Field Scale Monitoring and Modeling of Salinity and Waterlogging in the Lower Arkansas River Basin of Colorado

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INTRODUCTION

Salinity and waterlogging pose a great threat to the Lower Arkansas River Valley in southeastern Colorado. Salinity levels in the river range from 300 mg/L as it flows out of the foothills to over 4000 mg/L as it crosses the Colorado-Kansas state line (Malinski, 1990), making it the most saline river for its size in the United States (Valiant, 1995). Water with dissolved solids exceeding 2000 mg/L, which is often considered unsuitable for irrigation, has been used in the valley for years (Miles, 1977). Over 200,000 acres of land in the valley are being irrigated with Class C4 water (greater than 2,250 □mhos/cm), the U.S. Salinity Laboratory's highest classification for salinity hazard (Miles, 1977; USSL, 2000). Miles (1977) estimates that the crop losses in the 200,000 acres of the valley's salt-effected land was $30 million, which would be a conservative estimate if the situation has worsened in the last twenty years.

Salinity problems are not new to the region. The Arkansas River Valley has been irrigated and farmed since the 1870's. Since then salinity and waterlogging problems have become prevalent in the region at various times. Problems first began to surface in the early part of the twentieth century, at which time they were alleviated through the installation of subsurface drains. This remedy has only proven temporary because the salinity and waterlogging problems have returned and intensified over the past thirty years.

The increase in salinity of soils and irrigation waters in the valley has resulted in reduced crop yields, especially for salt-sensitive crops such as beans, onions, and corn. Often farmers turn to more salt-tolerant crops such as grain, sorghum or barley despite the fact that these crops are often less profitable. In the most severe cases, farmers may cease farming the effected land altogether.

A project has been funded by the Colorado Agricultural Experiment Station to obtain and analyze detailed field scale soil, depth to groundwater, salinity of irrigation water, salinity of groundwater and yield data. This information is being used to evaluate the impact of salinity on crop production and impacts on groundwater from agricultural activities. This project combines detailed field investigations and spatial interpolation of data gathered using Geographic Information Systems (GIS). This information is being used to develop maps and animations (a series of maps over time) to show the spatial and temporal variability of field measurements and to develop a model that utilizes GIS to predict relative reductions in crop yield due to salinity and waterlogging at a field-scale.

Location Description

The location of this project is in the Arkansas River Valley in southeastern Colorado. Two regions have been selected: one around La Junta and the other around Holly. In each region five fields have been identified for detailed data gathering and analysis; in some of the fields data has been gathered since 1999.

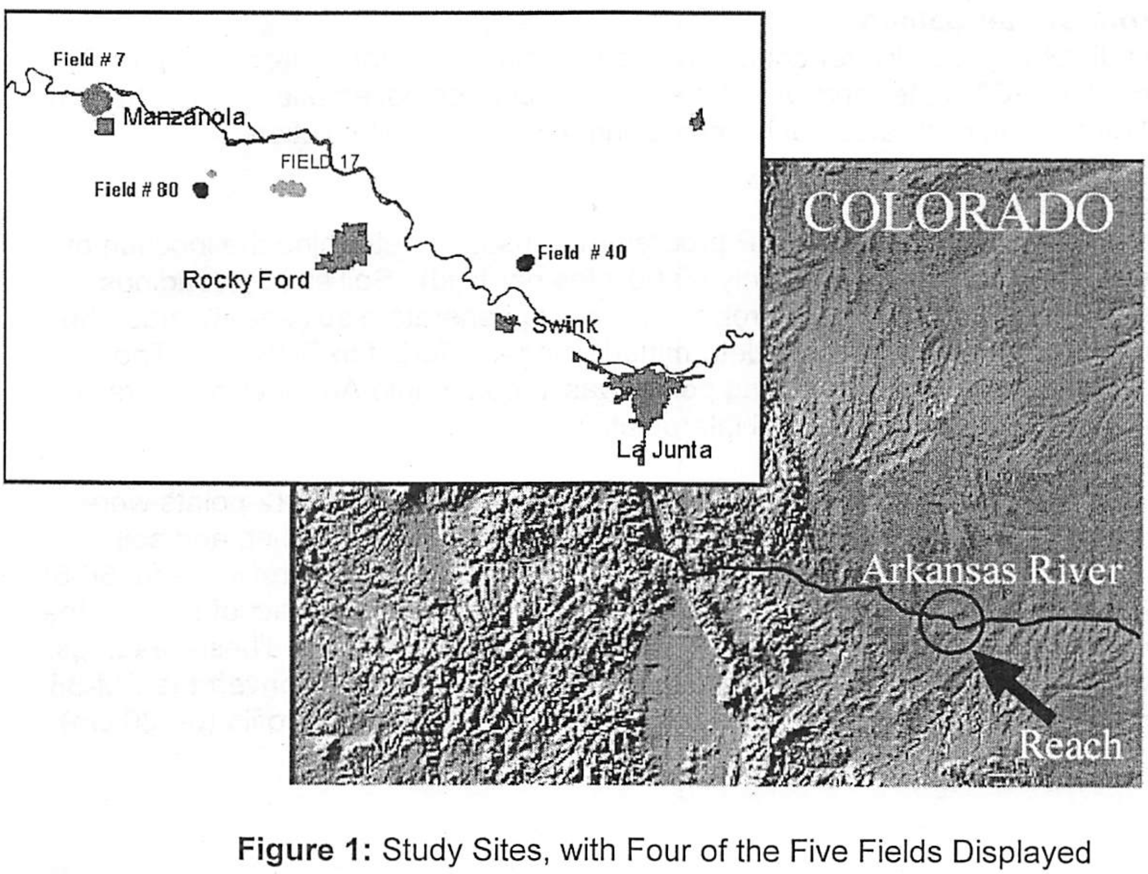

Figure 1: Study Sites, with Four of the Five Fields Displayed

Methods

Groundwater Well Installation

In order to obtain more detailed information about the field scale processes, observation wells with perforated screens were installed in or around each field. Each of the wells was installed and bentonite was applied around the casing. In order to generate maps, the location of each well was determined using a differential GPS unit. The observation wells were installed using a giddings rig provided by the NRCS. The location of the wells was determined in coordination with each of the farmers. Observation wells were installed uniformly within fields, in areas where boundary conditions were expected (next to canals or drains), and in areas of the field where high soil salinity had been determined or was expected.

Depth to Groundwater

Depth to groundwater was measured using a Solinst model 101 water level indicator and were taken at least weekly at each observation well. Automatic level recorders were installed in field 17 in 1999 and in field 80 in 2000. These units measured depth to groundwater instantaneously and were equipped with data loggers to record the water level over the growing season. Instantaneous weekly readings corresponded well to these readings.

Groundwater Salinity

Readings of groundwater conductivity and temperature measured using a YSI Model 30 SCT Meter and were taken weekly at each observation well. The YSI 30 probe was calibrated each week using a standard salt solution.

Soil Salinity

The US Soil Salinity Lab ESAP program was used to determine the location of the soil sampling (approximately 40-60 sites per field). Soil salinity readings were taken using an EM-38 probe. In order to generate a soil salinity map, the location of each sample was determined using a differential GPS unit. The location of each of the sampling points was imported into ArcView, and a raster map was generated by spatial interpolation.

In order to verify the values obtained from the EM-38 probe, 8-12 points were selected in each field. An EM-38 reading was taken at each point, and soil samples were taken at four 30-centimeter intervals in the soil profile (0-30, 30-60, 60-90 and 90-120 cm). The salinity of the saturated paste extract of each of the soil samples was determined using a Hach soil salinity test kit. These readings are being used to modify the calibration equations applied to convert the EM-38 soil salinity readings to real soil salinity values for the full soil profile (0-120 cm).

Precipitation
At each of the selected fields a Davis Rain Collector was installed along with an Onset Hobo Event Logger. This provided detailed (0.2 mm increments) rainfall information that was used to determine the amount of rainfall that occurred in each field as well as the time when the rainfall occurred.

Biomass, Leaf Area Index and Crop Yields
For each of the fields where corn was grown data was collected on the germination rate by counting the number of plants in three areas of the field with low, medium and high salinity. For each area a plant count was conducted in three 10-meter sections of furrow. Every 2-3 weeks 10 plants were collected from each of these areas (high, medium and low salinity) and Leaf Area and Biomass data were collected. At the end of the season crop yields were taken for each field using point sampling (1.5 mts x 1.5 mts) and analyzing the samples in terms of bushels/acre.

A spatial model has been developed that uses the three data layers (soil salinity, depth to water table, and water table salinity) as well as the irrigation schedule to determine the expected crop yield. This model has been calibrated using some of the field data. The description of the model and its results are shown in the next section.

MODEL DEVELOPMENT

Modeling Salinity and Waterlogging Effects

The primary concern in the Arkansas Valley with respect to the waterlogging and salinity problems is the economic losses the region experiences. Therefore, quantifying crop yield reductions due to salinity and waterlogging is essential to understanding the extent of the problem.

Many methods have been developed for determining crop yield losses due to salinity. Simple empirical linear relations between soil salinity and relative yield losses have been developed for most crops (Maas and Hoffman, 1977; Maas, 1986). In contrast, elaborate water and solute movement models predict salt regime given specified irrigation and drainage methods and estimate yield losses from the results (van Genuchten, 1987; Simunek et al., 1998). Given the fact that the simplistic models neglect important factors such as spatial and temporal variability, and that it may be difficult to attain the necessary data to run a complex dynamic model, a model of intermediate complexity may be of practical use.

The model presented in this paper provides a method for quantifying the waterlogging and salinity effects within individual fields. This method utilizes soil and water data commonly collected in field-scale studies. The result is a GIS-integrated model that does not require extraordinary data collection but will provide practical insight into the spatial effects of salinity and waterlogging on crop yields.

General Description

The model developed herein determines relative reductions in crop yield based on spatially and temporally variable soil salinity and depth-to-water-table data, in combination with temporally variable crop, climatic and irrigation data. The model was integrated into the Geographic Information System (GIS) ArcView 3.2. The sections below describe the equations and algorithms applied by the model to an individual cell. The model executes these computations simultaneously for all cells in one raster map. Therefore, the resulting relative yield is a single number for each cell, and when applied in the raster format it creates a spatially correlated image or surface.

The model calculates relative yield based on the amount of water the plant is able to uptake under the given conditions compared to the amount of water the plant would uptake under normal conditions (i.e. no soil salinity or waterlogging). Input includes soil parameters, plant properties, climatic conditions, irrigation timing, water table conditions, and soil salinity levels. This input is used in a water balance approach to calculate the plant water uptake over a period of time.

Soil Hydraulic Properties

Soil properties are estimated based on the predominant type of soil existing in the field to be modeled. Therefore, all soil properties are assumed uniform throughout the root zone over the entire area of the field. The user has a choice 11 different texture classes: sand, loamy sand, sandy loam, loam, silt loam, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay. Based on the selected texture class, hydraulic soil properties are assigned based on empirical data developed in Rawls and Brakensick (1982).

Rooting Depth

The rates of root system extension vary widely from plant to plant. In general, the principal vertical roots of a plant grow at a relatively constant rate until reaching a maximum rooting depth (Kramer, 1983). Therefore, the depth of the root zone, or rooting depth, (L) is a time dependent parameter determined by the initial root length (L_o) at any time t, and a crop specific rate of root growth (RG) in cm/day up to a certain crop-specific maximum root depth (L_{max}).

In actuality, the depth of the root zone can be curtailed by waterlogging. Lieffers and Rothwell (1986) and Boggie (1977) reported that maximum rooting depths were strictly limited by the depth to the water table. When the water table encroaches into the root zone, the roots that are already present in the saturated region suffer from oxygen deficiency (Kramer, 1983). The model developed as part of this research allows the user to specify the relative number of days it takes for roots to die after continuous submergence. The model assumes a rate of necrosis that is proportional to the depth of submerged roots. For example, if it takes 5 days of submergence for the roots of a plant to completely die, and 50 cm of root depth are submerged; the root depth will decrease by 10 centimeters per day of submergence.

Potential Evapotranspiration

The potential evapotranspiration (ET_c) in a field is determined by climatic conditions and by the crop type. The potential evapotranspiration of the planted crop is calculated as the product of a reference evapotranspiration (ET_o) and a crop coefficient (K_{cr}) as shown in Equation 1.

$$ET_c(t) = K_{cr}(t)ET_o(t) \qquad [1]$$

ET_o represents the climatic conditions effecting potential evapotranspiration, and is time dependent. K_{cr} represents the crop specific characteristics affecting the potential evapotranspiration, and is also time dependent. The reference crop ET and crop coefficient must correspond to a single method for calculating the evapotranspiration of the crop (e.g. Blaney-Criddle, Penman, etc.). The total potential transpiration of water by a crop (TP) can be assumed to be equal to the resulting ET_c rate (cm/d) (Cardon and Letey, 1992b).

The evapotranspiration potential is calculated on a daily basis and can be totaled at the end of the simulation, which results in the total possible evapotranspiration (TP_{season}).

The evapotranspiration potential is then distributed throughout the root zone by determining the pattern in which the water is taken up by the plant. Equation 2 gives the depth-dependent, root-water-uptake distribution as developed by van Genuchten (1987).

$$\lambda(z) = \begin{cases} \dfrac{5}{3L} & , \quad z \le 0.2L \\ \dfrac{25}{12L}\left(1-\dfrac{z}{L}\right) & , \quad 0.2L \le z \le L \\ 0 & , \quad z > L \end{cases} \qquad [2]$$

This distribution can be rewritten in terms of incremental depths and applied to the total potential evapotranspiration ($TP(t_i)$) found in Equation 2 to obtain the potential evapotranspiration in any incremental depth ($TP_j(t_i)$).

Water Balance

The soil moisture content is represented as a time and depth variable volumetric content of water, which is typically defined as the ratio of the volume of water in the soil over the total volume of the soil within a control surface. The range of water content that is useful to plants is known as the total available water. Because this model is only concerned with the water available to plants, any water content above field capacity or below the permanent wilting point will be ignored.

A water balance approach is applied to the root zone to estimate the percent of available water distribution in the root zone at any time *t*. Water balance computations are run over the *J* increments of depth covering the effective root zone depth. This water balance is done repeatedly over *I* number of consecutive time increments of one day throughout the duration of the simulation (typically one growing season). Any individual time increment is denoted by the subscript *i*. Figure 2 is a schematic of the water balance approach that is used.

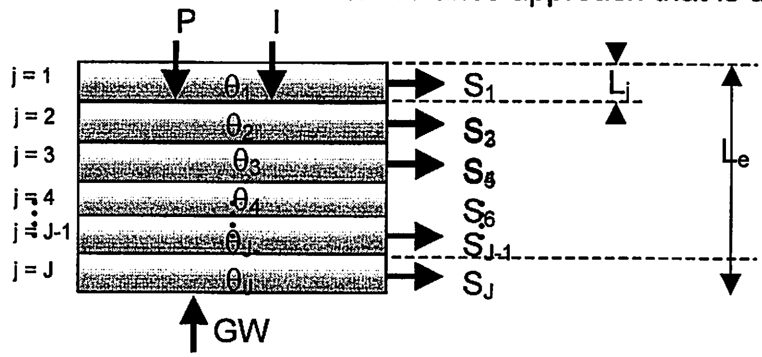

Figure 2. Water Balance Schematic

Water can input into the system in three ways: 1) precipitation (P), 2) irrigation (I), and 3) groundwater inundation (GW). The output is through root extraction, or plant water uptake (S).

Precipitation

If a precipitation event occurs at time t_i, it is input as the total depth ($P(t_i)$) that accumulated during that time increment (one day). This depth is then converted into a volumetric water content relative to the available water holding capacity of a soil depth increment. The total precipitation water content is distributed into the soil increments in a cascading effect starting with the first root zone increment (i.e. the one closest to the surface) , $j = 1$.

Groundwater

After the water table recedes, there is water left behind in the soil layers that were previously saturated. These layers drain only to the point of reaching field capacity, and therefore will have a full available water capacity. The groundwater term for each incremental depth is determined from consecutive effective depths ($L_e(t_i)$ and $L_e(t_{i-1})$) in terms of $J(t_i)$ and $J(t_{i-1})$.

Irrigation

The model assumes that when irrigation water is applied, it is done to the point that the entire root zone reaches field capacity. It is assumed that the entire amount of water applied during irrigation would be applied within a relatively short amount of time (approximately one day). Under this assumption, water applied by irrigation is added as a lump sum at the specified time interval.

Therefore, the only input required for irrigation is the time in which it occurs. The term $I_{time}(t_i)$ is the input that designates an irrigation application for any time t_i.

Matric Potential

Matric potential is the inherent ability of a soil matrix to retain water by absorptive forces, which hold the water around and between soil particles. As water contained in the spaces of the soil matrix decreases, water ebbs into the crevasses between particles and the adsorptive forces become greater. Therefore, as soil water content decreases matric potential increases.

How matric potential changes with soil water content in a natural setting depends on many factors, especially the soil texture. Van Genuchten (1978) developed a model for predicting the relation between matric potential (as pressure head) and soil water content using shape parameters, which are derived from soil properties. Equation 3 gives the van Genuchten relation, and Equations 4 and 5 are parameter relations.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|h|)^n\right]^m} \qquad [3]$$

$$m = 1 - \frac{1}{n} \qquad [4]$$

$$\alpha = \frac{1}{h_b}\left(2^{1/m} - 1\right)^{1-m} \qquad [5]$$

θ = volumetric soil water content, θ_r = residual water content, θ_s = saturated water content (effective porosity), h_b = bubbling pressure (air entry pressure), n = an empirical shape parameter. Values for *n* were empirically derived in Carsel and Parrish (1988) for each of the 11 soil texture classes. The values for *n* are given in Table 3.2 along with the calculated m and α parameters.

An equation to solve for matric pressure head, h, as a function of water content, θ, for different soil texture classes can be derived from equation 3. Therefore, the model calculates the matric pressure head in any incremental unit of depth, j, at any time increment, i, ($h_j(t_i)$) based on Equation 6.

$$h_j(t_i) = \frac{1}{\alpha}\left[\left(\frac{\theta_s - \theta_r}{\theta_j(t_i) - \theta_r}\right)^{1/m} - 1\right]^{1/n} \qquad [6]$$

Soil Water Salinity

Experimentally derived salinity values are expressed in terms of saturated electrical conductivity, which means the soil water content is at saturation. As water content decreases, the salts in the soil water are concentrated. The relation with which salinity (measured as EC_e) increases with decreasing water content is given in Equation 7.

$$\pi = EC_e \frac{\theta_e}{\theta + \theta_{pwp}} \qquad [7]$$

θ_e = is the effective saturation (assumed to be saturation when EC is measured), EC_e = the electrical conductivity of the soil, θ_{pwp} = permanent wilting point water content, and π = salinity of the unsaturated soil (measured in electrical conductivity).

The soil salinity will be averaged throughout the depth of the root zone; therefore, EC_e is only variable with time. Equation 7 can be rewritten to find the soil water salinity for any depth increment *j* at any time t_i:

$$\pi_j(t_i) = EC_e \frac{\theta_e}{\theta_j(t_i) + \theta_{pwp}} \qquad [8]$$

Plant Water Uptake

A relation for water extraction to osmotic and matric pressure potentials in a certain specified depth of soil was developed using work from Cardon and Letey (1992b) and from van Genuchten and Hoffman (1984):

$$S = \frac{TP}{1 + \left(\frac{ah + \pi}{\pi_{50}}\right)^3} \qquad [10]$$

where S = the water extracted by roots (units of depth); TP = the total potential evapotranspiration of the plant (units of depth); π = the level of salinity in the soil water (units of dS/m or MPa); π_{50} = the level of salinity in the soil water (in dS/m or MPa) that produces a 50% reduction in uptake; a = h_{50}/π_{50}, where h_{50} is the ratio of the matric pressure head resulting in a 50% loss in yield; h = matric pressure head, which is a function of water content.

Equation 11 is used to compute the water extraction in any increment *j* of the root zone at any time increment t_i.

$$S_j(t_i) = \frac{TP_j(t_i)}{1 + \left(\frac{ah_j(t_i) + \pi_j(t_i)}{2\pi_{50}}\right)^3} \qquad [11]$$

The salinity terms, $\pi_j(t_i)$ and π_{50}, are calculated and input in terms of electrical conductivity, in units of dS/m. Both are converted to terms of equivalent pressure head in units of cm as estimated for soil conditions in Kramer (1983). The π_{50} term is input as the electrical conductivity of the soil at saturated conditions. In Equation 11 the soil salinity is computed at the actual soil water conditions, which never exceed field capacity. The π_{50} term is multiplied by two as a general rule of thumb to adjust from full soil saturation to field capacity. The total water uptake by the roots at any time t_i can then be calculated by summing the uptake terms over all of the incremental depths.

Relative Yield
Relative yield is the ratio of the actual yield to the maximum potential yield. Doorenbos and Kassam (1979) developed a method to calculate relative yield based on a direct relation to ratio of cumulative water uptake over cumulative potential transpiration (Equation 12).

$$RY = 1 - k + k\left(\frac{\sum_{i=1}^{I} S(t_i)}{\sum_{i=1}^{I} TP(t_i)}\right) \quad [12]$$

The k in Equation 12 is the crop-specific yield response coefficient as given by Doorenbos and Kassam (1979). This coefficient can be adjusted to reflect magnitude of the effects of water stress on a plant.

Model Output

Grids/Surface Plots
After a simulation is complete, three grids are displayed in the same view in which the model was run. The cumulative evapotranspiration and cumulative plant water uptake over the season are displayed as grids in units of cm. Plant water uptake will vary spatially, but potential evapotranspiration will not. The relative yield throughout the area of the field is displayed as a ratio, between zero and one, of the expected yield to the potential yield. If the ratio is 0.0, no yield is expected. If the ratio is 1.0, the full potential yield is expected.

Time-dependent Tables
In addition to the grid output, two tables are output into the "Tables" list of the project. The first table is the "Relative Yield Statistics," which displays the relative yield at each time interval of the simulation averaged over the entire area of the field. This table also contains the maximum relative yield value, the minimum relative yield value, and the standard deviation of the relative yield values. The cumulative potential evapotranspiration and cumulative plant water uptake at each time interval are also displayed in the table. All relative yield values are dimensionless, and the cumulative evapotranspiration and water uptake are in units of cm. Figure 3 gives a simple example of this table.

The second table is the "Root Growth Characteristics" table. This table displays the following rooting depth values for every time interval: maximum rooting depth, potential root zone depth, actual root zone depth, effective root zone depth, and the depth to water table. All of the values are in units of cm. Figure 4 gives an example of how this table may appear.

Relative Yield Statistics

Time	RY Min	RY Max	RY Mean	RY SD	S Mean	TF Mean
5/7/00	1.00000000	1.00000000	1.00000000	0.00000000	0.14135100	0.14135100
5/8/00	1.00000000	1.00000000	1.00000000	0.00000000	0.06400800	0.06400800
5/9/00	1.00000000	1.00000000	1.00000000	0.00000000	0.09715500	0.09715500

Figure 3. Relative Yield Output Table

Root Zone Characteristics

Time	Depth to Water Table	Actual Root Depth	Effective Root Depth	Potential Root Depth
5/7/00	400.000000	200.000000	200.000000	200.000000
5/8/00	400.000000	200.000000	200.000000	200.000000
5/9/00	400.000000	200.000000	200.000000	200.000000

Figure 4. Root Zone Characteristics Output Table

Field 80 Simulation

The model described above was applied to Field 80 using the data collected for the 2000 growing season. The output from the simulation consisted of: 1) a table giving the root zone characteristics over the duration of the simulation; 2) a table with the relative yield statistics for each time interval; and 3) a grid map showing the spatially distributed final relative yield. These results will be discussed and analyzed in the subsequent sections with respect to validating the model.

Root Zone Characteristics

The output table of root zone characteristics contains the daily values of the depth to water table, actual rooting depth, effective rooting depth and potential rooting depth. Because three of these four sets of values are spatially variable, the daily value is a spatial average. The results from Field 80 are plotted over the duration of the simulation as shown in figure 5.

As seen in figure 5, the potential rooting depth increases at a constant rate of 5 cm per day until the maximum depth of 150 cm is reached on the thirtieth day. This is the expected behavior based on the input root growth rate and maximum rooting depth. The effective root depth equals the potential up until the point where the water table rises enough to influence it. At this point the effective root depth follows the rise of the water table, but is actually at a shallower depth due to the capillary rise in the soil. When the water table drops drastically (near June 30th) the effective root depth drops, but only to the point where it reaches the actual root depth. The actual root depth appears to rise at a rate proportional to the depth of submergence and drop at the constant growth rate.

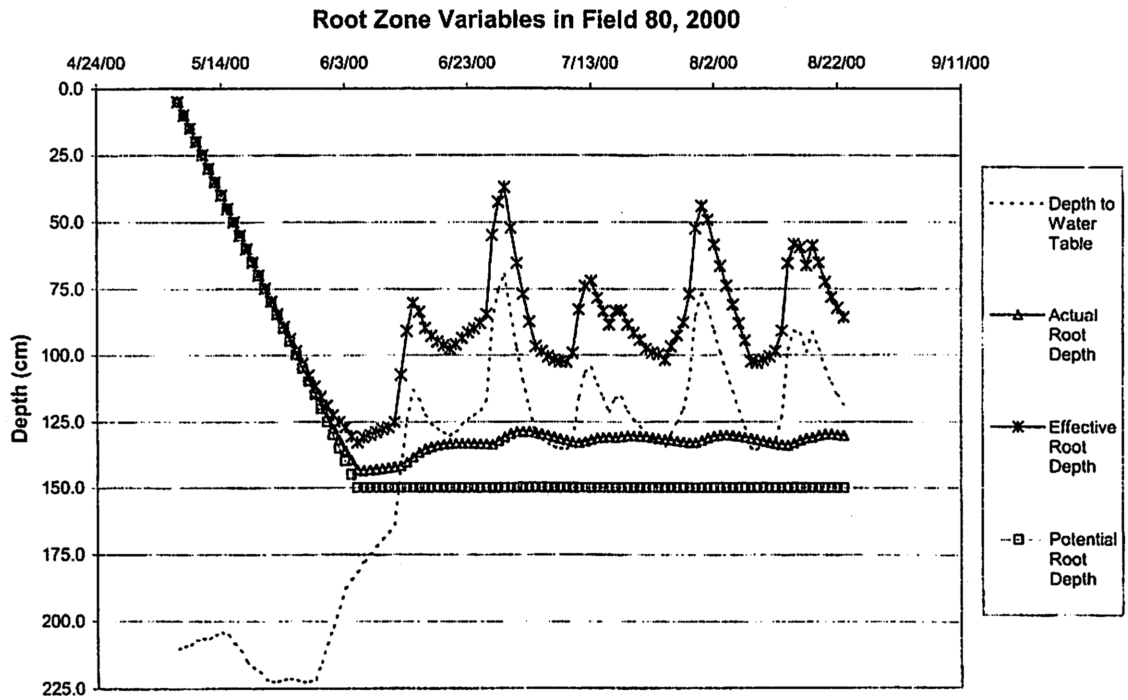

Figure 5. Root zone characteristics for field 80

Relative Yield Statistics

The relative yield statistics table contains the average relative yield for the whole field for each day of the simulation. In figure 6 the cumulative relative yield is plotted along with the change in relative yield over each time interval. The first notable characteristic of figure 6 is the fact that the average relative yield immediately begins at less than 100% (77%). From the first time interval the reduced plant water uptake caused by the existing waterlogging and salinity conditions results in a reduced crop yield. In general, the relative yield continues a downward trend, but the rate of decrease varies greatly as shown in figure 6.

Final Relative Yield

The model produces a final (end of growing season) relative yield map. The map is raster representation (10-meter by 10-meter cell size) of the final yield represented by a graduated color scale. Due to the black and white nature of this publication the final map was not included. The relative yield varied greatly throughout the field, ranging from 25% to 83%.

The relative yield pattern presented on the map is similar to the results from field estimates of crop yield. The model predicted the relative yield for a majority of the field area within 20% and followed the trend observed from the field observations. These results indicate that model may accurately predict the relative in most regions of the field but that there are other factors affecting yield that are not taken into account in the current model (fertilizer, spatial variation of irrigation amount, etc.)

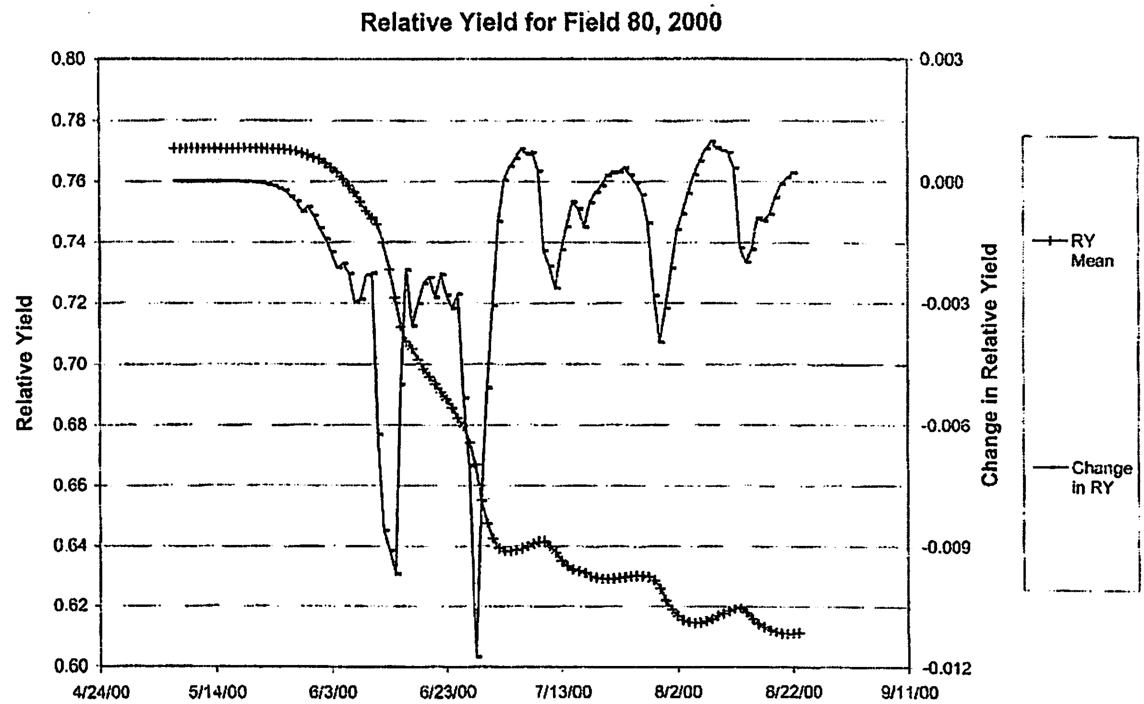

Figure 6. Relative yield statistics for field 80

SUMMARY AND CONCLUSIONS

Salinity and waterlogging is a current and imperative issue for irrigated agriculture throughout the world. The Arkansas River Valley is one region where these concerns have manifested. As a result, concerted valley-wide efforts to ameliorate this growing problem should be enacted. Field 80 is representative of many fields in the Arkansas River Valley. It is effected by salinity and waterlogging problems that degrade the ability of its soil to produce yield. This is evident simply by observation. Detailed data collection and GIS-based modeling can provide more insight into these problems. Results from the 2000 growing season show that Field 80 has areas that only produce 25% of the potential yield for that land while other areas produce in upwards of 80% of the potential yield.

The model presented herein provides a general indication of the impact of spatially and temporally variable waterlogging and salinity on crop yield at the field scale. The model can also be used to evaluate what-if scenarios and quantify the potential impact of different potential corrective actions, which can then be translated directly into economic benefits. Knowledge of economic damages and benefits is an important aspect in decision making when it comes to assessing potential solutions. Model results for several fields will provide insight into how the waterlogging and salinity problems vary from field to field, or crop to crop. In addition, the spatial and temporal aspects of the model will provide insight into the variability of these problems within a single field or a single season. This insight may help to develop more specific and appropriate solutions to the waterlogging and salinity problems at the field scale.