Toward Optimal Water Management in Colorado's Lower Arkansas River Valley:

Monitoring and Modeling to Enhance Agriculture and Environment

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For several years, Colorado State University has been documenting flow and water quality conditions in Colorado's Lower Arkansas River Valley with the goal of providing data and models that water users and managers can use to enhance both agriculture and the environment in the Valley. Extensive measurements are being made in the field, and some previously gathered data are still undergoing analysis. Models of the irrigated stream-aquifer system are under development, calibration, and refinement. Potential strategies for improving conditions in the river valley are being formulated and investigated. Small-scale pilot testing of solutions are scheduled to begin during the summer of 2006.

The results presented in this technical report are published as a benchmark to document completion of the first phase of this work. They also provide broad information in support of current decision making in the river valley and hopefully will stimulate feedback and discussion. Some of the information presented here is provisional since it is still undergoing refinement and expansion; hence, this document is made available in *pdf* format on the worldwide web at *CSUArkRiver.colostate.edu* and will be updated periodically. Portions of the detailed database and modeling tools also will be made accessible at this website.

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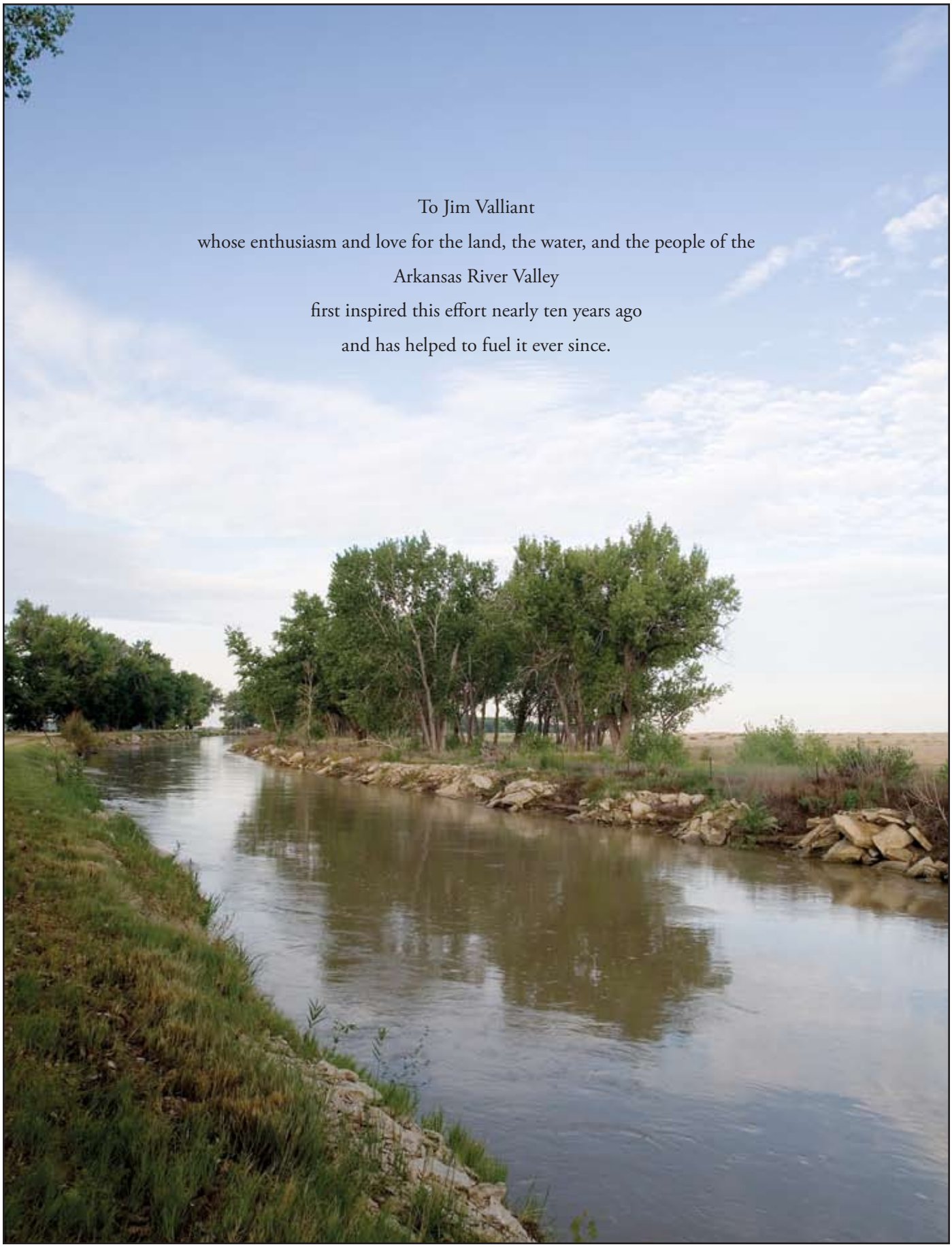
Cover Photo (left):
Courtesy of *Pueblo Chieftain.*



To Jim Valliant
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Arkansas River Valley
first inspired this effort nearly ten years ago
and has helped to fuel it ever since.

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Extensive field data and modeling tools are being developed and incorporated into a decision-making framework that focuses on meeting multiple criteria:

1. maximize the net economic benefits to agricultural production via reduction in salinity and waterlogging;
2. minimize salt and Se concentrations in the river at key locations, including the Colorado-Kansas state line; and
3. maximize "liberated" water via reduction in nonbeneficial consumptive use from high water tables under fallow alluvial land and from invasive phreatophyte vegetation (Tamarisks) along the river corridor.

Executive Summary

The Arkansas River has long sustained a belt of valuable agricultural production, an appealing rural lifestyle, and scenic vistas across Colorado's southeastern high plains. Now, it seems that without sound and timely intervention, the Lower Arkansas River Valley eventually may succumb to the ill effects of shallow ground water tables (waterlogging), excessive salt buildup, and high selenium (Se) concentrations, both on the land and in the larger river ecosystem. Options for mitigating these problems, that are based upon an accurate knowledge of field conditions and that comply with legal and economic constraints, are needed to ensure sustainability of the Valley's productive agricultural base, to preserve and revitalize its rural communities, and to enhance the overall river environment.

This document describes results of the first phase of on-going research by Colorado State University that seeks to develop insight into the current water-related problems and to identify promising solution strategies for consideration by water managers and users in deciding how to best meet the needs of the Lower Arkansas River Valley. Extensive field data and modeling tools are being developed and incorporated into a decision-making framework that focuses on meeting multiple criteria: (1) maximize the net economic benefits to agricultural production via reduction in salinity and waterlogging; (2) minimize salt and Se concentrations in the river at key locations, including the Colorado-Kansas state line; and (3) maximize "liberated" water via reduction in nonbeneficial consumptive use from high water tables under fallow alluvial land and from invasive phreatophyte vegetation (Tamarisks) along the river corridor.

Field data and calibrated flow and salt transport models are being used to characterize the spatial and temporal patterns of salinity and waterlogging along the Valley. Since 1999, field data have been measured or gathered on river flow and salinity, reservoir storage and releases, irrigation diversions and efficiencies, canal flow and salinity, drain and tributary flow and salinity, canal seepage, physical properties of soils, aquifer characteristics, water table depth and salinity, irrigation methods, soil salinity, crops and crop yield, climate and crop water use, return flows and salt loads to the river and tributaries, and Se and iron (Fe) concentrations in ground water and surface waters. Over the three irrigation seasons within 1999 – 2001, average seasonal aquifer recharge from irrigated fields in a 50,600 ha (125,000 ac) study area, upstream of John Martin Reservoir, ranged from 0.59 to 0.99 m (1.9 to 3.2 ft), including contribution from precipitation. Salinity of irrigation water varied from 531 to 1331 mg/L over the period 1999 – 2004. Over the irrigation seasons within 1999 – 2001, the water table was found to be quite shallow below much of the area, with 32 to 43% of irrigated land underlain by an average water table less than 2.5 m (8.2 ft) deep. Preliminary findings indicate average water table depth less than 2.5 m (8.2 ft) beneath 27% and 30% of the irrigated land in 2002 and 2003. Average water table salinity measured in monitoring wells ranged from 2,100 to 4,000 mg/L over the period April 1999 – June 2005. Average soil water salinity was moderate to high, ranging from about 2,800 to 4,200 mg/L. Regional average relative crop yield reductions from salinity and waterlogging were estimated to range from 11 to 19 percentage points over the period 1999 – 2001.

Upflux from shallow water tables under fallow ground in the Upstream Study Region was estimated to contribute to about 65 million m^3 (52,600 ac-ft) per year of nonbeneficial consumption during 1999 – 2001. Considering additional water extractions by invasive Tamarisks along the river banks, indications are that a substantial volume of water loss is occurring that might be recouped for the benefit of the Basin.

Field studies in a second study region, a 55,200-ha (136,300 ac) area downstream of John Martin Reservoir, began in 2002. Regional average water table depth measured in monitoring wells ranged from 2.83 m to 4.47 m over the period April 2002 – June 2005. Albeit during a drought period, the water table in 2002 and 2003 was found to be less than 2.5 m (8.2 ft) deep under about 30% of the cultivated area. The regional average water table salinity ranged from about 3,100 mg/L to 4,700 mg/L over the period April 2002 – June 2005. Measured irrigation water salinity ranged from about 800 mg/L to 3,400 mg/L. Surveys conducted during the irrigation seasons within 2002 – 2005 indicated an average soil water salinity ranging from 4,800 to 5,600 mg/L over the study region, contributing to substantial losses in crop yield.

Not only have soils and crops throughout the Valley been degraded by waterlogging and salinity buildup, but river water quality also has been diminished. Annual salt loading to the river from subsurface return flows, generated in large part by dissolution from irrigation recharge and canal seepage, averaged about 276 kg per ha (irrigated and nonirrigated) per km along the river (396 lb per acre per mile) in the Upstream Study Region over the period 1999 – 2001. Increasing Se concentration in the river and its tributaries, derived both from natural and from irrigation-induced return flows, also has become a major concern. Investigations in the Downstream Study Region revealed Se concentrations that exceeded the Colorado standard of 4.6 µg/L in all but two of 105 samples gathered at six river locations over the period April 2003 – July 2005. The average concentration of river samples was 9.4 µg/L, while that of 749 samples gathered from 54 monitoring wells over the same period was 16 µg/L. Preliminary estimates suggest a Se loading rate of about 1,000 kg/year (2,200 lb/year) from tributary drainages and from the alluvial aquifer to the 60-km (37-mile) stretch of the river within the study region.

Beyond problem identification, a database and models being developed by this on-going research provide a basis for effectively addressing these problems through a systematic and comparative assessment of alternative solutions. Interventions that are being considered for adoption within multiple subregions of the Valley fall into the following classes: reduction of recharge from field irrigation, seepage reduction from canals, improved drainage options, lowering the water surface elevation along the river, and phreatophyte removal along the river corridor. To date, a total of 38 solution alternatives incorporating varying degrees of recharge reduction, canal seepage reduction, subsurface drainage installation, and pumping volume increases have been modeled for the Upstream Study Region over the historical period 1999 – 2001. Six performance indicators were used to evaluate the effectiveness of these alternatives in improving agroecological conditions, compared to existing baseline conditions. Average regional increase in water table depth [as much as 1.8 m (5.9 ft) over the irrigation season] was predicted for selected alternatives, as well as the spatial mapping of results for the different solution alternatives. Decreases in soil water salinity concentration (with regional and seasonal average reductions as much as 600 mg/L) also have been predicted and mapped. Estimated ground water salinity changes, reduction in total salt loading to the river (by as much as 40%), increase in average regional relative crop yield (by up to 10 percentage points), and changes in net water consumption indicate the potential for marked regional-scale enhancement to the irrigated stream-aquifer system.

Efforts are continuing toward gaining further insight into options available to water managers and users, from which the best solutions for the entire river valley can be selected. Databases and models are being refined and expanded, working toward a comprehensive set of tools that will support wise water management decisions, not only at the field and regional levels, but also at the overall river-basin scale. The most promising improvement strategies will be publicized, and improvement efforts that already have begun in the field will be used for preliminary assessment of the field-practicality of proposed strategies and to serve as demonstrations of their feasibility and potential. An adaptive modeling process will be used to engage stakeholders in understanding the problems and solution options and in defining the best solution strategies based upon calibrated model predictions, refined also by field assessments and demonstrations. As a result of this process, a full-scale pilot program will then be designed to allow the most promising solution strategies to be evaluated within representative canal command areas. In conducting the assessment, consideration will be given to incentives to adopt new water management practices, benefit and cost analysis of various proposed strategies, organizational issues affecting proposed strategies, and constraints related to financing options, Colorado water rights, river operations, and interstate compact issues between Colorado and Kansas.

Interventions that are being considered for adoption within multiple subregions of the Valley fall into the following classes:

- reduction of recharge from field irrigation,
- seepage reduction from canals,
- improved drainage options,
- lowering the water surface elevation along the river, and
- phreatophyte removal along the river corridor.

Introduction

Vast canal systems, made up of more than 1,000 miles of channels, have diverted and distributed the waters of the Arkansas River to the fertile alluvial soils.

BACKGROUND AND PROBLEM STATEMENT

For more than a hundred years, vast canal systems, made up of more than 1,000 miles of channels, have diverted and distributed the waters of the Arkansas River to the fertile alluvial soils in southeastern Colorado (Figure 1). Irrigation has made possible productive agricultural economies and scenic rural landscapes in the Valley, but not without extracting a cost. Over the years, while the benefits of an impressive irrigation infrastructure have been enjoyed, an insidious side effect has taken form. The ground water table has risen and grown saline due to excessive irrigation, seepage from earthen canals, and inadequate drainage facilities. Upward flow from the high water table has salinized and waterlogged many of the rich soils of the Valley, which can cause crop yields to diminish. Not only have soils been degraded, but river water quality also has suffered. In addition to the evaporative concentration of solutes in applied waters, intensive irrigation of the alluvial soils, which are derived from underlying marine sedimentary rocks, also may have accelerated the dissolving of inherent salts and other natural mineral pollutants [e.g., selenium (Se) and iron (Fe)] into the underlying alluvial aquifer that discharges to the river. Consequently, solute concentrations in river water can rise to levels that threaten not only the productivity of the land but also the ecological health of the river. In addition, over-irrigation has created shallow water tables not only under irrigated land but also under adjacent fallow land. Evaporative upflux from the water table under this fallow ground, along with evapotranspiration from invasive plants along the river, may amount to significant volumes of nonbeneficial consumptive use.

Until recently, evidence of irrigation-related problems in the Arkansas River Valley has been mostly anecdotal, but it has been ample: salt deposits and ponded water on field surfaces, poor crop stands, and reduced crop yields. Over the years, substantial changes have taken place in the way the water system is managed, often aggravating the problems. For example, two major reservoirs have been constructed on the river: John Martin Reservoir in 1948 and Pueblo Reservoir in 1975. Pueblo Reservoir, the centerpiece of the Fryingpan-Arkansas project, allows additional water from west of the Continental Divide to be transferred and stored for increased irrigation in the basin. Both reservoirs have allowed winter water storage for later use in the irrigation season. However, they also have resulted in reduced sediment loads in river waters, likely contributing to increased seepage from Valley canals due to a reduction in perimeter sealing by sediments. The dampening of scouring flood flows by the reservoirs and the backwater created by John Martin Reservoir seem to have contributed to aggradation of sediments and consequent rise of water levels in the river. The higher river levels decreases the gradient that drives drainage from the land to the river. Also, in response to a recent court ruling regarding Colorado's violation of the Arkansas River Compact, pumping from wells in the Valley, that not only provided irrigation water supply but also served to reduce high water table levels, has greatly diminished.

Conditions along the Arkansas River are typical of those in many other intensively irrigated regions. Waterlogging and salinization are age-old challenges to irrigated agriculture, and they continue to plague irrigated areas both in the western United States and abroad. In fact, saline high water tables affect 20-25% of the world's irrigated lands, including 27% of those in the United States (Tanji 1990, Ghassemi et al. 1995, NRC 1996, WWPRC 1997), and pose serious threats to our most productive agroecological systems – the settings that provide the medium and the resources to support crop production. Arresting this degradation of the world's most fruitful land, while protecting the broader natural resource base of irrigated watersheds, may prove one of the great challenges of the coming decades.

PROSPECTS FOR IMPROVEMENT

In assessing the outcome of irrigation development along the Arkansas River Valley, J. E. Sherow (1990) wrote in his history, *Watering the Valley*:

In the Arkansas Valley, people have built functioning water systems for their ditch companies and for industries and cities. They have maintained their operations in the midst of countervailing forces marked by conflict and cooperation with nature, aid and control from the federal government, and contention and cooperation among themselves. To those who first settled the Arkansas River Valley, supplying their water needs seemed simple: Construct a small headgate in the riverbank; dig a ditch leading to their farms, cities, or factories; and reap the

bounty of nature harnessed. The domination of nature, though, proved considerably more difficult. Each organizational or technological "solution" fashioned through conflict and/or consensus triggered new problems …

Later, seeming to temper his cynicism toward development in the Valley, Sherow (1990) observed that irrigation ditch companies

… resembled living organisms because each responded to climate and pulsated with water that fed growing crops in soils teeming with organic life. Through these organizations, people invaded an environment and established ecological niches in the valley.

When any invading organism assumes a niche in an environment, it may make alterations to that environment. Quickly or slowly, the changes produced could then destroy the environment and render the organism's occupation difficult or impossible. On the other hand, the organism may successfully adjust to the environment and share a symbiotic relationship with its natural surroundings. What makes a particular organism adaptable or maladaptable depends on its own nature.

In keeping with Mark Fiege's (1999) history of irrigation development along Idaho's Snake River, it is the opinion of the authors of the present report that it is possible to achieve a "symbiotic" (though complex) relationship between irrigated agriculture (and the communities it supports) and the river valley itself. However, if agricultural production is to be sustained and the environmental integrity of the watershed is to be protected, well-designed, economical changes in water management may need to be made throughout the Lower Arkansas River Valley. Old irrigation habits might need to be altered to become more efficient; aging water-delivery infrastructure may require rehabilitation and maintenance, and in some instances new drainage systems may need to be installed; and new and more salt-tolerant crop varieties may need to be adopted. Results from field and modeling studies by Colorado State University researchers, outlined in this report, suggest that such changes have substantial potential for lowering the saline shallow water table, reducing soil water salinity, and increasing crop yields on Valley lands. Beyond this, these changes might result in substantial reductions in salt and Se loads to the river and may diminish the amount of water that currently is lost to nonbeneficial consumption.

If agricultural production is to be sustained and the environmental integrity of the watershed is to be protected, well-designed, economical changes in water management may need to be made throughout the Lower Arkansas River Valley.

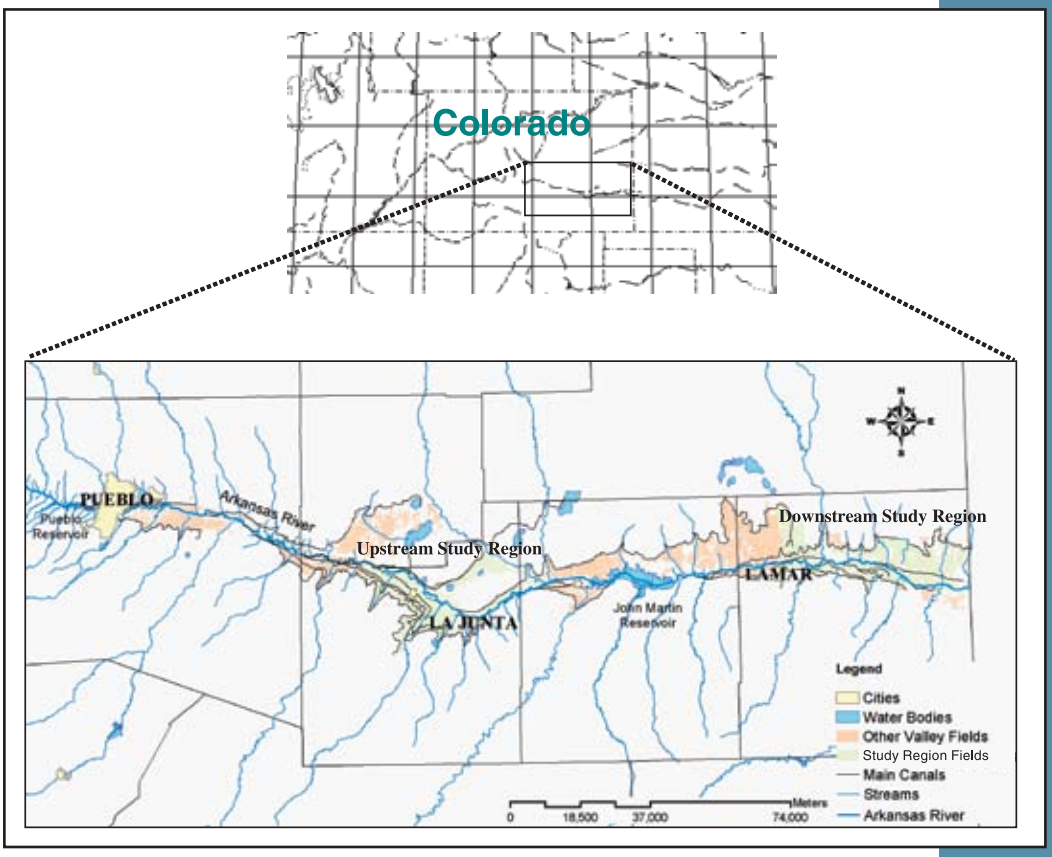


Figure 1. Lower Arkansas River Valley in Colorado highlighting Upstream and Downstream Study Regions.

Until recently, evidence of irrigation-related problems in the Arkansas River Valley has been mostly anecdotal, but it has been ample.

FUNDAMENTAL ISSUES GUIDING THE RESEARCH

Only recently have extensive studies, conducted by Colorado State University researchers, been focused on accurately measuring and diagnosing the irrigation-related problems in the Arkansas River Valley and on systematically probing for viable solution strategies. It is recognized that such strategies cannot be adopted independently or out of context. Instead, actions taken by farmers and agencies at the field and regional scales will need to be informed by guidelines that are based upon valley-wide objectives and constraints.

The entire Lower Arkansas Valley system can be likened to an interlocking web of scale-dependent components, in which local changes ripple upstream and downstream via irrigation-stream-aquifer interactions and water rights issues. For example, increases in irrigation efficiency and lining of earthen canals in a given region of the Valley would reduce excess recharge to the underlying alluvial aquifer. Not only would this cause a reduction in soil water salinity and waterlogging with a consequent increase in crop yields, but also the return flows to the river would be substantially altered. Salt and Se loads in these return flows probably would be markedly reduced, enhancing river water quality. However, the associated change in the rate and timing of irrigation diversions and return flows might materially alter the pattern of river flows available for downstream diversion and in-stream use. It is essential that the flow pattern in the river not only preserve in-state water rights but also respect the requirements of the Arkansas River Compact (particularly, Article IV-D) between Colorado and Kansas. Hence, it appears that basin-scale changes in river operations, both upstream and downstream, will be needed to dampen the effects of actions taken to improve regional conditions on the land. For example, it may be possible to offset the impact on river flows that would be brought about by regional improvements that might result in reduced diversions from the river. This might be done by establishing new accounts in existing on-stream and off-stream reservoirs to store volumes of water resulting from reduced canal diversions and then releasing this water in a manner that would adequately preserve historic river flow patterns in compliance with Colorado water rights and with the Arkansas River Compact. Even if historic flow patterns could not be fully preserved, tradeoffs with benefits derived from improved river water quality might justify the proposed changes.

These issues, along with a variety of other political and economic concerns, press for basin-scale changes through conservation, altered operations, and redistribution of water resources in the Valley. For example, cities along Colorado's Front Range are looking to acquire water rights historically used for irrigation in the Valley to meet increasing urban demands. In May 2002, rules for a pilot water bank, facilitating water leasing, loans, and exchanges of stored water, were implemented for the Arkansas River. As a result, over the last few years, canal companies and cities increasingly have entered into short-term water lease agreements, requiring rotational fallowing of irrigated land. These changes will impose new constraints on how water needs to be managed for agriculture and for the environment. New water management practices on the watershed landscape, aimed at jointly improving agricultural productivity and river water quality, must be carefully planned, tested, and implemented to satisfy these other varied constraints.

Specifically, questions like these will need to be addressed by water users and managers:

1. How can water be conserved and redistributed in the Lower Arkansas River Basin to meet an array of competing demands at the basin scale (dimensions on the order of tens of thousands of hectares) while at the same time complementing efforts to protect irrigated agriculture from waterlogging and salinity problems at the regional scale (order of thousands of hectares)?

2. How can the input of growers and agencies be garnered in developing sound Valley-wide solutions that can be effectively implemented at the field scale (order of tens of hectares)?

3. What options are available to set up and manage storage accounts for water volumes derived from reduced diversions (associated with improved irrigation efficiency and reduced canal seepage) and to release these stored volumes to mimic historic return-flow patterns?

4. How might the exercise of dry-year leasing options (intra- and interbasin) under the pilot water bank program affect salinity and waterlogging problems in the Valley over the long term?

5. How will alteration in the magnitude and the spatio-temporal pattern of return-flow rates, associated with contemplated system interventions, affect instream flows, downstream diversions, and compliance with the Arkansas River Compact?

6. How will changes in the rates, timing, and quality of river flows as impacted by proposed new projects (e.g., the Southern Delivery Project and the Preferred Storage Options Project) affect instream flows, downstream diversions, and compliance with the Arkansas River Compact?
7. How might the recovery of "liberated" water from nonbeneficial upflux from high water tables and/or from phreatophyte evapotranspiration along the river corridor affect instream flows, downstream diversions, and compliance with the Arkansas River Compact?
8. How can findings about the prospects for improving the sustainability and productivity of irrigated agriculture, while enhancing the environmental quality of the river-aquifer system, support a larger vision for socioeconomic revitalization of the Arkansas River Valley's agricultural communities?

OVERALL RESEARCH GOAL

The long-term goal of Colorado State's research is to provide water managers and users with information that will help them to enhance overall water utility and redress water quality degradation in the Lower Arkansas River Basin of Colorado. This is to be accomplished in dialogue with Valley farmers and agencies and through the discovery and the widespread adoption of water management practices that will (a) reduce detrimental waterlogging and salinity impacts to agriculture in the Arkansas River watershed, (b) enhance water quality in the Arkansas River by diminishing nonpoint source salinity and Se loads, and (c) lead to real water conservation in the river by reducing nonbeneficial upflux from high water tables and extraction by invasive phreatophytes along the river corridor.

It may be possible to offset the impact on river flows that would be brought about by regional improvements that might result in reduced diversions from the river. This might be done by establishing new accounts in existing on-stream and off-stream reservoirs.

Photos of reservoirs and release from Pueblo Reservoir: Courtesy of *Pueblo Chieftain*.

Scope of the Report

This report summarizes benchmark findings of the first phase of Colorado State University's on-going research in the Lower Arkansas River Valley and briefly outlines the next directions of an effort to discover feasible long-term solution strategies. The focus is on identifying problems and prospective solutions related to water management for irrigated agriculture and for the environment, specifically addressing soil and water quality. The report also lays out plans for continued research toward an eventual widespread implementation of effective remedies in the field.

Benchmark Field Data and Modeling Tools for the Irrigated Stream-Aquifer System

Several years ago, Colorado State University researchers initiated projects with the aim of gathering extensive field data and building data-founded models to facilitate progress toward long-term solutions of the long-recognized irrigation-induced water quality and waterlogging problems of the Arkansas River Valley. In 1996 – 1997, literature from previous studies was examined, and existing data were compiled and analyzed. A preliminary reconnaissance-scale data gathering effort was conducted in the field in 1998, and in 1999, a full-scale field data-collection program was designed and initiated in a study region upstream of John Martin Reservoir. In 2002, similar field studies were extended to a region downstream of John Martin Reservoir. Activities in the Downstream Study Region were expanded in 2003 to include evaluation of Se and Fe in the ground water and surface water systems. Though these studies are continuing, the first phase has provided an emergent picture of current conditions in the Valley and has established a strong data-supported benchmark for the structural and management changes that may need to be adopted in the Valley.

FIELD DATA FOR CHARACTERIZATION OF PROPERTIES AND PROBLEMS IN THE UPSTREAM STUDY REGION

Over the last several years, extensive data have been obtained in both the Upstream and Downstream Study Regions to describe the nature and variability of the Arkansas River and its tributaries, the reservoirs, and the ground water aquifer within the lower river valley. Information on the properties of soils and crops and of the irrigation and drainage system serving the Valley lands also has been collected and analyzed.

Since 1999, a data set has been gathered over the Upstream Study Region (Figures 1, 2), which extends 62 km along the river and covers an area of about 50,600 hectares (125,000 acres) [of which 26,400 ha (65,300 ac) are irrigated]. The region was selected to be representative of hydrogeologic and agronomic conditions upstream of John Martin Reservoir. Within the study region, there are six major irrigation canals, numerous smaller irrigation and drainage ditches, eight tributary drainages, three main reservoirs, and more than 280 active pumping wells. Major irrigation canals are allocated water based on prior-appropriation water rights. Cultivated crops include alfalfa, corn, grass, wheat, sorghum, cantaloupe, watermelon, and onions. The most common irrigation methods in the area are furrow irrigation and border irrigation using open ditches with siphon tubes or, in some cases, using gated pipe. Less than five percent of the region currently is irrigated with sprinkler and drip irrigation systems.

Investigations in this study region include ground water monitoring, well installation and observation, analysis of river and tributary flows, analysis of flows diverted to irrigation canals, surface water salinity measurements, intensive soil salinity monitoring, topographic and hydrographic surveying using differential global positioning systems (GPS), drilling boreholes to explore lithology and bedrock, measurement of soil and aquifer properties, measurement of seepage from irrigation canals, measurement of irrigation applications and runoff, measurements of crop yield, and other related activities (Gates et al. 2002, Burkhalter 2005, Burkhalter and Gates 2005, Jaramillo et al. 2005). In 2004, a more detailed study of irrigation practices on selected representative fields was initiated. Tens of thousands of measurements have been taken in more than 100 monitoring wells; at about eight locations along the river; at a total of about 160 locations in canals, drains, tributaries, and selected reservoirs; and in about 80 irrigated fields. Details about data collection procedures and equipment are given in Burkhalter (2005) and Burkhalter and Gates (2005) and will be described further in forthcoming print and internet documents.

Ground Water Data in the Upstream Study Region

A total of 139 observations of water table depth were made in the monitoring wells of the Upstream Study Region over the period April 1999 – June 2005. Figure 3 shows a plot illustrating the distribution of measured water table depths over the period April 1999 – June 2005. On the average during April 1999 – June 2005, about 35% of monitored wells were dry in any given week, indicating a water table below the known elevation at the bottom of the well bore. Average observed water table depth (not including dry well observations) over all sampled locations for

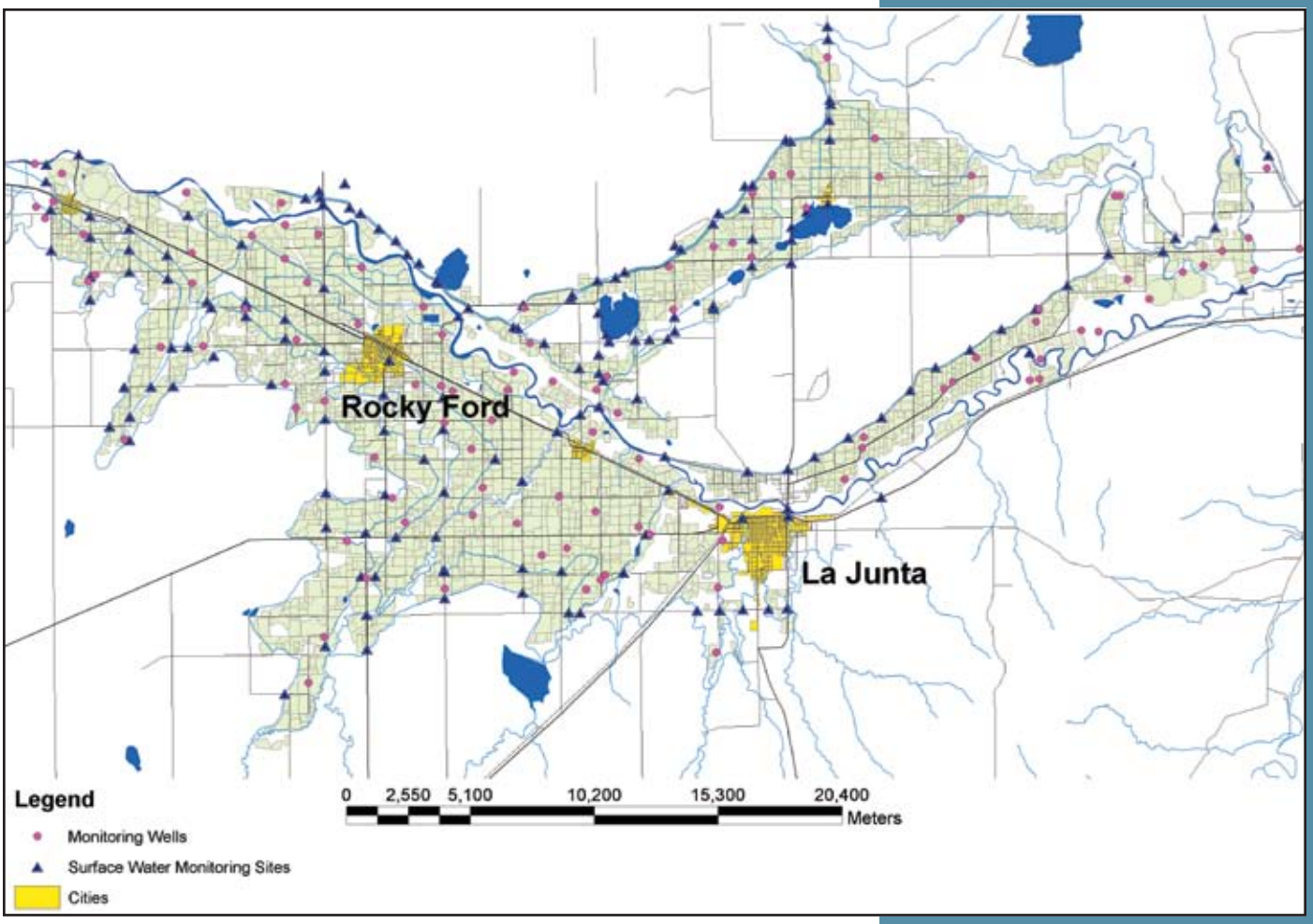


Figure 2. Upstream Study Region showing ground water and surface water monitoring sites.

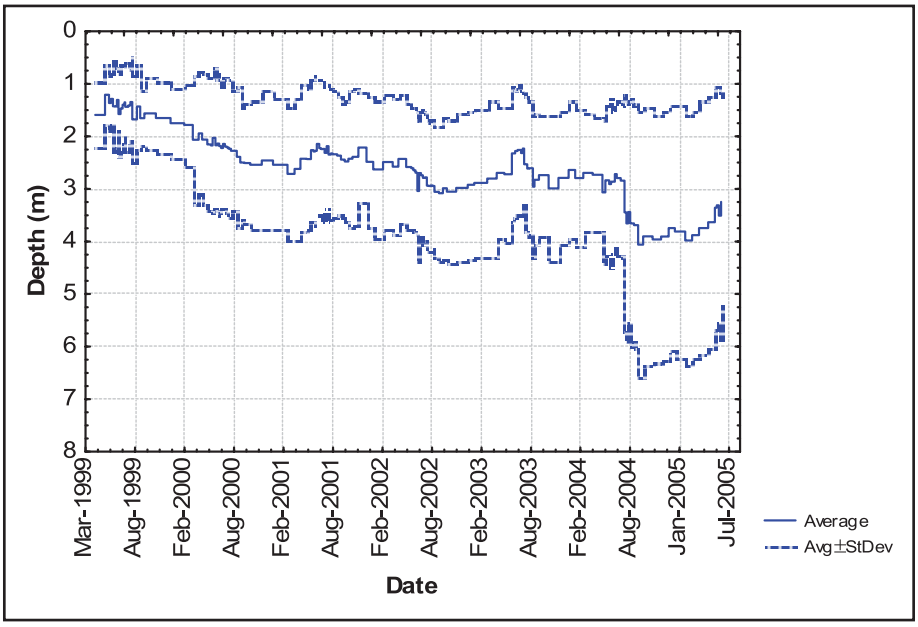


Figure 3. Average and range of variation in observed water table depth in the Upstream Study Region over the period April 1999 – June 2005.

each reading during the observation period ranged from 1.21 to 4.06 m (3.97 to 13.32 ft). It has been estimated from field data that a water table depth of 2 to 3 m is necessary to prevent detrimental upflux of saline water into the soil root zone. Observation-period coefficients of variation (*CV*) (absolute value of ratio of standard deviation to mean) computed over the study region ranged from 0.33 to 0.65, indicating a moderate degree of spatial variability. Example plots of water table depth and specific conductance [or electrical conductivity (*EC*) standardized at 25°C] for four representative wells are given in Figure 4. Average observed depths to the water table generally increased over the first part of the study period, associated with reduced flow diversions and lower irrigation applications due to drought conditions. Depths to the water table were observed to decrease again in the wetter years of 2004 and 2005. Data from the sampled monitoring well locations have been used to calibrate the flow and salt transport model and, coupled with the model's approximation of the governing flow and transport equations, have been used to estimate water table depth and salinity contours over the entire Upstream Study Region over the period April 1999 – October 2001, as described in a following section. Work is on-going to extend the modeled period of estimation through October 2004.

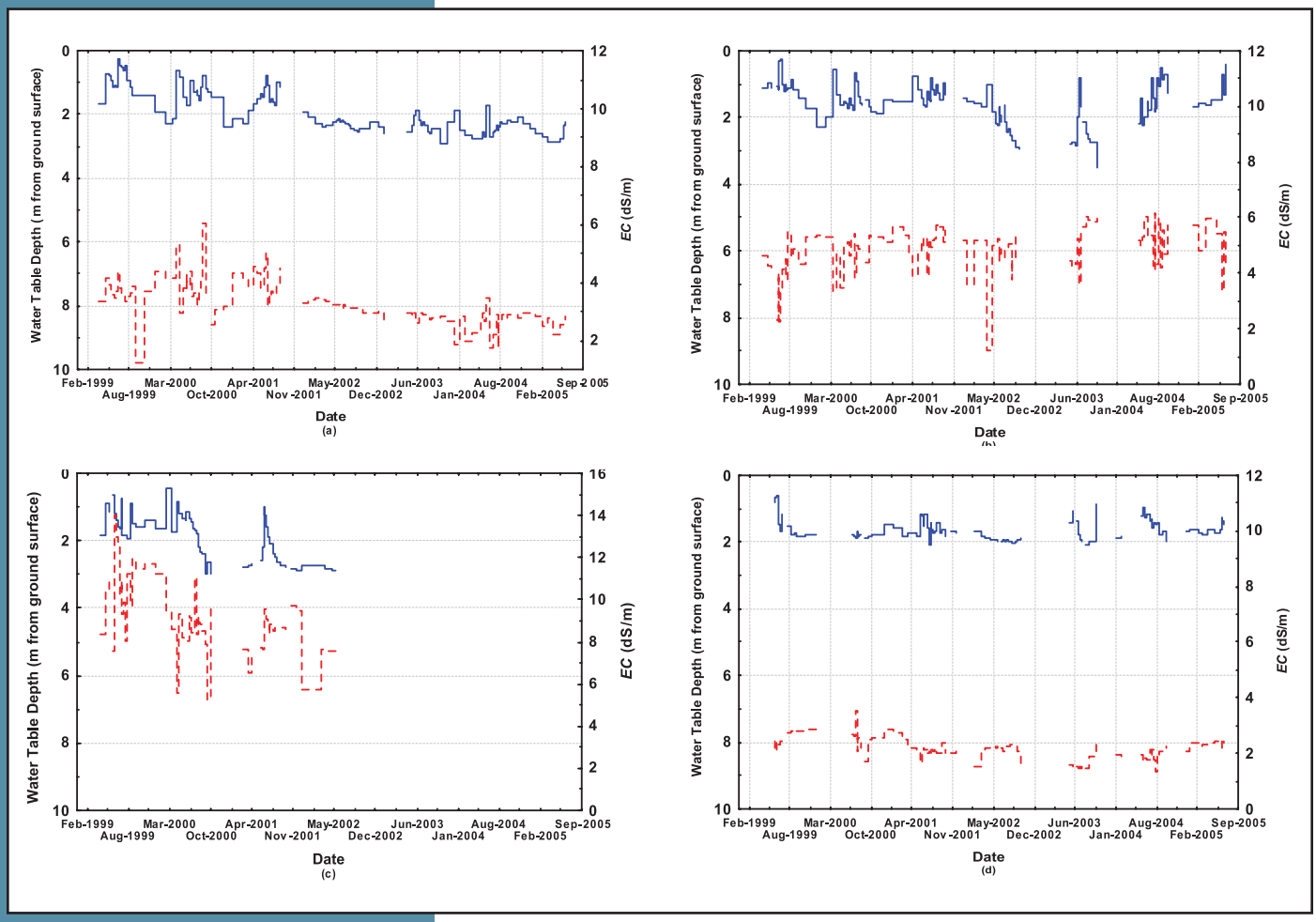


Figure 4. Example time series plots of water table depth and *EC* in (a) well 9B, (b) well 41, (c) well 61, and (d) well 70 in the Upstream Study Region over the period April 1999 – June 2005.

A plot illustrating the distribution of *EC* measured in the ground water monitoring wells over the period April 1999 – June 2005 is given in Figure 5. Average measured *EC* in the monitoring wells over the period April 1999 – June 2005 ranged from 2.42 to 4.66 dS/m, corresponding to total dissolved solids (*TDS*) concentrations of about 2,100 to 4,043 mg/L. Period *CV* values ranged from 0.11 to 1.46. *EC* was translated into *TDS* using a relationship developed from lab testing of 55 ground water samples (*TDS* = 867.6*EC*, r^2 = 0.935).

Intensive monitoring has been carried out since 2000 to evaluate the variability of salinity and waterlogging inside representative individual fields within the Upstream Study Region. Over the years 2000 – 2005, 10 to 20 fields have been intensively monitored. Between four and eleven monitoring wells were installed in or around each of these fields. In addition to weekly manual readings of water table depth and *EC* in the wells, selected wells were equipped for periods of time with an automatic water-level recorder (AWLR). Data loggers attached to the AWLRs were programmed to take readings at 1-hr intervals. At three times during each irrigation season, spatially referenced (using a GPS unit) soil water salinity readings were taken in each of the fields using Geonics™ EM-38 electromagnetic induction probes.

Figure 6 shows a depth to water table graph generated for Field 7 in the Upstream Study Region. The graph shows the water table depth in each of 14 observation wells and the average depth over the entire field (dark black line), depicting the degree of spatial and temporal variability in water table depth that occurs at the field scale.

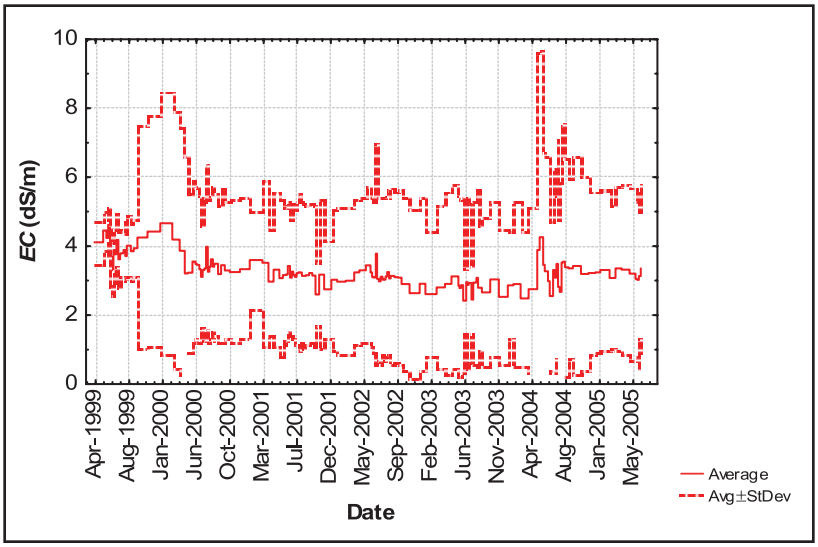


Figure 5. Observed average *EC* of the water table and range of variation in the Upstream Study Region over the period April 1999 – June 2005.

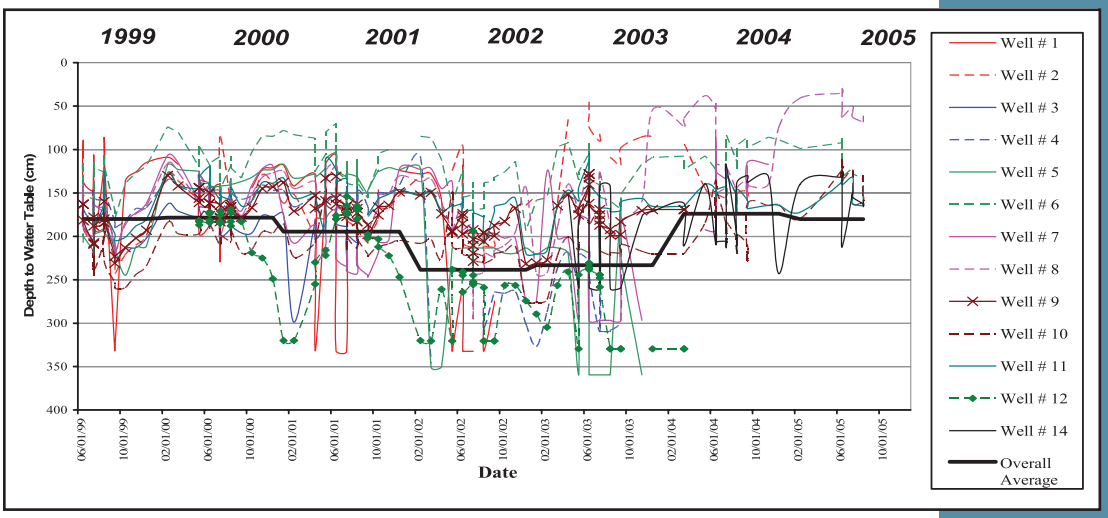


Figure 6. Depth to water table data for the observation wells in Field 7.

Investigations in this study region include ground water monitoring well installation…. Tens of thousands of measurements have been taken in more than 100 monitoring wells….

Horizontal hydraulic conductivity in the upper 2 to 3 meters (6.56 to 9.84 ft) of the water table aquifer has been measured at about 95 locations using slug tests (Chin 2000). Results indicate values ranging from about 0.001 m/day to about 10 m/day. Analysis of data from Hurr and Moore (1972) indicates deep aquifer hydraulic conductivity in this region ranging from about 13 m/day (42.6 ft/day) to about 625 m/day (2,050 ft/day).

Surface Water Data in the Upstream Study Region

The study period April 1999 – November 2004 spanned a broad range of hydrologic conditions in the Arkansas River watershed. This is illustrated in Figure 7, which shows plots of daily average flow rate at four gauging stations in the Arkansas River over the study period within the Upstream Study Region. For comparison to normative conditions, Figure 7 also shows a plot of the ratio of daily average flow rate at each gauging station to the mean daily average flow rate at the respective station over the last 30 years (since Pueblo Reservoir began operation). This ratio is referred to as the "normalized flow rate." While the years 1999 – 2001 could be considered wet to moderately wet, the years 2002 – 2004 were drought years. Figure 8 shows daily average diversions (expressed as flow rates and as flow depths over the respective command areas) to the six major canals that deliver direct flows to the region and to one canal (Fort Lyon Storage Canal) that delivers flow to storage. Also shown is a plot of the normalized diverted flow rates.

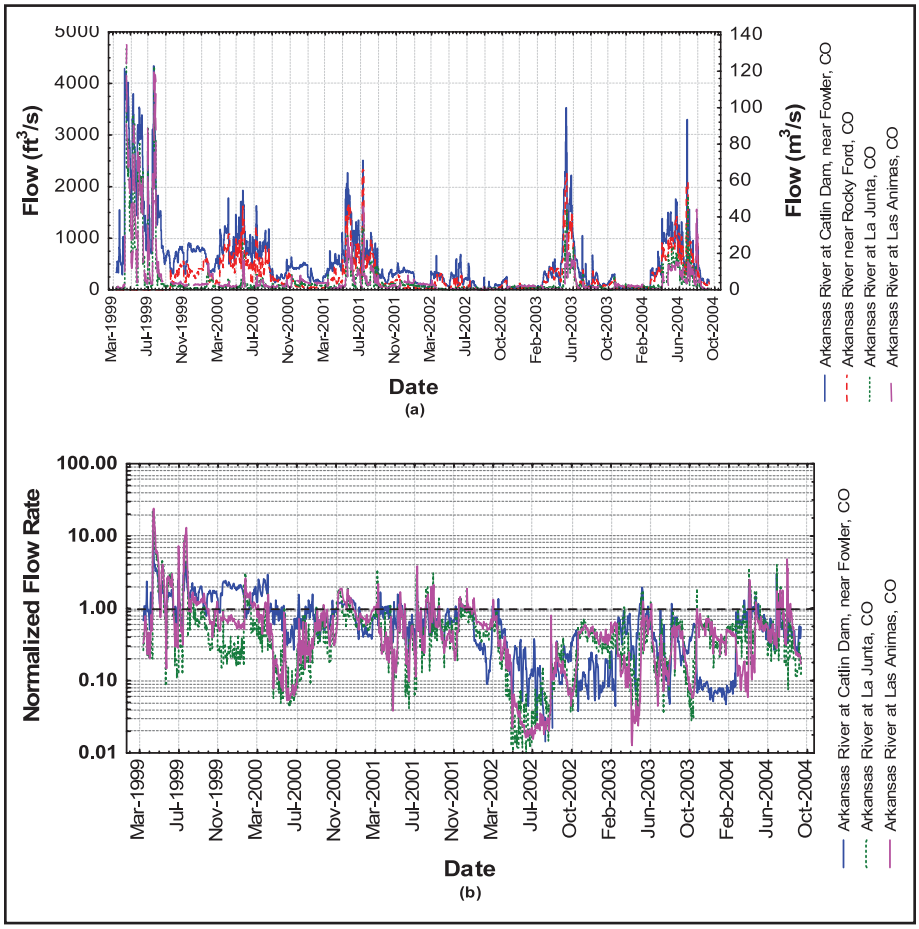


Figure 7. (a) Daily average flows measured at the four gauging stations on the Arkansas River in the Upstream Study Region over the period April 1999 – November 2004 and (b) daily average flows at three of the four gauging stations normalized by the corresponding mean flow rate for that day computed over the period 1975 – 2004.

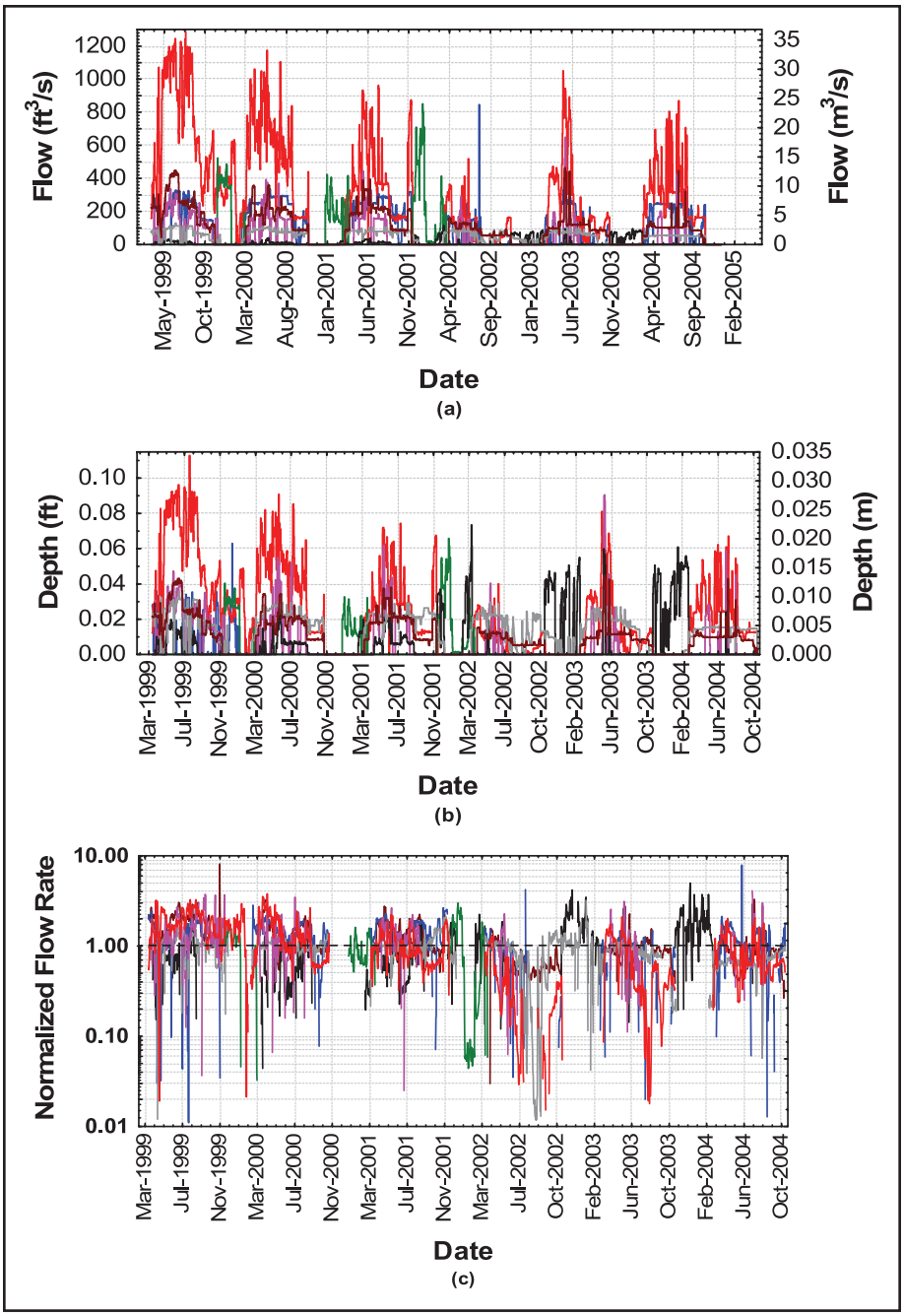


Figure 8. Daily average flow diversions to the major canals in the Upstream Study Region over the period April 1999 – November 2004, expressed as (a) diverted flow rate, (b) flow depth over the entire command area of each respective canal, and (c) ratio of diverted flow rate to mean diverted flow rate over the period 1975 – 2004.

Average measured salinity of flows delivered by the six major canals into the region ranged from 0.71 dS/m (635 mg/L) to 1.05 dS/m (897 mg/L) in 1999, from 0.93 dS/m (806 mg/L) to 1.39 dS/m (1,150 mg/L) in 2000, from 0.75 dS/m (667 mg/L) to 1.19 dS/m (1,002 mg/L) in 2001, from 1.00 dS/m (860 mg/L) to 1.64 dS/m (1,331 mg/L) in 2002, from 0.58 dS/m (531 mg/L) to 0.91 dS/m (791 mg/L) in 2003, and from 0.72 dS/m (643 mg/L) to 1.29 dS/m (1,076 mg/L) in 2004. Average salinity measured in the Arkansas River near the upstream and downstream ends (the downstream end was near the Otero-Bent county line in 1999 but was moved further downstream to Las Animas after 1999) of the study region was 0.85 dS/m (745 mg/L) and 0.97 dS/m (837 mg/L), respectively, during the 1999 irrigation season, 0.94 dS/m (814 mg/L) and 2.85 dS/m (2,167 mg/L) during the 2000 season, 0.95 dS/m (822 mg/L) and 2.20 dS/m (1,725 mg/L) during the 2001 season, 1.48 dS/m (1,215 mg/L) and 2.99 dS/m (2,261 mg/L) during the 2002 season, 0.90 dS/m (783 mg/L) and 1.19 dS/m (1,002 mg/L) during the 2003 season, and 1.02 dS/m (875 mg/L) and 1.47 dS/m (1,208 mg/L) during the 2004 season. A separate *EC-TDS* relationship, derived from 74 field samples, was used for surface water ($TDS = 859.7EC^{0.88}$, $r^2 = 0.988$). The measured *EC* at each of nine sampling locations along the Arkansas River within the Upstream Study Region is plotted for the period April 1999 – June 2005 in Figure 9.

Canal Seepage Data in the Upstream Study Region

Inflow-outflow tests for seepage have been conducted in the Rocky Ford Highline Canal, the Catlin Canal, and the Fort Lyon Canal in the Upstream Study Region. Results indicate significant seepage losses ranging from about 0.004 m^3/s per km along the canal (0.3 ft^3/s per mile) to about 0.065 m^3/s per km (3.7 ft^3/s per mile).

Data on Irrigation Practices and Field Conditions in the Upstream Study Region

During June – August 2004, a study of field-scale irrigation activities commenced both in the Upstream and Downstream Study Regions. In 2004, a total of 15 fields were monitored to evaluate on-going irrigation practices with an eye toward potential improvement. In 2005, the total number of fields on which irrigation practices were measured increased to 27, with 13 in the Upstream Study Region and 14 in the Downstream Study Region. Where possible, measurements of total irrigation water inflow and outflow were made (see example in Figure 10) for numerous irrigation events. To carry out these activities, flumes (Cutthroat and Parshall), flow meters (for sprinkler and drip systems), GPS units, and pressure transducers (water-level sensors) were employed. Rainfall was measured with a rain gage placed at each field. Crop evapotranspiration (*ET*) for each field was estimated using measurements made with ET-Gage™ atmometers, the

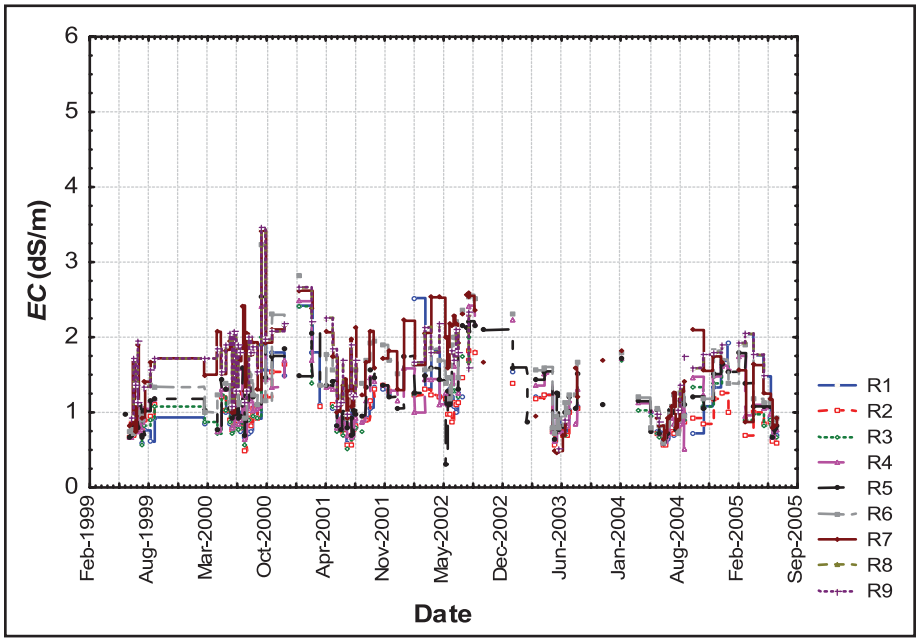


Figure 9. Measured *EC* at eight sampling locations along the Arkansas River in the Upstream Study Region over the period April 1999 – June 2005 (sampling locations are labeled from R1 to R9 in upstream to downstream order with R1 located just west of Manzanola and R8 located at Las Animas).

Penman-Monteith equation using local climatic and crop data, and satellite imagery. Infiltration tests were conducted, and water was sampled for salinity, phosphate, and nitrate concentrations.

Figure 11 shows a distribution of applied irrigation depths, surface runoff depths, and infiltrated depths measured for selected irrigations in the Upstream Study Region between May and mid-August 2005. Over these measured irrigation events, the average applied depth was about 19.5 cm, and the average infiltrated depth was about 17.5 cm. Data suggest that about 45% of the infiltrated depth ends up as deep percolation below the root zone, contributing to recharge of the shallow water table. Preliminary analysis indicates an average irrigation application efficiency of about 55% over all of the irrigation events monitored in 2005, both in the Upstream and Downstream Study Regions. Multiple seasons are required to establish an accurate baseline and understanding of the region's water use practices; hence, this study will continue at least through the 2006 growing season.

Soil Salinity Data in the Upstream Study Region

Geonics™ EM-38 electromagnetic induction meters (Rhoades et al. 1999) were used to gather soil water salinity data within selected fields (average number of points per field was approximately 63) twice per irrigation season. A total of about 48,000 points (average of about 5 to 10 points per ha) were measured over the period May 1999 – August 2004. To calibrate the EM-38 meters, about 253 selected calibration sites were sampled within monitored fields across the upstream region over the period May 1999 – August 2003. A total of 15 soil samples were extracted at depths to 1.2 m (4 ft) from each site, consisting of three auger holes along the sampling axis of the meter. An additional 19 calibration sites were sampled in fields from May 2004 to August 2004 for use in testing the calibration equations. A summary of soil saturated paste electrical conductivity (EC_e) data for the period 1999 – 2004 is given in Table 1. In interpreting the values in this table, it is useful to keep in mind that a value between about 2 to 4 dS/m marks the threshold above which significant yield losses occur in corn and alfalfa, the predominant crops in the region (Maas and Grattan 1999).

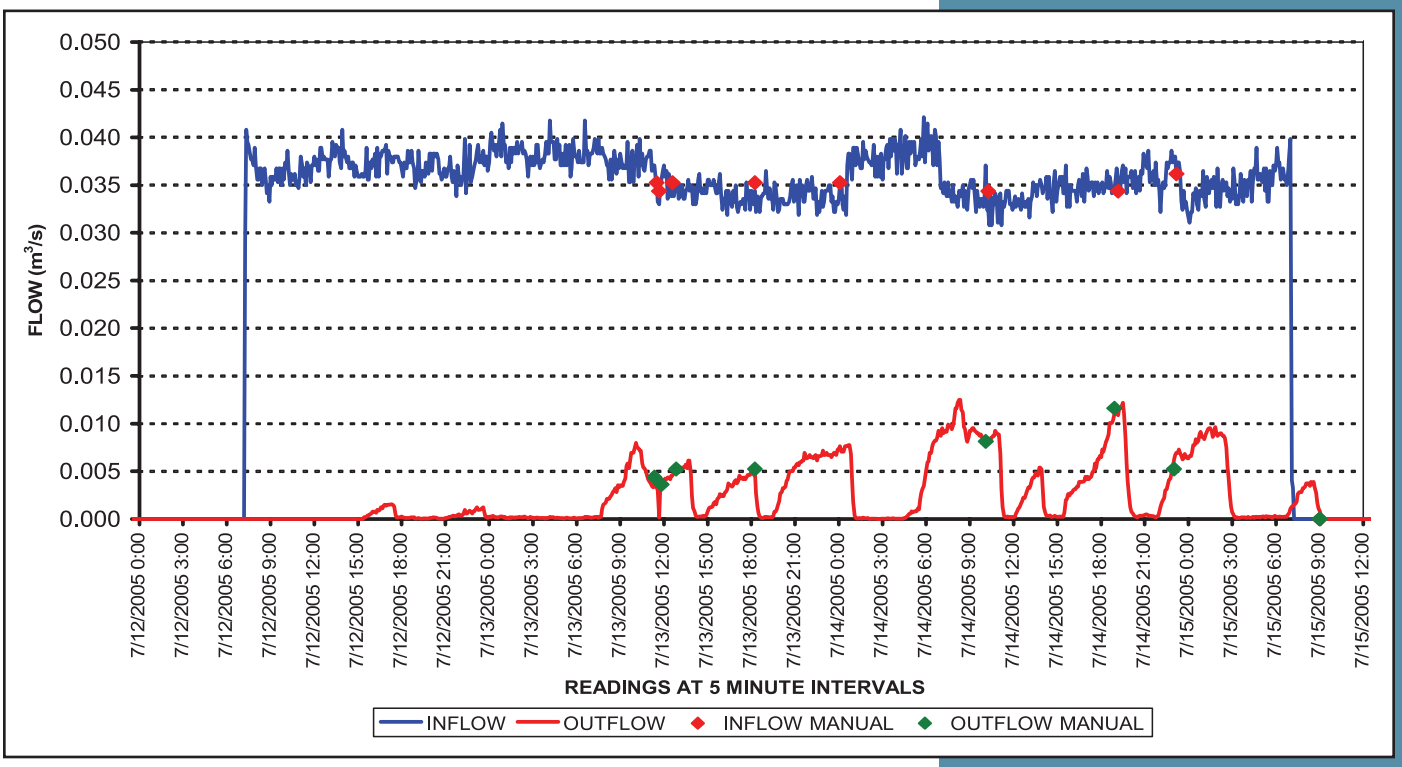


Figure 10. Example inflow and outflow hydrographs for one irrigation event monitored in Field 5, Upstream Study Region. Automatic pressure transducer readings and periodic manual readings are shown.

Geonics™ EM-38 electromagnetic induction meters (Rhoades et al. 1999) were used to gather soil salinity data within selected fields.

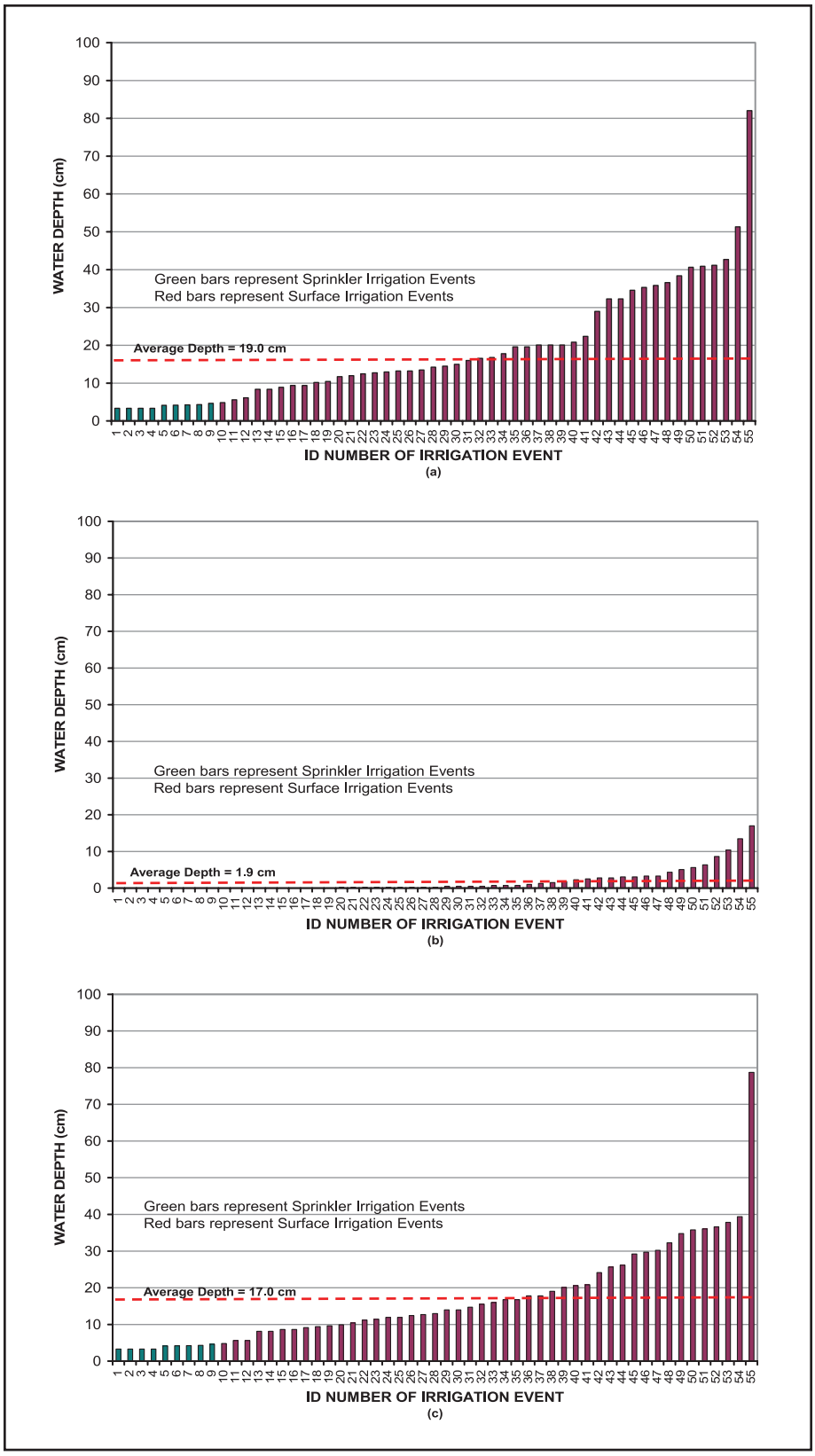


Figure 11. Distribution of (a) application depths, (b) surface runoff depths, and (c) infiltrated depths measured for selected irrigation events on fields in the Upstream Study Region during summer 2005.

Table 1. Summary of Soil Salinity (as EC_e) Measured with EM38 Probes in Fields in the Upstream Study Region.

Season	Number of Fields Surveyed	Number of Locations Surveyed per Field			Average EC_e (dS/m) Measured over Field		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
Early 1999	68	31	86	63	2.35	10.14	4.24
Late 1999	67	31	89	67	2.40	9.66	3.96
Early 2000	73	17	99	59	2.32	8.28	3.49
Late 2000	77	32	117	64	0.78	12.51	3.81
Early 2001	80	27	123	62	1.16	17.22	4.83
Late 2001	76	30	97	60	1.34	12.07	4.43
Early 2002	80	30	128	72	1.50	17.94	3.67
Late 2002	32	16	107	64	1.74	15.00	4.28
Early 2003	52	24	107	62	1.88	15.31	4.19
Late 2003	37	24	120	65	2.03	5.98	3.26
Early 2004	66	23	142	69	1.77	12.81	4.20
Late 2004	61	30	102	63	1.72	12.35	4.20

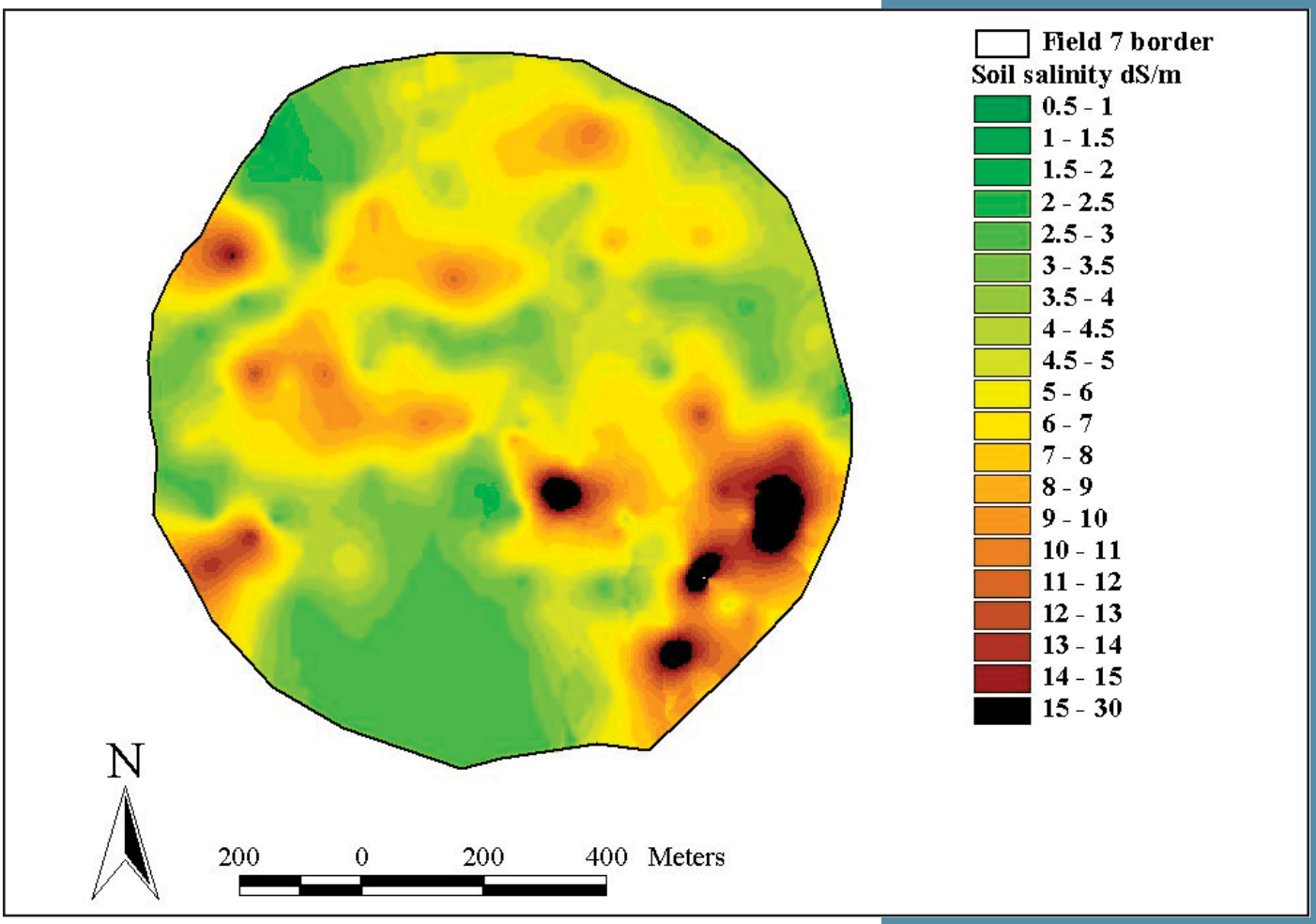


Figure 12. Color-gradient map of soil salinity for Field 7 in the Upstream Study Region (generated from EM-38 readings for which GPS locations were taken).

Inflow-outflow tests for seepage have been conducted in the Rocky Ford Highline Canal, the Catlin Canal, and the Fort Lyon Canal in the Upstream Study Region.

EM-38 readings were converted to EC_e (estimated using a Hach™ SIW kit calibrated against vacuum extract samples) using relationships developed from lab testing of soil samples acquired from calibration sites. These relationships depend upon a number of factors (such as soil water content, soil texture, soil structure, etc.) that affect EM-38 readings. Statistically significant relationships of EC_e with temperature-corrected vertical-orientation EM-38 readings of bulk soil conductivity, EM_v (dS/m), and with gravimetric soil water content, WC (dimensionless fraction), were found (Wittler et al. 2006):

$$EC_e = 0.45 + 7.23EM_v^{1.78} + 19.54WC - 34.06\ EM_v\ (WC);\ r^2 = 0.74$$

A single variate relationship between EC_e and EM_v was estimated for cases for which WC data were not available:

$$EC_e = 2.31 + 2.29\ EM_v^{2.3};\ r^2 = 0.68$$

Over the years, detailed geo-referenced data on soil salinity have been gathered on selected fields in the Arkansas River Valley. In these cases, global positioning systems (GPS) were used to record the spatial coordinates of each point in the field where a measurement was taken with the EM-38, allowing spatial contour plots of soil water salinity to be developed. As an example, Figure 12 shows such a map generated for Field 7 in the Upstream Study Region during the middle of the irrigation season, illustrating the significant variability in soil water salinity over the field.

Data gathered from ground water monitoring wells in conjunction with data on soil water salinity has revealed a significant relationship between depth to the saline water table and EC_e in the overlying soils. Figure 13 is a plot of average EC_e estimated by EM-38 surveys in fields in the Upstream Study Region versus the average water table depth measured over the four-week period prior to the date that the respective EM-38 survey was conducted. Surveys conducted between June 1999 and August 2001 of soil salinity (to a depth of 2 m) in 173 cultivated fields were used to estimate the plotted regression equation (Burkhalter and Gates 2006). There are many factors, including the amount and frequency of irrigation, the salinity of the irrigation water, the chemical and physical characteristics of the soils, as well as other unknown or unidentified processes, that influence soil salinity. The variability in these factors accounts for some of the scatter in the data points about the regression curve in Figure 13. However, the curve reveals the significant trend of increasing soil water salinity with decreasing depth to the saline water table. When saline high water tables are present, substantial capillary upflux of saline water takes place in response to ET demand, with the rate of upflux increasing as the water table rises closer to the ground surface. These conditions diminish the long-term ability to leach salt downward and away from crop root zones. The fitted curve indicates that soil water salinity in this region is not appreciably affected by saline water tables deeper than 2 to 3 m below ground surface, providing guidance for installation of subsurface drains. Data gathered after 2001 will be analyzed to further refine this relationship.

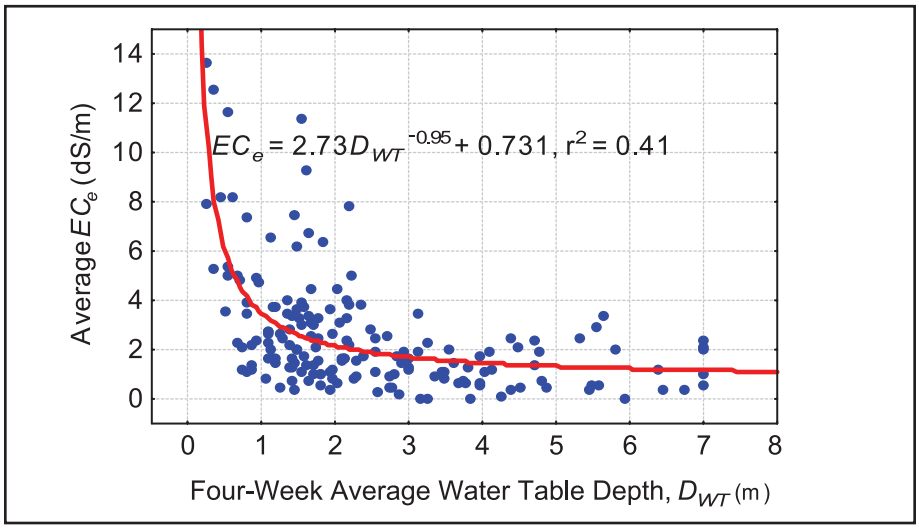


Figure 13. Average measured EC_e versus measured water table depth, D_{WT}, (averaged over four weeks) in fields in the Upstream Study Region, showing fitted regression relationship (adapted from Burkhalter and Gates 2006).

Data on Crop Yield in Relation to Soil Water Salinity

For the first time in 2005, crop cuttings were taken at multiple locations within each of eight alfalfa fields in the Upstream Study Region and within each of five alfalfa fields and five corn fields in the Downstream Study Region. Soil water salinity was estimated at locations nearby the cuttings using EM-38 surveys within these fields. The crop yield at each location was divided by the maximum measured yield in the respective study regions for each respective crop to estimate relative crop yield. These relative crop yield values (varying in value between 0 and 1) are plotted together in Figure 14 against soil water salinity. These preliminary results, which will be refined through additional data collection in coming years, clearly suggest that soil water salinity is a dominant factor in determining crop yield for EC_e values exceeding about 4 to 6 dS/m (Shani et al. 2005). However, crop yield reductions due to salinity appear to be lower than similar studies outside the Arkansas River Valley would indicate. This may be due to the preponderance of low-soluble calcium and magnesium salts, in contrast to highly soluble sodium salts, in Arkansas River Valley soils (Cooper 2006). There are many factors that determine crop yield (e.g., cultivation practices, pesticides, fertilizers), as indicated by the wide range of relative yield values at lower EC_e levels in Figure 14. As EC_e increases, however, there is a trend of decreasing relative yield, and the scatter in relative yield values also diminishes, suggesting that other factors have less influence on crop yield since soil water salinity plays a dominant role in limiting growth and productivity.

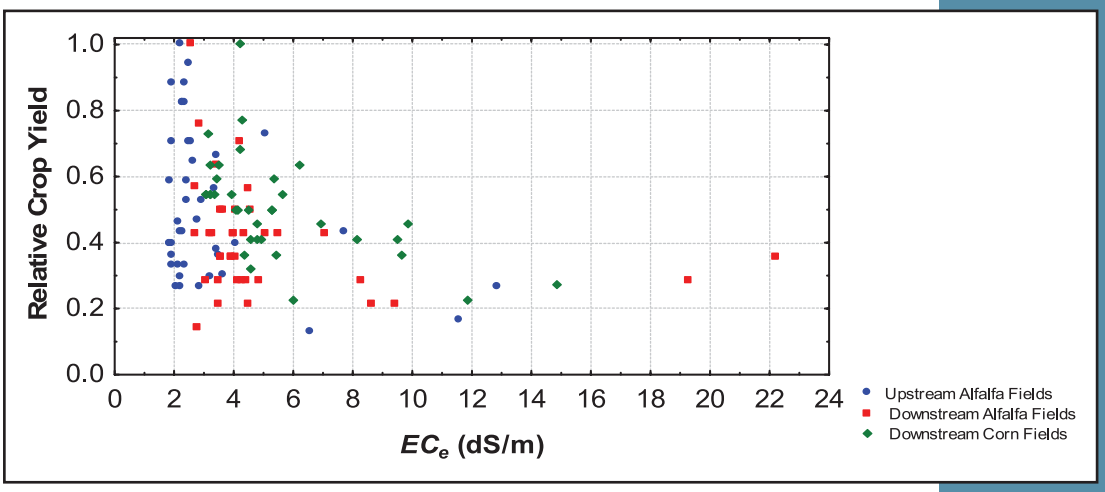


Figure 14. Relative crop yield versus soil water salinity for cuttings taken in alfalfa and corn fields in the Upstream and Downstream Study Regions in 2005.

Remote Sensing to Estimate Crop Evapotranspiration and Relation to Soil Water Salinity

Crop ET often is reduced when osmotic potential in soil pore water is decreased due to salinity. ET can be estimated using satellite imagery by applying an energy balance approach. This approach uses the thermal information from the infrared band as well as the crop reflectance (NDVI).

The Colorado State University (CSU) research group has developed and implemented a remote-sensing algorithm similar to the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al. 1998, Bastiaanssen 2000), which is a satellite image-processing methodology used for computing ET for an entire satellite image. Unlike SEBAL, however, the CSU-developed program, called RESET (Remote Sensing of ET) takes into account spatial and temporal variability. RESET can estimate the actual crop ET at the time when the satellite image was taken.

To date, daily ET has been estimated for a total of 15 days during the years 2001 and 2003. ET estimates now are being developed for the entire irrigated area of the Lower Arkansas River Valley Basin for the growing seasons of 2001 and 2003. This is being accomplished by relating the daily crop ET computed at weather stations to the ET developed from the analysis of the satellite image. Seasonal ET is calculated using a procedure for interpolating between available images. The RESET model uses a new methodology to address the spatial and temporal variability. Figure 15 shows a map of ET estimated by RESET from a satellite image of an area in the Upstream Study Region.

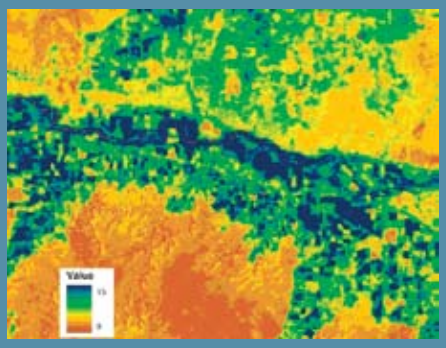


Figure 15. Map of ET (mm/day) estimated by the RESET energy balance algorithm from a satellite image of an area within the Upstream Study Region (image was taken on 6 July 2003 by Landsat 5).

The degree to which crop ET is reduced due to soil water salinity in the Arkansas River Valley is being investigated by examining ET estimates calculated by RESET for fields where soil water salinity surveys have been conducted. Figure 16 shows a plot of ET estimated by RESET from a satellite image taken in July 2001 for selected locations within five corn fields in the Upstream Study Region where geo-referenced data on soil water salinity had been measured. It also shows a similar plot for selected locations in a corn field from a satellite image taken in July 1999. Although there are many factors that influence crop ET at a given location in a field, this plot suggests a clear correspondence between ET and soil water salinity. Rates of ET appear to fall off markedly when EC_e values exceed 2 to 4 dS/m.

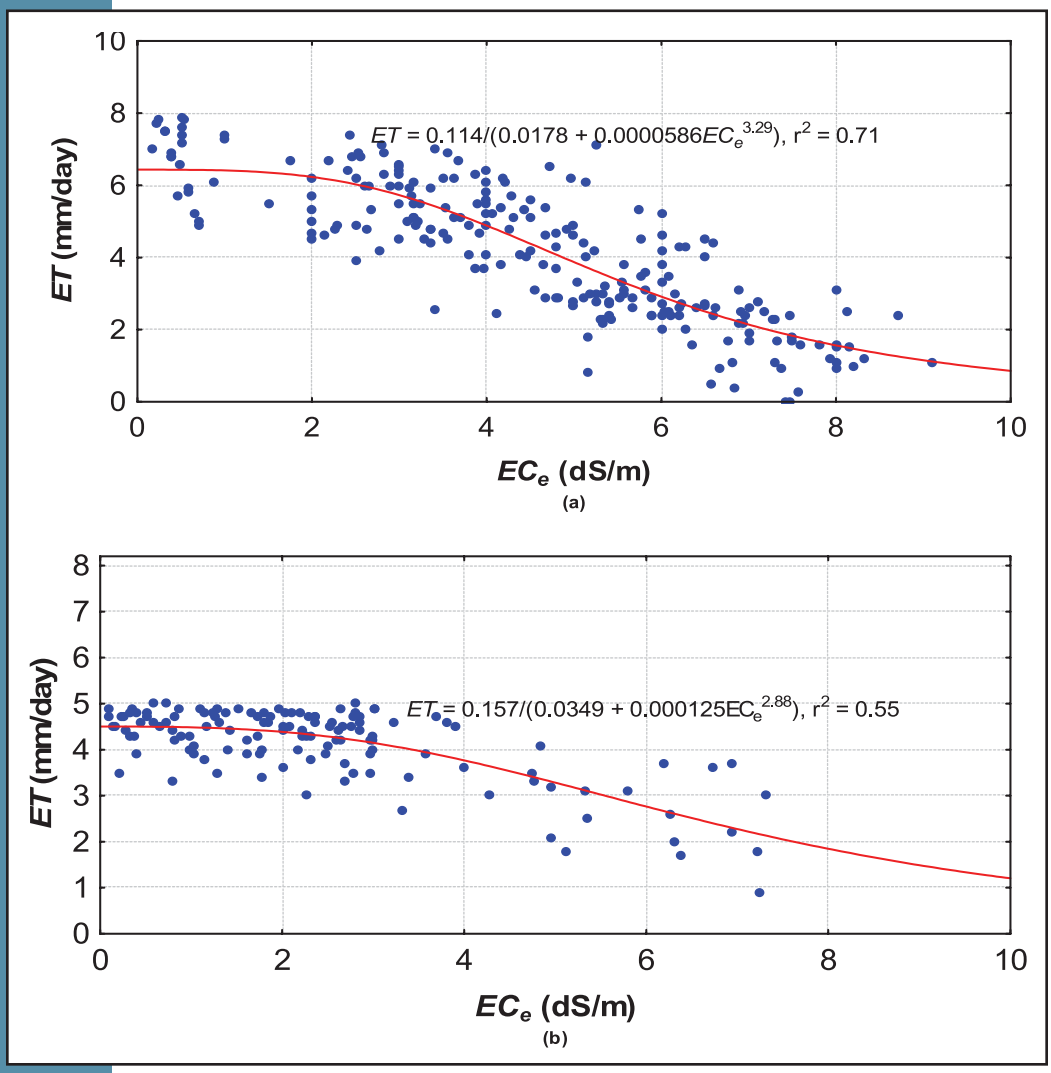


Figure 16. Crop ET estimated by the RESET energy balance algorithm at points within (a) five fields contained in a satellite image taken within the Upstream Study Region on 8 July 2001 by Landsat 5 and (b) one field contained in a satellite image taken in the Upstream Study Region on 19 July 1999 by Landsat 5 versus EC_e measured with EM-38s at the corresponding locations within the fields.

FIELD DATA FOR CHARACTERIZATION OF PROPERTIES AND PROBLEMS IN THE DOWNSTREAM STUDY REGION

Data were collected for the first time in April 2002 from the Downstream Study Region, which covers about 55,200 hectares (136,300 acres) and extends about 60 km (37 mi) along the river from Lamar to the Colorado-Kansas state line (Figures 1, 17). About 33,000 ha (81,600 acres) within this region are irrigated.

Ground Water Data in the Downstream Study Region

As of June 2005, about 76 sampling events for water table depth and salinity had been conducted in a total of 118 monitoring wells. A plot illustrating the distribution of measured water table depths over this period is given in Figure 18. Average observed water table depth (not including dry well observations) over all sampled locations for each reading during the observation period ranged from 2.83 to 4.47 m (9.28 to 14.66 ft). On the average, about 31% of the monitored wells were dry during any given observation period. Observation period coefficients of variation (*CV*) (absolute value of ratio of standard deviation to mean) computed over the region ranged from 0.48 to 0.85. Example plots of water table depth and specific conductance [or electrical conductivity (*EC*) standardized at 25°C] for four representative wells are given in Figure 19. Similar to the conditions that were observed in the Upstream Study Region, the average observed water table depths generally increased over the dry period of April 2002 – March 2004, then began to decrease in the wetter year of 2004. Albeit during a drought year, the water table in summer 2002 was still less than 2.5 m (8.2 ft) deep under about 20% of the cultivated area.

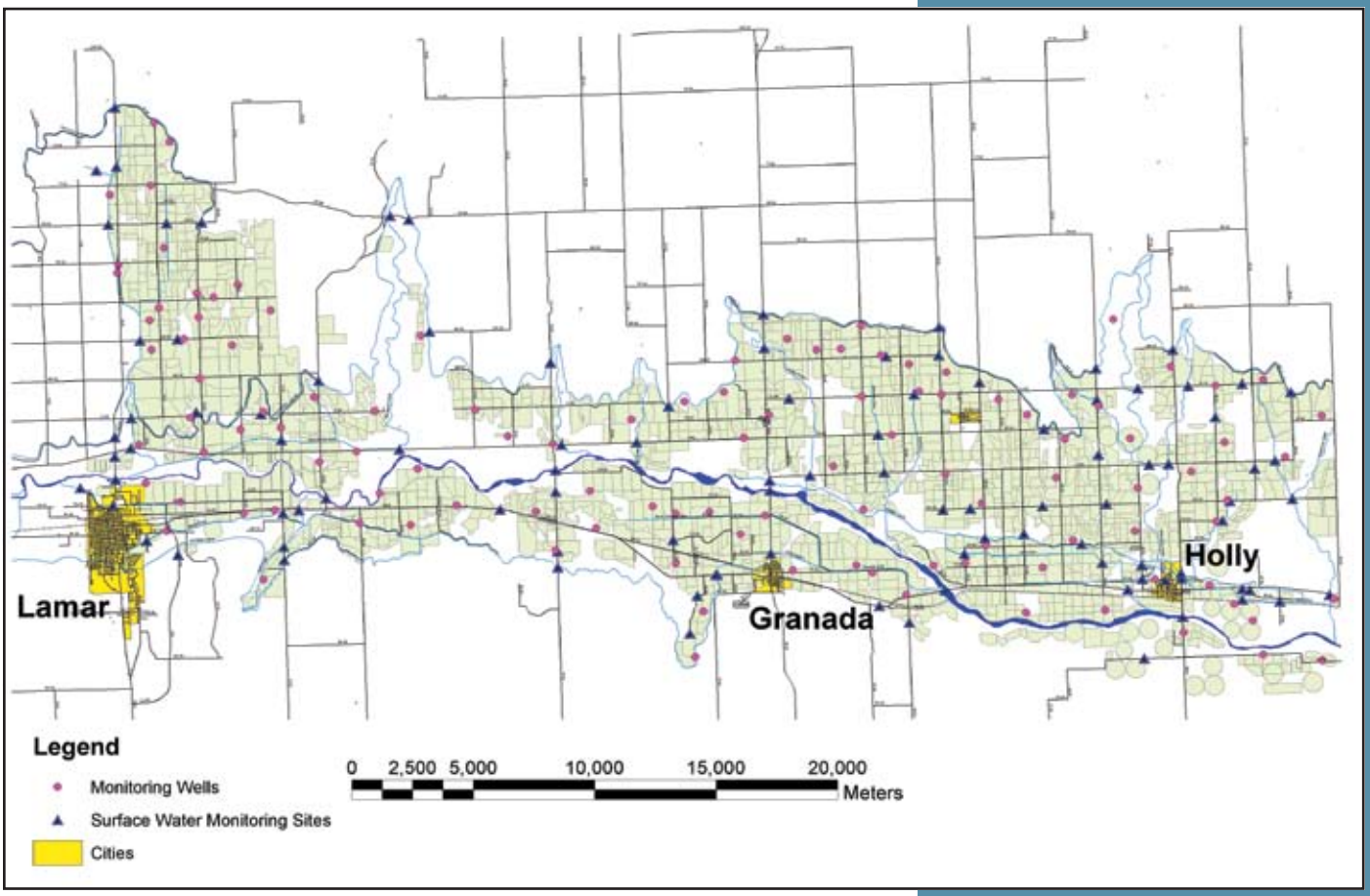


Figure 17. Downstream Study Region showing ground water and surface water monitoring sites.

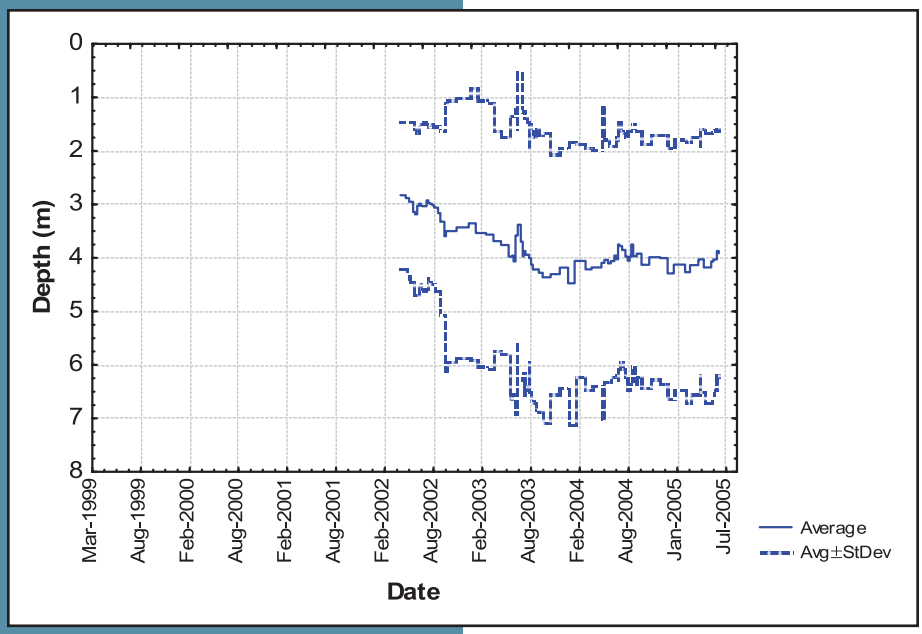


Figure 18. Observed average water table depths and range of variation in the Downstream Study Region over the period April 2002 – June 2005.

Horizontal hydraulic conductivity has been measured in the top 2 to 4 meters of the water table aquifer at 59 locations using slug tests. Results indicate values ranging from about 0.001 m/day to about 26.7 m/day. Hydraulic conductivity in the underlying sands and gravels ranges from about 80 m/day to about 370 m/day (Major et al. 1970).

A plot depicting the distribution of *EC* measured in the ground water monitoring wells over the period April 1999 – June 2005 is given in Figure 20. Measured salt concentrations in the water table aquifer were markedly higher in the Downstream Study Region, compared to those measured in the Upstream Study Region. Average measured *EC* in the monitoring wells over the period April 2002 – June 2005 ranged from 3.58 to 5.46 dS/m, corresponding to total dissolved solids (*TDS*) concentrations of about 3,081 to 4,699 mg/L. Period *CV* values ranged from 0.27 to 0.88. The relationship for converting *EC* into *TDS* in the Downstream Study Region was estimated using data from laboratory testing of about 273 ground water samples (*TDS* = 860.7*EC*, r^2 = 0.95).

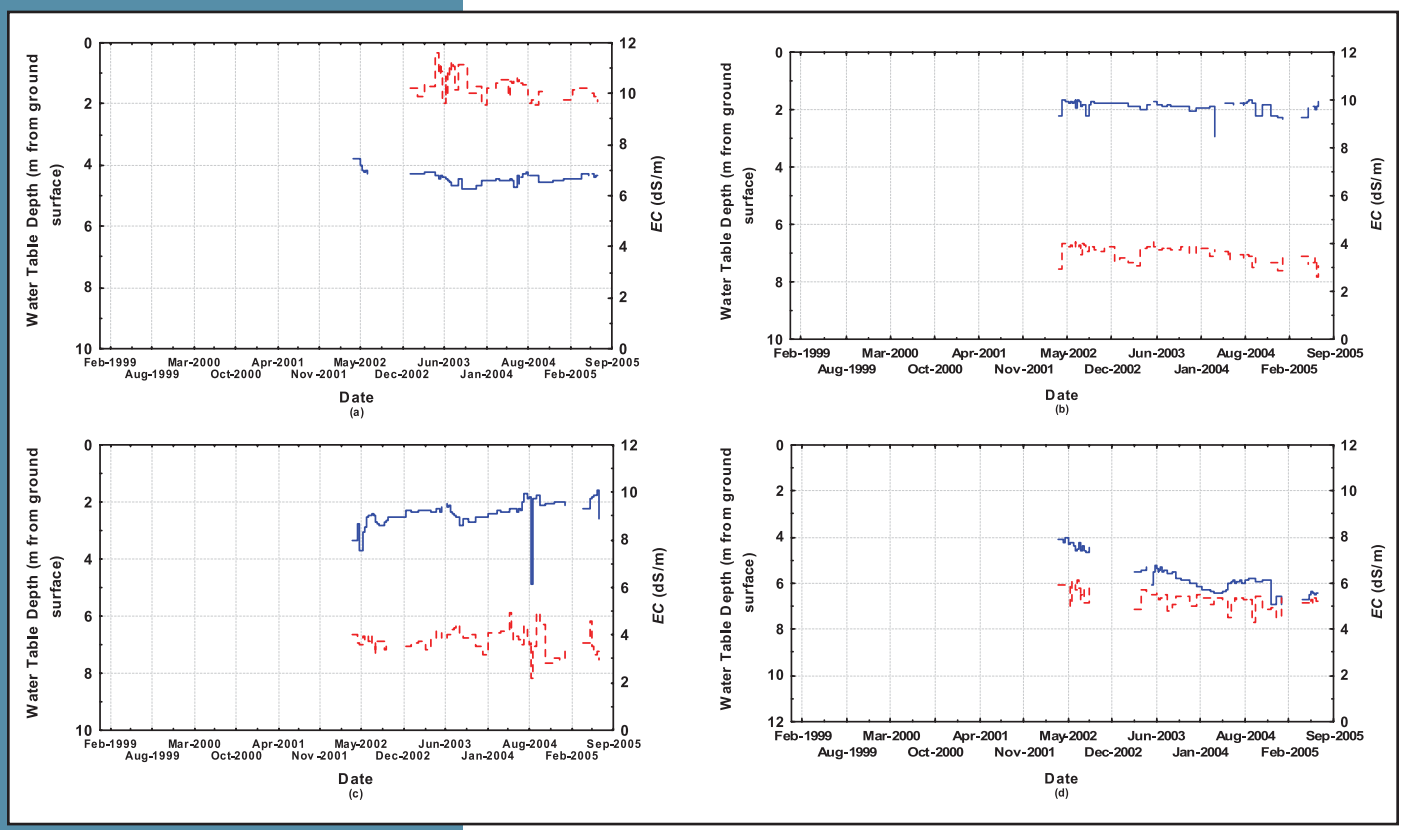


Figure 19. Example time series plots of water table depth and EC in (a) well 302, (b) well 331, (c) well 349, and (d) well 370 in the Downstream Study Region over the period April 2002 – June 2005.

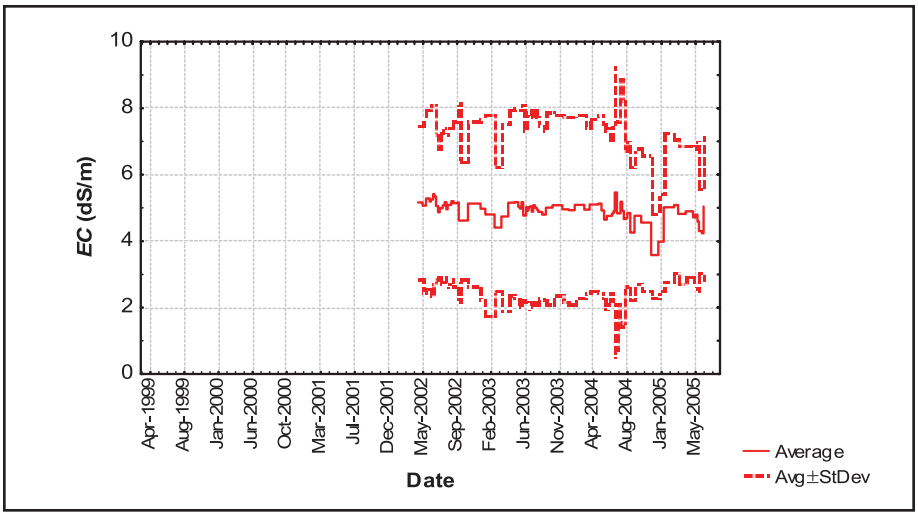


Figure 20. Observed average *EC* of the water table and range of variation in the Downstream Study Region over the period April 2002 – June.

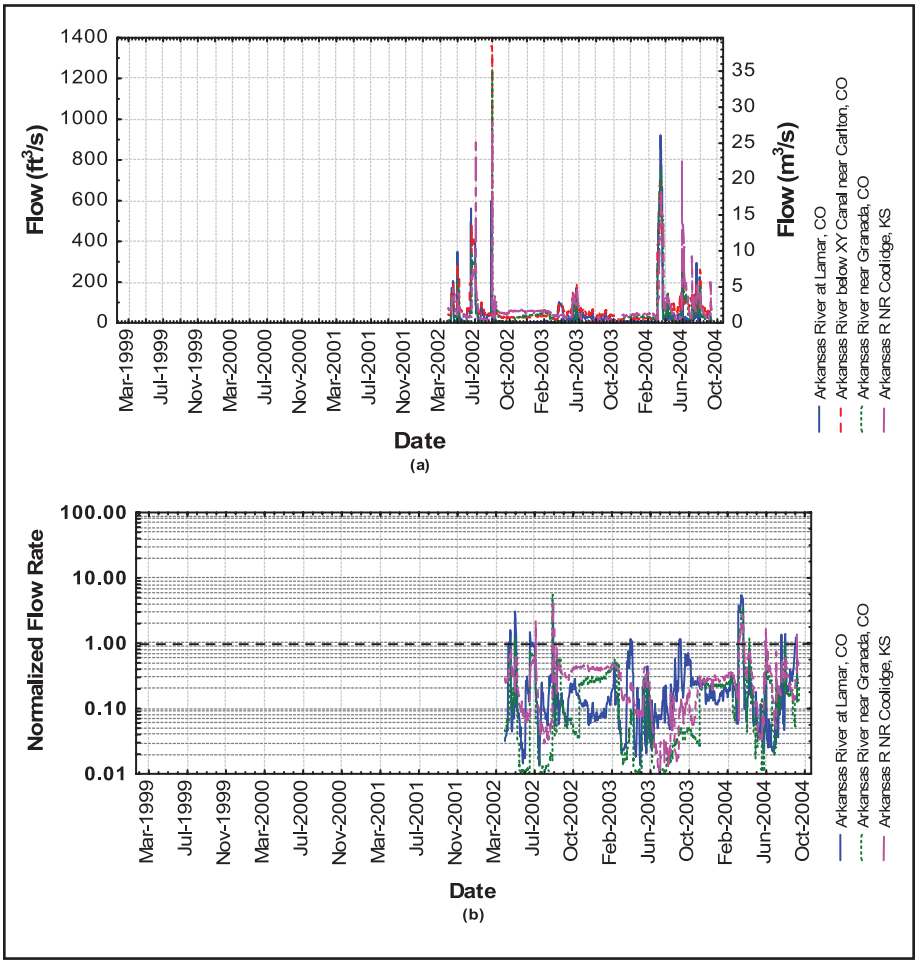


Figure 21. (a) Daily average flows measured at the four gauging stations on the Arkansas River in the Downstream Study Region over the period April 2002 – November 2004 (including the gauging station at Coolidge, Kansas, located about three miles downstream of the eastern boundary of the study region) and (b) daily average flows at three of the four gauging stations normalized by the corresponding mean flow rate for that day computed over the period 1975 – 2004.

Surface Water Data in the Downstream Study Region

The study period April 2002 – November 2004 spanned a very dry period in the Arkansas River watershed. This is illustrated in Figure 21, which shows plots of daily average flow over the study period in the Arkansas River at four gauging stations within the Downstream Study Region. For comparison to normative conditions, Figure 21 also shows a plot of the ratio of daily average flow at each gauging station to the mean daily average flow at the respective station over the last 30 years (since Pueblo Reservoir began operation). Figure 22 shows daily average diversions (expressed as flow rates and as flow depths over the respective command areas) to the six major canals that deliver direct flows to the Downstream Study Region. Also shown is a plot of the ratio of the daily average diverted flow to the respective mean daily average diverted flow over the last 30 years.

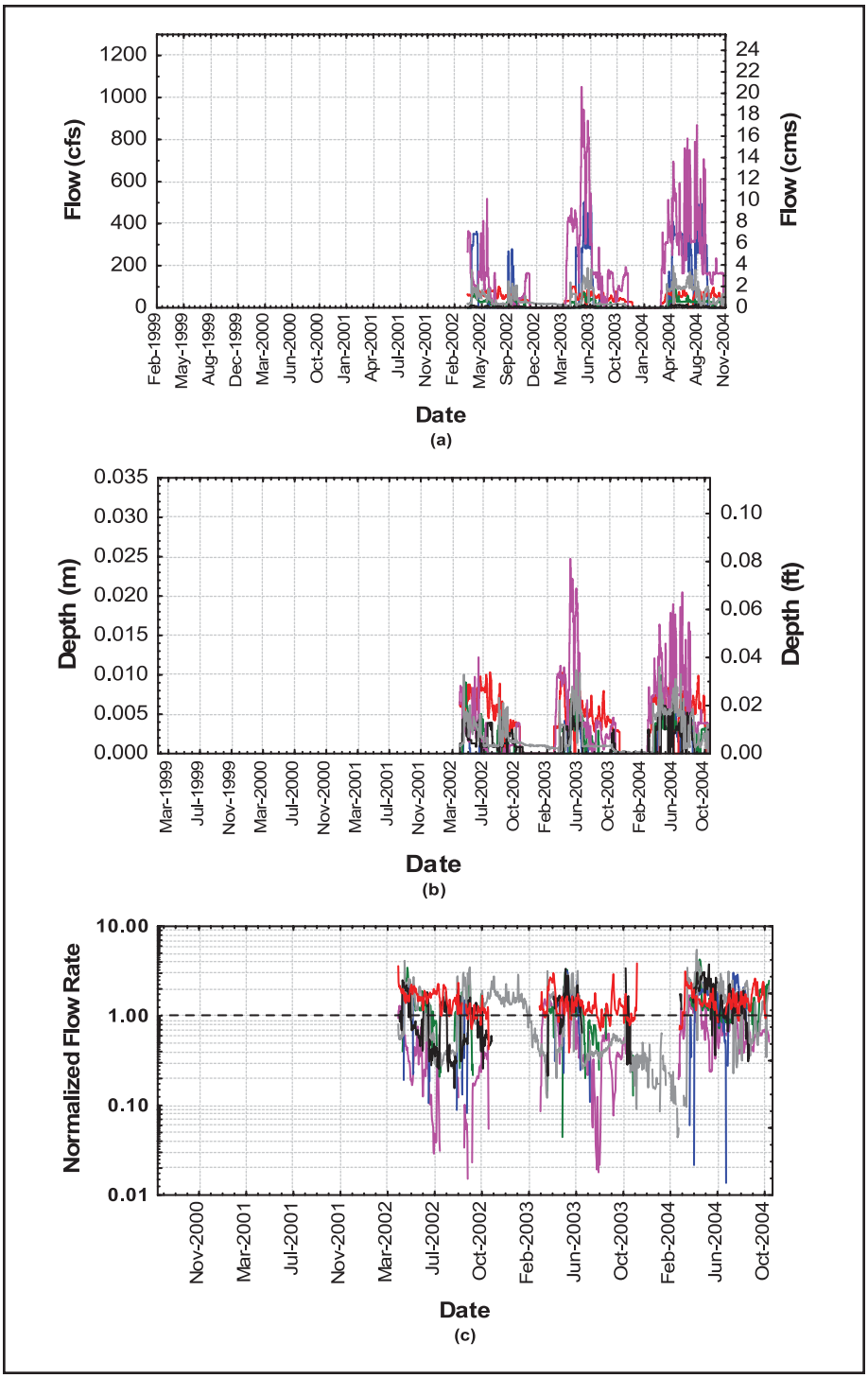


Figure 22. Daily average flow diversions to the major canals in the Downstream Study Region over the period April 1999 – November 2004, expressed as (a) diverted flow rate, (b) diverted flow depth over the command area of each respective canal, and (c) ratio of diverted flow rate to mean diverted flow rate over the period 1975 – 2004.

Surface water salinity has been routinely measured at 6 locations along the Arkansas River and at 94 additional locations within canals, drains, and tributaries in the Downstream Study Region. In general, concentrations were about two to four times greater than those measured in the Upstream Study Region. Average measured salinity of flows delivered by the five major irrigation canals into the region ranged from 1.61 dS/m (1,228 mg/L) to 3.63 dS/m (3,002 mg/L) in 2002, from 1.54 dS/m (1,169 mg/L) to 4.06 dS/m (3,396 mg/L) in 2003, and from 1.10 dS/m (807 mg/L) to 3.50 dS/m (2,884 mg/L) in 2004. Average salinity measured in the Arkansas River near the upstream and downstream ends of the study region was 3.19 dS/m (2,604 mg/L) and 4.11 dS/m (3,442 mg/L), respectively, during the 2002 irrigation season, 3.14 dS/m (2,560 mg/L) and 4.31 dS/m (3,626 mg/L) during the 2003 season, and 2.67 dS/m (2,141 mg/L) and 3.79 dS/m (3,148 mg/L) during the 2004 season. A separate *EC-TDS* relationship, derived from 105 field samples, was used for surface water ($TDS = 727.0EC^{1.1}$, $r^2 = 0.963$). The measured *EC* at each of six sampling locations along the Arkansas River within the Downstream Study Region is plotted for the period April 1999 – June 2005 in Figure 23.

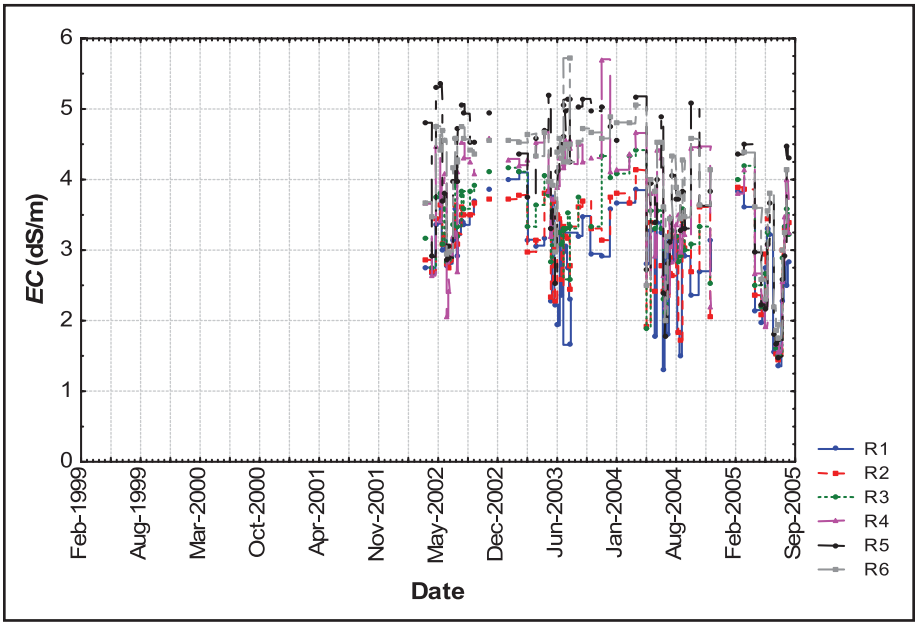
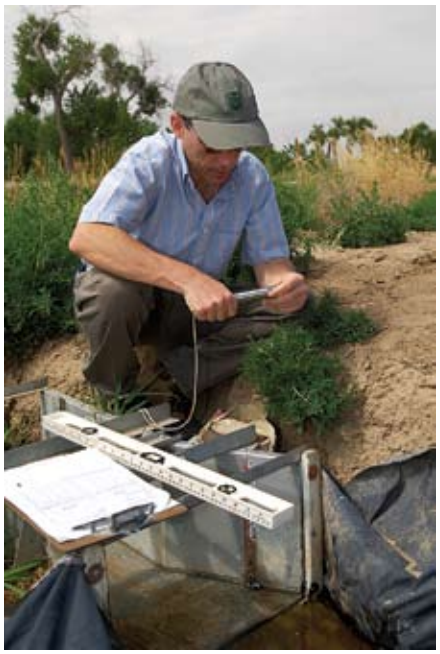


Figure 23. Measured *EC* at six sampling locations along the Arkansas River in the Downstream Study Region over the period April 1999 – June 2005 (sampling locations are labeled from R1 to R6 in upstream to downstream order with R1 located at Lamar and R6 located near Holly).

In 2005, the total number of fields on which irrigation practices were measured increased to 27, with 13 in the Upstream Study Region and 14 in the Downstream Study Region.



Canal Seepage Data in the Downstream Study Region

Inflow-outflow tests for seepage have been conducted in the Amity Canal, the Buffalo Canal, and the Lamar Canal. Seepage losses were found to range from about 0.003 m^3/s per km along the canal (0.2 ft^3/s per mile) to about 0.025 m^3/s per km (1.4 ft^3/s per mile).

Data on Irrigation Practices and Field Conditions in the Downstream Study Region

In the summer of 2005, irrigation practices were measured on 14 fields in the Downstream Study Region. A distribution of applied irrigation depths, surface runoff depths, and infiltrated depths measured for selected irrigations between May and mid-August in 2005 is shown in Figure 24. The average applied depth measured over these irrigation events was about 20.2 cm, and the average infiltrated depth was about 17.6 cm.

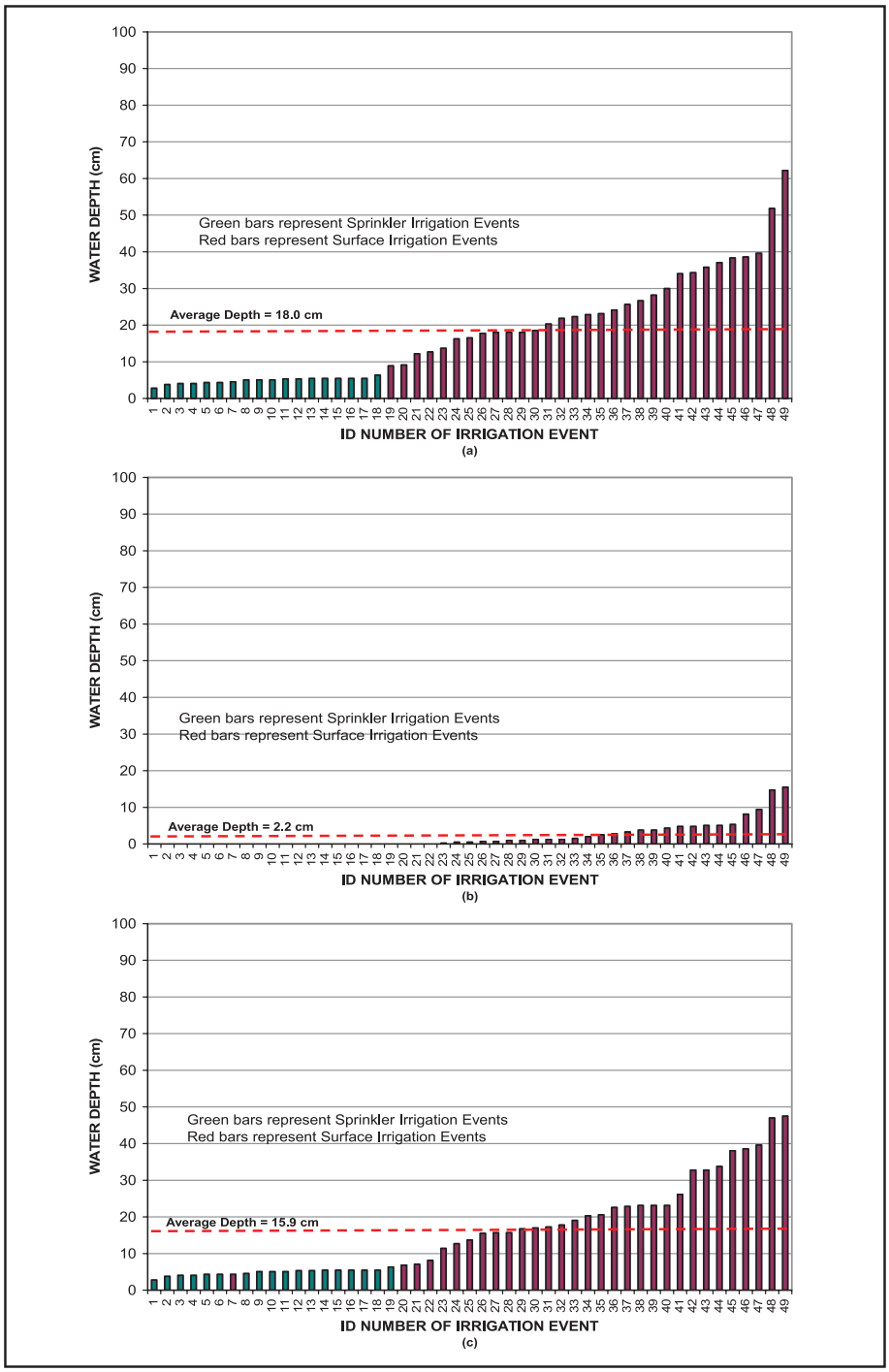


Figure 24. Distribution of (a) application depths, (b) surface runoff depths, and (c) infiltrated depths measured for selected irrigation events on fields in the Downstream Study Region during summer 2005.

Soil Salinity Data in the Downstream Study Region

Over the period 2002 to 2005, between 35 and 81 fields in the Downstream Study Region were surveyed in both the early and late parts of the irrigation seasons for soil water salinity (EC_e) using calibrated EM-38 meters. Relatively few fields could be successfully surveyed in late 2002 and in late 2003 due to dry conditions. A statistical summary of the results is given in Table 2. Over a similar period, EC_e values measured in the Downstream Study Region were found to be about 2 dS/m higher than those measured in the Upstream Study Region.

Table 2. Summary of Soil Salinity (as EC_e) Measured with EM38 Probes in Fields in the Downstream Study Region.

Season	Number of Fields Surveyed	Number of Locations Surveyed per Field			Average EC_e (dS/m) Measured over Field		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
Early 2002	81	21	125	70	3.41	13.88	5.69
Late 2002	38	29	128	79	3.69	15.17	6.37
Early 2003	69	26	137	69	3.36	12.75	6.50
Late 2003	35	33	168	72	3.17	10.00	5.96
Early 2004	77	10	168	79	3.36	14.78	6.39
Late 2004	74	30	127	66	3.40	15.67	6.03
Early 2005	79	30	134	75	2.28	10.30	5.59

About 161 selected calibration sites were sampled within monitored fields across the Downstream Study Region over the period May 2002 – August 2003. An additional 30 calibration sites were sampled in fields from May 2004 to August 2004 for use in testing the calibration equations. The respective bivariate and single variate calibration equations determined for the downstream site were (Wittler et al. 2006, Wittler 2005):

$$EC_e = 2.33 + 7.16 EM_v^{1.44} + 9.41 WC - 23.18\ EM_v\ (WC);\ r^2 = 0.54$$

and

$$EC_e = 2.59 + 4.48\ EM_v^{1.08};\ r^2 = 0.51$$

The values of EC_e measured in the laboratory for samples taken at different depths from the EM-38 calibration sites in the Downstream Study Region were grouped according to the depth to saline water table that was measured in the respective fields. Results are shown in Figure 25 which, similar to Figure 13 for the Upstream Study Region, reveals a clear relationship of increasing soil water salinity with decreasing depth to the saline water table.

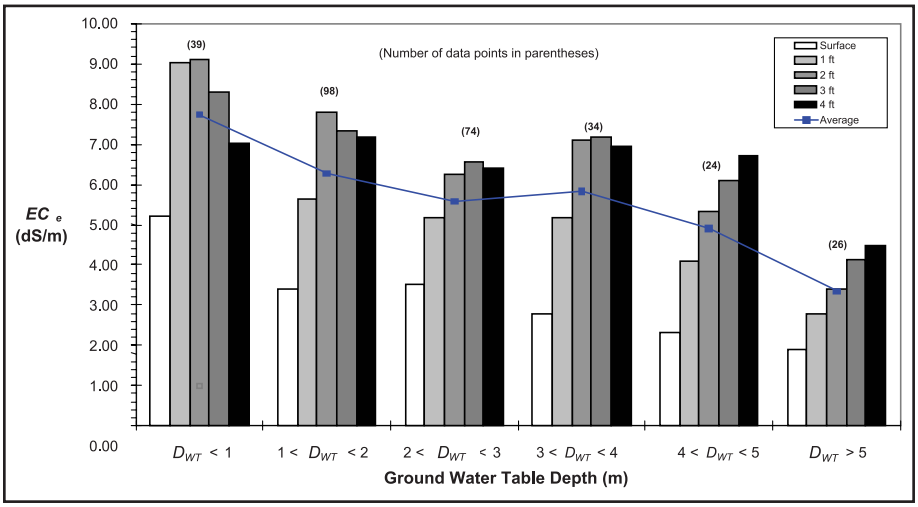


Figure 25. As water table depth decreases, soil water salinity tends to increase in samples taken at different depths from EM-38 calibration sites in fields in the Downstream Study Region.

Water quality data on dissolved Se concentration … in the ground water and surface water have been gathered 16 times over the period April 2003 – July 2005 in the Downstream Study Region.

Data on Dissolved Selenium in the Downstream Study Region

Water quality data on dissolved Se concentration (C_{Se}), dissolved Fe concentration (C_{Fe}), total recoverable Fe concentration ($C_{Fe\text{-}trec}$), pH, temperature, *EC*, dissolved oxygen (DO), oxidation-reduction potential (ORP), and concentrations of all major ions in the ground water and surface water have been gathered 16 times over the period April 2003 – July 2005 in the Downstream Study Region. Data were routinely collected from 21 surface water locations in the irrigation-stream system, including six locations in the Lower Arkansas River, and from 54 monitoring wells in the unconfined alluvial aquifer. An additional 36 monitoring wells and 40 surface water locations were sampled one time in the study region along with 19 additional monitoring wells located in the Lower Arkansas River Valley but outside the Downstream Study Region. Results from this water quality-monitoring network constitute one of the largest temporal and spatial data sets of this type ever compiled in an irrigated alluvial valley (Donnelly and Gates 2005, Donnelly 2005, Herting and Gates 2006, Mueller and Gates 2006). Data collection and analysis are expected to continue through April 2007.

Geographic information systems (GIS) and statistical analysis were used to characterize the spatial and temporal occurrence and severity of dissolved Se. Results indicated dissolved Se concentrations in the ground water ranging from less than 0.4 to approximately 3,760 µg/L. The median concentration was about 16 µg/L. Ground water Se concentrations were found to correspond well with geological formations in the region. Samples taken from wells located in alluvial material over the period April 2003 – November 2004 ranged from less than 0.4 to 166 µg/L with a median concentration of 12.2 µg/L, while samples taken from monitoring wells located in slopewash and shale-derived material ranged from less than 0.4 to 3,760 µg/L with a median concentration of 30.8 µg/L. A "box-and-whisker" plot, illustrating the variability in observed ground water Se concentration, C_{Se}, is given in Figure 26.

The C_{Se} values in water samples taken from the Arkansas River ranged from approximately 4.2 to 23 µg/L with a median concentration of about 9.4 µg/L. The U.S. Environmental Protection Agency's (USEPA) nationally recommended Se criterion for protection of aquatic life in streams is 5 µg/L. Figure 27 shows a "box-and-whisker" plot of observed C_{Se} in the Arkansas River. Linear and nonlinear relationships between C_{Se}, and more easily monitored indicators such as *EC* and ORP, and all major ions have been developed and evaluated. The average loading rate of Se from ground water, tributary, and direct surface return flow was estimated as about 15.3 kg per km (54.2 lb per mile) along the river in 2003 – 2004 and about 21.1 kg per km (74.7 lb per mile) in 2004 – 2005.

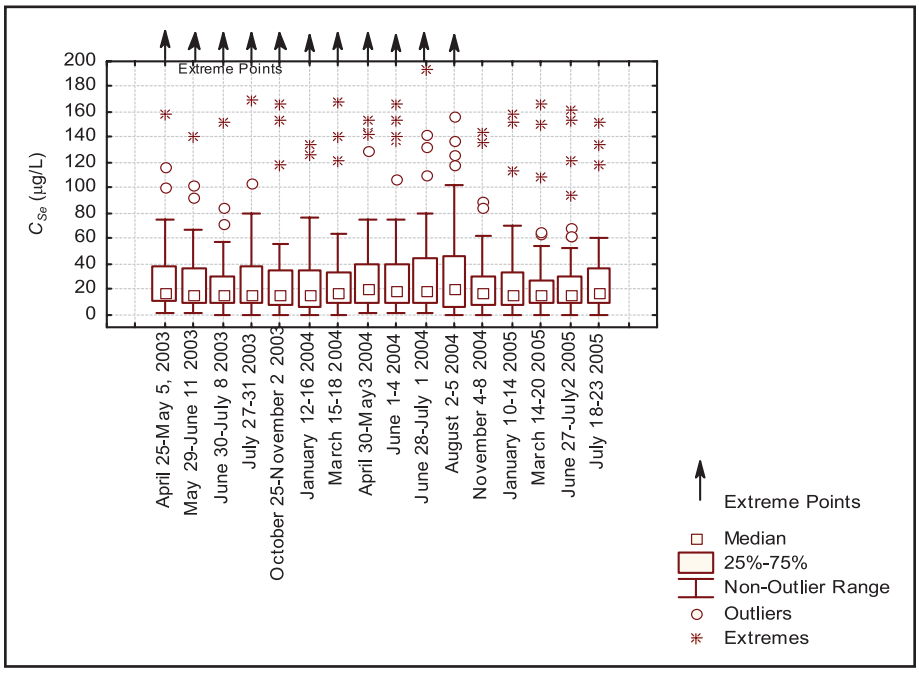


Figure 26. "Box-and-whisker" plot of Se concentration measured in ground water monitoring wells within the Downstream Study Region.

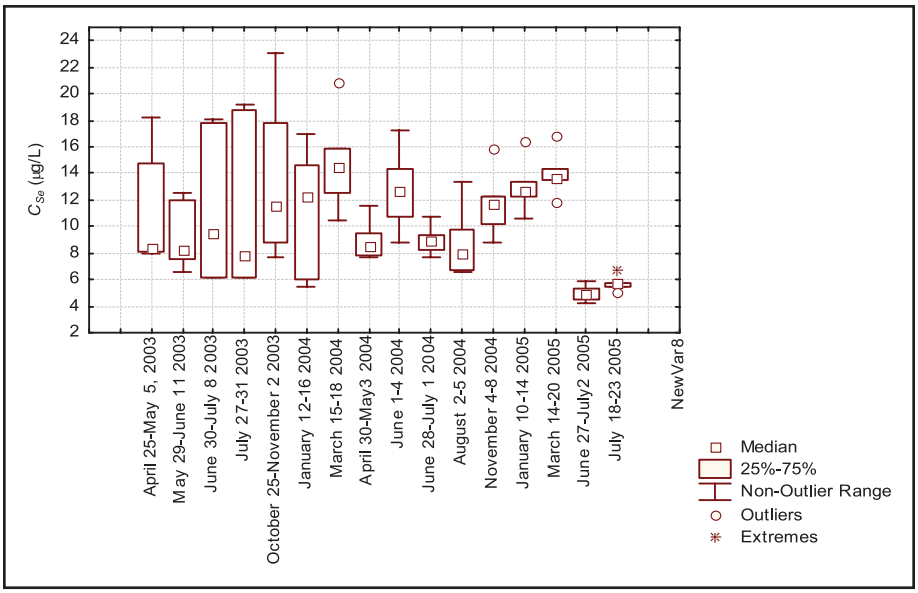


Figure 27. "Box-and-whisker" plot of Se concentration measured at locations in the Arkansas River within the Downstream Study Region.

REGIONAL-SCALE MODELING IN SEARCH OF PROMISING SOLUTIONS

Modified and calibrated Groundwater Modeling System (GMS) models have been developed to help assess the impact of various strategies for improving water and salinity management along the Arkansas River Valley. The GMS software package links the MODFLOW (McDonald and Harbaugh 1988) ground water flow model and the MT3DMS (Zheng and Wang 1999) contaminant transport model for solving finite-difference approximations of the flow and salt transport equations within a spatially referenced geographic information system (GIS) (BYU 1999). The model has been amended to include analyses of soil water content and salinity and subsurface drainage. Details of model development, calibration, and application are provided in Burkhalter and Gates (2005, 2006). GMS is being used to systematically predict, among other things, water table depth and salinity, soil water salinity, crop yield, rate and concentration of ground water return flows to the river, and nonbeneficial consumptive use under fallow land in response to a suite of discrete improvement alternatives that could be adopted in subregions within both of the modeled study regions. Alternative strategies under consideration include:

1. Reducing recharge from over irrigation by increasing irrigation efficiency through
   a. improved irrigation scheduling and monitoring of applied water volumes,
   b. reduction in irrigation set sizes to increase unit flow rates,
   c. land leveling,
   d. use of gated pipe, surge valves, drip irrigation, and sprinkler irrigation, and
   e. other structural/management measures to improve uniformity of applications and to reduce over-irrigation.

2. Reducing seepage from irrigation canals through
   a. polyacrylamide (linear-linked polymer) additives,
   b. soil liners with permeability reduced by amendments,
   c. buried plastic membranes, and
   d. other lining materials.

3. Increasing pumping rates from existing pumping wells with excess flows (above legal permit) routed through drains to the river.

4. Installing horizontal subsurface drains with
   a. alternative depths and spacing of relief drains,
   b. possible use of multiple depths and valving,
   c. alternative collection networks and pumping stations, and
   d. possible use of temporary storage of effluent for release to river at optimal times for river health.

5. Lowering of water surface elevation along the river by dredging of excess sediments from the river channel.
6. Eradicating invasive phreatophytes (Tamarisk) from along the river corridor.
7. Implementing combinations of the above strategies.

Dynamic modeling of the Upstream Study Region (weekly time steps) has predicted impacts of 38 different interventions to date, including reduced recharge through increased irrigation efficiency, decreased canal seepage, installation of subsurface drains, increased well pumping, and combinations of these alternatives (Burkhalter 2005, Burkhalter and Gates 2005, Gates et al. 2005, Burkhalter and Gates 2006). Results suggest that substantial reductions in water table elevation and in salt loads in return flows to the river could be achieved. For example, a reduction of recharge from over-irrigation by 50%, combined with a reduction of canal seepage by 90% and subsurface drainage (2.5-m depth and 50-m spacing) on selected fields would have reduced the average water table elevation by about 1.78 m over the period 1999 – 2001 (Figure 28) and the average soil water salinity by about 580 mg/L (Figure 29). A 30% reduction in recharge with 50% reduction in seepage losses from canals was predicted to result in about a 0.78 m reduction in average water table elevation and 390 mg/L reduction in average soil salinity. Reductions in the salt load in return flows to the river under these two alternatives were predicted at about 40% and 20%, respectively. Predicted reductions in salt load to the river in the Upstream Study Region under alternative improvement strategies are illustrated in Figure 30. The average annual salt load to the river in the Upstream Study Region was estimated at about 17,200 kg per ha (7.7 tons per acre) of valley land (including both irrigated and nonirrigated parcels) over the period 1999 – 2001. This is equivalent to about 5.3 kg/week per hectare (4.7 lbs/week per acre) per km along the river. Though reduced salt load is a perceived benefit, the timing of reductions in ground water return flows (i.e., improved surface and subsurface drainage management) must be carefully considered to evaluate potential impacts on river flow rates available to downstream users and at the state line, as discussed in a preceding section. Relative crop yield, as affected by decreased soil water salinity, was predicted to increase on the average between 1 and 7 percentage points over all considered improvement alternatives and by up to 10 percentage points by the end of the modeled period. Results also suggest that nonbeneficial consumptive use from shallow water tables under fallow fields [estimated as high as 50,000 acre-ft in the Upstream Study Region over the period 1999 – 2001 (Burkhalter and Gates 2005)] might be reduced, perhaps resulting in significant real-water savings of up to several thousand acre-feet under these alternatives.

The GMS model of ground water flow for the Upstream Study Region is being enhanced with updated and refined topographic, crop survey, evapotranspiration, and irrigation water delivery data. The enhanced model will be calibrated and applied to a period extended from the current period of April 1999 – October 2001 to the period April 1999 – October 2004. This will allow examination of the effects that improvement strategies would have had on conditions during the drought period extending from 2002 through 2004.

Models have been developed to help assess the impact of various strategies for improved water and salinity management along the Arkansas River valley.

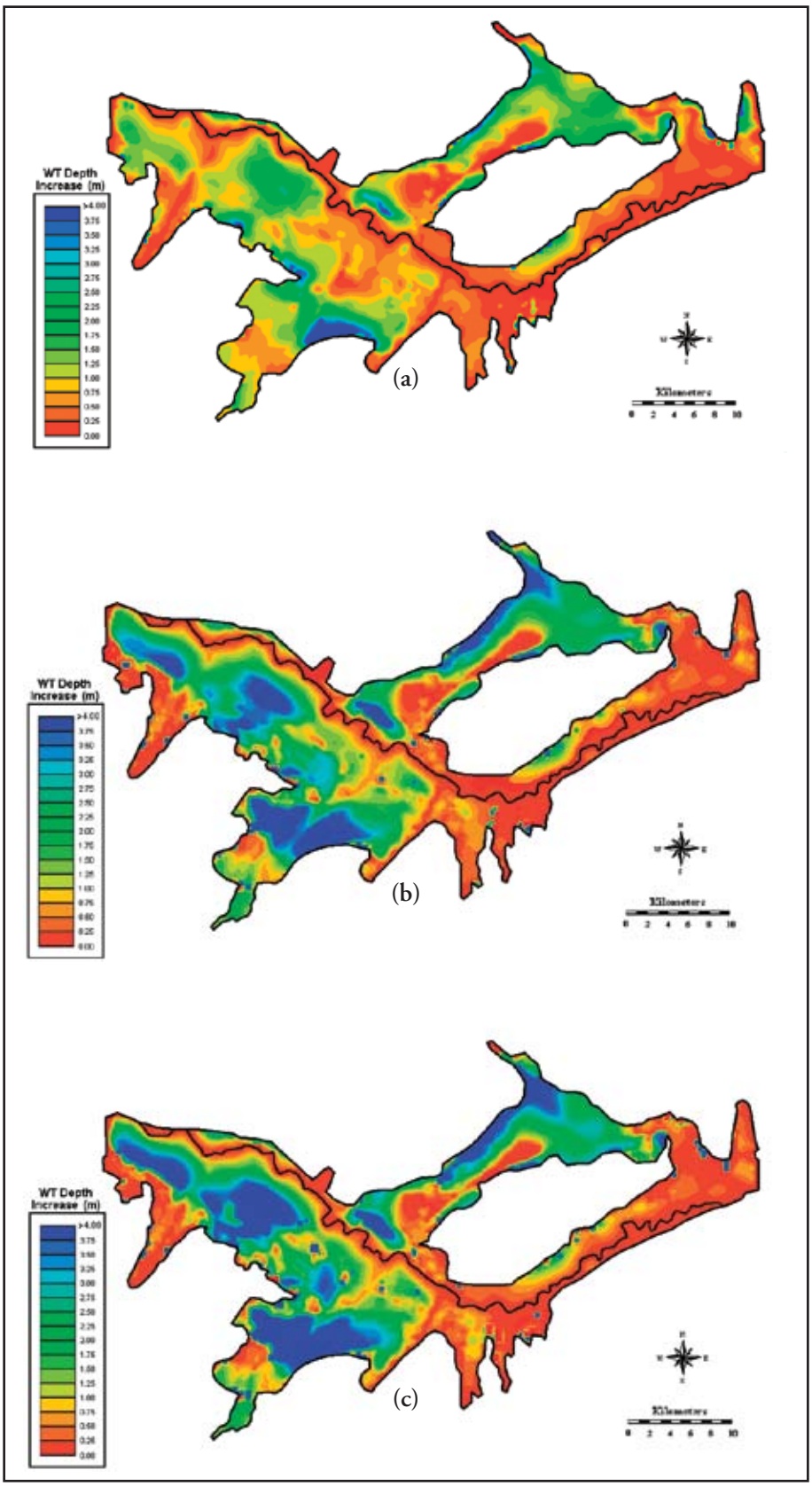


Figure 28. Average *change* in water table depth predicted by calibrated simulation model over irrigation seasons (a) 1999, (b) 2000, and (c) 2001 in the Upstream Study Region for reduction in recharge from over-irrigation by 50%, reduction in seepage losses from canals by 90%, and subsurface drainage installation (2.5-m depth, 50-m spacing) on selected fields.

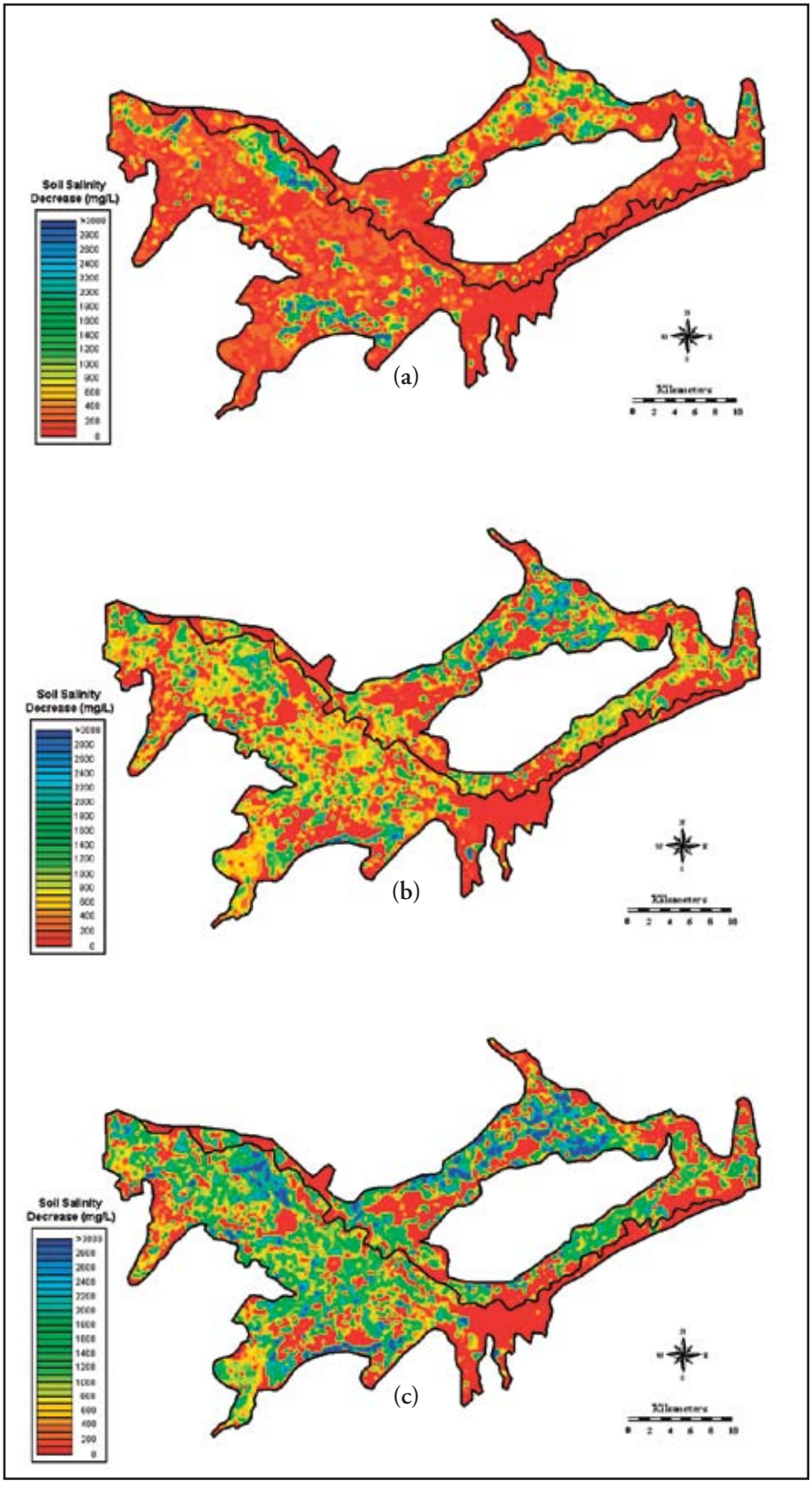


Figure 29. Average *change* in soil water salinity predicted by calibrated simulation model over irrigation seasons (a) 1999, (b) 2000, and (c) 2001 in the Upstream Study Region for reduction in recharge from over-irrigation by 50%, reduction in seepage losses from canals by 90%, and subsurface drainage installation (2.5-m depth, 50-m spacing) on selected fields.

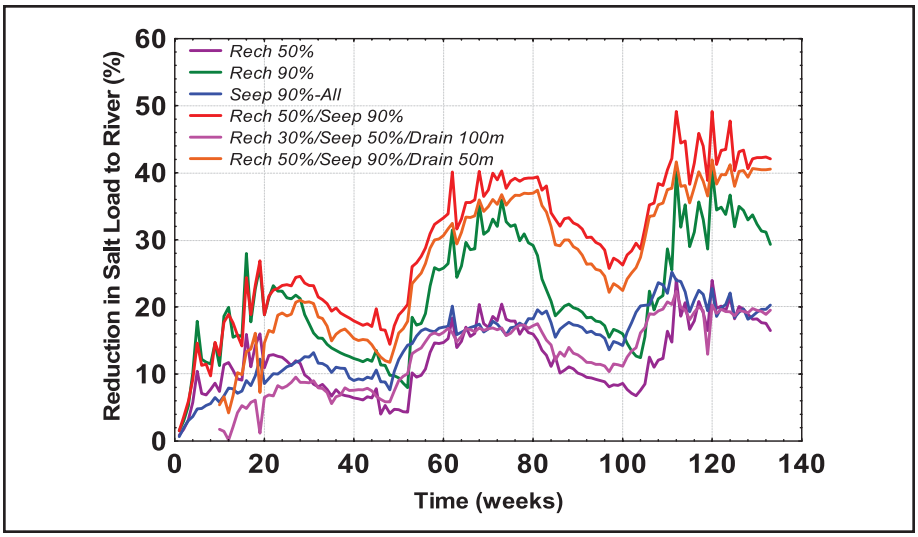


Figure 30. Percent reduction in salt load to the river in the Upstream Study Region under selected solution alternatives over the modeled time period (amended from Burkhalter and Gates 2006).

Preliminary results also have been obtained from the GMS model applied to the Downstream Study Region. As in the Upstream Study Region, the model has been initially applied using a steady-state flow and mass transport approach that estimates long-term conditions under average field characteristics. Calibrating the model for dynamic flow and transport conditions is made easier by first obtaining calibrated values of model parameters under steady-state conditions and then using these values as initial estimates to be refined under dynamic conditions. Figure 31 shows steady-state water table depth color gradients for 2002 average conditions. Development of a transient model for the period April 2002 to October 2004 is underway. Modeling of Se transport in the system for the period April 2003 – April 2006 also has been initiated.

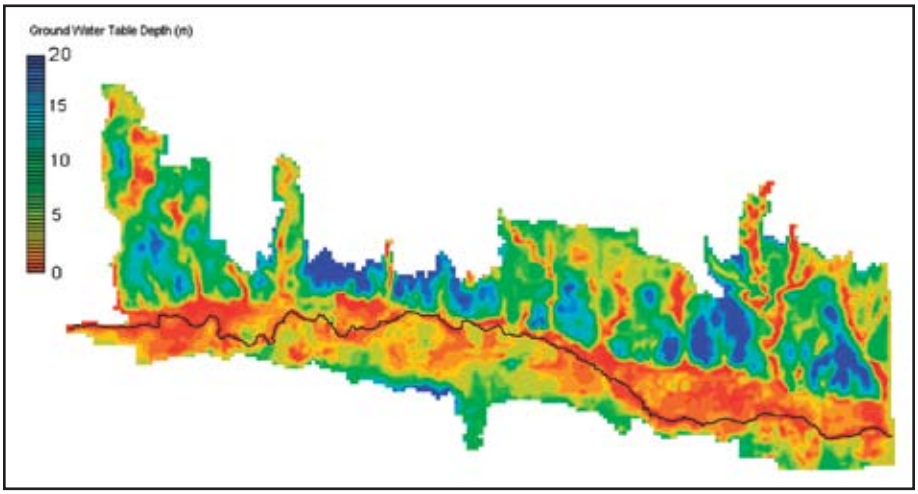


Figure 31. Color gradients of water table depth in the Downstream Study Region predicted by steady-state simulation of 2002 average conditions.

To date, model predictions have indicated that reductions in irrigation recharge and canal seepage could result in reduced soil salinity, increased crop yields, reduced nonbeneficial consumptive use under fallow fields, and lower return flow and salt loads to the river. It is essential to realize, however, that recharge and seepage reductions must be judiciously managed and must not be excessive. A minimum amount of irrigation in excess of that stored for crop ET will be needed to leach harmful salts below the crop root zone, as noted by Burkhalter and Gates (2006) in their investigation of recharge reduction strategies using the regional scale model. This will be especially important to keep in mind in cases where highly efficient drip and sprinkler irrigation systems are adopted to replace surface irrigation. Also, though saline high water tables can be detrimental to crop productivity and environmental quality, they can serve as an important subsurface storage reservoir, providing upflux of water to the soil root zone during brief or extended periods of drought. Thus, further study will be conducted to estimate the proper balance to achieve over the Arkansas River Valley between a water table that is too high and a water table that is too deep.

FIELD-SCALE MODELING TO TEST PRACTICAL IMPLEMENTATION OF SOLUTIONS

Improvement strategies considered in the regional-scale models prescribe field-averaged reductions in over-irrigation and in drainage design features. The practicality of actually achieving these targets, and their likely impact, at the field scale must be examined. As part of the multi-scale modeling effort, the Colorado State University Irrigation and Drainage Model (CSUID) has been enhanced and applied to predict field-scale effects on water table depth and salinity, soil water salinity, and crop yield associated with irrigation rates, quality and timing, and drain depths and spacings to achieve regional-scale targets. Such modeling is necessary to ensure that regional-targets actually can be implemented effectively at the field scale. CSUID (IDS 1994) has 3-D capabilities that make it an effective tool for modeling complex interactions in the soil profile. It includes irrigation scheduling, root growth calculation, flow and transport in the unsaturated and saturated zones, drain discharge and effluent water quality, and crop yield estimates (Garcia et al. 1995) and has been substantially enhanced under the current project (Gillham 2004).

A surface-irrigated field in the Downstream Study Region has been used for CSUID model calibration, for sensitivity analysis, and for evaluating management alternatives. Field data sets were gathered between 2001 and 2003. Water table depth and salinity and potential evapotranspiration were measured weekly during these periods. Soil water salinity was measured three times each season. Horizontal hydraulic conductivity of the shallow aquifer was measured at each well to obtain a distribution throughout the field, and deep aquifer conductivity was estimated from regional data. CSUID was calibrated using ASTM Standards D 5981-96, D 5909-94, and D 5610-94 as general guidelines. A 20-meter cell size was chosen to perform the calibration modeling. Figure 32 shows example model output for the considered field. The field grid was built in CSUID according to the dimensions of the bounding rectangle for the sample field. Calculations described by McCuen (2003) were employed to quantify parameter sensitivity using the calibrated model. Results of the sensitivity analysis show that the model is most sensitive to soil-water retention curves and to the value of shallow hydraulic conductivity. The model is least sensitive to deep hydraulic conductivity.

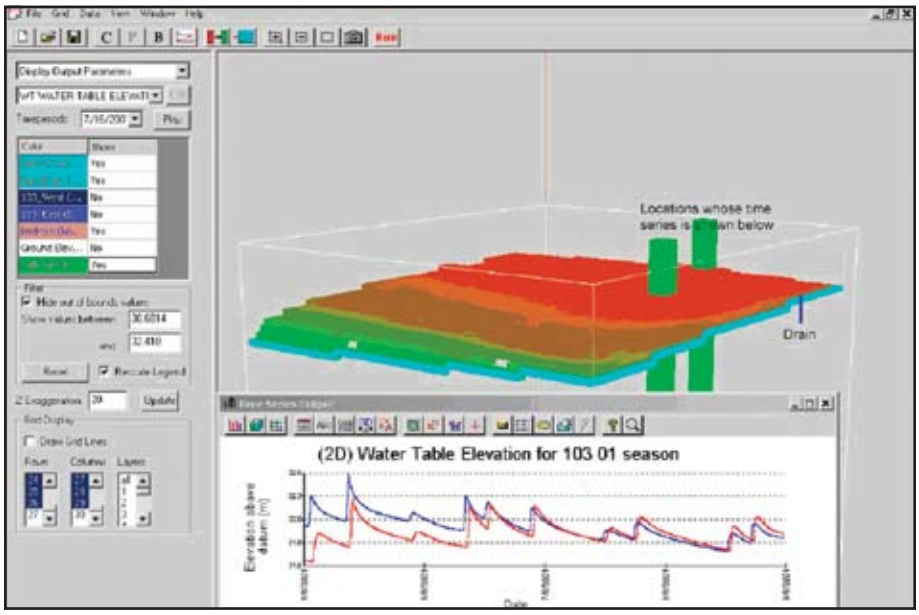


Figure 32. Example output of CSUID for a field in the Downstream Study Region where a surface drain was installed to help alleviate problems with waterlogging and salinity.

BASIN-SCALE MODELING TO EXAMINE RIVER EFFECTS AND COMPATIBILITY WITH STATE AND INTERSTATE LAW

A Spatial Decision Support System (GeoDSS) has been designed to assist with the assessment of water management options across the entire river basin scale from the Pueblo Reservoir to the Colorado-Kansas state line. The GeoDSS integrates geographic information systems (GIS), surface and ground water quantity and quality models, and Artificial Neural Networks (ANN) into a robust tool for conjunctive surface and ground water modeling. ANNs are "massively parallel interconnected networks of simple elements and their hierarchical organizations which are intended to interact with the objects of the real world in the same way as biological nervous systems do," or simply a "system of interconnected computational units" (Kirby 1993). GeoDSS is a geo-spatio-temporal database-centered system, built in the ArcGIS environment with seamless interaction between the components. Figure 33 illustrates the structure and the interaction between the GeoDSS components.

The database has been assembled with detailed information from the USGS, the U.S. Army Corps of Engineers, the Colorado Division of Water Resources, USDA NRCS, the National Oceanic and Atmospheric Administration (NOAA), CSU field data, and manually processed data. It contains spatial data such as hydrographic information, a digital elevation model (DEM), soil types, land use maps, irrigated field maps, aerial photos, satellite images, and surface and ground water monitoring points. Water rights data are associated with river diversion structures (water users). The temporal database contains measured time series of flow rates and water quality characteristics at USGS and Colorado Division of Water Resources gauging stations, at pumping wells, and at diversion structures. Daily reservoir storage volumes are included for the main reservoirs. Spatial-temporal information is stored in the database from the regional-scale GMS model results (MODFLOW/MT3DMS) and from Doppler radar based precipitation (NEXRAD) data.

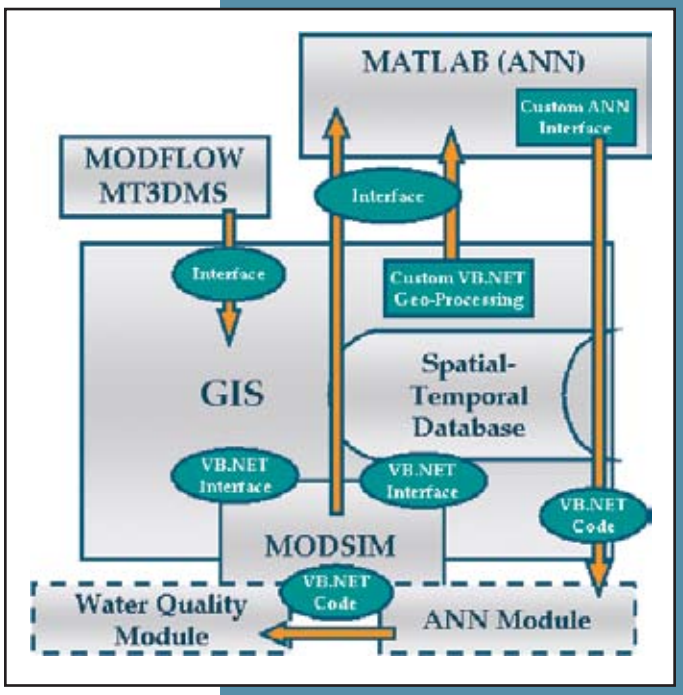


Figure 33. GeoDSS structure diagram.

Basin-scale modeling is achieved by integrating the MODSIM model (Labadie et al. 2000), a Water Quality Module, and an ANN module. The integration of these elements can be pictured as an enhancement of MODSIM using ANN predictions for complex return flow and salt loading processes and simultaneous water-quality modeling tied to the MODSIM flow solutions.

Stream-aquifer interaction is a difficult process to address in a river basin-scale model. Simplified, lumped stream-aquifer response models generally are incorporated into river basin models but fail to adequately capture the complex dynamic and spatial characteristics (Fredericks et al. 1998). An innovative methodology has been developed to represent the basin-scale stream-aquifer interaction modeling based on detailed regional-scale ground water modeling (Triana et al. 2003, 2004, 2005, 2006). This methodology trains ANNs to find relationships between spatially distributed system state variables that can be measured/estimated at the basin-scale and the spatially distributed aquifer response to stresses as embodied in the regional-scale GMS ground water model. In addition, this methodology allows the incorporation of regional-scale GMS model results into the GeoDSS for evaluating management options over the entire river basin. Embedding the ANN within the basin-scale decision tool eliminates the computational burden of directly incorporating realistic finite-difference models such as GMS over the entire basin. A VB.Net interface has been developed to process in GIS the enormous quantities of spatial-temporal data required for this analysis. The interface is docked into ArcGIS software (ESRI, Inc.), allowing the user to select options and data sources to build datasets for ANN training and for consequent basin-scale modeling.

The Lower Arkansas River has been divided into segments of approximately 15-km length. Adjacent areas to the river segments within the alluvial valley have been delineated following the corresponding sub-watersheds (Figure 34). The explanatory variables are physical characteristics within the sub-watersheds of the system that provide information concerning known system states for use in predicting the stream-aquifer interaction. They are grouped into area buffers to capture the spatial variability. The area buffers are constructed inside the river-adjacent areas defined relative to their distance from the stream segment at 1.5, 3, and 4.5 km (Figure 34). The spatial variables within the sub-watersheds used to predict the target return-flow phenomena are canals

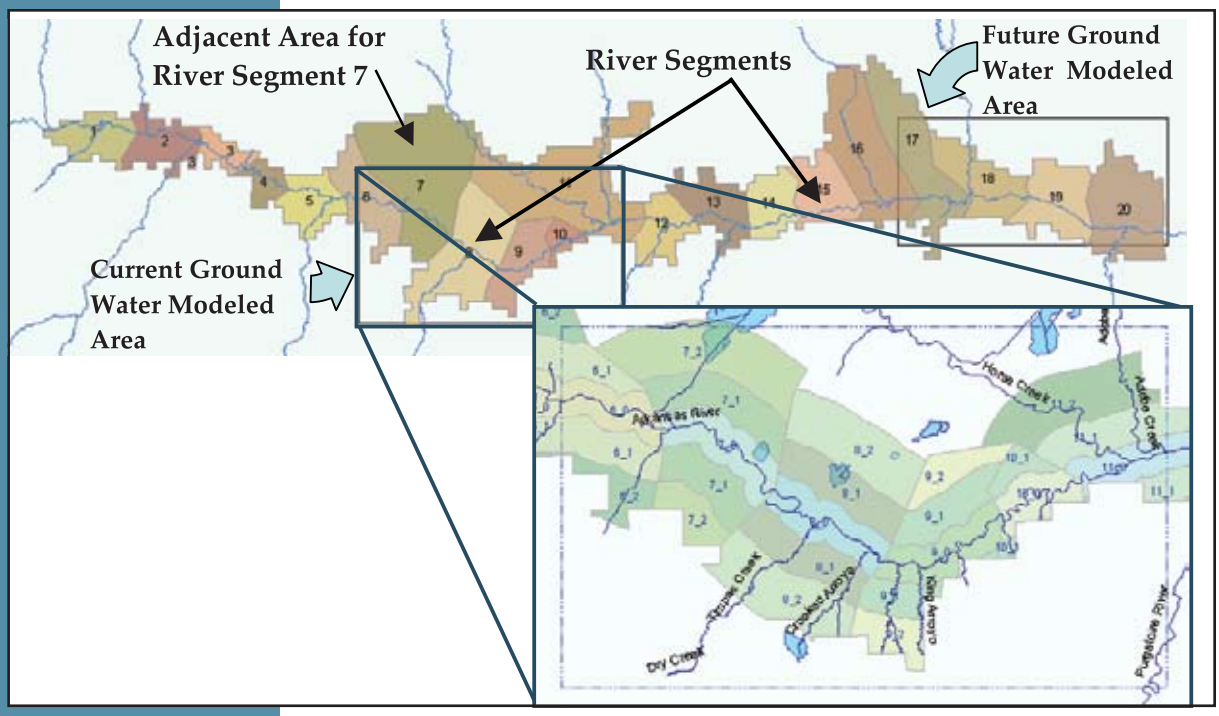


Figure 34. Modeling of river segment adjacent areas and area buffers along the Arkansas River.

(length, area, and elevation), water bodies (area and elevation), irrigated area, river elevation, area buffer average elevation, and bedrock elevation. Spatial temporal variables used to explain the return-flow phenomena are pumping wells, river flow, potential water applied to the irrigated area, and precipitation. The target return-flow phenomena are the total river depletion, total river accretion, and salt load to the river for each modeled river segment. These values are obtained from combining the geo-referenced MODFLOW/MT3DMS output for all the finite difference cells in the river segment. A dataset is built for each modeled time step using the developed interface in GIS. Using the baseline scenario transient model described above and the modeled regional-scale improvement strategies (Burkhalter 2005, Burkhalter and Gates 2005, 2006), more than 22,000 datasets have been constructed to date.

A radial basis artificial neural network (RB-ANN) has been trained to predict net return flows and the salt loads to the modeled river segments. In this case, data from all of the modeled areas were included in the ANN training. Results indicate a reasonable ability to predict more than 26,000 modeled values using only 400 training datasets. The coefficient of determination (r^2) was 0.95 for the training and 0.94 for performance testing. The average residual error from the testing prediction was 8.7 [(m^3/week) per meter length along the river], with a standard deviation of 37.5 (m^3/week)/m. Figure 35 shows the comparison between the calculated versus modeled net return flow for the training and testing of the RB-ANN, trained using all modeled areas.

Estimation of the ANN prediction error in the stream-aquifer interface modeling when using the trained RB-ANN in non-modeled areas is based on several ANN training scenarios within the modeled area, isolating one region at a time from the training and then analyzing predictions and errors on the isolated areas. The assumption is that statistics on the predictions for these isolated areas are representative when applying the ANN to the vicinity of the modeled areas. It has been found that a more realistic evaluation of the ANN performance occurs when the number of modeled areas is increased. Figure 36 shows an example of a performance test on Area 6 using an RB-ANN trained on the remaining modeled areas.

MODSIM provides great flexibility to accommodate complex operational aspects and provides the tools for realistic water resources systems simulations (Fredericks and Labadie 1995). In addition, the modular design of MODSIM Version 8 (Labadie 2005) allows integration with other environments and models. MODSIM provides the tools to develop custom graphical interfaces and geo-referenced water resources system elements. Geometric networks have been constructed in ArcGIS™ to develop a geo-referenced MODSIM Model (GeoMODSIM). The object-oriented software development in MODSIM fashion allows linkage of model data to system elements in

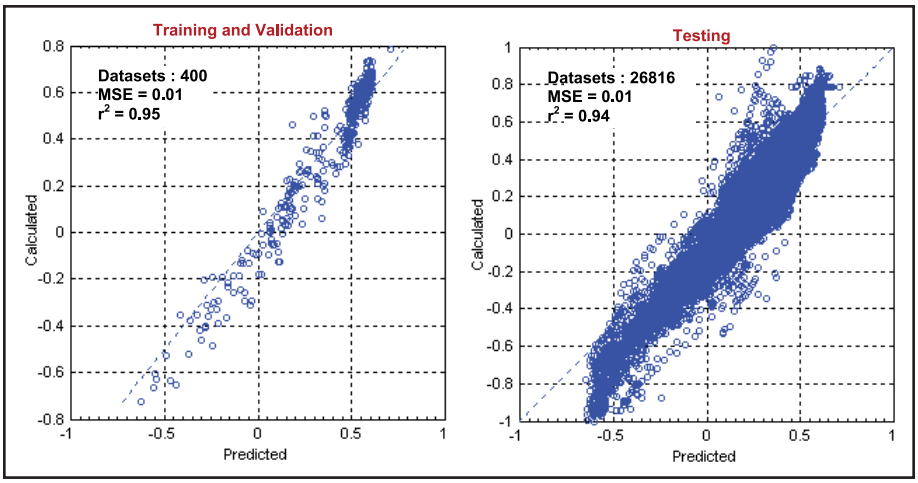


Figure 35. RB-ANN training and testing using all the modeled river segments and modeled improvement strategies (amended from Triana et al. 2005).

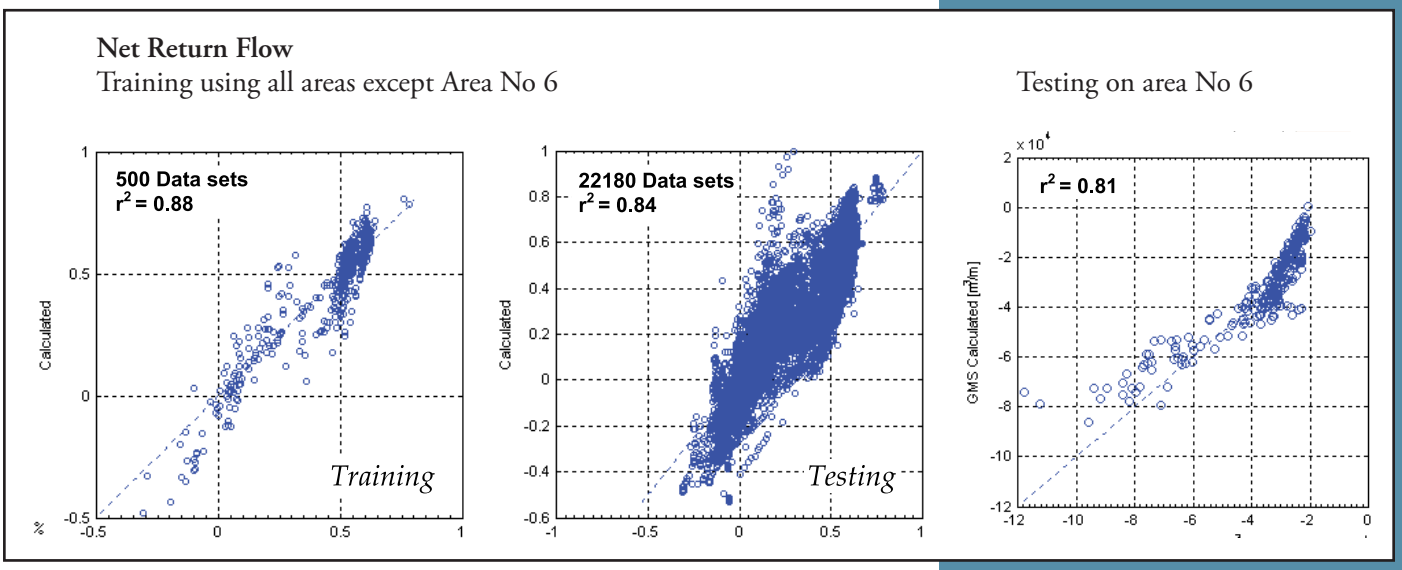


Figure 36. Example of the RB-ANN performance testing outside of the training areas (amended from Triana et al. 2005).

the geo-database. MODSIM allows development of custom applications in the Microsoft .NET framework in which modules can be attached and integrated with the model engine and solution.

The hydro-network of the Lower Arkansas River Basin is represented by a network of interconnected nodes representing reservoirs, system water demands, monitoring stations, points of diversion, and collections of surface drainage locations. The topology and infrastructure of the system is represented using a functional ArcGIS™ geometric network (Figure 37). ArcGIS™ geometric networks contain geometry and location of edges and nodes, in addition to connectivity information between edges and junctions and rules of behavior (such as which classes of edges can be connected to a particular class of junction or to which class of junction two classes of edges must be connected). ArcMap facilitates the construction of the hydro-network, and its tools facilitate the setting of flow directions and checking for connectivity errors as well as for integrity of the network.

GeoMODSIM has been implemented to bring together the advantages of spatial distributed information and MODSIM network flow modeling. The GeoMODSIM graphical user interface is integrated into the ArcMap environment. Tools have been developed to provide linkage and synchronization between the GUI/geometric network and the model, provide access to the model objects data entry user dialogues (Figure 37), and provide model output display directly from the geometric network elements in ArcMap (Figure 38). GeoMODSIM builds the model

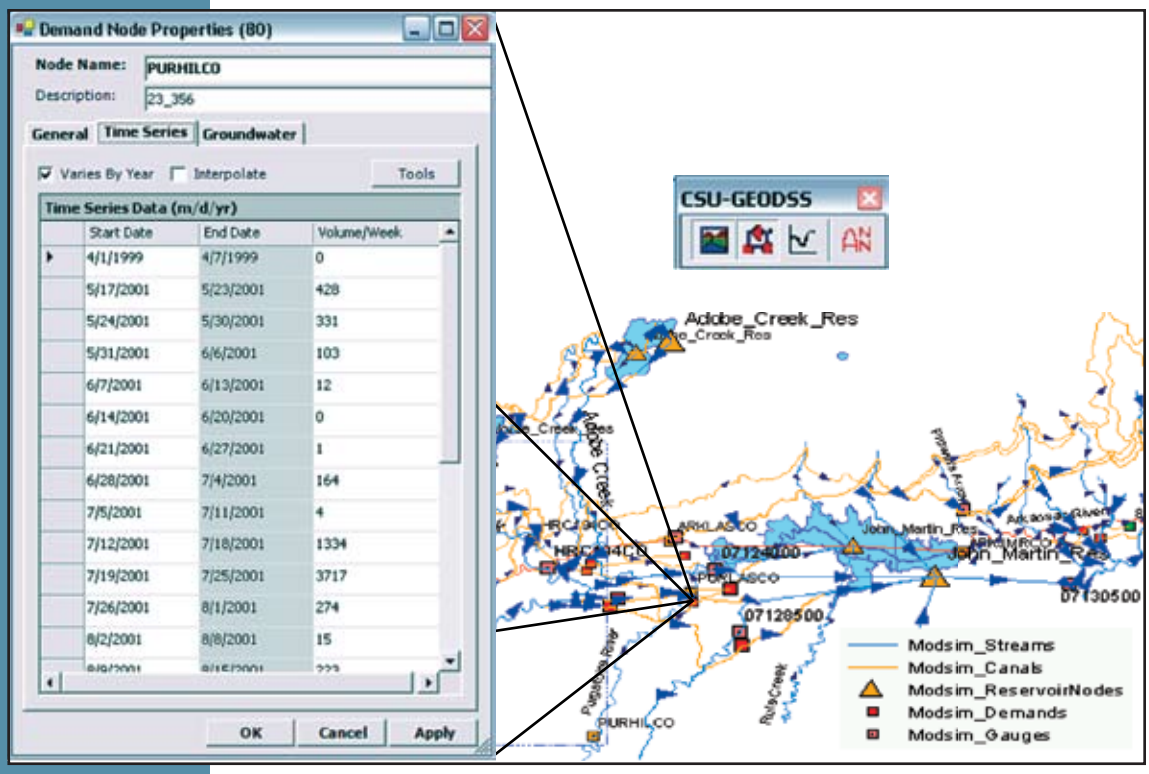


Figure 37. ArcGIS geometric network representing a portion of the Lower Arkansas River Basin.

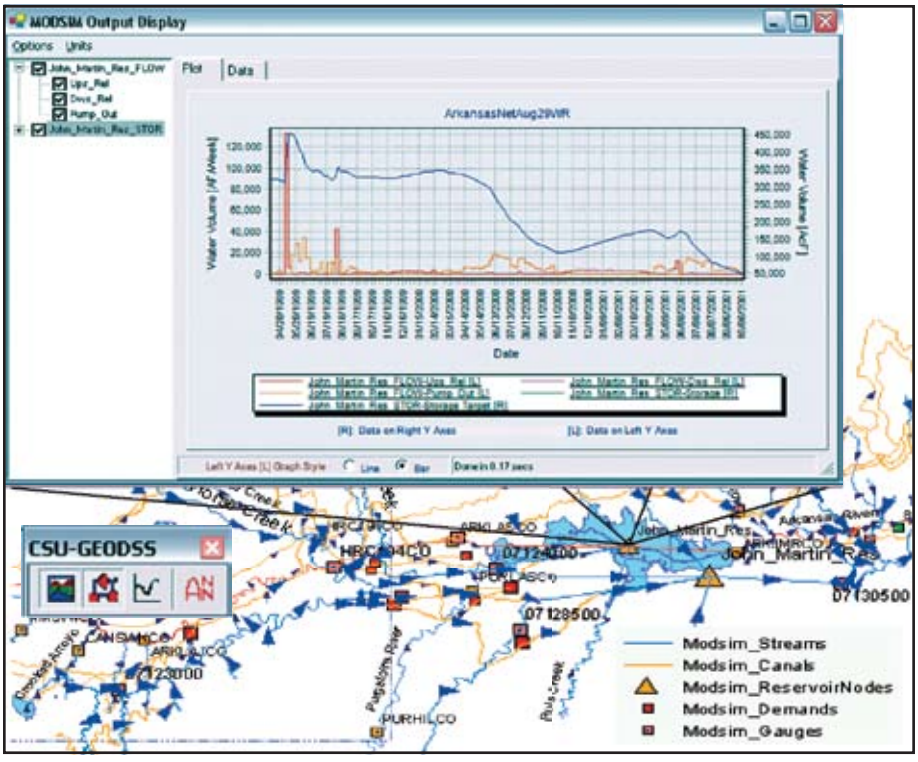


Figure 38. GeoMODSIM object oriented output in ArcMap.

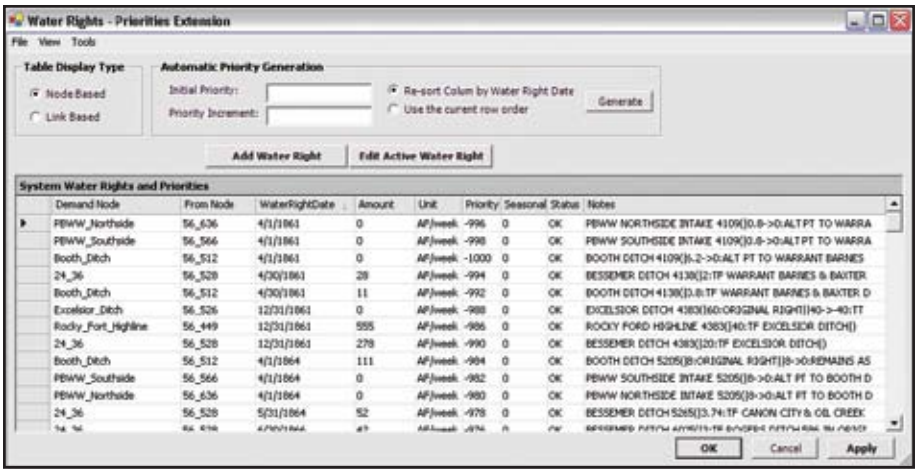


Figure 39. Water Rights Import Tool Interface for the Lower Arkansas River Basin.

network topology directly from the ArcGIS™ logical network. Geometric network nodes are used to create the MODSIM system nodes, and the logical network connectivity is used to create the links between nodes in the model. A series of tools has been developed in GeoDSS to assist with population and manipulation of time series in GeoMODSIM. The water rights import tool allows direct access to portions of the Colorado Division of Water Resources database and automatic creating of the user water rights in GeoMODSIM. The tool provides an interface (Figure 39) where the user can review the results of the database analysis and make necessary adjustments. Another tool has been developed to import and organize measured flows, reservoirs storage, and historical water diversions into GeoMODSIM. This tool reads the time series database compiled from different sources and processes the data to populate the model with these data over the selected time steps.

Several GeoMODSIM runtime modes have been implemented as interfaces in ArcMap (Figure 40) to expedite simulation and analysis of the basin network. A calibration run mode is implemented to automatically quantify gains and losses in the system based on observed historical flows. During the calibration phase, the goal is to simulate the system as closely as possible to the historical operation of the river. The Arkansas River is divided into reaches or segments between gauging stations. Each reach is automatically provided with an artificial construct that consists of a sink node connected to the downstream gauging station and an inflow node connected to the upstream gauging station of the reach. This allows quantification of gains and losses within the reach and provides the upstream gains for use within the reach (Figure 41). The reaches are modeled simultaneously in a cascading fashion, providing for each time step the measured water upstream of the reach. The water allocation is performed using water rights and the ANN prediction of the stream-aquifer interaction. Gains occur mainly from unmeasured surface runoff, direct runoff from agricultural activities, or unused diverted water that is returned to the river through the canals.

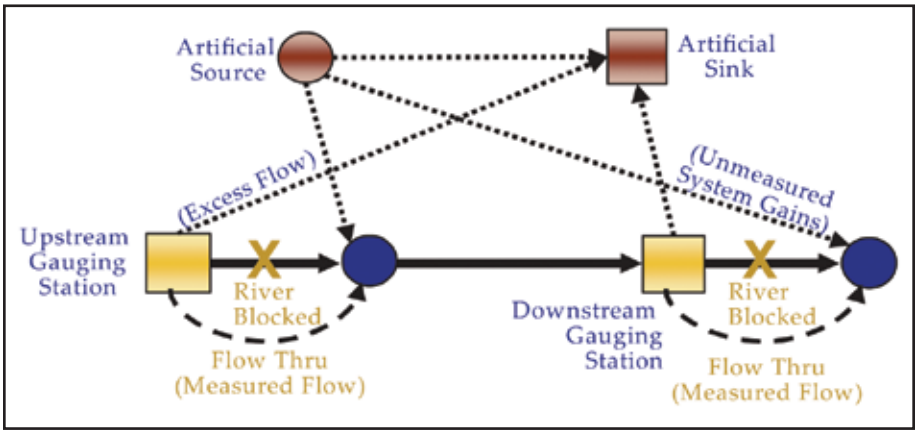


Figure 41. Schematic representation of the MODSIM calibration construct (amended from Triana et al. 2006).

Figure 40. GeoMODSIM running modes interface.

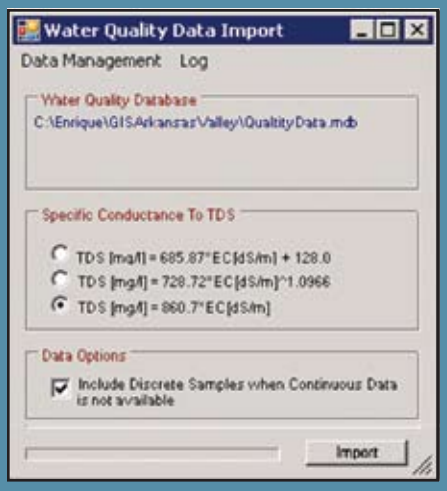


Figure 42. Water Quality Import tool (user interface).

GeoDSS provides the user with the ability to turn on/off the ground water returns that are predicted with the ANNs. In cases where ANN return-flow predictions are used, the model creates additional nodes and links to accommodate inflows to the system in the amounts predicted by the ANN, according to the spatial characteristics. A simulation mode is available in which the user can apply previously calculated gains and losses in a calibration run. In this case, gauging stations in the system are "neutralized," providing only a comparison of predicted results with historical flows. Finally, GeoDSS provides the infrastructure to run the system using only water from storage. A tool has been created to extract from the Colorado Division of Water Resources database those records on measured water from storage at the diversion points. Results from the storage-only run can be combined with results from other modes to separate storage water from direct flow in water allocation based on water rights.

GeoDSS provides tools to import and process both the sporadic and regular water-quality sampling that takes place in the river basin. Figure 42 shows the graphical user interface for the water-quality data import tool. Specific Conductance data is imported to the model as total dissolved solids using a user selected conversion equation. Data can be visualized, plotted, and manually entered in the ArcGIS environment through user dialogs activated by the water-quality tool in the GeoDSS toolbar (Figure 43).

The Water Quality Module is coupled with MODSIM and with the ANN Module at run time to provide salt mass routing throughout the modeled basin. Combined with the simulated flow results, this allows the user, at any point in the system, to monitor solute concentration within the river and at diversion points. Simulations using measured salt loads at the most upstream nodes of the modeled basin allow the user to observe at control points the difference between the measured and the modeled concentrations. This simulation provides valuable information about the magnitude of unmeasured salt load contributions within different sectors of the system. Figure 44 shows an example of the comparison between simulated and measured concentrations at the ARKMOFCO station. When the ANN module predicts return flow, the ANN predicted concentration of the ground water is incorporated in the salt mass routing. This combined water-quality modeling has demonstrated the effectiveness of the ANN prediction by providing a closer match of the water concentration at the control point, especially at control points further from the measured sources.

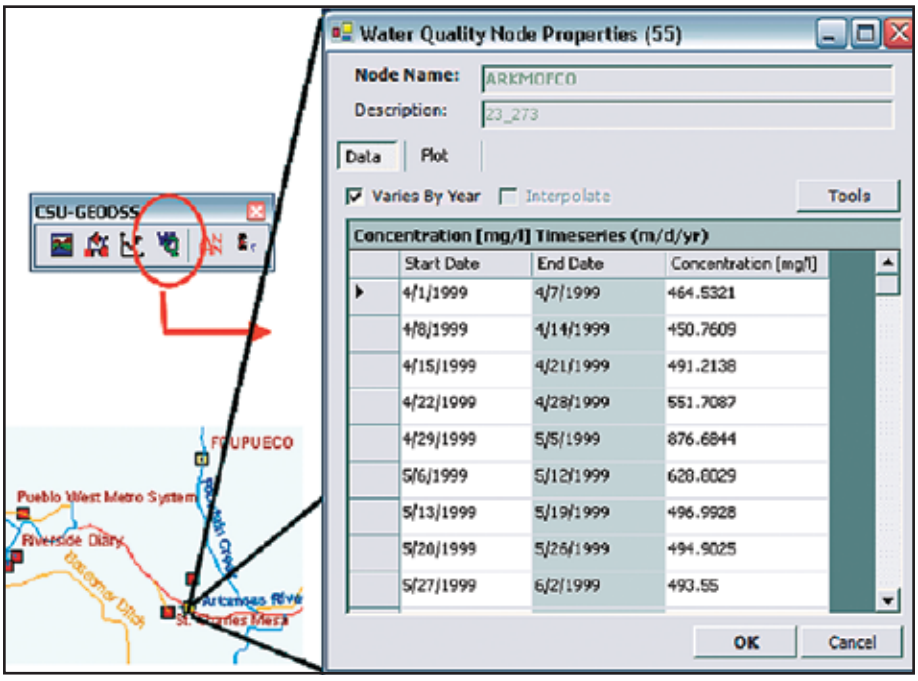


Figure 43. User interface for Measured Water Quality Import Data.

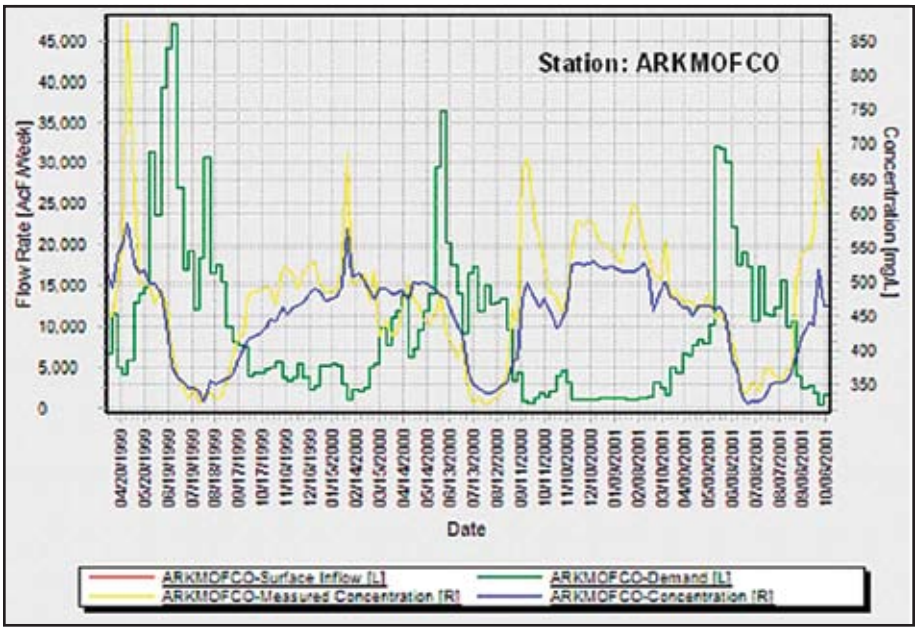


Figure 44. Graphical comparison of the measured vs. simulated water concentrations at "Arkansas River at Moffat Street at Pueblo" (ARKMOFCO) Station.

PRELIMINARY ECONOMIC ANALYSIS

Preliminary economic data have been gathered to estimate impacts of various management strategies on costs and returns at the field, regional, and basin scales. Economic data being used at the field level include crop prices, quantity and prices of farm inputs used, and costs of on-farm adjustments associated with the different improvement policies being evaluated. Available crop enterprise budgets are being used as the foundation for this information. Data have been collected to assess the costs of structural improvements and other policies implemented at the basin and regional levels. Overall revenue lost to waterlogging and salinity in the Upstream Study Region was estimated to average about $232/ha ($94/acre) over the period April 1999 – October 2001. Preliminary economic analyses indicate that remediation strategies have promising potential to boost net benefits from crop production in the Valley when basin-scale agroecological benefits are considered (Houk 2003). Cooperators and other experts in the study regions will be consulted to help determine and evaluate the appropriateness of the cost and economic return parameters that have been estimated.

Summary of Major Findings to Date

Courtesy of *Pueblo Chieftan.*

A thorough examination of field conditions has produced an emerging picture of the status of land and water resources in Colorado's Lower Arkansas River Valley. The picture reveals a variable spatial and temporal pattern of a number of properties that are associated with surface and subsurface flows, water quality, soil quality, and crop production. Using the extensive data that have been gathered, models have been constructed that allow investigation of promising ways to enhance the irrigated stream-aquifer system of the Valley. The major findings to date, though subject to revision and refinement, are summarized as follows:

1. Excess irrigation, canal seepage, and inadequate drainage have contributed to saline shallow water tables and saline soils under irrigated lands throughout the Arkansas River Valley. Average observed water table depths ranged from 1.2 to 4.1 m below ground surface in the Upstream Region over the period 1999 – 2005 and between 2.8 and 4.5 m in the Downstream Region over the drier 2002 – 2005 period. Average observed water table salinity over corresponding periods ranged from 2,100 to 4,043 mg/L in the Upstream Region and from 3,081 to 4,699 mg/L in the Downstream Region.

2. Soil water salinity in irrigated fields has been found to range from moderate to high. Average observed EC_e values ranged from 3.3 to 4.8 dS/m in the Upstream Region over the period 1999 – 2004 and from 5.6 to 6.5 dS/m in the Downstream Region from 2002 to 2005.

3. Significant reductions in crop yield due to soil water salinity have been documented. Average relative crop yield losses are estimated at about 10 to 15 percentage points. However, crop yield reductions appear to be lower than similar studies outside the Arkansas River Valley would indicate. This may be due to the preponderance of low-soluble calcium and magnesium salts, in contrast to highly soluble sodium salts, in Arkansas River Valley soils.

4. Seepage losses from earthen irrigation canals are substantial. Measured values range from 0.004 m^3/s per km along the canal (0.3 ft^3/s per mile) to about 0.065 m^3/s per km (3.7 ft^3/s per mile) in the Upstream Study Region and from 0.003 m^3/s per km (0.2 ft^3/s per mile) to about 0.025 m^3/s per km (1.4 ft^3/s per mile) in the Downstream Region.

5. Excess irrigation and canal seepage contribute to subsurface dissolution of native salts and Se, and drive these dissolved constituents toward the river. In conjunction with evapo-concentration of salts by crop ET, these processes result in substantial salt and Se loading to the river.

6. Salt concentrations in the river water and in applied irrigation water are moderate to high throughout the river valley. Values measured in the Arkansas River ranged from 745 to 2,261 mg/L in the Upstream Region over the period 1999 – 2004 and from 2,141 to 3,626 mg/L in the Downstream Region from 1999 to 2004. Average salt concentration measured over corresponding periods in canals within the Upstream Region ranged from 531 to 1,331 mg/L in the Upstream Region and from 807 to 3,396 mg/L in the Downstream Region.

7. A significant relationship exists between water table depth and salinity of overlying soils. Data indicate that soil water salinity increases as the depth to the saline water table decreases from a threshold level of about 2 to 3 m below ground surface.

8. Selenium concentrations in ground water and in surface waters are moderate to high in the Downstream Study Region. Mean observed ground water and river concentrations were about 16 µg/L and 9.4 µg/L, respectively, over the period 2003 – 2005. River concentrations routinely exceed the nationally recommended aquatic wildlife standard.

9. Upward flow from shallow water tables under fallow ground and under irrigated ground during the off-season contributes to substantial nonbeneficial water consumption. A value greater than 50,000 acre-ft per year was estimated over the period 1999 – 2001.

10. Soil water salinity and crop evapotranspiration can be accurately estimated using remote sensing with satellite imagery. Processed satellite images reveal marked reduction in crop evapotranspiration at locations in corn fields where soil water salinity levels exceed 2 to 4 dS/m.

11. Regional-scale and field-scale flow and salt transport models have been developed and initially applied to explore strategies for improving water management. Refinement and expanded applications of these models are underway.

12. Model results indicate that average water table depth can be increased markedly (as much as 1.8 m), average soil water salinity can be reduced significantly (as much as 600 mg/l), and average relative crop yields can be increased (as much as 10 percentage points in a given year) by improving irrigation efficiency, reducing canal seepage, and installing subsurface drains on selected sites upstream.

13. Salt dissolution and transport to the river can be reduced substantially (up to about 40%) in the Upstream Region by diminishing recharge to the saline water table through increased irrigation efficiency and reduced canal seepage (studies in the Downstream Region have not yet been completed). Also, it is likely that Se loads can be reduced significantly.

14. A spatial basin-scale decision support system has been developed that will simulate how the temporal and spatial patterns of in-stream and diverted flow rates and concentrations will be affected by implementation of field-scale and regional-scale improvement strategies or other changes in river management. The model allows for the examination of alternative strategies for river operation. The results of this examination can be used by water administrators and users in the Arkansas Valley to determine how to implement improvements in a way that ensures non-injury to Colorado water rights and compliance with the Arkansas River Compact.

The Next Phase: Planning Tools and Pilot Implementation

The prospect of achieving the goals of this project is heightened by the extensive database and calibrated modeling tools that already have been developed to date. These models will require further refinement and expansion toward the attainment of a comprehensive set of tools supporting rational water management decisions, not only at the regional level, but also at the river-basin scale. Models, calibrated and supported by extensive field data, provide (a) a picture of the extent and severity of existing problems in the watershed, (b) a methodology for systematically assessing alternative means to address these problems, and (c) an indication of the prospects for achieving marked improvements to the land and to the river when these solution strategies are implemented. With problem identification and the search for economic solutions effectively underway, steps toward preparation of a pilot implementation program also are now needed. Such a pilot program would implement and assess within representative canal command areas the most promising solution strategies that will have been identified to date. Interactive monitoring and assessment of pilot program results will lead to a comprehensive plan for large-scale implementation over the entire Lower Arkansas River watershed.

Three major objectives will guide the next phase (2006 – 2009) of investigation by Colorado State University:

1. Refine and apply calibrated regional-scale flow and solute (salt and Se) transport models, to evaluate proposed solution strategies based upon sound physical and economic field data. The impacts of alternative strategies will be comparatively ranked in a manner that is congruent with measured processes in the Upstream and Downstream Study Regions. Regional-scale solutions will be checked with field-scale models to help ensure that they can be practically implemented on individually managed field units.
2. Refine and apply the GeoDSS basin-scale decision-support model to assess the likely impacts of regional solutions on river flows and solute concentrations and to explore ways of operating the river to make possible regional-scale solutions that also will comply with Colorado water rights and with the Arkansas River Compact.
3. Implement and monitor pilot programs, designed in cooperation with Valley farmers and agencies, under representative canal command areas to field-test and refine top-ranking solution strategies.

This three-pronged effort will build upon the momentum gained by the results that have been obtained from on-going data collection and modeling studies. Proposed methodologies for accomplishing each of these objectives are laid out in a document entitled "Toward Optimal Water Management in Colorado's Lower Arkansas River Valley: Methods for the Next Phase of Investigation," available at *CSUArkRiver.colostate.edu.*

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