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PREDICTING AREAL DISTRIBUTIONS OF SALT-LOADING TO THE GROUNDWATER

by

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Summary:

The one-dimensional, solute transport model TETrans has been “loosely coupled” to the geographic information system ARC/INFO for the purpose of estimating areal distributions of salt-loading to the groundwater. Slightly less than 2400 hectares of the Broadview Water Distict located on the westside of central California’s San Joaquin Valley is used as the test site to evaluate the integrated GIS/transport model. A complete data set of input parameters has been assembled and entered into the geographic information system (GIS) database. TETrans uses the GIS as a spatial database from which to draw its input parameters. Preliminary simulations are presented for the main growing season of 1991. Display maps show spatial distributions of irrigation efficiencies, drainage amounts and salt-loading to groundwater over the 2396 hectares. These maps provide a visual tool for making irrigation management decisions to minimize the environmental impact of salinity on groundwater.

Keywords: ARC/INFO, contaminants, solute transport, geographic info systems, GIS, groundwater contamination, non-point source pollution, salinity.

INTRODUCTION

Groundwater is a major water resource in the United States accounting for half of the drinking water and 40% of the irrigation water used. Due to limited surface water resources and due to the continued contamination of surface water supplies, groundwater supplies are increasingly relied upon to meet growing water demands. The increased reliance upon and continued demand for groundwater has resulted in a growing public concern for the degradation of groundwater particularly by non-point source pollutants such as pesticides, fertilizers, salinity and trace elements. Non-point source pollutants from agricultural lands are potentially the greatest hazard to groundwater because of the areal extent of their contamination and the difficulty of effective remediation once groundwater is contaminated.

Groundwater quality is a primary environmental concern not only for health reasons, but because of the decrease in crop productivity which can accompany the use of poor quality (i.e., high salinity and high trace element concentrations) irrigation water. Concomitantly, irrigated agriculture is being threatened because of its potential to contribute unsafe amounts of organic chemicals, salts and toxic elements to groundwater supplies. On irrigated, agricultural soils, salt concentration increases as it moves through the root zone due to the selective uptake of water by plant roots. This process is at the core of groundwater quality because of the downward movement of salt into the groundwater.

The most obvious means of preventing groundwater degradation within agricultural areas is to minimize load-flow of solutes to the groundwater. Maintaining a high irrigation efficiency (i.e., low leaching) goes hand-in-hand with reduced salt-loading, but can result in the buildup of salts within the soil profile. The ability to locate sources of salt-loading within irrigated landscapes and to model the migration of salts through 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 non-point sources of contaminants 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. The coupling of the spatial data handling capabilities of a geographic information system (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.

Recently several hydrologic/water quality models of runoff and soil erosion have been used with a GIS to determine surface sources of non-point pollutants (Pelletier, 1985; Potter et al., 1986; Hession and Shanholtz, 1988; Oslin et al., 1988;.and Rudra et al., 1991). GIS has also been used for groundwater pollution hazard assessment by coupling to a weighted-index site assessment method such as DRASTIC (Merchant et al., 1987; Evans and Myers, 1990; Halliday and Wolfe, 1991; and Rundquist et al., 1991) and to a simple index-based model such as Rao et al.'s Attenuation Factor model (Khan and Liang, 1989). Only Petach et al. (1991) have coupled a solute transport model (i.e., LEACHM) to a GIS to assess the leaching potential of some common non-point source agricultural chemicals. However, the work of Petach et al. (1991) did not use field measurements of input parameters for the LEACHM model. Rather, the input parameters were generalized from sources such as Soil Conservation Service soil survey maps. In addition, Petach et al. (1991) found the computation time for execution of their numerical model to be very large and suggested the use of a more simplified leaching model.

It is the objective to develop and demonstrate a practical/and efficient methodology for estimating salt-loading to the groundwater on drainage-impacted and salt-affected land for the purpose of reducing water usage, minimizing load-flow of salts to the groundwater and ameliorating shallow water table conditions on irrigated agricultural land. Automated geophysical techniques in combination with conventional physical and chemical measurements techniques are utilized as a cost-effective means of measuring the spatially-variable input data needed to formulate a geographic information system. The GIS is coupled to a simplified model of solute transport through the vadose zone to provide an estimate of the spatial distribution of salt-loading to the groundwater.

METHODS AND MATERIALS

The one-dimensional, functional transport model TETrans, introduced by Corwin and Waggoner (1990) and Corwin et al. (1991), is integrated into the ARC/INFO geographic information system. TETrans is “loosely coupled” to ARC/INFO, implying that the GIS and modeling software are coupled sufficiently to allow the transfer of data and results; consequently, the GIS and modeling module do not share the same data structures.

A complete description of the theoretical development of TETrans is outlined in Corwin and Waggoner (1991) and Corwin et al. (1991). TETrans is a capacity 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 which actually occur in nature. Furthermore, each sequence of events or processes occurs within each depth increment 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. As a capacity-based model, TETrans is driven by the amounts of rainfall (or irrigation) and evapotranspiration (ET), and only considers time indirectly by using the time from one precipitation (or irrigation) event to another. From a knowledge of water inputs and losses, and of soil-solute chemical interactions, TETrans predicts the average concentration movement of reactive or nonreactive solutes through the vadose zone.

ARC/INFO was integrated with a new version of TETrans, called TETransgeo. The current work is a reformulation of the original TETrans code to provide spatial coverage in order to compute salinity profiles and salt-loading to the groundwater over a selected geographic area, Both the computed results and all data required by TETransgeo are stored in the GIS database to permit spatial representation of any physical, chemical or biological variable.

Thirty-seven quarter sections (2396 hectares) of the Broadview Water District in the San Joaquin Valley were chosen as a test site. This provided sufficient variability and magnitude to test the methodology and the GIS/TETransgeo model. 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 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 where planted. From the roughly 2350 sites, a total of 285 locations were statistically selected as representative soil sampling sites. The 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 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: O-0.3,0.3-0.6,0.6-0.9 and 0.9-1.2 m. When the TETransgeo program was run, the initial conditions required for the calculation were obtained from this table.

The boundary condition at the surface was established by the irrigation schedule for each quarter section. Irrigations generally occurred over a 2-3 day period. There were normally 4-7 such periods during the summer growing season. The TETransgeo 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 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 l-month intervals. The evapotranspiration (ET) was determined for each crop using CIMIS (California Irrigation Management Information System) data for the vicinity of the Broadview Water District.

Figure 1 shows the 37 quarter sections of the Broadview Water District test site and the 285 soil sampling sites. Thiessen polygons were created from the 285 sites. The TETransgeo model was applied for each of the map units defined by the Thiesseen polygons. Results of the TETransgeo simulations are presented for the main growing season of 1991. Prelimninary display maps show calculated area1 distributions of irrigation efficiency, 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 1995. In 1995 field measurements of salinity at the 285 locations will be measured for comparison with simulated results from the GIS/Transgeo model.

RESULTS

Simulated results for the top 1.2 m of soil calculated for the time period of April, 1991, to September 30, 1991, show the most significant change in salinity is seen in the top 0.3 m of the soil profile. Several noticeable salinity concentration increases occurred. In every instance the salinity peaks are located on soil which 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. The removal of water by surface evaporation results in the depletion of water in the O-O.3 m depth increment and the concentration of salts within that layer. TETrans does not replenish the depleted water with moisture from lower in the profile; consequently, the unexpectedly high concentrations of salinity in the top 0.3 m.

Figure 2 shows the calculated leaching fraction for the preliminary 6-month study period. Twelve quarter sections had calculated leaching fractions of less than 0.1. These areas were either fallow or had a crop of seed alfalfa (see Figure 3). The application and/or precipitation of water in these areas totalled less than 0.1 m. The spatial distribution of the calculated amount of drainage beyond the root zone is shown in Figure 4.

Figure 5 shows an area1 distribution of the amount of salt which has 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-month study period. Because little rainfall occurred in 1991, these fallow areas had virtually no net downward salt flux. In fact, evaporation exceeded rainfall over this time period.

DISCUSSION OF RESULTS

To minimize the environmental impact of a non-point source agricultural pollutant such as salinity upon groundwater, a spatial knowledge of the leaching efficiency and salt-load is necessary. Areal distributions of salt-loading to the groundwater define areas where the greatest attention must be given to reduce the irrigation water application and the downward flux of salt. Ideally, the root zone must be sufficiently leached of salts to maintain crop yields, and yet leaching needs to be minimized to reduce salt-loading to the groundwater.

The southeast quarter-section of Section 3 (see Figure 1) has a high drainage (see Figure 4), high leaching fraction (see Figure 2) and high salt-load (see Figure 5). Because this quarter section was cropped with cotton (see Figure 3), which is a high salt tolerant crop, it is obvious that the salt-load could have been reduced by applying less irrigation water over the 6-month preliminary study period than the 0.5-0.6 m of irrigation water that was applied. A close look at the initial soil salinity profile and the soil salinity profile at the end of the simulation (September 30, 1991) for this quarter section reveals that most of the salt which moved beyond the root zone came from the lower portion of the root zone (0.6-1.2 m). However, the low initial salinity in the upper portion of the soil profile (O-O.6 m) at the time of planting would have allowed the cotton to germinate and mature even at the suggested lower irrigation application amounts.

A similar evaluation can be made for each area that has an associated high salt-load. Though different factors may be responsible for the cause of the salt-loading, it becomes readily apparent from the displayed spatial information how to manage each situation.

SUMMARY

The functional solute transport model TETrans was coupled to the geographic information system ARC/INFO. Simulation modeling of water and salt movement and techniques of geographic information systems were used to integrate, condense and summarize the large-scale (i.e., thousands of hectares) behavior of spatially-variable soils to provide management guidance on issues related to salt-loading to the groundwater.

The approach was used to estimate salt-loading levels from current irrigation management, but can be used to predict solute loading for various irrigation scenarios. The information can be used to forecast the need for drainage systems; to aid in the s/election of crops; to assist in prescribing irrigation management strategies to minimize agricultural water usage; to assist in determining reclamation needs; to minimize the environmental impacts of irrigated agriculture; and to specify which lands are most appropriate for irrigated agriculture.

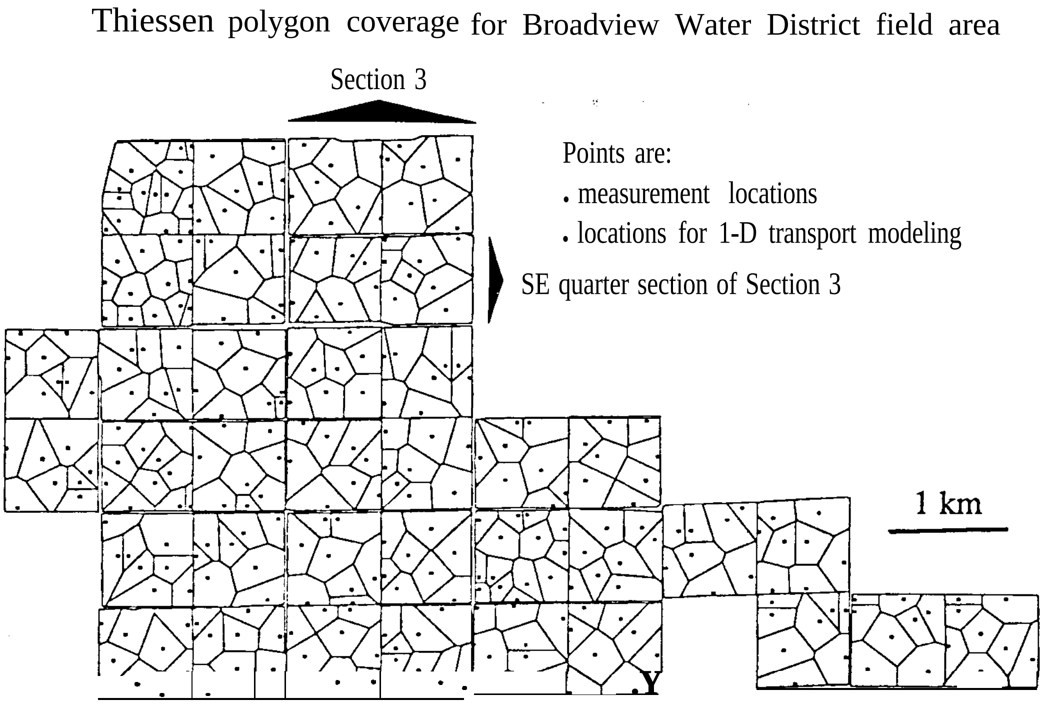

Figure 1. Boundary lines of the 37 quarter sections of the Broadview Water District test site and the 285 soil sampling sites. Thiessen polygons are also defined.

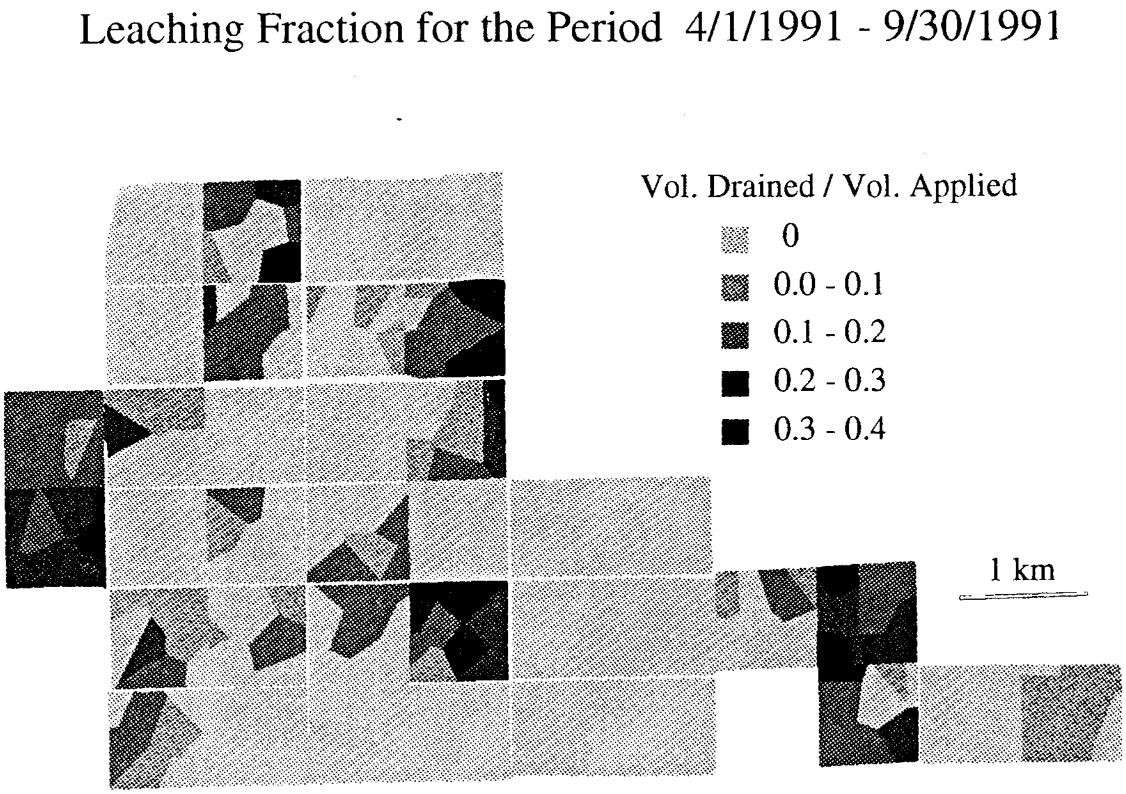

Figure 2. Areal distribution of the simulated leaching fractions for the preliminary 6-month study period of the Broadview Water District test site.

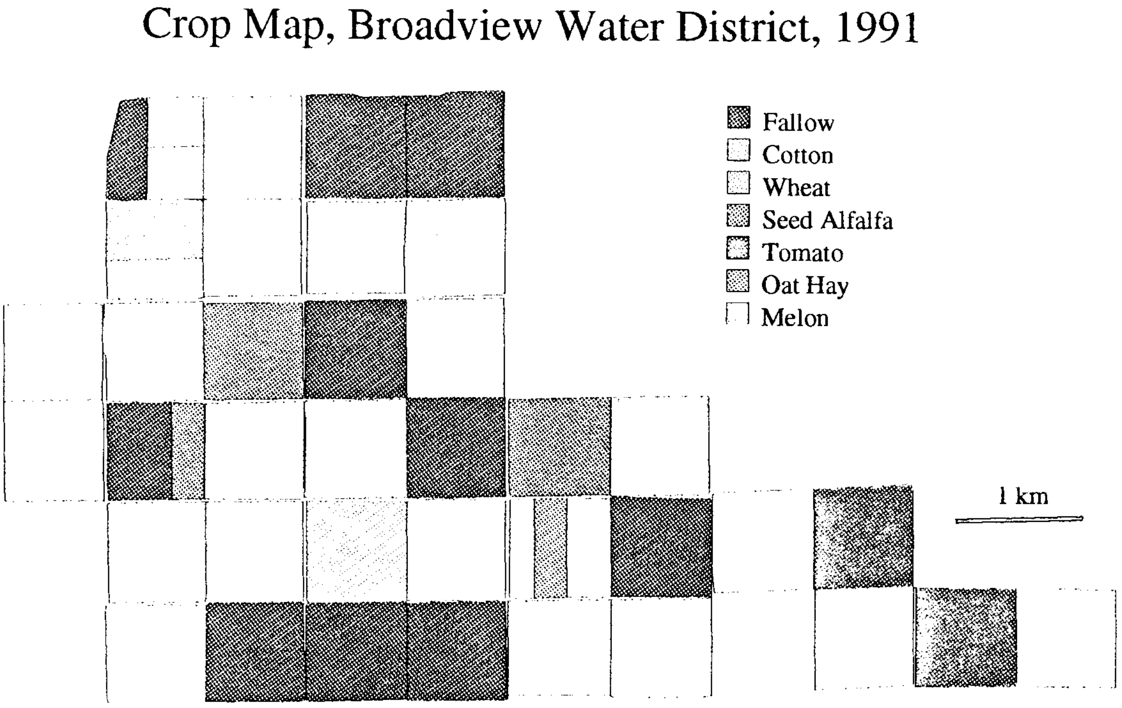

Figure 3. Crop map for the 1991 growing season (April to September, 1991).

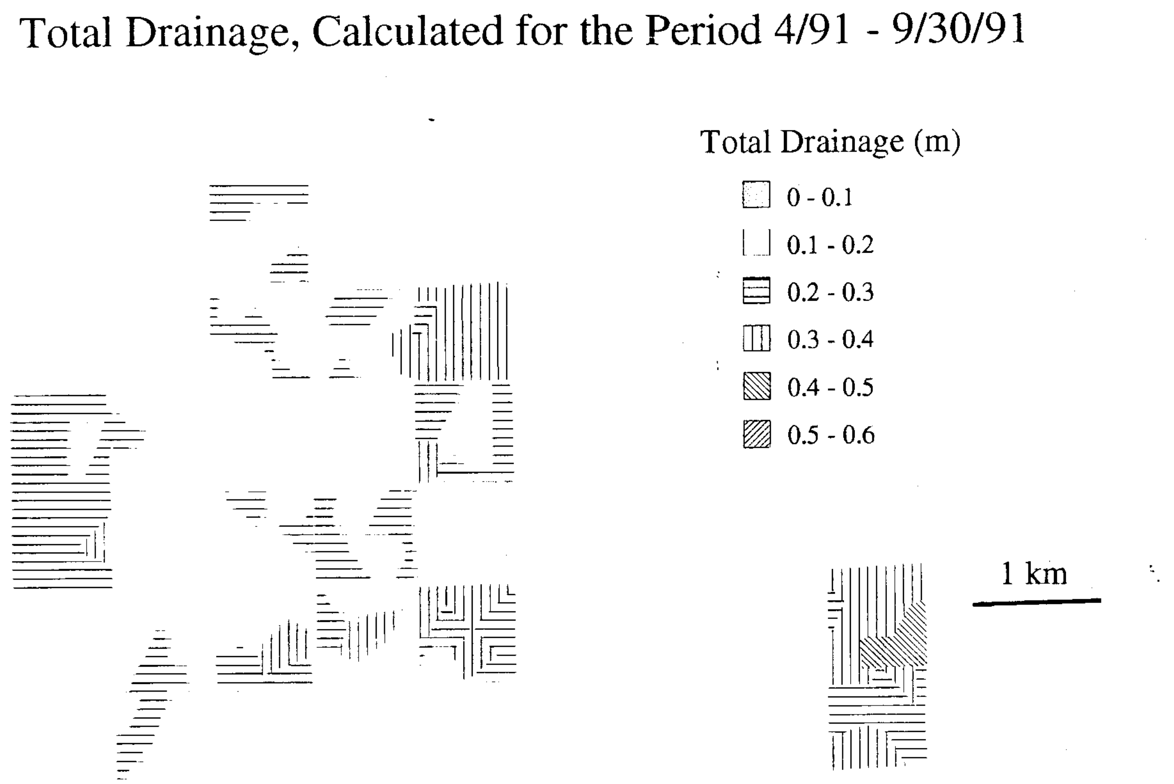

Figure 4. Areal distribution of the simulated amount of drainage beyond the root zone for the preliminary 6-month study period of the Broadview Water District test site.

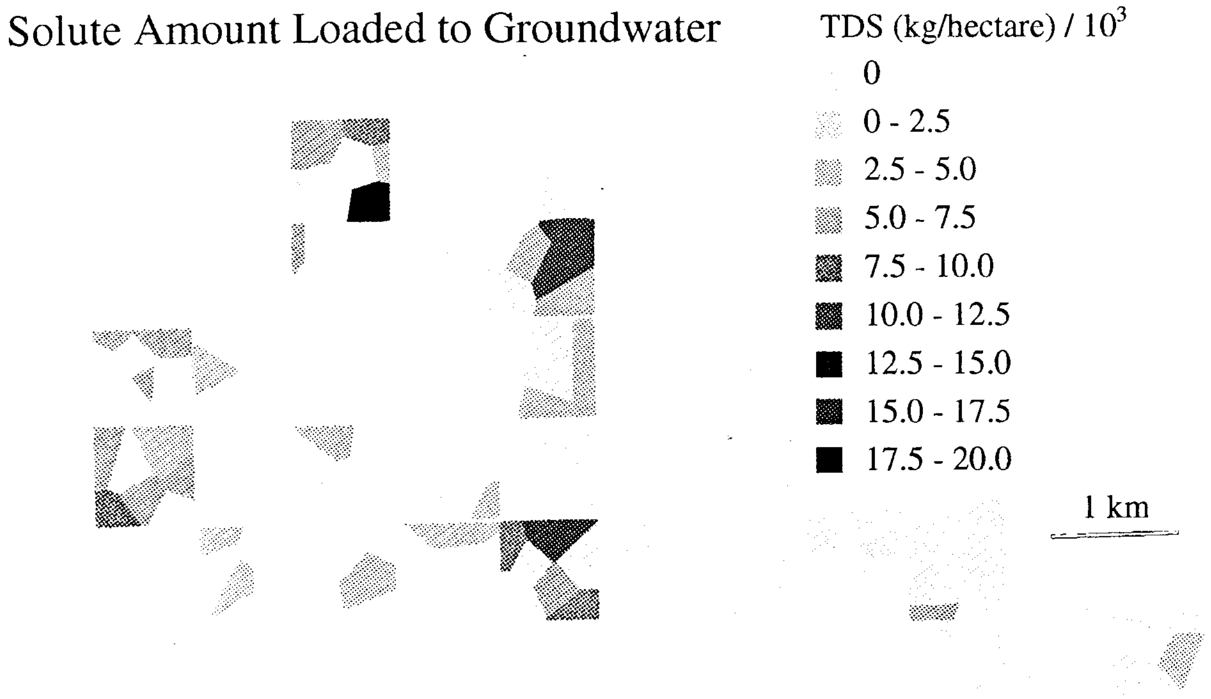

Figure 5. Areal distribution of the simulated amount of salt-loading to the groundwater for the preliminary 6-month study period of the Broadview Water District test site.

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