STRATEGIES FOR REGIONAL-SCALE RECOVERY OF A SALINITY-THREATENED IRRIGATED RIVER VALLEY

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ABSTRACT

Two major problems that inherently stem from irrigation practice threaten the vitality of many of today's agricultural regions. Salinity of soils and irrigation water and waterlogging of fields due to high water tables have caused significant adverse socio-economic and large-scale environmental problems worldwide. Currently, at least one-fifth of the total irrigated land in the world is damaged by salinity build-up, and this damage translates to an estimated US$11 billion in reduced farmer income (Postel 1999). In the study presented, an area comprising 26,400 irrigated hectares (65,300 ac) located within the Lower Arkansas River Valley of Colorado, was investigated through intensive data collection over a period of four years to quantify the current salinity and waterlogging crisis in the region. Additionally, utilizing the collected data, a three-dimensional, transient, finite-difference groundwater model was developed, calibrated, and applied to evaluate alternative solution strategies. Considered strategies include improvements in on-farm irrigation practices, upgrading of the irrigation-water-delivery infrastructure (e.g. canal lining), and investment in new surface and sub-surface drainage facilities (e.g. use of pumping wells as vertical drains, installation of horizontal "tile" drains). Predicted effects on water table depth and salinity are presented and discussed.

INTRODUCTION

Early explorers of the American plains noted that the waters of the Arkansas River are affected by a natural salinity source. The Long Expedition noted in 1820 that, "At the mountains the water was transparent and pure, but soon after entering the plains it becomes turbid and brackish" (Long's Journal July 18, 1820). And, in 1845, as part of the Frémont Third Expedition, Lieutenant James William Abert commented on a pool of water found near the present day city of La Junta, Colorado, as being, "…so highly impregnated with common salt and

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sulphate of soda as to be nauseous and bitter to the taste" (Carroll 1941). After irrigation was introduced within the region in the 1870's, saline high water tables began to develop in the early part of the twentieth century (Miles 1977). Since that time, the problems have fluctuated in severity in response to a variety of changes within the river basin. In the 1930's, a large-scale effort to install subsurface clay tile drains achieved some success in easing high water table problems. During the 1950's, installation and operation of a large number of pumping wells penetrating the alluvial aquifer had the indirect effect of maintaining lower groundwater levels.

Recently, however, changes within the Lower Arkansas basin have caused the waterlogging and salinity problems to seemingly worsen. Construction of two major reservoirs (Pueblo and John Martin) has not only allowed a much larger and more consistent supply of irrigation water (and, therefore, caused the overall application amount to increase), but also has changed the sediment transport and peak flow characteristics of the river. Reduced sediment load is suspected of causing a reduction in canal "sealing" and an associated increase in seepage. Additionally, the reduction in peak river flow has caused a gradual aggradation of the river bed which has elevated river levels and reduced the potential return flow drainage gradient from irrigated lands. Also, recent court decisions concerning the Arkansas River Compact between Colorado and Kansas have required that the utilization of existing pumping wells be significantly curtailed. Evidence also exists indicating that much of the subsurface drainage installed in the 1930's is no longer functional. Likely, all of these factors have played some role in the recent intensification of problems in this region.

Description of Study Area

The study area is comprised of approximately 26,400 ha (65,300 ac) of irrigated land within Otero and Bent Counties, Colorado, and stretches along a 62 km (38.5 mi) reach of the Arkansas River (see Figure 1). The western boundary is marked by the town of Manzanola, and the eastern boundary is defined by Adobe Creek. The cultivated crops consist of alfalfa, corn, grass, sorghum, wheat, melons, onions, and various other vegetables (FSA 2001). The prominent irrigation system employed is open-ditch furrow irrigation, although there are a significant number of farms now using gated pipe in lieu of the traditional open-ditch and siphon tube technique. The number of center pivot sprinkler and drip irrigation systems is still very small. Soils in the area are principally alluvial deposits dominated by silty-clay-loam surface layers and loam-to-sandy loam substrata (USDA 1972a, 1972b).

DATA COLLECTION AND ANALYSIS

Data collection began in 1998 in a limited fashion, with soil salinity being the only property investigated with intensity. By April, 1999, however, a rigorous data collection program was developed and initiated. Included in this program is the monitoring of water table depth and salinity, soil salinity and surface water salinity, as well as estimation of hydraulic conductivity through slug tests and topographic surveys of land and water features using GPS technology. This program is on-going; however, only data collected through 2001 are presented.

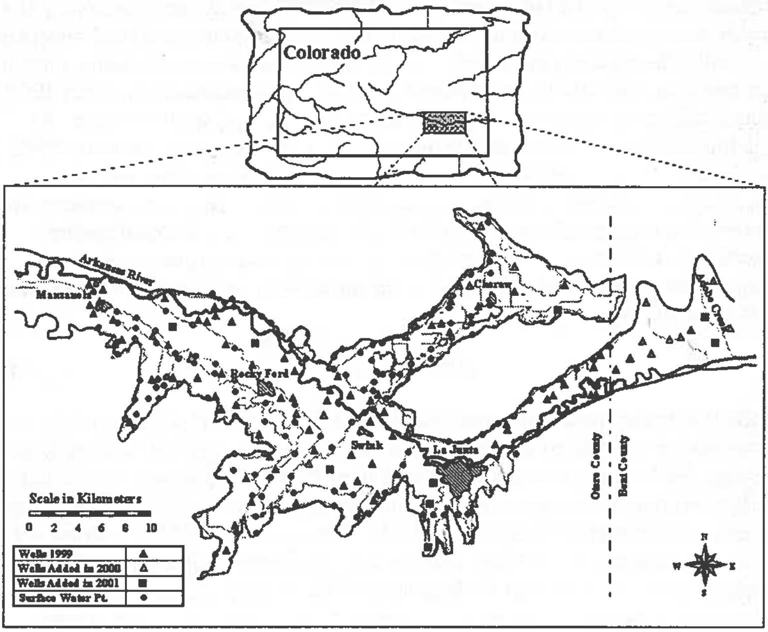

Figure 1. Study subregion located in the Lower Arkansas Valley, Colorado.

Data Collection Program

Initially, a total of 74 monitoring wells were utilized for collection of water table depth and salinity data (see Figure 1, "Wells 1999"). Of these 74 wells, 69 were installed as part of the program, and 5 were adopted from previous studies. Observation sites were selected using a stratified random sampling technique (Cressie 1991) to minimize any bias in well placement; although, a few wells were specifically placed near the eastern and western boundaries, and a few randomly selected sites were moved slightly to accommodate farmer preferences. Wells were cased using screened PVC pipe with an inside diameter of 6.4 cm (2.5 in), and, initially, were drilled to a depth of 3.05 m (10.0 ft). In 2000, 21 of the wells were deepened to a depth of 7.0 m (23.0 ft), and 23 additional wells ranging in depth from 3.05 to 7.0 m (10.0 to 23.0 ft) were installed (see Figure 1, "Wells added in 2000"). In 2001, nine more wells were added in locations specifically targeted to increase data density where needed (see Figure 1, "Wells added in 2001").

Measurements of water table depth and salinity are taken at each monitoring site weekly during the peak irrigation season (May through September) and biweekly to monthly during non-peak times. Depths are measured manually using a metal tape and float, and salinity is measured indirectly as electrical conductivity (EC) using a calibrated, temperature-compensating specific conductance meter. At each monitoring site, three measurements of EC (one just below the water table level, one at an intermediate depth, and one near the bottom of the well) are recorded and averaged to obtain a representative value. These measurements are converted to total dissolved solids (TDS), i.e. salinity, using the relationship described in equation (1). This relationship was derived from analysis of groundwater samples collected at 17 of the monitoring wells in 1999 and reflects an r^2 value of 0.98.

$$TDS = 882.2EC \tag{1}$$

In addition to the weekly monitoring of water table depth and salinity, a key component of the data collection program is the monitoring of soil salinity twice per year. Soil salinity to a depth of near 1.0 m (3.28 ft) is estimated at selected fields (corresponding to groundwater monitoring sites) utilizing electromagnetic induction techniques (Rhoades et al. 1999). Four Geonics™ EM38 instruments are used to measure 30 – 90 locations per monitoring site, depending on field size. Readings are taken once near the beginning of the irrigation season (late May) and once near the end of the irrigation season (late August). The approximate data density within a field is one point (including both vertical and horizontal instrument positioning) per 0.10 ha (0.25 ac). Measured values are converted to bulk soil salinity and soil extract salinity for modeling and analysis purposes using relationships developed by Rhoades et al. (1989). These relationships have been generally confirmed through the collection and analysis of soil samples from numerous monitoring sites (Cardon 2002).

Another component of the data collection program is the monitoring of surface water salinity. Like the groundwater measurements, salinity is measured indirectly by the measurement of EC using a conductance meter at 163 monitoring points (see Figure 1, "Surface Water Pt."). A relationship between EC and TDS with an r^2 value of 0.97 was derived from the analysis of 28 surface water samples. This relationship is shown below in Equation (2) and was used in all surface water EC-TDS conversions.

$$TDS = 1479.2EC^{0.668} - 617.8 \tag{2}$$

Additional data collection program activities include performing slug tests (Chin 2000) at each monitoring well to estimate hydraulic conductivity, as well as the surveying of land and water surface elevations using multiple GPS receivers

(Trimble 4600LS and Ashtech Locus systems) and differential correction techniques accurate up to ±0.03 m (0.1 ft). Also, numerous river, tributary, and canal cross-sections have been surveyed from bridges using a measuring tape and depth probe, and a separately funded study on seepage from the Fort Lyon Canal was performed in 2001.

Current Findings

Data obtained through the data collection program, as well as data gathered from outside sources, were used to describe and assess the current conditions within the study subregion. The following is a brief summary of the findings.

Water Table Depth and Salinity: A few important statistics which have been compiled from the collected water table depth and salinity data are shown in Table 1. These particular statistics are shown because they serve nicely as indicators of the general condition of the study subregion. A more detailed statistical analysis has been performed, but is not presented here due to space constraints (see Gates et al. 2002).

Table 1. Summary of Collected Water Table (WT) Depth and Salinity Data

Year	*Avg. # of Wells Read per Week*	*Seasonal Avg. WT Depth (m)*	*Est. % of Area with WT Depth < 1.5 m*	*Seasonal Avg. WT Salinity (mg/l)*	*Est. % of Area with WT Salinity > 2000*
1999	69	2.14	25	3117	27
2000	90	2.48	19	2850	33
2001	96	2.69	18	2706	48

The values presented above represent both spatial and temporal averaging. Spatial averaging was achieved by interpolating across the study area between data points using the inverse distance weighted (IDW) method (Shepard 1968). The values shown reflect "seasonal" conditions, i.e. the conditions which occur during the main growing season (April through October). Data collected between November through March was not included in the calculation of the statistics shown since this time period is less critical from an agricultural standpoint. These off-season months are, however, included in the numerical modeling. It should also be noted that the salinity data presented represents only the upper layer of the aquifer which is penetrated by the monitoring wells – the deep aquifer characteristics are likely quite different.

The data conclusively reveal that large portions of the study region are subjected to waterlogged conditions, with some areas exposed to very high groundwater salinity. Specific areas identified from the data collection as having particularly acute waterlogging problems are the Patterson Hollow area west of Rocky Ford, an area directly south of the town of Swink, the area surrounding the town of Cheraw, and an area just east of North La Junta along the Fort Lyon canal. Areas showing high levels of groundwater salinity are an area directly west of Rocky Ford, the Holbrook Reservoir area, the Cheraw Lake area, and the La Junta area.

Interestingly, the seasonal average water table depth has increased (i.e. the water table has lowered) in each of the study years. This trend is likely a result of water table response to reduced aquifer recharge stemming from decreased irrigation water supply and diversions. Over the course of the study, the Rocky Ford Weather Station (#057167) has reported seasonal (April – Oct.) total precipitation amounts of 30.38 cm (11.96 in) in 1998, 46.63 cm (18.36 in) in 1999, 17.04 cm (6.71 in) in 2000, and 24.41 cm (9.61 in) in 2001 (NCDC 2002). State engineer diversion records support this theory. Seasonal average water table salinity also decreased each study year. A possible explanation of this observation is, because of the decrease in overall aquifer volume, there was a lowering of overall salinity due to a decrease in dissolution of native salts from salt-bearing soil layers (which are derived from marine shales) (Zielinski et al. 1995).

Soil Salinity: Results of the soil salinity monitoring are shown in Table 2. Values are shown in terms of soil saturation extract electrical conductivity (EC_e) and represent spatial averages using IDW interpolation.

Table 2. Summary of Soil Salinity Monitoring Data

Year	*# of Fields Monitored*	*Early Season Avg. EC_e (dS/m)*	*Late Season Avg. EC_e (dS/m)*	*Est. % of Study Area with Avg. $EC_e > 2.0$*
1998	30	2.3	3.1	NA
1999	68	2.6	2.9	80
2000	77	2.4	2.0	69
2001	80	2.8	2.5	69

The data show a seasonal increase in average soil salinity during the "wet" study years (1998 and 1999); conversely, a decrease occurs in the "dry" years (2000 and 2001). Likely, this pattern is due to a greater upflux of salts through high water tables and less potential for leaching during 1998 and 1999, with less salt upflux and greater leaching occurring in 2000 and 2001.

Surface Water Salinity: Table 3 summarizes the average salinity (shown in terms of EC) for the Arkansas River and the six main canals for each study year. The values are reflective of the dilution that takes place in higher water supply years (such as 1999). Although only overall averages (spatial and temporal) are shown, it should be noted that the spatial variability in each watercourse was significant, with salinity levels increasing downstream in all cases. Major surface

Table 3. Summary of Surface Water Salinity Data in dS/m

Year	*Arkansas River*	*Rocky Ford Canal*	*Catlin Canal*	*Otero Canal*	*Rocky Ford Highline Canal*	*Holbrook Canal*	*Fort Lyon Canal*
1999	0.97	1.05	0.88	1.35	0.70	0.80	1.00
2000	1.33	1.06	0.93	1.48	0.84	1.04	1.35
2001	1.19	1.00	0.91	1.35	0.77	0.97	1.18

drains were also monitored and yielded an overall seasonal average EC of 2.61 dS/m in 1999, 3.19 dS/m in 2000, and 3.10 dS/m in 2001. Additionally, three major storage facilities were monitored. The Fort Lyon Storage Canal had a seasonal average EC of 1.89 dS/m in 1999, 2.03 dS/m in 2000, and 1.91 dS/m in 2001. Holbrook Reservoir was found to have a season average EC of 1.31 dS/m in 1999, 1.66 dS/m in 2000, and 1.32 dS/m in 2001, and Cheraw Lake, which receives drainage from the northern portion of the study area, had a seasonal average EC of 13.87 dS/m in 1999, 13.27 dS/m in 2000, and 15.06 dS/m in 2001.

Additional Items: Analysis of collected data, as well as diversion records obtained from the State Engineer's Office and data from the Colorado Climate Center, has indicated that existing irrigation efficiencies range from 30 to 50% over the study subregion. Slug tests were performed at 95 of the monitoring well sites, and analysis has yielded estimates of hydraulic conductivity from 0.003 m/day (0.01 ft/day) to 10.24 m/day (33.60 ft/day) in the upper aquifer layer. Seepage tests have indicated that conveyance losses are approximately 0.25 % (of total flow diversion) per km (0.40 % per mi) to 0.33 % per km (0.53 % per mi); however, to date, only the Fort Lyon Canal has been tested.

MODELING

Numerical modeling of potential solution strategies was performed utilizing MODFLOW (McDonald and Harbough 1988) to simulate groundwater flow and MT3DMS (Zheng and Wang 1999) to simulate salinity transport. A graphical user interface known as the Groundwater Modeling System (GMS), version 3.1 (BYU 1999), was used in initial model development and in the analysis of model output. The applied models use finite-difference techniques to approximate the governing non-linear flow and mass-transport partial differential equations. The study area is represented by a three-dimensional grid containing 16,188 active cells. These cells have a uniform X-Y dimension of 250 m (820 ft) and vary in cell height depending upon aquifer thickness. The aquifer is represented by two layers of cells: the top layer represents the shallow, low-permeability portion of the aquifer which contains the root zone, and the bottom layer represents the deeper, higher-permeability portion of the aquifer which lies between the root zone and the confining bedrock. Surface features including field boundaries, the river, tributaries, irrigation canals, pumping wells, and reservoirs were digitized within the GMS interface (or digital representations were imported into the interface) which translated the associated input data into the correct MODFLOW and MT3DMS format. This conceptual model, along with the finite-difference grid, is shown in Figure 2.

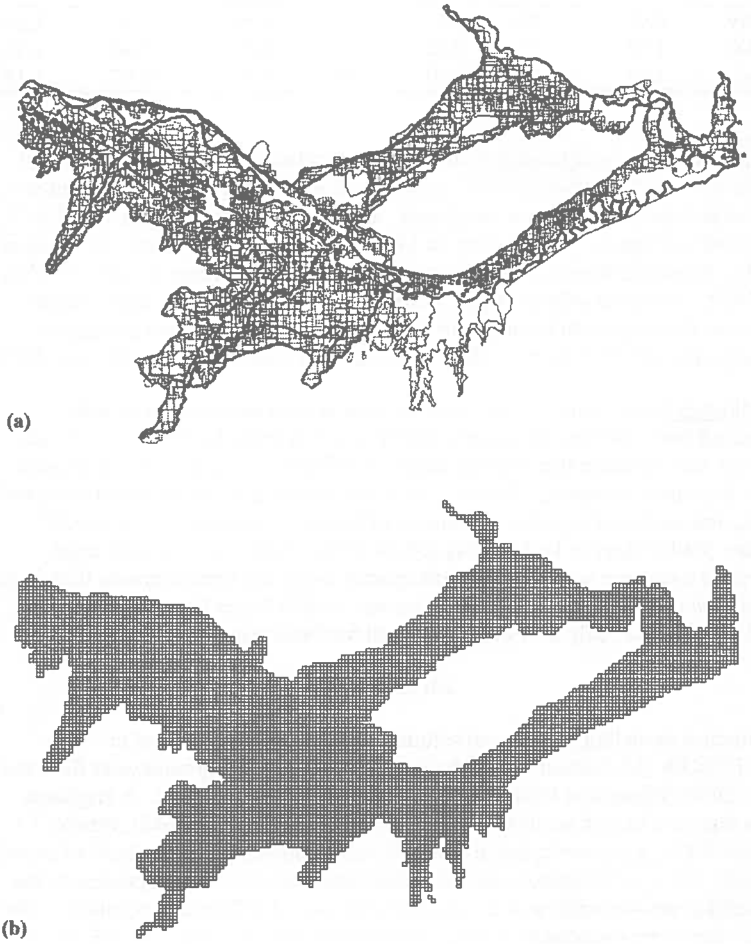

Figure 2. (a) Conceptual model of study area; (b) Finite-difference grid

Both the MODFLOW and MT3DMS models simulate time-varied changes using a weekly time step. The modeled time period (April 1999 – Oct. 2001) includes a total of 133 time steps. The source-sink modeling packages utilized in the MODFLOW model include the *General Head*, *River*, *Well*, *Evapotranspiration (ET)*, *Recharge*, *Time-Variant Specified Head*, and *Drainage* packages. The preconditioned conjugate-gradient (PCG2) method was selected for flow calculations within MODFLOW. Within MT3DMS, the *Advection* and *Source/Sink Mixing* packages were utilized along with the third-order total-variation-diminishing (TVD) solution method to simulate the system solute flux and advective transport. To support this modeling, numerous collected data sets, along with data obtained from outside sources, were incorporated into the model or used for model calibration and verification. The model data sets are summarized in Table 4.

The MODFLOW model was calibrated to within a mean absolute elevation error of 1.0 m (3.28 ft) and an overall mean elevation error of 0.2 m (0.66 ft) using the collected 1999 data on groundwater elevation by adjusting the more uncertain parameters such as hydraulic conductivity and canal seepage (which is controlled by assigned conductance values in the *General Head* package). Values for these parameters were constrained within a range known by data collection and analysis as actually occurring within the study region. Additionally, model-calculated return flows for the river and its tributaries were compared to existing streamflow gaging data to insure that the model represents realistic behavior.

The MT3DMS model was adjusted to replicate the observed groundwater salinity data; however, because the contribution of salts from salt-bearing soil layers has not been investigated to the extent required for quantification and incorporation in the model, there is a significant degree of uncertainty inherent in modeled salinity input. Still, the solute-transport model is extremely useful for the purposes of examining solutions strategies on a comparative basis.

Weekly-varied recharge values for each field polygon were estimated based on the following factors: annual crop type data obtained from the Farm Service Agency (FSA); estimated crop ET requirements; a randomly-assigned, unique application efficiency selected from a truncated normal distribution with a mean equal to the overall canal command area irrigation efficiency (minimum cutoff = 0.15, maximum cutoff = 0.85, standard deviation = 0.2); irrigation frequency (dependent upon crop type); irrigation schedule (randomly assigned); deep-percolation fraction (based on Walter 1995); and effective precipitation. The equation used for recharge estimation for each field polygon for time step *t* is as follows:

$$\left[Q_R = DP(1 - E_A)(Q_{ET} - Q_P)\right]_t \tag{3}$$

Table 4. Model data set summary

Data Set	*Source*	*Use/Model Package*
Ground Elevation	USGS, GPS surveying	Block-Centered Flow
Bedrock Elevation	Weist '62, Major et.al '72	Block-Centered Flow
Shallow Hydraulic Cond.	Data Collection Program	Block-Centered Flow
Deep Hydraulic Cond.	Wilson '65	Block-Centered Flow
Crop Evapotranspiration	Farm Service Agency, Colorado Climate Center, CropFlex98 calculations (Broner and Lorenz 1998)	Recharge calculations, ET Package
Effective Precipitation	National Climatic Data Center	Recharge calculations
Aquifer Recharge	Calculated using estimated efficiency and leaching fraction	Recharge Package
Pumping	State Engineer's Office	Well Package
Seepage (Conductance)	Data Collection Program	General Head Package
Salinity	Data Collection Program	Source/Sink Mixing
Surface Water Levels	GPS surveying	General Head, River
Specified Head	Data Collection Program	Time-Variant Specified Head Package
Specific Yield/Porosity	USDA '72, Data Collection Program	Block-Centered Flow, Advection Package

where Q_R = recharge estimate (m), DP = deep-percolation fraction, E_A = application efficiency, Q_{ET} = evapotranspiration estimate (m), and Q_P = effective precipitation (m).

Modeled Scenarios

Six separate scenarios were modeled to investigate effects of various solution strategies. Scenarios were formulated in an attempt to represent realistic strategies which might be employed on a regional scale. They are as follows:

Scenario 1: *Baseline Conditions.* This is the baseline scenario which simulates actual conditions measured during the data collection program. This scenario is used to evaluate the comparative effects of changes to the system as modeled in the five other scenarios.

Scenario 2: *Reduce Recharge Rates by 25%.* This scenario simulates the impacts of uniformly increasing application efficiencies over the entire study region so that recharge rates are reduced by 25%.

Scenario 3: *Increase Pumping Rates by 50%.* This scenario examines the effects of increasing the pumping rates of currently active wells within the study region by 50%. Additional flow is assumed to by routed directly into nearby surface drains which flow back to the river.

Scenario 4: *25% Reduction in Canal Seepage.* This scenario models the aquifer response to reducing canal seepage through structural improvements or otherwise in all canals by 25%.

Scenario 5: *Subsurface Drainage Installed over 25% of Waterlogged Area.* In this scenario, it is assumed that effective subsurface drainage is installed in 25% of all fields which are waterlogged (i.e. the water table depth is less than 1.5 m). These fields were randomly selected, and it was assumed that "effective" subsurface drainage would lower the water table to a depth greater than 1.5 m (4.9 ft).

Scenario 6: *Combination of Scenarios 2 and 5*: This scenario explores the impacts of reducing recharge rates by 25% (Scenario 2) while simultaneously maintaining effective subsurface drainage over 25% of the currently waterlogged area (Scenario 5).

Modeling Results

The results of the modeling runs are summarized in Table 5. These results indicate that the current situation, although serious, is recoverable. As expected, Scenario 6 offers the most widespread benefits in reducing waterlogging problems; however, all modeled solution strategies yielded a net decrease in waterlogged area. The results of the preliminary salinity modeling were inconclusive (i.e. no significant changes in water table salinity were predicted). Model improvements are needed which will address uncertainty and which will extend the modeled time period to include a long planning horizon.

Table 5. Summary of Modeling Results

Performance Indicator	*Scen. No. 1*	*Scen. No. 2*	*Scen. No. 3*	*Scen. No. 4*	*Scen. No. 5*	*Scen. No. 6*
Predicted Seasonal Reduct. in WT Elev. (m)						
1999	NA	0.142	0.008	0.015	0.206	0.268
2000	NA	0.592	0.123	0.299	0.138	0.308
2001	NA	0.460	0.022	0.056	-	0.101
Predicted % of Area with WT Depth < 1.5 m						
1999	19.1	16.9	18.8	18.4	17.6	15.7
2000	13.1	11.5	12.9	11.6	12.0	10.9
2001	11.5	10.5	11.5	10.2	10.7	9.7

CONCLUSIONS AND FUTURE WORK

The on-going comprehensive data collection program has revealed a subregion whose agricultural productivity is currently hampered by significant waterlogging and salinity problems. If strategies are not employed to alter the current conditions, the future economic vitality of the area will be in jeopardy. Modeling indicates that regional-scale solutions do exist and can have very significant effects. These effects are amplified when strategies involve multiple approaches to reducing aquifer recharge or to artificially lower water table levels through subsurface drainage or increased pumping. Further study of more detailed solution strategies and further refinement of the existing models (including stochastic modeling of uncertain parameters) will continue, and should yield solid evidence upon which the best solutions can be formulated and implemented. Specifically, work is underway at Colorado State University to develop detailed unsaturated zone modeling of fields within the study area. This work will give insight into the impacts that solution strategies will have on soil salinity, and, therefore, on actual crop productivity. Also, studies are underway to examine the overall economic viability of regional-scale solutions. In concert, these studies should allow for informed planning which will insure the sustainability of the Lower Arkansas Valley's agricultural productivity and protect the livelihood of its rural communities.

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