spatial interpolation was performed by an inverse-distance-squared algorithm.

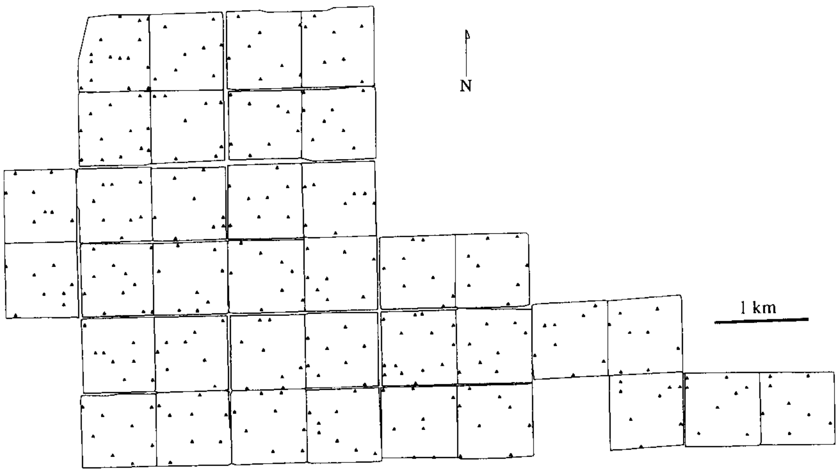


Fig. 3. Sampling sites for in situ electrical conductivity measurements (triangles) were located using the global positioning system (GPS), Electrical conductivity (EC,) was measured on cored samples taken at 4 depths (0-1.2 m) at each site. TETransgeo was run for all of the locations shown.

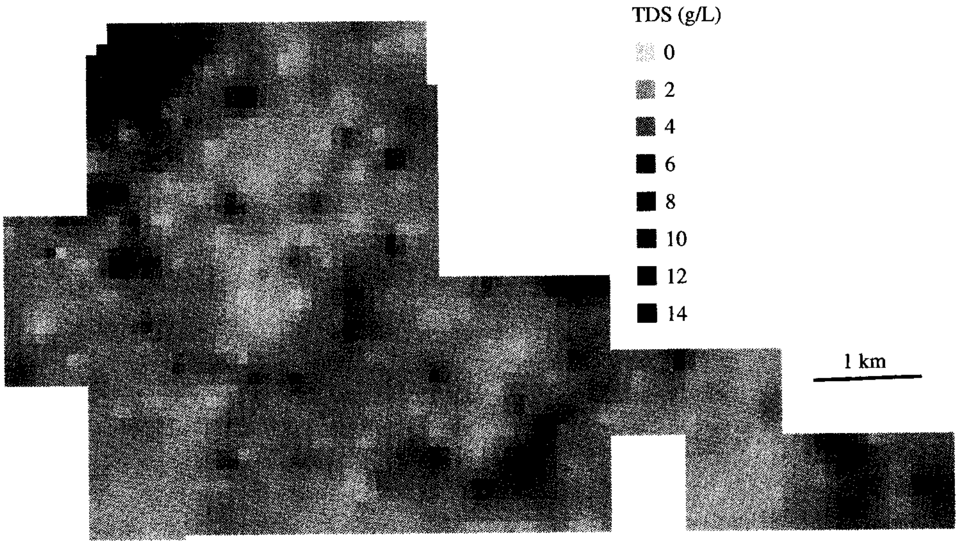


Fig. 4. Initial TDS concentration in soil water estimated from ECe measurements. Samples taken 4/91-5/91 at 315 sites, TDS values were interpolated onto a grid using an inverse-distance-squared algorithm.

## 3. Procedure

The first part of this section consists of a discussion of the water and solute transport model called TETrans (Corwin et al., 1991). Following this is a description of the new geographically-based model called TETransgeo which interfaces with the GIS. Finally, a description of each main type of data required by TETransgeo is provided.

### 3.1. *Unsaturated zone water flow and solute transport model -- TETrans*

A simplified treatment of flow is provided by functional models (Bresler, 1967; Addiscott, 1977; Bond and Smiles, 1988). These models treat unsaturated zone flow by making assumptions regarding the capacitance in a soil profile. TETrans is a functional model of vertical water redistribution in the unsaturated zone that has been described in detail elsewhere (Corwin, 1991; Corwin and Waggoner, 1991; Corwin et al., 1991). TETrans is intended as an appraisal of vertical transport for use in a management context, it does not attempt to provide a detailed mechanistic description of unsaturated-zone transport (Corwin et al., 199 1). For this reason the term redistribution is preferable to infiltration which could be construed as mechanistic. TETrans places limits on the water content occurring in a specified depth range. A lower limit is established by the minimum water content of the soil defined by the wilting point. An upper limit is the field capacity or the water content above which the soil drains freely. The depth range of the simulation is divided into compartments each one being assigned a field capacity and a minimum water content. When an irrigation or precipitation event occurs, the water content of the top compartment increases due to infiltration. If the field capacity is exceeded, then water drains into the next lower compartment. This process continues downwards through all compartments until all water from the irrigation/precipitationevent is accounted for. Water draining from the bottom compartment is assumed to enter the groundwater.

After redistribution of water from an irrigation event has been calculated, removal of water from the soil by plant root water uptake takes place. The total plant root water uptake is the sum of amounts removed from all the compartments. The amount of water removed from a given compartment during a single day is therefore defined as some fraction of the total evapotranspiration on that day. The fractional amount for each compartment is prescribed by a parameter called the plant root water uptake distribution. By summing the evapotranspiration amounts over successive days during the period between irrigation events, an evapotranspiration “event” is defined as the removal of water between irrigation events by evaporation and transpiration processes.

The description of the algorithm, provided above, assumes that all water being transported through the soil is moving by piston displacement. A more realistic description of water flow through soils includes preferential flow owing to variable water velocity. Preferential flow is due to several effects including mobile/immobile water fractions and macropore flow (Nielsen and Biggar, 1962; Biggar and Nielsen, 1976; Deans, 1963; Coats and Smith, 1964; Beven and Germann, 1982). The TETrans model lumps these effects together with dispersion into a single parameter called the mobility coefficient, $\gamma$, which defines a fractional amount of water involved in piston-type flow (Corwin et al., 199 1) . The fraction of water involved in bypass is represented by $1-\gamma$. Earlier non-mechanistic models that have also treated bypass (Addiscott, 1977, 1981; Van Ommen, 1985) can be classified, along with TETrans, as transient-state functional models.

Separation of flow into two distinct water fractions also affects calculated water chemistry because TETrans assumes that the two fractions do not interact chemically. Using a conservative tracer Corwin and Waggoner ( 199 1) calculated the mobility coefficient for Arlington loam soil (Haplic Durixeralf) in a weighing soil lysimeter. Experimental results indicated that a value for the mobility coefficient of 0.5 provided a much better fit to the data than a value of 1 .O (complete piston-type displacement). In a more extensive study utilizing 24 lysimeters, values of the mobility coefficient were calculated for various depth ranges from several years of data from both winter and summer months. The mobility coefficient was found to increase with depth, an effect that was greater during the summer months (Corwin et al., 1991) Calculations described here utilized values of the mobility coefficient ranging from 0.4 to 0.6.

The following description of the TETrans algorithm summarizes how an irrigation event is processed (Corwin and Waggoner, 1991; Corwin et al., 1991). Prior to an irrigation event, the mass of solute in a volume, $V_t$, is given by ( $V_{BI}C_{BI}+V_t\rho_bC_{ad}$) where $V_{BI}$ is the volume of soil water in $V_t$; $C_{BI}$ is the concentration of solute in the soil water (kg/m") ; $\rho_b$ is the soil bulk density (kg/m') and $C_{ad}$ is the adsorbed solute concentration (kg/kg soil). The quantity $V_{fc}$ is the volume of water in $V_t$ at field capacity. Three cases arise, the first in which the volume of irrigation water entering $V_t$ is greater than $[V_{fc}-(1.0-\gamma)V_{BI}]$ has:

$$V_{out}=V_{in}-V_{fc}+V_{BI} \tag{1}$$

$$C_{out}=[\gamma V_{BI}C_{BI}-V_{fc}C_{in}+V_{in}C_{in}+(1.0-\gamma)V_{BI}C_{in}]/V_{out} \tag{2}$$

$$V_{AI}=V_{fc} \tag{3}$$

$$C_{AI}=\{(1.0-\gamma)V_{BI}C_{BI}+[V_{fc}-(1.0-\gamma)V_{BI}]C_{in}\}/V_{fc} \tag{4}$$

where $V_{in}$ is the volume of water entering $V_t(\mathrm{m}^3)$; $C_{in}$ is the solute concentration of the entering water (kg/m'); $V_{out}$ is the volume of water leaving $V_t$ (m'); $C_{out}$ is the solute concentration of the exiting water (kg/m'); $\gamma$ is the mobility coefficient, or more specifically, the fraction of $V_{BI}$ which is subject to piston-flow (where $0<\gamma\leq 1$, $\gamma=0$ represents total bypass, $\gamma=1$ represents complete piston-type flow); $1.0-\gamma$ is the fraction of $V_{BI}$ which is subject to bypass; $V_{AI}$ is the volume of soil water in $V_t$ after an irrigation (m'); and $V_{fc}$ is volume of water in $V_t$ at field capacity (m') ; $C_{AI}$ is the concentration of solute in the soil water after an irrigation (kg/m'). The second case is essentially the same as the first with the exception that the concentration remaining after the irrigation is dependent on the amount of irrigation water. Thus, for $V_{fc}-V_{BI}<V_{in}\leq V_{fc}-(1.0-\gamma)V_{BI}$ in place of Eq. (4):

$$C_{AI}=[(V_{fc}-V_{in})C_{BI}+V_{in}C_{in}]/V_{fc} \tag{5}$$

The third case occurs when the entering water volume, $V_t$, is less than or equal to the volume required to bring the water content up to field capacity $[V_{in}-V_{fc}-V_{BI}]$:

$$V_{out}=0 \tag{6}$$

$$C_{out}=0 \tag{7}$$

$$V_{AI}=V_{BI}+V_{in} \tag{8}$$

$$C_{AI}=(V_{BI}C_{BI}+V_{in}C_{in})/(V_{BI}+V_{in}) \tag{9}$$

When a new irrigation event is taken from the list of events, the algorithm tests the amount of water being applied to determine which of the above cases is relevant.

TETrans requires certain assumptions regarding the mechanics of fluid flow in the unsaturated zone and the transport of solutes. These assumptions render the model useful from a management perspective because of diminished requirements in terms of computational resources and greatly simplified input data. Some assumptions related to water flow are: (1) water redistribution occurs instantaneously after an irrigation, (2) only downwards movement of water is permitted, (3) the soil profile can be divided into a small number of homogeneous compartments, and (4) water contents of adjacent compartments are unrelated except when the field capacity is exceeded and water drains from one compartment to the compartment beneath it. Considering solute transport, a significant assumption of the model is the lumping of dispersion with macropore flow.

### 3.2. *Application of TETrans to a regional flow problem — TETransgeo*

TETrans was originally formulated to provide an assessment of water and solute redistribution at a single location. In a regional flow context the model is capable of predicting soil water content and solute concentration at various depths for a point location. Thus, the geographic version, called TETransgeo, computes water and solute redistribution at a selected set of point locations. From the users point of view a significant difference between the two programs is the lack of interactivity in TETransgeo. Data requirements for TETransgeo are so much greater than those of TETrans that it is unrealistic to expect a user to enter a complete data set by hand prior to a run. Instead, TETransgeo reads a formatted text file and writes its output as another formatted text file. Thus, the program could run completely independently of the GIS. When data is read by TETransgeo it is stored in one of two hierarchical data structures that have the organization shown in Fig. 2. These data structures, established within TETransgeo, provide a relational structure that is similar in concept to the organization of attribute data within the GIS. The only real difference between the two types of data organization is that TETransgeo stores all needed data in main memory whereas the GIS database stores individual tables as separate files on disk. The essence of the algorithm is a single complete run of the TETrans program at each location in turn. After calculations at all locations are complete then an output file is written from the stored results.

TETransgeo is a separate entity from the GIS itself. But execution is initiated by a program written in the GIS macro language. This arrangement, while seemingly more complex than simply making all calculations within the GIS, has several advantages: (1) TETransgeo is compiled and therefore runs much faster than an analogous interpreted program written in a macro language, (2) because TETransgeo is fully external to the GIS it can work with different GIS programs without modification, and (3) program development was rendered more efficient by the use of a standard computing language and all the associated development tools.

A major disadvantage of the separate program design is the usage of text files as a medium for transferring data between the GIS and TETransgeo. The reading and writing of these files by the GIS is the limiting factor determining the efficiency of operation of the entire calculation. A hierarchical set of macro language programs (specifically, ARC Macro Language) carry out all the operations referred to here.

### 3.3. *Description of data gatheredfor TETransgeo*

The following summaries provide details on what the data are and how they were obtained. The TETransgeo input data are very similar to those required by TETrans, but, because the application is a held area rather than a single location, the methods utilized to obtain data for certain variables are different.

Soil Type: A preliminary soil survey map of this area was produced by the Soil Conservation Service (SCS) in 199 1 using a geographically-referenced area1 photo as a base map. Although the SCS soil survey map and accompanying soil descriptions are preliminary, we consider this map to be more accurate than the previously published soil map for this area drawn in the 1940's. The new SCS map was digitized and the accompanying soil descriptions were entered as part of the GIS database. Two maps, created using GIS methods, represent the soil type and the crop type during the summer of 1991 (Fig. 1) .

Soil Samples: Core samples taken at 1 -foot increments down to 4 feet were collected at 8 sites per quarter-section (Fig. 3). Each sample was analyzed in the laboratory for soil salinity and percent water (Lesch and Rhodes, 1992). For 37 quarter-sections, complete sets of data defining the initial conditions for the model were obtained for 3 1.5 locations. The initial condition of total dissolved solids (TDS in mg/l) in the soil water, has been calculated from measurements of electrical conductivity of the saturation paste extract (EC,) : TDS = 640 $x$ EC,. Percent water was determined by gravimetric methods.

Crop Type: The crop-type map follows the geographic boundaries of quarter-sections except in those areas where a crop has been planted in an area smaller than the entire quarter-section (Fig. 1) Data for the crop type map were obtained from observations made by US Salinity Laboratory personnel in May, 199 1. These observations have been verified and, in a few quarter-sections modified, by comparison with sketch maps prepared by personnel from the Broadview Water District staff. Modification was occasionally necessary because crops are sometimes plowed under before they reach maturity. For the calculations discussed here it is assumed that such areas are equivalent to fallow areas because no irrigation water was applied. The GIS database contains a table which is a crop schedule and stores the succession of crops planted at each location within the field. This is necessary for simulations that may run for several years. Each record in this table also contains planting, maturity and harvest dates.

Crop Data: For each crop these include maximum root depth; plant root water uptake distribution; root distribution coefficient; dates of planting, maturity and harvest; and 3 evapotranspiration coefficients with associated dates. The 3 evapotranspiration coefficients were provided for each crop by the California Irrigation Management Information System (CIMIS). These crop coefficients ($K_c$) are used to calculate the daily evapotranspiration from the equation, ET, = ET, $x K_c$, where $ET_0$ is the reference crop evapotranspiration for grass (Jensen et al., 1990). The 3 $K_c$ values define a continuous, piecewise linear function representing variation in $K_c$ due to growth of the plant. The other crop variables have been estimated based on discussions with experts familiar with growing conditions in the western San Joaquin Valley (D. Cone and D. Wichelns. personal commun., 1992). Crop data are stored in a table in which each record consists of a crop ID number and the various coefficients listed above.

*Evapotranspirtaion:* Daily values of reference crop evapotranspiration (ET,) were obtained from the California Irrigation Management Information System (CIMIS) station at Firebaugh, California located about 10 km from the Broadview Water District.

*Field Capacity/Minimum Water Content:* The clay content of each soil type was determined from soil survey data supplied by the Soil Conservation Service. Field capacity and minimum water content were estimated from the clay content.

*Mobility Coefficient:* The mobility coefficient is the water fraction involved in piston-type flow as opposed to bypass flow. A range of values for the mobility coefficient of 0.4 to 0.6 was estimated based on the results of lysimeter experiments (Corwin et al., 1991) .

*Irrigation:* During a growing season in the Broadview Water District, 4-6 irrigations occur in planted fields. Each irrigation runs for a period of 2-3 days and supplies, on average, 90 mm depth of water. All irrigations in the district utilize the same source of irrigation water so irrigation water chemistry is assumed to be spatially invariant. But the water chemistry is time-dependent so a complete chemical analysis including EC measurements was conducted on a monthly basis. All irrigation data including quarter-section ID numbers, dates, irrigation amounts and TDS concentrations are stored in an irrigation table.

## 4. **Results and discussion**

Optimization of irrigation management has, as one of its goals, the minimization of total salt discharge from irrigated areas. Reduction of solute-loading to groundwater by judicious application of irrigation water can be a contributing factor. One use of TETransgeo in this context is the estimation of solute-loading to groundwater for varying irrigation strategies. A TETransgeo simulation was run for the Broadview Water District for the summer growing season of 1991 (Corwin et al., 1993). During May and June of that year, field work was performed to characterize the initial conditions of salinity and percent water. The starting date for the calculation is set, for each quarter-section, to the date when samples were taken from that quarter-section. The ending date for the calculation was 9/30/ 199 l for all quarter-sections. The mobility coefficient was set to a constant value of 0.6 for the results shown in Fig. 5. Irrigations occurred in only 28 out of 37 quarter-sections during the modeling period, but evapotranspiration was calculated at all locations assuming that unirrigated quarter-sections had constant $K_c = 0.1$. TETransgeo was run for 3 15 locations (Fig. 3) within the field area and required about 1 minute of elapsed time to read the input file, make the calculation and write the result file (Sun SPARC 2). The TETransgeo calculations are very rapid compared to the amount of time required by the GIS to read and write files (more than I hour for both). This suggests that a more detailed coverage of the field area using raster data and increasing the number of locations by a factor of 10 would not lead to unreasonable execution times for the external program. However some technique for improving the efficiency of external file manipulation operations within the GIS would be necessary.

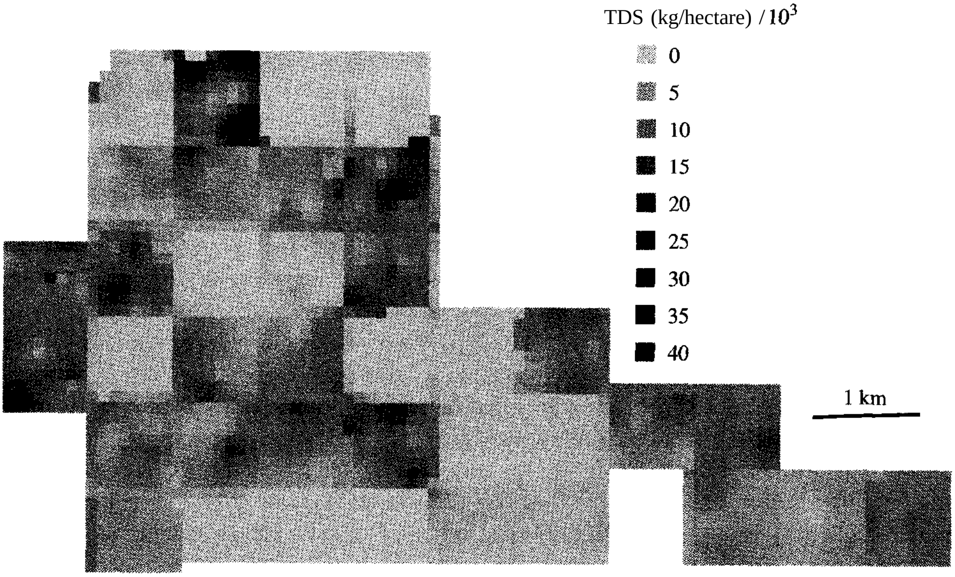


Fig. 5. Calculated total solute-loading to groundwater during the period 4/91 to 9/30/91. Interpolation of calculated results was accomplished on a per-quarter-section basis because irrigation amount is strongly controlled by quarter-section boundaries. The mobility coefficient was 0.6.

Results of the TETransgeo calculation suggest that initial soil salinity and irrigation management are both likely factors determining the TDS loaded to groundwater. Both factors exhibit significant spatial variability within the field area making it possible to assess relative influence by visual inspection of maps. Variability in amount of irrigation water applied can be gauged from the crop map (Fig. 1) because cotton, tomatoes and melons are the most highly irrigated crops (0.3-0.6 m) while quarter-sections cropped in alfalfa and wheat received O-O.3 m. Spatial distribution of irrigation amounts is bimodal, 9 quarter-sections were not irrigated, 14 received 0.4-0.5 m, whereas only 3 received 0.2-0.3 m. Initial soil salinity is very high near the northeast corner of the field area and smaller patches of high salinity occur in many other quarter-sections (Fig. 4). TDS concentrations shown in Fig. 4 were computed by an inverse-distance-squared interpolation algorithm utilizing measured values at the 3 15 soil core sites and a 1 km search radius for data points.

Irrigation amounts are strongly controlled by quarter-section boundaries. The kind of interpolation scheme used to create Fig. 4 would not be very useful for interpolation of the calculated solute-loading to groundwater because of this quarter-section control. TDS loaded to groundwater is more likely to correlate with irrigation amounts at distant points in the same quarter-section than a nearby point in a different quarter-section. Therefore, the inverse-distance-squared interpolation algorithm was applied to the calculated TDS loaded to groundwater on a per quarter-section basis (Fig. 5). The calculated result demonstrates correlation with irrigation amount: fallow quarter-sections had very low solute loading to groundwater whereas quarter-sections cropped in cotton exhibit higher values. Notably, TDS loading to groundwater was low in the quarter-section with highest soil salinity because the irrigation amount was insufficient to generate substantial flux out of the root zone. Significant variability occurring within quarter-sections correlates with initial soil salinity

(Fig. 5). For example, the location of the highest TDS loaded to groundwater near the northern boundary of the field area is identical to a location of high soil salinity (Figs. 4 and 5).

## 5. Conclusion

A one-dimensional functional model for computing water and solute redistribution in unsaturated zone soil profiles has been reformulated to run for an arbitrary number of locations. The reformulation, called TETransgeo, is designed to work within the framework of a GIS in order that the facilities of data manipulation and representation provided by the GIS may be utilized. A data set collected for an agricultural field area located in the San Joaquin Valley was stored following an organizational framework designed to maximize accessibility of the data and minimize data duplication. The test runs on this data set consisting of 3 15 locations indicate that the design of the data organization is effective in an operational sense. The execution time for TETransgeo including its file manipulation operations is only about 2% of the total time required to run a full calculation because a large amount of time is required by the GIS to read and write text files. Optimization of the reading/ writing of external files by the GIS is the most significant potential area of improvement.

The influence of the variables, irrigation amount and initial soil salinity, on the TDS loading to groundwater was confirmed by comparison of maps of crop distribution, initial soil salinity and calculated TDS loaded to groundwater. Quarter-sections left fallow or cropped in wheat or alfalfa had very low TDS loading to groundwater corresponding to zero or small irrigation amounts. Quarter-sections cropped in cotton generally received more than 0.4 m total depth of irrigation water and showed relatively high TDS loading to groundwater. Within individual quarter-sections, irrigation amounts are constant and variability of TDS loading to groundwater is spatially correlated with initial soil salinity.

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