DESCRIBING AND MODELING SALINE SHALLOW WATER TABLE PROBLEMS IN THE LOWER ARKANSAS RIVER VALLEY, COLORADO

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SALINITY AND WATERLOGGING PROBLEMS IN THE ARKANSAS RIVER VALLEY

Salinity and drainage problems usually appear in intensively-irrigated alluvial valleys within a few decades to a few hundred years of the commencement of large-scale irrigation. Eventually, the artificially high rate of application of water to land exceeds the natural rate of drainage, the water table rises, and artificial drainage is needed to regain an acceptable water and salt balance. In the lower Arkansas River valley in Colorado, saline high water tables began to appear in the early part of the twentieth century. Installation of subsurface drains in the 1930s seemed to assuage the problems for awhile (NRCS, Rocky Ford Field Office, personal communication). However, water tables began to rise again in the late 1970s, presumably due to increased diversions from the river for irrigation application and associated reduction in groundwater pumping (Watts and Lindner-Lundsford 1992).

In the 1960-70's, two reservoirs were built that have drastically changed the river. Flushing from floods was substantially reduced and controlled releases were made from the reservoirs allowing year-round, or at least prolonged, supplies of water to the canals on the perimeter of the valley. Seepage from these canals and reduced velocities in the river has caused the channel to widen, sediments to deposit on the bed, and the river level to rise. Our recent investigations of water levels in the reach of the Arkansas River upstream of John Martin Reservoir indicate an increasing trend since about 1989. The overall rise in the river level (about 0.6 m (2 ft)) may have significantly reduced the gradient that drives drainage flows from irrigated lands to the river. Also, since 1991, irrigation water supplies from snow pack and rainfall have been far above average. Many of the large supply canals in the area have diverted more water in each of the last three years than in their 100+ year histories and have increased seepage throughout the basin. In response to the recent Kansas-Colorado court ruling, groundwater pumping in the valley, which serves to reduce water table levels, has diminished. These and other factors have contributed to a growing body of evidence that the irrigated lands of the lower Arkansas are suffering from the effects of severe waterlogging and salinization.

FIELD DATA TO DESCRIBE THE PROBLEMS

To date, most of the evidence of salinity and waterlogging has been informal and anecdotal: salt crusting on soil surfaces, seepage and wet spots in selected fields, stunted growth of crops, and reduced yields. Recently, however, in response to these concerns, Cooperative Extension and the Civil Engineering Department at Colorado State University began a study in the region to scientifically diagnose the extent and severity of the problem and to explore alternative solutions. Data were collected in thirty fields of ten to twenty acres size in Otero County over the summer of 1998. Thirty to seventy measurements were made within each field (to a depth of about 1 meter) early and late in the growing season using a Geonics™ EM-38 electromagnetic induction probe. *Box and whisker* plots of the results are given in Figures 1 and 2 for the early season and late season measurements, respectively. The upper and lower *whiskers* indicate the maximum and minimum values, respectively, that were measured in each field. The upper and lower edges of each of the large boxes represent the 75th percentile value (i.e., exceeded 75% of the measured values in a given field) and 25th percentile value, respectively. The median (50th percentile) value is represented by the dark square.

Preliminary analysis shows field-averaged soil salinity ranging from 575 to 6600 mg/liter in the early season, with an average of 1870 mg/liter over the fields surveyed. In the late season, field-averaged salinity ranged between 370 to 7600 mg/liter with an average of 2450 mg/liter. These values are indicative of crop yield reductions of about 0 to 90 %, with an average reduction of about 15 to 20%. In addition, measurements taken to date in about 15 observation wells indicate an average water table depth of only about 1.5 m (5 ft) below land surface. In some locations, the water table has been observed at depths as shallow as 0.30 m (1 ft). These shallow water tables also adversely impact crop yields through waterlogging. To better understand the extent and severity of the problem, plans have been made to survey additional fields over the next three years. In addition, direct measurements will be made of crop yields on affected fields, allowing correlation to be derived between salinity and waterlogging and consequent impacts on production in the valley.

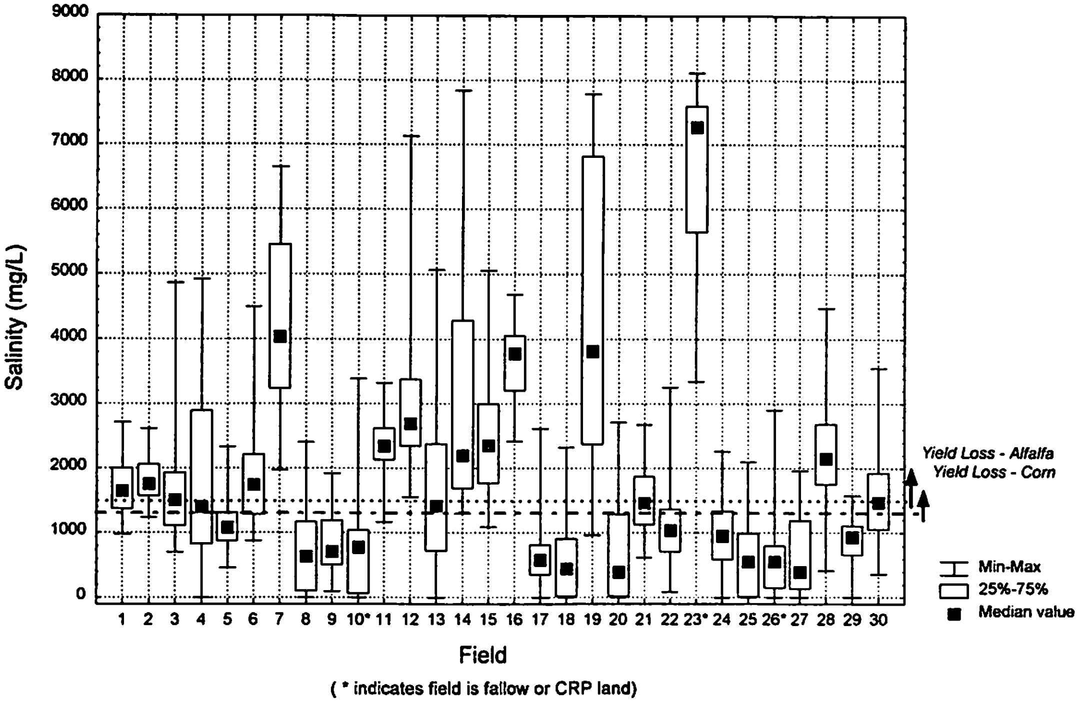

Figure 1. Salinity of soil saturation extract for fields sampled in Otero County during early summer 1998 (threshold salinity levels for corn and alfalfa indicated on the plot)

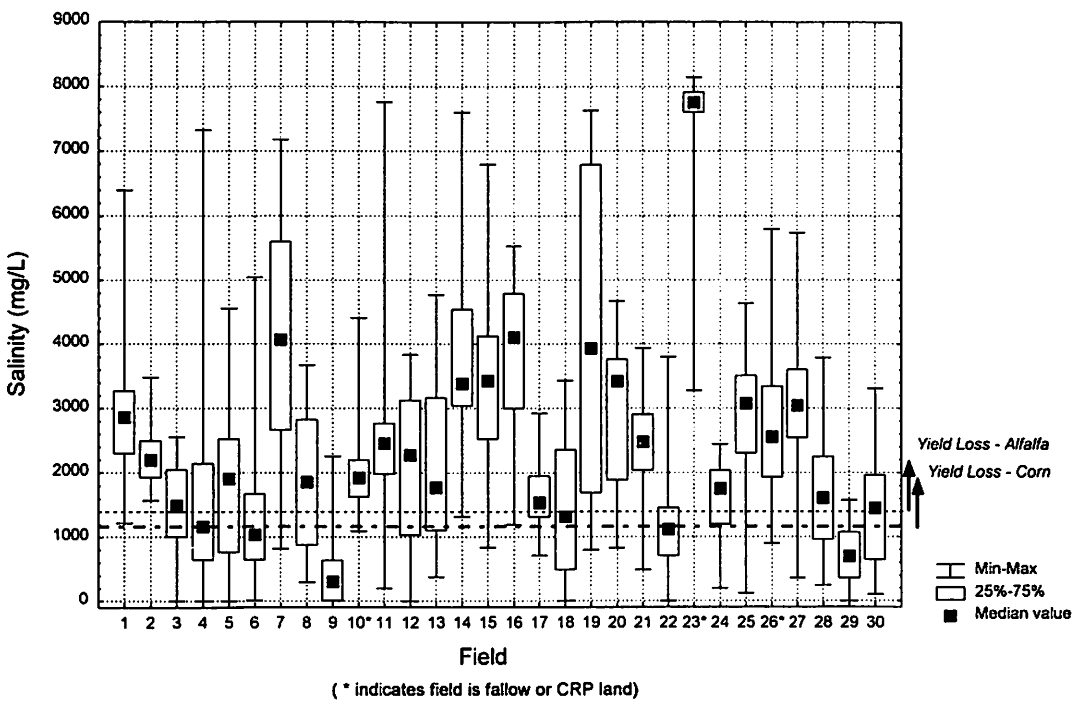

Figure 2. Salinity of soil saturation extract for fields sampled in Otero County during late summer 1998 (threshold salinity levels for corn and alfalfa indicated on the plot)

MODELING TO PRESCRIBE SOLUTIONS

In addition to field measurements, work has been initiated in developing a computational model of shallow groundwater flow and salt transport in the Arkansas River valley between Manzanola and the Otero-Bent county line. The model is an implementation of the GMS software (BYU 1997) which links models for solving the flow and transport equations to a spatially-referenced geographic information system (GIS). Preliminary runs have been completed, indicating that the model will prove a powerful decision-making tool. However, additional data need to be collected in the field to serve as required input information to the model. Systematic analysis must then be conducted to assess alternative strategies for solving the saline high water table problem.

Analyzing complex river basins, such as the lower Arkansas River in Colorado, to determine the effects of agricultural water conservation on available water, water quality and socioeconomic impacts is a complex proposition. A comprehensive river basin network flow and water rights simulation model is needed which can simultaneously assess water quantity and quality impacts in both surface waters and groundwater, and is capable of analyzing the effects of implementing improved irrigation practices on total flows in the river, water quality and water rights. MODSIMQ is an integrated water quantity/quality river basin management model developed at Colorado State University through a previous project supported by the Colorado Agricultural Experiment Station (Dai, 1996). MODSIMQ is comprised of two existing models: MODSIM (Fredericks and Labadie 1995) and QUAL2E (Brown and Barnwell 1987), along with a soil column model and a convective transport model for predicting salinity loadings in irrigation return flows. Unlike other integrated water quality and water quantity models, MODSIMQ has the ability to optimally allocate water subject to water quality restrictions and water quantity demands based on administrative priorities, water rights, or other ranking mechanisms such as economic evaluation.

MODSIMQ incorporates groundwater flow routines for analyzing stream-aquifer interactions, which are crucial to accurate representation of the flow regime in the Arkansas Valley of Colorado. Elements modeled include irrigation return flows, canal seepage, reservoir seepage, deep percolation, and river depletion due to pumping. Response coefficients from these stream-aquifer interactive elements are being upgraded based on results from the GMS modeling effort. Application of the conjunctive MODSIMQ/GMS modeling systems focuses on examining possible ways of alleviating existing water quality problems without violating any legal operation agreements.

The MODSIMQ/GMS modeling system is applied to finding the best strategies for solving salinity and waterlogging problems. Both technical and economic feasibility will be included to assess and rank the following categories of approaches: upgrading of irrigation-water-delivery infrastructure (including lining of canals); improvements in on-farm irrigation practices; investment in new surface and sub-surface drainage works (including use of pumping wells as drains and installation of horizontal *tile* drains); shifts in cropping practices; improvements in river operations to lower water levels; possible storage and management of drainage effluents; and other changes in policy, operation, monitoring, and maintenance of the irrigation-drainage systems. Strategies will be ranked based upon effects on water table depth and salinity, soil salinity, crop yield, river water quality and socio-economic viability. The investigation currently focuses on Otero and Bent Counties as a representative region.

GMS MODEL DESCRIPTION

The modeling system selected for application to the study reach is the GMS (Version 2.1) package developed by the Engineering Computer Graphics Laboratory at Brigham Young University in cooperation with the U. S. Army Engineer Waterways Experiment Station (BYU 1997). This package incorporates a number of numerical models (MODFLOW, MT3D, RT3D, FEMWATER, MODPATH, SEEP2D) into a graphically driven format in which GIS and database files are used to develop the required input files for each of the different models. The two numerical models of interest for this study are MODFLOW and MT3D. The MODFLOW model is used to simulate depth-averaged groundwater flow through the study reach for estimation of water table elevations. In conjunction with this flow modeling, MT3D is used to estimate the depth-averaged salinity transport. Both of these models employ three-dimensional, finite-difference numerical analysis techniques. Due to data availability, however, they are being applied as two-dimensional models utilizing depth averaging within the vertical dimension. For more information on the GMS package, refer to the BOSS International website at http//:www.bossintl.com.

Data Requirements

Application of the GMS model to the study reach begins with creation of a background image which serves as the base on which other data layers are constructed. This image was created using Landsat TM data of the area collected on July 5, 1997. A false-color image was derived by processing data from Bands 3, 4, and 5 using the image processing capabilities of the IDRISI GIS software package (Eastman, 1997). Figure 3 provides a gray-scale representation of this image after importation into GMS using the *Import* command under the *Image* menu within the *Map* module.

The importation procedure included registration of the image using the Universal Transverse Mercator (UTM) coordinate system. All other data layers were also converted to this spatial referencing system before importation into GMS.

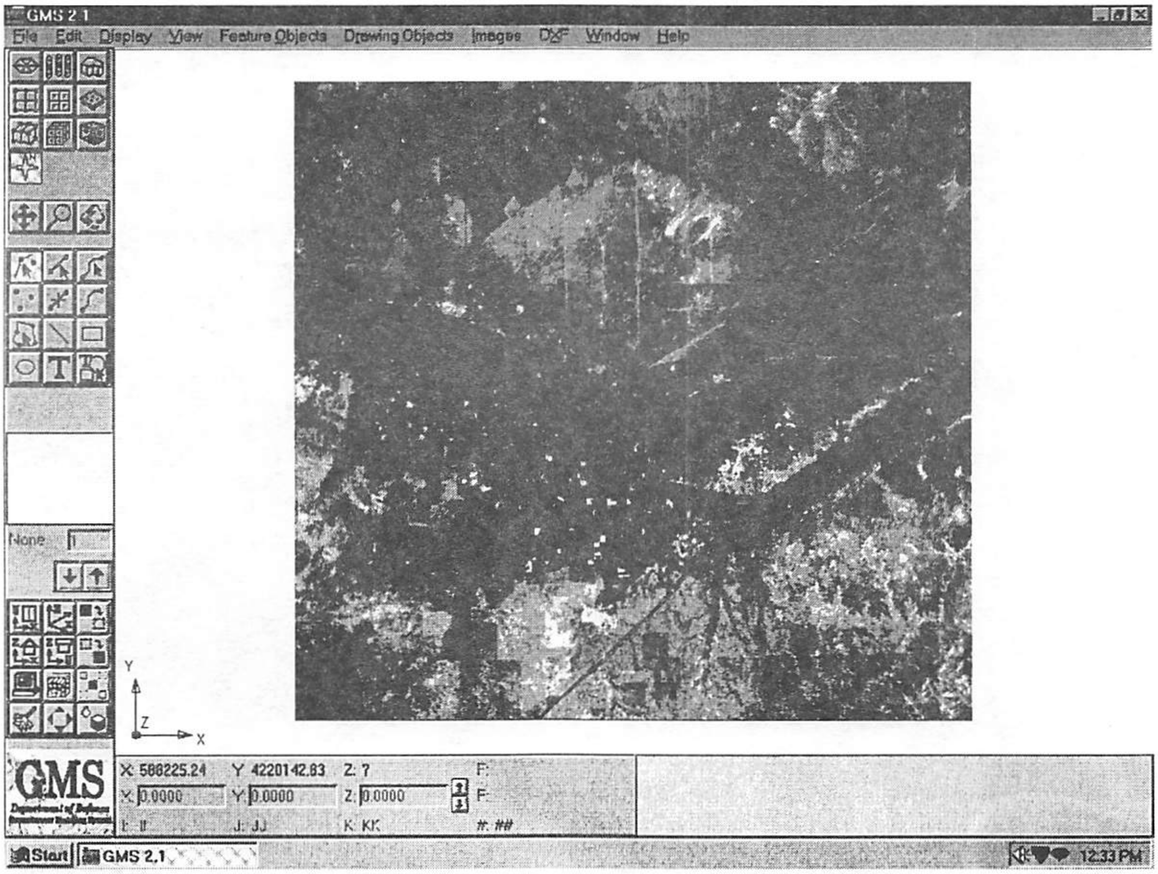

Figure 3. Landsat image of study area imported into GMS

Construction of the model continued with the building of the conceptual model of the surface water system. A representation of the surface water system within the study reach was created using the *Map* module of GMS with data obtained from USGS maps, the satellite image, field investigations, and other references. Components of this system include the Arkansas River and its tributaries, the irrigation canal network, numerous reservoirs, and several ditches for both water delivery and drainage. Definition of these components includes the incorporation of geometric data, water surface elevation, flow, conductance, as well as layout and connectivity. Much of these data were obtained from local agencies including the USGS and the Natural Resources Conservation Service (NRCS). A significant portion of the water surface elevation data were collected in the field using Trimble GPS equipment. The conceptual model is displayed in Figure 4.

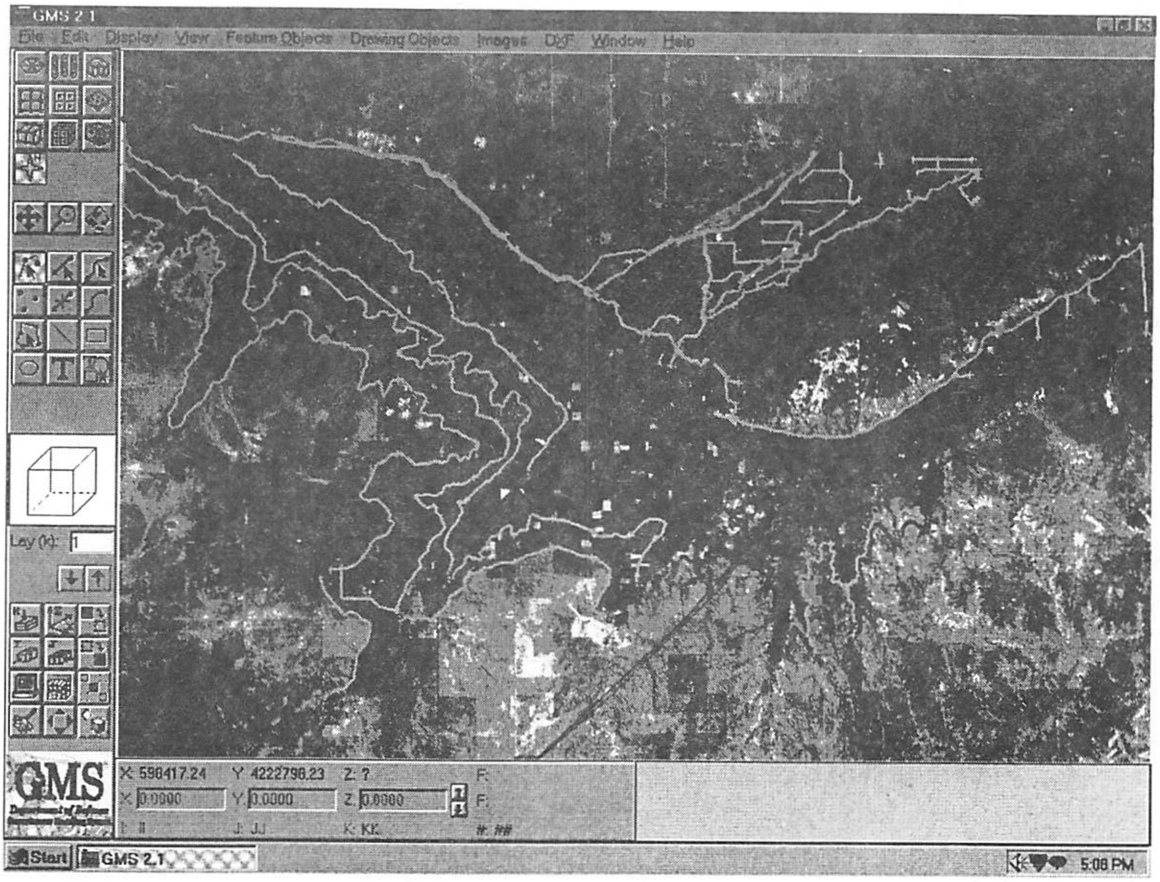

Figure 4. Conceptual model of the study area

Upon establishing the conceptual model, the finite difference grid structure was defined. Grid cell size was derived from an independent analysis of crop data provided by the Colorado Farm Service Agency which revealed an average field size of approximately 6.27 hectares. A standard cell size of 250 m by 250 m was selected to reflect this average. Sizing the cells to emulate an average field is useful for applying the model is applied to investigation of on-farm BMP's for salinity control. Figure 5 shows the defined grid overlain onto the satellite image, and Figure 6 gives shows a close up of a portion of the grid system with underlying field boundaries made visible.

Besides the creation of the conceptual model and the definition of the finite difference grid, the development of the GMS model of the study reach included the entry of the following data groups:

- <u>Water Table Elevation</u> - Data obtained from the USGS and from field investigations were used to define initial water table elevations. These data were imported into GMS within the *Scatter Point* module, and interpolation was performed using the *Natural Neighbor* (constant) analysis option. These values were then input into the finite difference grid under the *Basic Package* within the *3D Grid* module.

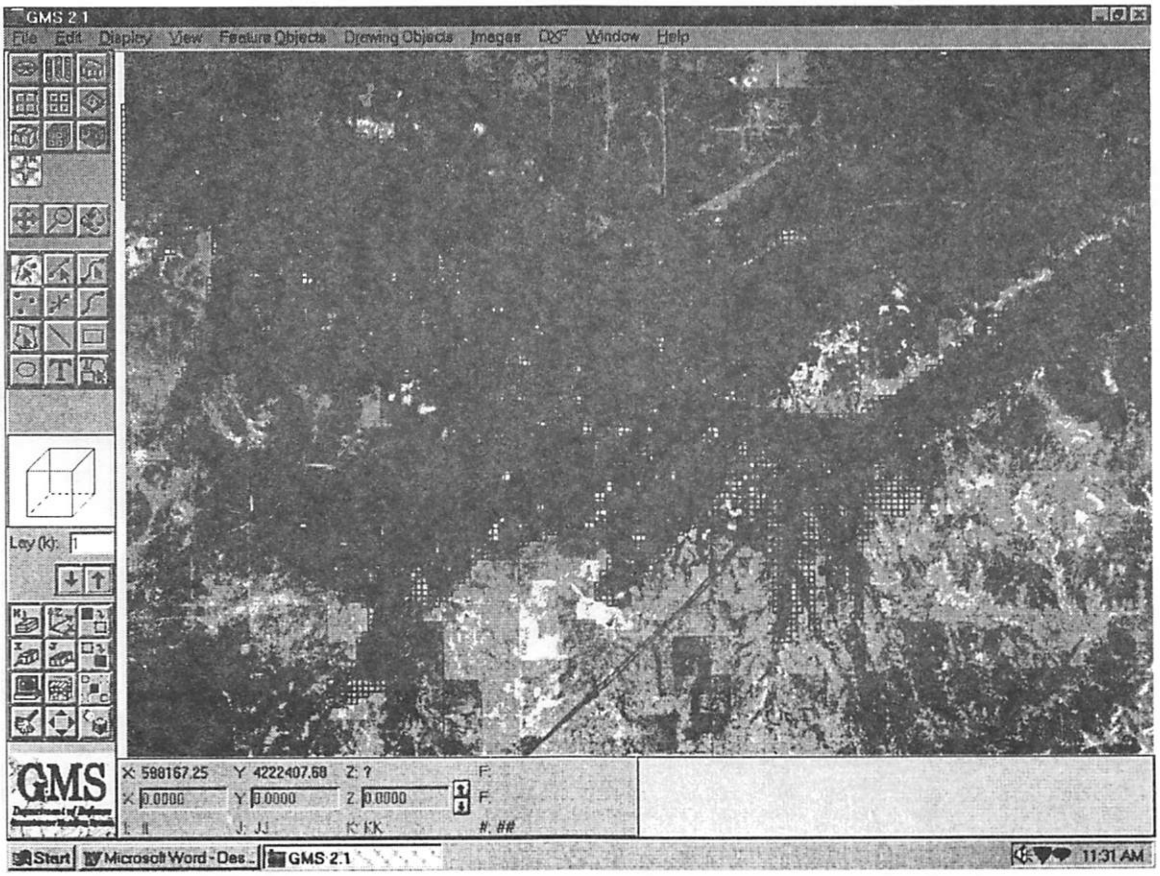

Figure 5. Finite difference grid system for study area

- Hydraulic Conductivity - Data obtained from USGS reports were imported into GMS within the *Scatter Point* module, and interpolation was performed using the *Inverse Difference Weighted* (Shepard's) analysis option. The interpolated values were input into the finite difference grid under the *BCF3* (confined/unconfined) package within the *3D Grid* module.

- Field Boundaries - Data were digitized within ARC/INFO GIS (ESRI, Inc.) from aerial photographs obtained from the Colorado Farm Service Agency and input into GMS within the *Map* module. Field polygons will be used in future model applications to vary individual field parameters such as irrigation efficiency.

Much of the data mentioned above were processed for the study area and prepared for GMS model input utilizing ArcView GIS (ESRI, Inc.), along with use of spreadsheet analysis.

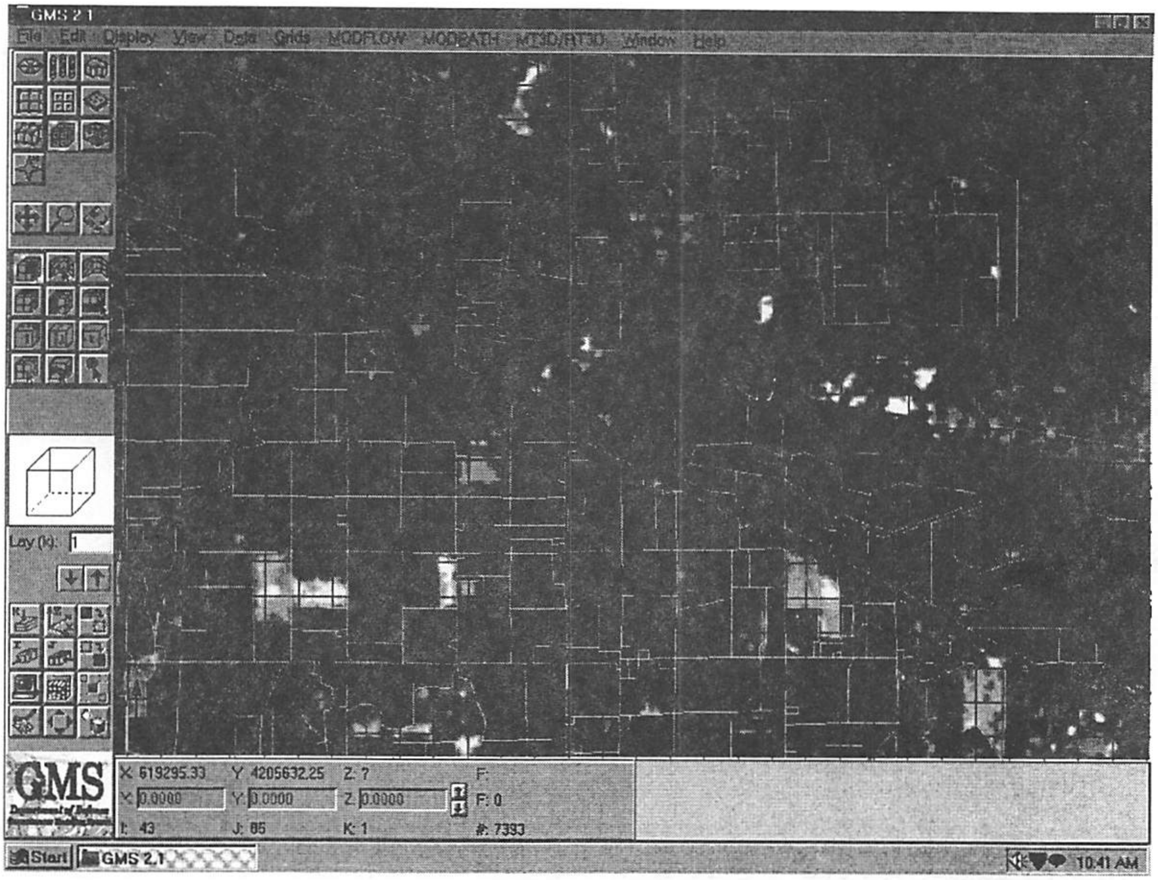

Figure 6. Close up view of finite difference grid cells showing field boundaries

- Ground Surface Elevation - Data obtained from the USGS were imported into GMS within the Scatter Point module. The *Linear analysis* option under the *Interpolation* menu was then used to create an interpolated contour plot. These interpolated data were then input into the MODFLOW finite difference grid under the *BCF3* (confined/unconfined) package within the *3D Grid* module.

- Aquifer Bottom Elevation - Data obtained from the USGS and from well logs were imported into GMS within the *Scatter Point* module. Interpolation was performed using the *Natural Neighbor* (constant) analysis option, and the interpolated data were input into the finite difference grid under the *BCF3* (confined/unconfined) package within the *3D Grid* module.

Current Model Status

The GMS model of the study area currently includes the data layers mentioned above. However, before meaningful estimates of water table elevation and salinity transport can be generated, the model must incorporate the following layers of data:

- Salinity Concentration - Data on surface water have been obtained from the USGS and the NRCS. Additional field measurements of surface water and groundwater TDS concentrations were collected during the summer of 1998. These values will be input into the MT3D model using the GMS interface.
- Recharge and Evapotranspiration Rates - Analysis is currently underway to evaluate data obtained from the Colorado Climate Center. This analysis will yield estimates of aquifer recharge using assumed irrigation efficiencies, as well as estimates of appropriate evapotranspiration rates for evaluation of losses due to upflux from high water tables.
- Pumping Wells - Data have been obtained from the Office of the Colorado State Engineer and are currently being incorporated into the model within the *Map* module of GMS. Data include monthly groundwater pumping quantities for approximately 300 wells within the study reach.
- Subsurface Drainage Rates - Data have been collected from the NRCS on existing subsurface drainage systems in the study area. In the future, these data will be incorporated into the *Map* module of GMS.

The current model operates under a weekly time step. This time period was selected in an attempt to roughly approximate the irrigation interval within the region. Additionally, the data requirements necessary for a shorter time step are not reasonable within existing constraints.

Model Application

The GMS model of the study area will be used to analyze a number of groups of management scenarios. These groups include the following:

- Pumping Wells - Pumping patterns as well as rates will be varied to assess impacts on high water tables and salinity transport.
- Irrigation Efficiency - On-farm water management scenarios will be evaluated to determine regional impacts of improved practices and incorporation of BMP's.
- Cropping Patterns - Shifts in cropping patterns will be analyzed to determine if effects are significant.
- Regional Alternatives - Strategies such as canal lining, drainage installation, and others will be evaluated to estimate regional impacts.

Results obtained from GMS include water table elevation (or depth), return flow quantities, and salinity concentrations of the groundwater and return flows. A sample plot of a generated water table elevation surface using the current model is shown in Figure 7 (Note: This plot is for illustrative purposes only since results have not been verified).

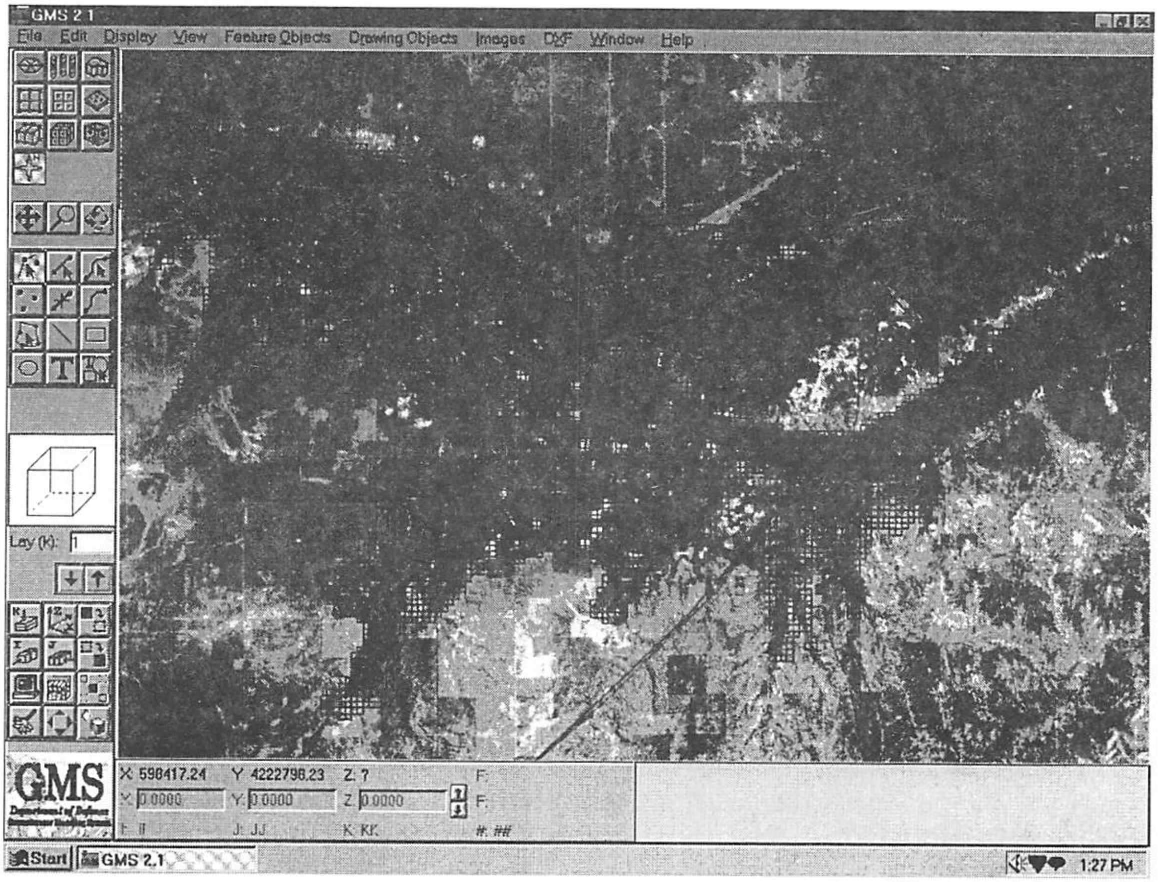

Figure 7. Sample results from GMS model (Water Table Elevation)

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