

# Colorado Water Resources Research Institute

## Annual Technical Report

### FY 2003

## Introduction

### **FY 2003 Colorado Water Resources Research Institute Research Program**

*Lysimeter Installation* The addition of a lysimeter to collect water data in Colorado should improve the quality of data available for the purpose of determining water usage and water quality in the Lower Arkansas Basin. Current water use calculation methods require crop coefficients for which there is no local data. The crop coefficients used are based on data collected in projects on experiment station projects in Texas and Idaho.

To insure that sound science is employed in all phases of the design, construction, installation, operation and maintenance of the new lysimeter facility at Rocky Ford, leading scientists and technicians in the area of lysimeters and ET estimates are being engaged in the process. The plan is for a set of two (2) monolithic continuous weighing lysimeters (direct load cell, 2 to 3m x 2 to 3m x 2.5m deep) to accurately measure evapotranspiration of a reference crop and of production crops under a variety of field conditions typical of the lower Arkansas River Valley in Colorado.

To date, funding for design of the lysimeter has been made available from the Colorado State Engineers Office, under the guidance of Tom Ley and Dale Straw. Thomas Marek, Texas A&M University, has been retained to design the facility. Contacts have been made with ARS personnel in Bushland, Texas and Fort Collins, Colorado regarding both scientific and administrative experience with such facilities.

#### *Research Projects In Progress:*

2002CO2B: Luis Garcia, Enhancements to the South Platte Mapping and Analysis Program

2002CO6B: Tim Gates, Evaluating Strategies to Mitigate Waterlogging and Salinization in Colorados Lower Arkansas River Valley, Phase 2

2003CO71B: Yaling Qian, Urban Landscape Irrigation with Reclaimed Wastewater: Water Quality Assessment and Community Experience

2003CO72B: John Wilkins-Wells, Canal Modernization for Addressing Salinity Issues in the Arkansas Valley, Colorado

2001CO261G: Eileen Poeter, Use of Low-Cost Data to Simulate Fractured-Aquifer Watersheds for Management of Water Quality and Quantity

2002CO46G: Robert Siegrist, Occurrence and Fate of Emerging Organic Chemicals in Onsite Wastewater Systems and Implications on Water Quality Management in the Rocky Mountain Region

2002CO103B: Joseph Ryan, Microbe Transport in Saturated Filter Sand and Karst Media

*Graduate Student Funding For Research* Three Ph.D Fellows are funded by a second USDA grant to conduct research on water management issues critical to Colorado agriculture in the Western United States. The Cooperative State Research, Education, and Extension Service (CSREES) awarded the \$207,000 grant to Jim Loftis, Civil Engineering Department, CSU and Jessica Davis, Soil and Crop Sciences Department, CSU. The doctoral fellowships carry a stipend of \$22,000 per year for three years plus a travel allowance to attend two national technical conferences.

Alisa Wade began her doctoral work at CSU Fall Semester, 2003, studying in the Forest, Rangeland, and Watershed Stewardship Department. Alisa's research interests are in landscape ecology, focusing on how public land management actions impact watershed health. She plans to use geographic information systems (GIS) to assess how various suites of management options impact watershed ecology.

Curtis Cooper, born in Colorado, received his Master of Science Degree from Colorado State University in Watershed Science, examining the in-reservoir salt concentrations in the South Platte River Basin, with Dr. John Stednick. Curtis is currently conducting research and assisting on the interdepartmental and interagency examination of the Salinity and Waterlogging issues in the Arkansas River Valley under the specific guidance of Dr. Timothy Gates in Civil Engineering.

Travis Schmidt is a Ph.D Candidate in the Fishery and Wildlife Sciences Department studying ecotoxicology. His work complements research on global climate change as it affects ultraviolet radiation, dissolved organic carbon, and heavy-metal interaction with stream benthic communities.

*CWRRRI Activities and Accomplishments* Colorado Water Archives Ditch and Reservoir Company Alliance (DARCA) has designated the Water Resources Archive as the repository for their archival records and transferred the first batch of records to the archive in November 2003. The webpage for the organization is [www.darca.org](http://www.darca.org), which states that DARCA's purpose is Serving Colorados Mutual Ditch and Reservoir Companies, Irrigation Districts, Incorporated Laterals and Private Ditches.

The Upper Yampa Water Conservancy District (UYWCD) funded two scholarships during its third year of support to CSU students preparing for careers in water-related fields. The scholarship program is administered by the CSU Water Center. The two scholarship recipients for the 2003-4 school year are Joel Wixson and Dan Woolley. Joel Wixson is a junior majoring in both Fishery and Wildlife Biology and Mathematics. Joel, who is from Hayden, Colorado, plans to pursue a career in some aspect of managing fisheries. Dan Woolley, a junior majoring in Watershed Sciences at CSU, is from Glenwood Springs, Colorado and plans to work in the general area of river restoration somewhere in Colorado.

Fall 2003 Water Resources Seminar The seminar was held 4:10pm Tuesday afternoons in Room C-142, Clark Bldg. on the Colorado State University campus. All interested faculty, students and off-campus water professionals are encouraged to attend and participate. Topics and presenters for the 2003 seminar were:

The Agricultural Water Conservation Morass: What Water Managers Should Know - Ray Huffaker, Department of Agricultural and Resource Economics, Washington State University, Pullman, Washington (Dr. Huffakers presentation is sponsored by the American Institute of Economics)

The Colorado Legislature and Future Water Managers Rep. Bob McCluskey, Representing District 52 of Larimer County in the Colorado Legislature

Technical and Scientific Contributions in the Legal Environment of Water Courts. Veronica Sperling, Water Attorney, Boulder

Water Leadership: Delph Carpenter and the Colorado River Compact Dan Tyler, Emeritus Professor, Department of History, Colorado State University and author of the new biography of Delph Carpenter, Father of the Colorado River Compact (Dr. Tylers presentation is sponsored by the American Institute of Economics)

The International Arena and New Water Managers Michel Scoullou, Senior Visiting Scholar, Onassis Foundations University Seminars Program, Athens, Greece

*Additional CWRRI Activities Involving Local, State and Federal Agencies and other organizations*

Colorado Water Congress 46th Annual Convention During the Colorado Water Congress 46th Annual Convention held January 29-30, 2004, at the Holiday Inn in Northglenn, CWRRI organized special sessions on water infrastructure and water quality and new tools to conjunctively manage ground and surface water. In the first session, Jim Loftis and Tim Gates, CSU Department of Civil Engineering, presented results of CWRRI research projects and Regan Waskom, Colorado State University State Water Extension Specialist, described USDA programs to manage water quality. In the second session, Luis Garcia, CSU Department of Civil Engineering, updated the CWC on recent improvements to his CWRRI co-sponsored South Platte Mapping and Analysis Program and its use in implementing Senate Bill 73. Tom Sale, also with CSU Civil Engineering, described his efforts to characterize the Denver Basin Hydrostratigraphy using visual logs.

New Developments in Water Management CWRRI and the Bureau of Reclamation organized a workshop on River Systems Management held November 4-6, 2003 at the University Park Holiday Inn in Fort Collins. The workshop was the eighth in a series focused on priorities and new developments in Reclamation water resource management and this year the topic was reduction of conflict in water resources management. More than 100 reclamation managers, technical staff and invited speakers from other government agencies, universities, stakeholder organizations and the private sector participated in both technical sessions and breakout workshops on topics such as water resources modeling and optimization; collaboration in water data collection and sharing; legal issues impacting water allocations; ecologically based system developments; and real-time flow forecast modeling.

*Staff* CWRRI Director Robert C. Ward serves as Past President of NIWR for 2003-2004 and chair of the Water Section of National Association of State Universities and Land Grant Colleges. He is also a member of the National Water Quality Monitoring council, the Colorado Water Quality Monitoring council, the Bureau of Reclamations Research Steering Committee, Scientific Organizing Committee for Monitoring Tailor-made Workshop in the Netherlands, and the Poudre Heritage Alliance. In addition he supports and participates in activities of the Colorado Water Congress, a state-wide organization of water users and managers.

Reagan Waskom, Water Resources Specialist for the Colorado Water Resources Research Institute is principal or co-principal investigator on the following research/education projects: an investigation of selenium on Colorados West Slope, an agricultural education project funded by the U.S. Department of

Agriculture, a phosphorus runoff project funded by the U.S. Department of Agriculture and the Environmental Protection Agency, and a project on ground water education funded by the Colorado Department of Agriculture.

*Advisory Committee on Water Research Policy* Advisory Committee on Water Research Policy (ACWRP) membership is provided for in CWRRIs by-laws. The ACWRP is comprised of: the Chair of the Colorado Senate Committee on Agriculture, Natural Resources and Energy, the Chair of the Colorado House Committee on Agriculture, Livestock and Natural Resources, the Executive Director of the Colorado Department of Natural Resources, the Executive Director of the Colorado department of Public Health and Environment. The Commissioner of the Colorado Department of Agriculture; and six members of the general public selected based on their participation in setting Colorado water policy in the legislative process and involvement in obtaining funding for such policy. The ACWRPs mandate is to address two functions: to advise CWRRIs regarding research to be undertaken as part of the federally supported, state-based water research program; and to seek state and local water research funding to provide the state match required. Membership of ACWRP as of November 12, 2003 is:

#### **Member by position**

Chair, Senate Agriculture, Natural Resources and Energy Committee Senator Dave Wattenberg, 1999; Senator Jim Dyer, 2000; Senator Jim Isgar, 2001, Senator Lewis Entz, 2002-3

Chair, House Agriculture, Livestock and Natural Resources Committee Representative Brad Young, 1998-2000; Representative Diane Hoppe, 2001-2003

Executive Director, Department of Natural Resources now represented by Frank McNulty. From 1998-2002, the representative was Kent Holsinger

Executive Director, Department of Public Health and Environment -- represented by Greg Parsons 1998-2001, represented by Mark Pifher 2002

Commissioner, Department of Agriculture -- Don Ament, 1998-2002

#### **Appointed by CWRRIs Director**

**Fred Anderson, former President, Colorado Senate, 1998-2002**

**Sara Duncan, Denver Water, 1998-2002**

**Eric Kuhn, Colorado River Water Conservation District represented by David Merritt, 1998-2002**

**John Porter, former Manager, Dolores Water Conservancy District, 1998-2002**

**David Robbins, Hill & Robbins, 1998-2002**

**Ralph Curtis, Manager, Rio Grande Water Conservation District, 1998-2002**

#### **Ex-Officio**

**Lee Sommers, Director, Agricultural Experiment Station, CSU, 1998-2004**

**Milan Rewerts, Director, Cooperative Extension, CSU, 1998-2004**

**Jim Hubbard, Director, Colorado State Forest Service, CSU**

# **Research Program**

# Enhancements to the South Platte Mapping and Analysis Program (SPMAP)

## Basic Information

<b>Title:</b>	Enhancements to the South Platte Mapping and Analysis Program (SPMAP)
<b>Project Number:</b>	2002CO2B
<b>Start Date:</b>	3/1/2003
<b>End Date:</b>	2/28/2004
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	4th
<b>Research Category:</b>	None
<b>Focus Category:</b>	Agriculture, Groundwater, Water Use
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Luis Garcia

## Publication

1. Garcia Luis and Bob Lange, 1998, An Update on the Development of the South Platte Mapping and Analysis Program (SPMAP), Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Colorado Water, February, pp. 14-15.
2. Garcia, Luis and Bob Lange, 2000, SPMAP Provides Comprehensive Tool for Mapping and Analysis of South Platte, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Colorado Water, December, pp. 7-13.
3. Lange, Robert William, 2001, A Methodology for Estimating Detectable Change in Water Quality Due to Prescribed Fire in Northern Colorado, MS Thesis, Department of Chemical and Biorecourse Engineering, Morgan Library, Colorado State University, Fort Collins, CO, Call No. TD224.C6 L35 2001.
4. Shrier, Catherine J., 2002, Habitat Potential Assessment Tool (HPAT): Planning Tools to Support Development of Recharge Ponds and Wetland Habitat in the Lower South Platte of Colorado, in South Platte Forum Proceedings, Information Series 94, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, p. 32.
5. Shrier, Catherine, 2004, A Knowledge-based Spatial Methodology for Evaluation of Groundwater Recharge Pond Sites for Stream Augmentation and Waterfowl Habitat, Ph.D Dissertation, Department of Civil Engineering, Morgan Library, Colorado State University, Fort Collins, CO.

## **1.0 Critical Regional or State Water Problem**

Water managers of the South Platte basin are facing competing demands for water including sustaining irrigated food production, providing high quality water to growing populations, and establishing flow conditions to protect habitats for threatened and endangered species. Since the alluvial aquifer along the South Platte can be impacted by groundwater withdrawals for irrigated agriculture and other uses, it is critical to accurately determine the timing and amounts of groundwater withdrawals for water management. (This is also a legal requirement.) In addition to augmentation requirements the conjunctive use of ground and surface water offers an alternative way to meet surface flow requirements for threatened/endangered species and to provide wetland and open water habitat for migrating species and fish rearing grounds. Groundwater recharge can be used to manage river flows by percolating the water through recharge basins located nearby.

In order to meet water supply challenges, local water management organizations in the Lower South Platte have turned to the development of computer-based tools tailored to the modeling needs of this unique area. Water managers are looking to cutting-edge technology that will help them to manage both the conjunctive use of ground and surface water resources and to determine augmentation requirements in the South Platte basin. The basin's water resource systems are complex and require data and models that can work with both large and small areas and time periods. The SPMAP collection of computer tools has been used successfully to manage this data and run models specifically designed for this problem.

*“In this current severe drought and with increasing pressures to maintain and secure augmentation supplies, the computer software of SPMAP has become indispensable.”*

***--Jon Altenhofen, Northern Colorado Water Conservancy District, Supervisory Water Resources Engineer and Coordinator for South Platte Lower River Group Inc. (SPLRG)***

*“The tools and software developed by the team under the direction of Dr. Luis Garcia have proven very useful to GASP in our daily operations.”*

***-- Jack Odor, GASP Manager***

*“SPMAP is here to stay as the computer software for management of augmentation supplies in the South Platte River Basin. Water users will continue to support the maintenance and enhancement of SPMAP and feel our working relationship with CSU-IDS will be a long and fruitful one.”*

***--Jon Altenhofen, Northern Colorado Water Conservancy District, Supervisory Water Resources Engineer and Coordinator for South Platte Lower River Group Inc. (SPLRG)***

In the current drought, SPMAP tools are proving themselves to be very valuable, but there is a need to maintain the spatial database to run these tools as well as to develop additional enhancements that better address the needs of local water providers.

*“This ongoing effort is vital to the implementation of Central's administration of well depletions, replacement sources, and water rights activities.”*

***-- Forest Leaf, CCWCD District Engineer***

## **2.0 Statement of Results or Benefits**

Kunhardt and Fontane (1995) state that the South Platte River system is operating closer and closer to its absolute capacity due to an exploding urban population, steady agricultural demand

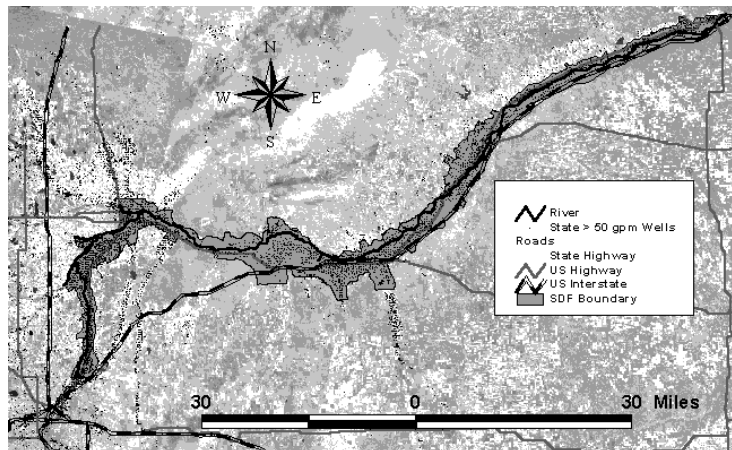
and new mandates for instream flows. The authors believe that the water scarcity problem might be mitigated by further development of conjunctive use of ground and surface waters and more innovative trading and cooperation between decreed water users. The focus of the SPMAP project is to develop tools for conjunctive management of ground and surface water that will allow for a more flexible supply while maintaining obligations for downstream water users required by law. The current drought is making the refinement of the SPMAP tools even more imperative.

*“A drought causes water suppliers to consider numerous new options for meeting demands. SPMAP’s flexibility and ease of use has allowed rapid evaluation and accounting of numerous water supplies.”*  
**--Jon Altenhofen, Northern Colorado Water Conservancy District, Supervisory Water Resources Engineer and Coordinator for South Platte Lower River Group Inc. (SPLRG)**

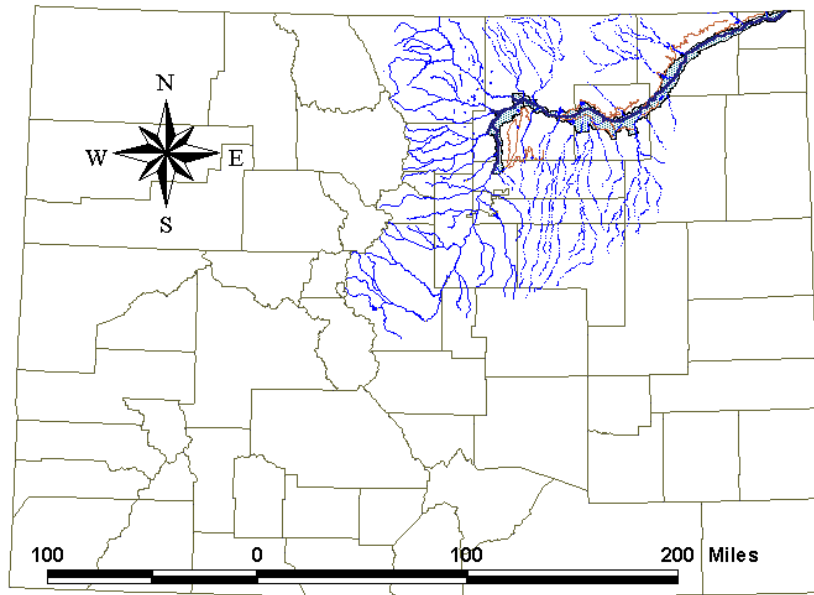
SPMAP currently provides valuable tools for managers in the South Platte basin who provide water mostly to agricultural users (the highest water use category in the basin). As mentioned previously, these tools have been designed to develop augmentation plans and manage conjunctive use of ground and surface water. These modeling challenges require accurate spatial data, a way to determine consumptive use from groundwater withdrawals, and a method to estimate the stream depletion, or accretion in the case of groundwater recharge. Current tools meet these needs, but this project will provide improved and updated data layers for modeling and better tools for projecting water use scenarios into the future. The goal of this project is to continue to identify gaps in water management tools currently available in the Lower South Platte River Basin and implement computer systems and data to fill these gaps. This effort requires the ability to match data acquisition system design, modeling, and user interfaces to meet manager's needs.

### **3.0 Nature, Scope, and Objectives**

Since 1995 the Integrated Decision Support (IDS) Group at Colorado State University’s Water Center, has been working with a number of local and regional water management organizations along the Lower South Platte River to develop decision support tools for water management. The result of this effort is the development of a set of computer tools that are collectively called SPMAP for the shallow riverine aquifer along the South Platte denoted by the Stream Depletion Factor (SDF) Boundary (Figure 1).







*Figure 1: Lower South Platte Project Boundary in Colorado with County Boundaries*

The scope of this research has focused on the development of three computer tools collectively called the South Platte Mapping and Analysis Program (SPMAP). The first tool is the South Platte Geographic Information System (SPGIS) which serves as a spatial database for the region with data for running the South Platte Consumptive Use (SPCU) Model. The final tool is a Stream Depletion Factor model called SDF View that can be used to estimate stream depletions from groundwater wells to meet the agricultural consumptive use calculated with SPCU and to determine lag times from groundwater recharge sites.

The project has been very successful with the participating organizations currently using some or all of the tools developed for the project (See Section 6.0). The participants want to continue this work by updating data layers and enhancing the software and have identified the following objectives:

1. Refine the daily SDF View module.
2. Develop options for distributing annual pumping on a monthly basis.
3. Incorporate additional database links for individual water organizations (GASP, CCWCD, LSPWCD).
4. Incorporate data from the Water Commissioner's real-time Water Information Sheets.
5. Develop options for overall augmentation plan management to analyze water supplies versus demands.
6. Continue to document, test and revise all enhancements to SPMAP.
7. Continue to provide module maintenance, upgrades and access through the IDS web site.

This funding will enable the close cooperation that has been established over the last seven years to continue and for the SPMAP tools to be improved and maintained. Letters of support for this proposal from water user groups and from the Office of the State Engineer are attached.

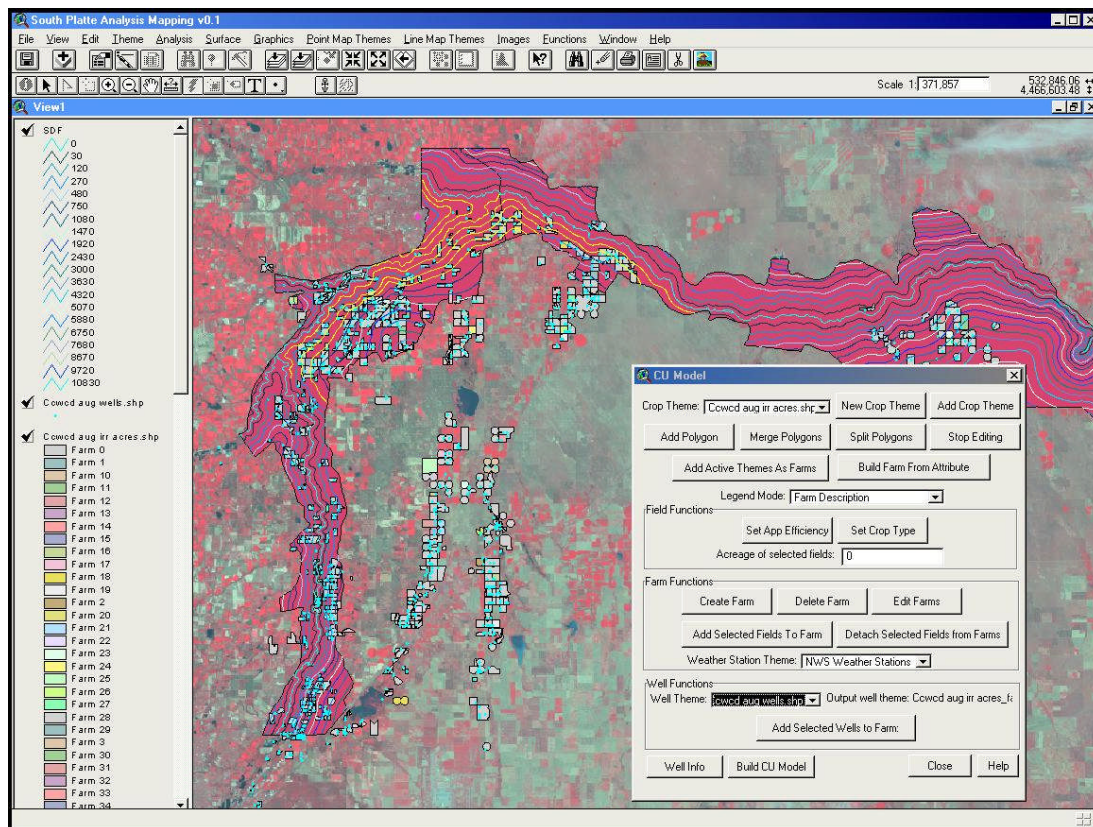
*“... this effort has been more productive and has provided far more benefits to water users than any previous CSU effort that Central has been involved in.”*

*-- Forest Leaf, CCWCD District Engineer*

#### **4.0 Methods, Procedures, and Facilities**

The SPMAP modeling effort implements a “data-centered” approach, meaning that river basin data are stored in a common database (in this case, SPGIS) and accessed by the various models as components with model interaction built into the software. Development has proceeded with a “modular” approach, meaning that models can be used as stand-alone components or used in conjunction. New models can also be substituted or added to the system with minimal changes to the other components. As the water providers have used the tools, they have identified some additional needs that will be addressed through this project.

SPGIS is the component of SPMAP that deals with GIS information. Users can view layers that include the river, wells, SDF lines, and farms. SPGIS contains an interface for building input to the SPCU and SDF View models to calculate consumptive use or well depletions. In the next year, IDS will continue to work with water users to coordinate image and data acquisition efforts and to develop a long-term data management system.



*Figure 2: The South Platte Mapping and Analysis GIS Spatial Database*

The second component of SPMAP that will be enhanced is the SPCU Model. The SPCU model can compute CU by using the Blaney-Criddle, Kimberly-Penman, Penman-Monteith, or ASCE techniques. The model is scalable, allowing the user to compute consumptive use for an entire

river basin or for an individual field. Scenarios can be run to reflect expected land-use or water supply changes. The model has been used to determine consumptive use for potential climate changes on water resources in the Great Plains (Ojima et al., 1999). The SPCU Model (Figure 3) currently computes CU on either a daily or monthly basis. New work would include calculating monthly well pumping from annual records. Also, since many user groups keep their data in databases, tools for reading generic input data from Access or dBase files will be developed. Similarly, the ability to read diversion records from Water Commissioner's real-time Water Information Sheets will be added.

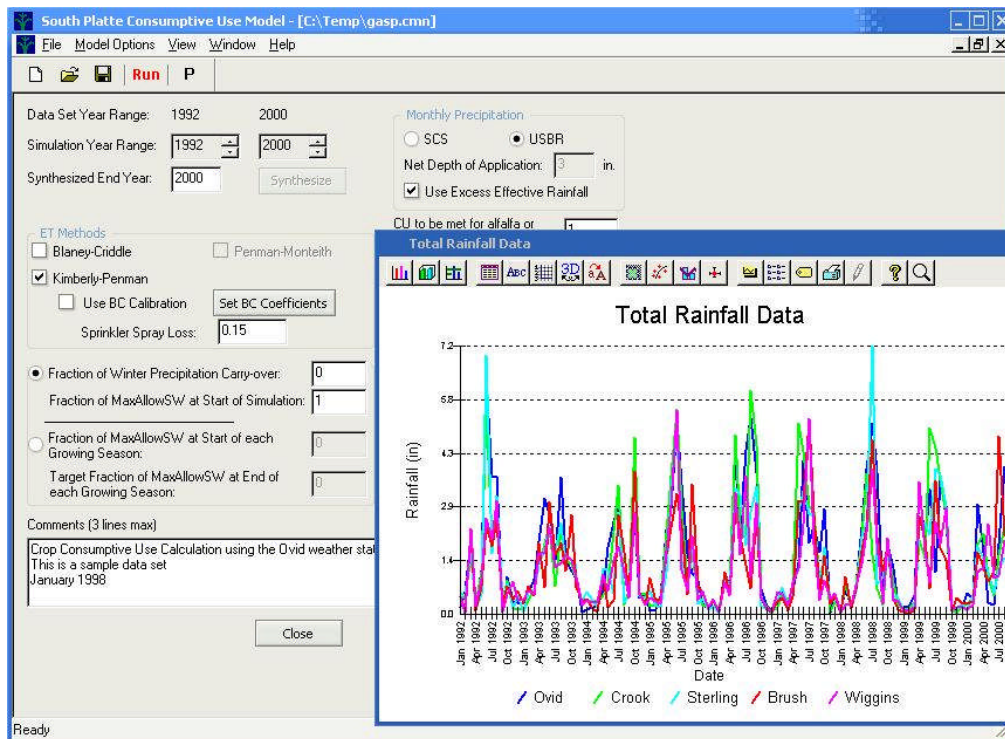


Figure 3: SPCU Interface with Display of Rainfall Data.

The third component of SPMAP that will be enhanced is the SDF View Model. Stream Depletion Factors (SDF) are used to determine the lag time from when irrigation well water is pumped from, or water is recharged to, an alluvial unconfined river aquifer and when a depletion or accretion happens in the river. Required input information for SDF View is consumptive use from well water or net recharge amounts and SDF values for irrigation wells or recharge basins. Data can also be entered as recharge or consumptive use amounts or pumping records that will be converted to consumptive use amounts based on gross pumping and an application efficiency (Figure 4). In the past, SDF was only presented in a monthly format. Recently the model has been enhanced to compute daily depletions and accretions. However, in the coming year, there is a need to document, test and revise this daily SDF model and incorporate the ability to import data from the CU model.

Most importantly, facilities for developing options for overall augmentation plan management to analyze water supplies versus demands will be prototyped. This effort will enhance all of the SPMAP components.

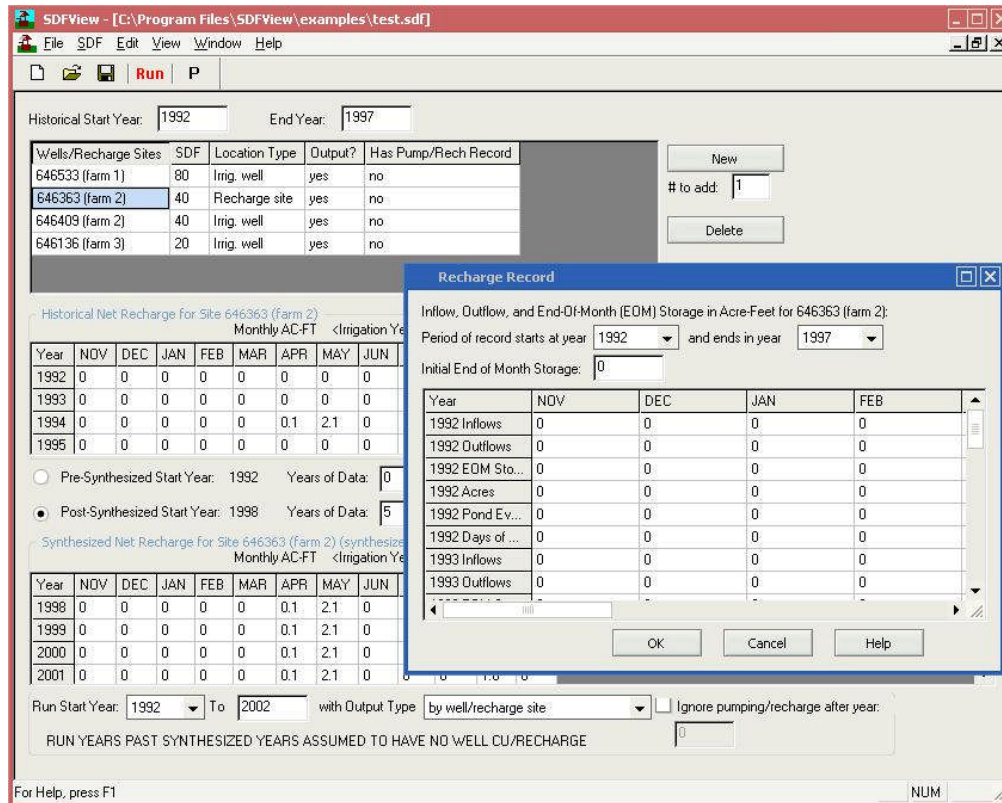


Figure 4: Stream Depletion Factor Model and Interface, with Pumping Record Displayed

*“There are parts of the project which still need development, in particular the augmentation calculation component. This is the tool which will allow all of the supporters of SPMAP to answer the most pressing question facing us, that being, what are the augmentation requirements for each well?”*

**-- Jack Odor, GASP Manager**

All the work that will be developed under this new project will be documented. At each major stage of development the software will be provided to the participating organizations via the World Wide Web. On-line documentation will be created, and also hard-copy documentation will be available to be downloaded and printed from the internet site:

- <http://www.ids.colostate.edu/projects/spmap>

*I believe distributing the software through the Web is very effective. It is critical that the documentation keeps pace with the product which generally happened on this project.”*

**-- Jim Hall, Colorado State Engineer Office, Division 1**

## **5.0 Related Research**

The Lower South Platte River basin has been a testing ground for computer-based decision support systems since the early eighties. Due to the complex nature of the river basin, computer tools promise significant benefits for improving water management. Tools such as SPWRMS (South Platte Water Rights Management System), SAMPSON (Stream Aquifer Model for Management by Simulation and Optimization), and others have been evaluated and presented in a number of CWRI publications (Raymond et al., 1996; Sullivan, 1995; Fontane 1995; Warner

et al., 1994; and Klein, 1994). In addition to these efforts, the State of Colorado has begun a feasibility study to evaluate the implementation of a decision support system for the South Platte River Basin.

The evolution of decision support systems has resulted in data-centered approaches that utilize independent and flexible modeling components. These components can interact within the framework of the decision support system or operate independently for specific modeling tasks. Data gathered for the system should be accessible to all the models and tasks. The models should utilize output from other models as needed but not require it. This approach calls for the development of tools and databases that are tailored to the water management needs for a particular river basin.

The SPCU Model and SDF View make use of computational programs that were developed for other projects. The Original CU Model was developed by IDS as part of the Colorado River Decision Support System (CRDSS); its capabilities were enhanced to include groundwater demands for the South Platte Version. The SDF View computational program was developed by the USGS, and only minor revisions were made for use in this project. To make the programs easier to use and provide new options for building input files and viewing output, Graphical User Interfaces (GUIs) were constructed with Visual C++. SPGIS was constructed using Avenue scripts that customize analysis options and menu items in ArcView, a standard GIS package. The development and user platform is a PC running Windows 95/98/NT.

Long range plans of the Colorado Water Conservation Board and the Division of Water Resources include a South Platte Decision Support System (SPDSS). As shown in Section 6.0 the State of Colorado is one of the participants in the SPMAP project, and some of the SPMAP data and software may become part of the SPDSS effort. The SPMAP project members attend meetings for SPDSS. Since these tools were built to meet the needs of the local water managers specifically, the more general and comprehensive effort of the SPDSS does not constitute a duplication of effort. Also, since the SPCU computational model evolved from the CRDSS CU Model, which is the root of all the CU Models implemented in the Colorado Decision Support efforts, compatibility should be possible.

## **6.0 Training Potential**

Since the focus of any modeling or data development project should be to meet the needs of software users, close coordination with water providers in the basin at all stages is essential to this project's success. This close coordination is achieved by having regular meetings with the Advisory Committee (every 4-6 weeks) to review the development of the software and identify enhancements. The committee is comprised of representatives from:

- Northern Colorado Water Conservancy District (NCWCD)
- South Platte Lower River Group, Inc. (SPLRG)
- Central Colorado Water Conservancy District (CCWCD)
- Groundwater Appropriators of the South Platte (GASP)
- Colorado State Engineers Office (SEO), Division 1
- Lower South Platte Water Conservancy District (LSPWCD)
- Colorado Water Resources Research Institute (CWRRI)

*“The feedback loop of water users applying the modules in decision support with the CSU-IDS group making modifications as needed on a quick turn around has been tremendous and we need to continue it.”*

*--Jon Altenhofen, Northern Colorado Water Conservancy District, Supervisory Water Resources Engineer and Coordinator for South Platte Lower River Group Inc. (SPLRG)*

These meetings also allow for training in the use of the software. Training sessions for larger groups of users will be evaluated if the need arises.

## **7.0 References**

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- Fontane, Darrell G., (1995). “Initiating a Water Management Decision Support System for the South Platte River Basin”, Colorado Water Resources Research Institute Water in the Balance Report, No. 2.
- Klein, Kathleen C., ed. (1994). “Seeking an Integrated Approach to Watershed Management in the South Platte Basin”, Proc. of the 1993 South Platte Forum. 26-27 Oct. 1994, Greeley. Colorado Water Resources Research Institute.
- Ojima, D., Garcia, L., Elgaali, E., Miller, K., Kittel, T., and Lockett, J. (1999). “Potential Climate Change Impacts on Water Resources in the Great Plains”, Journal of the American Water Resources Association, 35(6)1443-1454.
- Raymound, John H., Luis A. Garcia, and Robert Lange (1996). “Evaluation of SAMSON for Use in a South Platte Decision Support System”, Colorado Water Resources Research Institute Completion Report No. 191.
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# Evaluating Strategies to Mitigate Waterlogging and Salinization in Colorado's Lower Arkansas River Valley, Phase 2

## Basic Information

<b>Title:</b>	Evaluating Strategies to Mitigate Waterlogging and Salinization in Colorado's Lower Arkansas River Valley, Phase 2
<b>Project Number:</b>	2002CO6B
<b>Start Date:</b>	3/1/2003
<b>End Date:</b>	2/28/2004
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	4th
<b>Research Category:</b>	None
<b>Focus Category:</b>	Water Quality, Groundwater, Agriculture
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Timothy Gates, John W. Labadie, Grant E. Cardon, W. Marshall Frasier

## Publication

1. Burkhalter, J.P., T.K. Gates and J.W. Labadie, 2002, Strategies for Regional-scale Recovery of a Salinity-threatened Irrigated River Valley, in Proceedings of Conference on Energy, Climate, Environment and Water -- Issues and Opportunities for Irrigation and Drainage, USCID and EWRI, San Luis Obispo, CA.

### **Statement of critical regional or state water problems:**

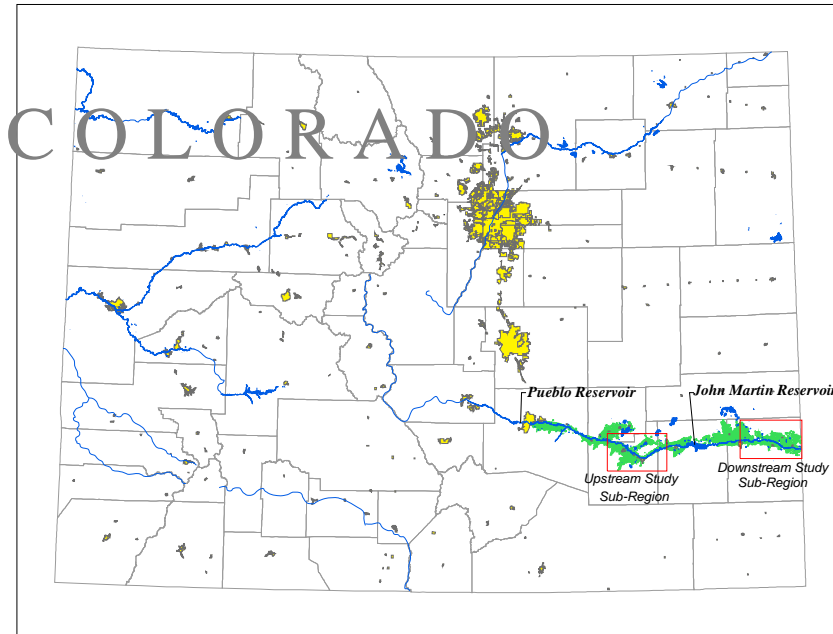
The research proposed herein focuses on one of the most salinity-affected irrigated regions in the U.S., the Lower Arkansas River Basin in Colorado (Figure 1). Irrigated since the 1870s, the lower Arkansas began to develop saline high water tables in the early part of the twentieth century. Over the years, the problems have advanced and ebbed in response to sporadic human intervention and varying climatic conditions. Recently, however, due to a variety of interacting factors, conditions have progressively worsened. In a recent survey, Frasier, et al. (1999a) found that about half of all respondents in three counties (Otero, Bent, and Prowers) in the Arkansas Valley expressed significant concern about high salt concentrations. At a time when conjecture about the causes and prognosis of the problems is growing, some feel that conditions already have reached a crisis stage. Anecdotal evidence abounds: salt crusting on soil surfaces, seepage and wet spots in selected fields, stunted growth of crops, and reduced crop yields. Such losses threaten the economic well-being of the rural communities in the Valley and, by extension, diminish the agricultural base of Colorado. Until recently, however, scientific investigations have been sparse, limited in their scopes, and piecemeal in their approaches, failing to provide a coherent understanding of the extent and severity of the problems. A systematic examination of alternative remedies, based upon sound data, is long overdue.

If agricultural production is to be sustained, well-designed, economical changes must be made in fields and subregions along the entire Lower Arkansas Valley. Actions taken by farmers at the field scale should be informed by guidelines based upon valley-wide objectives and constraints. Such guidelines must be developed using accurate models calibrated to extensive field data, and with input from farmers and valley agencies. Models must account for interacting processes at the basin (regional)-scale (dimensions on the order of  $10^4$ - $10^5$  m) and subregional-scale (order of  $10^3$ - $10^4$  m) that shape decisions for integrated management of water quantity and water quality. Furthermore, models must be available for evaluation of large-scale planning targets in view of detailed design and management issues that arise at the field scale (order of  $10^2$ - $10^3$  m). Educating and interacting with stakeholders, through use of reliable field observations and proven modeling tools, will be necessary to inspire interest and confidence in tackling difficult problem-solving issues. Specific questions arise: What are the expected outcomes of investing in alternative field-, subregional- and basin-scale measures? How can water be conserved and redistributed in the Lower Arkansas River Basin to meet an array of competing demands at the basin scale while complementing efforts to protect irrigated agriculture from waterlogging and salinity problems at the subregional scale? How are targets developed at these scales translated to actual implementation at the fundamental management unit, the field scale? How can the input of growers and agencies be garnered in developing sound valley-wide solutions that in turn will be effectively implemented at the field scale?

### **Statement of results or benefits:**

Without sound and timely intervention, the Lower Arkansas Valley and similar areas will eventually succumb to the ill effects of waterlogging and salinization. This proposed project should prove valuable in support of decision-making and intervention in the Valley by developing feasible solution strategies in dialogue with valley farmers and agencies and by evaluating those strategies using calibrated models based upon sound physical and economic field data.





**Figure 1.** Map of Colorado Highlighting the Lower Arkansas River Valley with the Upstream and Downstream Study Subregions Indicated.

An existing flow and salt transport model, developed from complimentary projects, will be used to comparatively rank the impact of strategies in a manner that is congruent with measured processes in representative subregions of the valley. Solutions based upon accurate knowledge of field conditions will be needed to insure sustainability of the Valley’s productive agricultural base, preserve its rural communities, and enhance the overall environment of the river.

**Nature, scope, and objectives of research:**

In this proposal we present an approach that builds upon on-going studies to apply and refine sound modeling tools, rooted in and calibrated by extensive field data, and founded upon strong working relationships with numerous agencies and with over 130 valley farmers. The goal of the proposed first phase (March 2002 – February 2003) of this project was to build, through application of an existing calibrated model and through comparative economic analysis, a framework for evaluating strategies to support a productive irrigated agriculture in a salinity-threatened valley. Through extension and education activities, farmers and agencies in the valley will provide input in developing strategies for a representative valley subregion and in evaluating these strategies for their practicality at the field scale. The second phase (March 2003 – February 2004), proposed herein, aims to refine the proposed strategies through consideration of their features over a long-term (20-year to 30-year) planning horizon. The final phase (March 2004 – February 2005), if funded, will consider their impact over the larger scale of the entire river basin. The underlying motive is to assure that river operations and irrigation-and-drainage systems in the valley are conjunctively designed and managed to effectively control salinity from the basin, the subregional, and the field perspectives.

The results of this study will be a proposed set of the most-promising strategies for lowering saline high water tables and reducing river salinization – strategies whose technical and economic impacts have undergone preliminary assessment based on an estimation of their long-term performance. This assessment will, to a lesser extent, also include consideration of legal/institutional constraints. Strategies to be considered will include:

- (1) Increased 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, trickle irrigation, and sprinkler irrigation, and
  - e. Other structural/management measures to improve uniformity of applications and reduce overirrigation.
- (2) Reduced seepage from irrigation canals through
  - a. Soil liners with permeability reduced by amendments,
  - b. Buried plastic membranes,
  - c. Polyacrylamide (linear-linked polymer) additives, and
  - d. Other lining materials.
- (3) Increased pumping rates from existing pumping wells with excess flows (above legal permit) routed through drains to the river.
- (4) Installation of 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
  - a. Altered operations of Pueblo and John Martin Reservoirs, and
  - b. Dredging of excess sediments from the river channel.
- (6) Conversion to more salt-tolerant crop varieties.
- (7) Combinations of the above strategies.

Possible improvements to extensive salinity-affected irrigated areas, like those listed above, cannot be evaluated through field trials. The scope and complexity of such efforts would make them far too costly and time-consuming. Instead, they can be analyzed using simulation models to identify those strategies that come close to maximizing economic net benefits over the area derived from reduced waterlogging and salinity (Gates and Grismer 1989, Gates, Wets, and Grismer 1989, Grismer and Gates 1991, Garcia, Gates, and Manguerra 1995, Manguerra and Garcia 1996, 1997). Along with economic criteria, Fredericks, Labadie, and Altenhofen (1998) emphasize the need for stream-aquifer system management strategies that simultaneously account for hydrological, geochemical, and administrative/legal impacts. An multidisciplinary approach, that considers multiple interacting features, is needed. In addition, these multiple

features display differing degrees of variability, interaction, and importance over the various scale of river basin modeling under consideration.

The approach described above is proposed for the second phase (2003-2004) of a recommended three-year project. We plan to pursue this course through the following objectives and general procedures, implemented by a multidisciplinary team of two engineers, an economist, and a soil scientist, with direct input from stakeholders in the Arkansas River Valley:

- (1) Refine the solution strategies listed above through interaction with farmers and agencies, via meetings and information-transfer technologies;
- (2) Evaluate the strategies for application in the representative upstream study subregion near La Junta and in the representative downstream study subregion near Lamar (Figure 1). Data collected by *on-going projects* in these subregions will be used to refine and support transient models for predicting long-term outcomes of implementing the alternative strategies. Cooperation with ongoing projects will allow evaluation of the practical implementation of target strategies, with input from farmers and agencies, at the field scale for selected representative fields in the study subregions;
- (3) Refine target strategies and rank their effectiveness according to predefined economic, environmental, and legal/institutional criteria using multicriteria decision analysis; and
- (4) Work with farmers and agencies to propose development of organizations and schemes for implementing the most promising alternatives.

A third phase (2004-2005), if funded, would allow application of a basin-wide network simulation model (MODSIMQ) for integrating hydrologic processes governing surface water distribution, river basin operations and administration, stream-aquifer interactions, and water quality criteria using target strategies developed for the two study subregions. *This proposal seeks to build upon the momentum gained by on-going data collection and modeling studies, including the first phase of this project, currently funded by CWRRI. On-going projects and the proposed project individually are insufficient to support the entire data collection and analysis effort required. Collectively, the full scope of information on impacts of salinity and water table control measures on the hydrochemistry and economics of the stream-aquifer system and on crop production can be realized.* The emphasis of the project proposed herein will be on the assessment of solutions at the subregional scale, with the emphasis on technical (environmental) and economic assessment.

### **Methods, procedures, and facilities:**

#### **Use of Data from On-Going Projects**

The proposed project will focus on modeling and evaluation of strategies to solve waterlogging and salinization problems in the Lower Arkansas Valley. These efforts will be supported by data obtained from on-going complementary projects directed by the principal investigators. These databases are being developed for two study subregions: upstream of John Martin Reservoir and downstream of John Martin Reservoir. The upstream study subregion extends eastward about 62 km, from just west of the town of Manzanola in Otero County to Adobe Creek in western Bent County (Figure 2). The study area covers about 50,600 ha (125,000 acres) of land of which about 26,400 ha (65,300 acres) are irrigated. The downstream study subregion extends for a distance of about 45 km along the river from the May Valley Drain near

Lamar on the west to the Colorado-Kansas line on the east (Figure 3). It encompasses about 52,900 ha (130,600 acres) including about 25,700 irrigated hectares (63,400 acres) of crops. Each study subregion is served by six major canals and several minor canals. Data elements available from the study subregions will include water table depth and salinity; soil salinity; flows, water levels and salinity in the river, irrigation canal, and drains; hydraulic conductivity, texture, and pressure-saturation characteristics of soils; crop yields; and costs and benefits of irrigated agricultural enterprises. Data on the upstream subregion have been collected over five irrigation seasons and plans call for continuation over two or three additional seasons. Data collection on the downstream subregion commenced in 2002 and should continue for two or three additional seasons.

### Interaction with Stakeholders for Defining Solution Strategies

These studies link research and education/extension by using sound field data and models, applied in the context of two-way interaction with stakeholders. In the first phase of the project, data describing the extent and severity of the problems will be communicated to cooperating farmers and agencies, through meetings and the Internet, to prompt input in refining initial solution strategies, starting with the list cited above, using a developed steady-state and short-term transient subregional-scale model. These target strategies will then be examined, with the help of farmers and agencies, using a field-scale model to evaluate field-level practicality and impacts on crop production. If necessary, target solutions will then be refined at the subregional scale in light of this evaluation. In this proposed second phase, refined target solutions will be assessed for their long-term transient effects and by a basin-scale model to evaluate suitability to larger-scale economic, environmental, and legal/institutional objectives. Multidisciplinary issues of engineering, economics, soil and water science and crop production will be addressed. Final refinement will result in recommended solution strategies based upon accurate knowledge of field conditions in the context of the larger basin-scale issues for insuring sustainability of the valley's productive agricultural base and preservation of its rural communities.

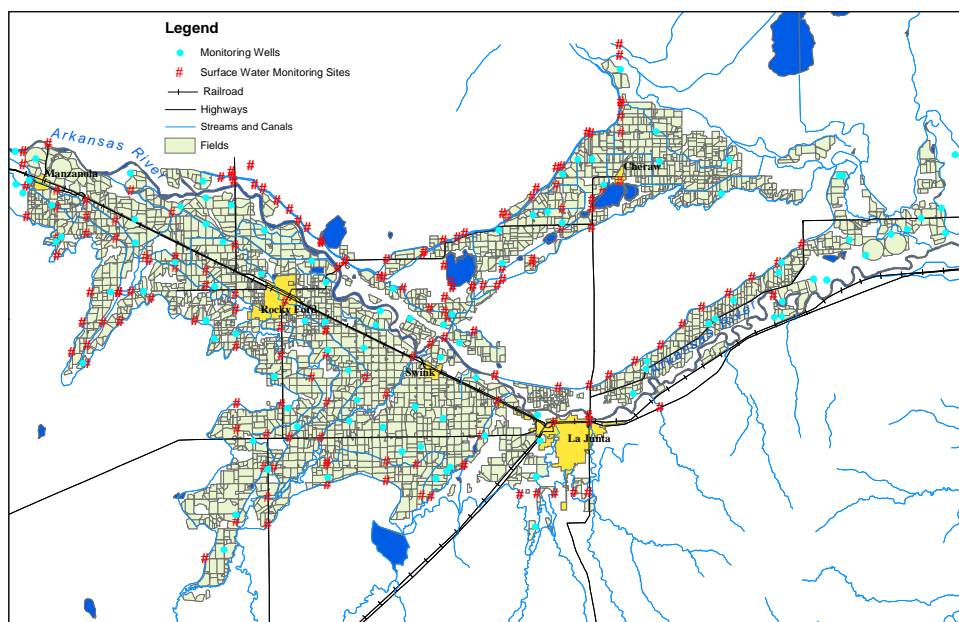
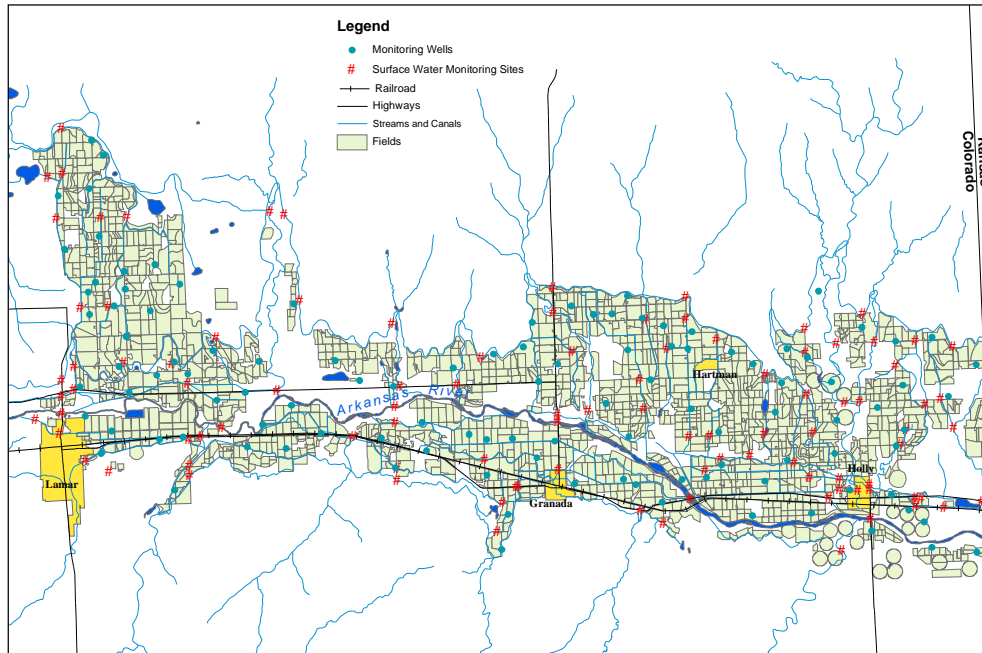


Figure 2. The upstream study subregion near La Junta, Colorado.



**Figure 3.** The downstream study subregion near Lamar, Colorado.

### **Application of Subregional-Scale Model for Estimating Impacts of Proposed Strategies**

The Groundwater Modeling System (GMS) will be applied to simulate impacts of various salinity control strategies in the upstream study subregion. The GMS software package links the MODFLOW (McDonald and Harbaugh 1988) groundwater flow model, and the MT3DMS (Zheng and Wang 1999) contaminant transport model for solving the flow and transport equations within a spatially-referenced geographic information system (GIS) (BYU 1999). In the first phase of this project, MODFLOW and MT3DMS are being applied to conditions of steady state and short-term transient flow to explore the comparative order of magnitude of effects to be expected from scenarios associated with proposed strategies. That is, a feasibility-stage approach is being taken that uses steady-state and short-term transient simulation under constant seasonal-average properties and boundary conditions (conditions representative of those measured in the 1999, 2000, and 2001 irrigation seasons). The governing flow and transport equations are solved in GMS to estimate conditions of water table depth and salinity, and rates and salinity of return flows to the river. Also, mass-balance models and relationships developed from field-scale analysis will be used to predict soil salinity, crop yields, and net economic returns. The purpose of the first phase is to make a relative comparison between strategies, thereby providing a basis for actions to be taken to initiate implementation in the valley.

While the process for implementation progresses, the proposed second phase of the project will examine the most promising alternatives under more-detailed and more-accurate dynamic modeling that allows consideration of the important timing of flows, salt concentration changes, and storage changes that will occur in the irrigation-aquifer-river system and will consider

issues related to more-extensive basin-wide application. Also, during this phase, the uncertainty associated with spatial and temporal variability in system properties, boundary conditions, and sinks/sources, as estimated from sampled field data, will be addressed in cooperation with complementary projects (using methods similar to those conducted by Gates and Grismer 1989, Gates, *et al.* 1989, and Gates and Al-Zharani 1996a, 1996b).

### **Evaluation and Ranking of Solution Strategies**

After the most-promising alternatives have been identified for the representative upstream study subregion in the first phase of this project, long-term transient modeling will be applied to ascertain the time-varying characteristics of the different solution strategies. Also, a similar approach will be applied to the representative study subregion downstream of John Martin Reservoir. The best strategies that arise from analysis of both subregions will then be coalesced to consider likely impacts at the larger basin scale.

#### *Overall Summary and Ranking of Strategies*

For the results to provide useful information to aid policy makers, the outcomes must be meaningfully summarized. To identify preferred strategies, economic, environmental, and legal/institutional impacts resulting from each strategy must be weighed. Alternatives exist for completely ranking outcomes with multiple attributes, however parameterizing such models for public policy decisions is not a trivial matter. To avoid imposing undue subjectivity into the analysis, a presentation with varying levels of detail will be used. Each primary criteria (maximize economic benefit, minimize environmental impact, and maximize legal/institutional acceptability) requires enumeration of several more-detailed subcriteria, or specific objectives. For example, estimation of the environmental impact criterion,  $C_E$ , might consider the following specific objectives: maximize depth to water table, minimize aquifer salinity, minimize soil degradation, minimize wetlands decline, and minimize salt and sulfate loading to the river.

The considered solution strategies have a strong spatial character, and can be well represented in a GIS. Within each general strategy are many possible spatial characterizations of their implementation, both in extent and intensity. In the third phase, maps of primary criteria,  $C_{EB}$ ,  $C_E$ , and  $C_{LI}$ , using appropriate scales of measurement (ratio or ordinal), along with appropriate measures of subcriteria, will be developed in a GIS, and automated to allow generation of these maps for each set of strategies evaluated. The outcomes estimated for each strategy will also be summarized and presented in tabular form following Frasier, *et al.* (1999b). To reduce dimensionality, methods will be applied to remove dominated strategies, as described in Yeh and Labadie (1997) and Ko, Fontane, and Labadie (1992). Finally, appropriate multicriteria decision analysis (MCDA) methods will be selected for ranking of alternatives, including pairwise comparison methods such as the analytical hierarchy process (Saaty, 1980), fuzzy preference function methods such as PROMOTHEE (Brans, *et al.*, 1986), or displaced ideal concepts such as compromise programming (Gershon and Duckstein, 1983). As demonstrated by Eastman and Jiang (1996) and Tkach and Simonovic (1997), evaluation using these MCDA methods can be directly performed within a GIS. More than one MCDA technique will be applied for comparison purposes. Sensitivity analysis evaluations will be used to determine sensitivity of strategy ranking to possible errors in measure of the evaluation criteria.

### **A Cooperative Effort**

The study described above is believed to be essential to arresting salinization in the lower Arkansas Valley. However, it will be time-consuming and costly, and can only be accomplished with the assistance of other interested parties in the Valley and with funding supplemented by other projects as described below. In their recent and on-going work in the Arkansas Valley, the principal investigators have established partnerships with Southeastern Colorado Water Conservancy District, the United States Department of Agriculture (USDA), the USDA-NRCS Area Office, the Pueblo Subdistrict Office of the United States Geological Survey (USGS), the Eastern Colorado Area Office of the U.S. Bureau of Reclamation (USBR), the USBR Denver Technical Support Offices, the District 2 Office of the Colorado Division of Water Resources, the USDA Farm Services Agency, the Bent County Soil Conservation Board, the Catlin Canal Company, and the Fort Lyon Canal Company. Continued cooperation from these agencies is expected in the proposed project.

### **Related research:**

#### **Related Projects Involving the Principal Investigators**

The principal investigators currently are engaged in a related project entitled “Managing Irrigation-Induced Salinity and Pollutant Loading to Enhance the Agroecosystem of the Lower Arkansas River Basin in Colorado,” sponsored by the Colorado Agricultural Experiment Station (CAES). This study is an extension of previous CAES projects that resulted in initial development of the integrated water quantity/quality river basin management model MODSIMQ (Dai and Labadie 2001) and that focused on description of the nature and extent of salinity-related problems and on calibration and verification of the GMS numerical models of shallow groundwater flow and salt transport at the subregional scale. The project has applied GMS for initial assessment of a few strategies for solving saline-high-water-table problems inside the study subregion upstream of John Martin reservoir (Figure 2) under average steady-state conditions (Gates et al. 2002). Work on unsteady flow and salt transport modeling, using weekly time steps, has been initiated with the aim of producing results that can be incorporated into an expanded version of MODSIMQ. MODSIMQ will draw on these results, as well as results to be derived from the downstream study subregion (Figure 3), to assess solution strategies in light of complex water rights, interstate compact, and other legal issues that control allocation and use of both surface water and groundwater at the basin scale.

The CAES project has been joined by support from two other projects in deriving an extensive data set for supporting the development and modeling of solution strategies in the upstream study subregion. The first related project, entitled “Description and Interpretation of Salinization in the Lower Arkansas River Valley, Colorado”, was sponsored by CWRRI and was conducted by the principal investigators from March 1999 to March 2002. A second related project, entitled “Identification, Public Awareness, and Solution of Waterlogging and Salinity Problems in the Lower Arkansas River Valley Colorado,” has been sponsored by the Water Management and Conservation Program of the USBR (Great Plains Regional Office) from October 1998 to the present. The USBR Denver Technical Center, the Bent County Soil Conservation District, the Catlin Canal Company, and the Fort Lyon Canal Company also have provided supplemental funds in support of data collection.

Over the last four years, under support of the above-described projects, intensive measurements have been conducted in the study subregion upstream of John Martin reservoir. Water table depth and salinity (as electrical conductivity, EC) were measured weekly to bi-weekly in monitoring wells (3 m to 7 m deep) underlying a total of 74 fields distributed over the subregion in the summer of 1999, underlying 95 fields in the summer of 2000 (Gates et al 2001), and underlying 101 fields in the summers of 2001 and 2002. Surface-water EC, calibrated to total dissolved solids (TDS), was measured weekly to bi-weekly throughout most of the 1999 season, the 2000 season, the 2001 season, and the 2002 season at a total of more than 170 locations, including sites along the Arkansas River, in six major canals, six lateral canals, twelve drainages, and two off-stream reservoirs. Records of daily diversions to the canals in the subregion allowed assessment of irrigation efficiency and salt loading under each of six canal command areas. Soil salinity was measured in 30 fields (each field five to twenty acres in size) in Otero County during summer 1998 (Gates, *et al.*, 1999), in 68 fields (five to eighty acres in size) in Otero and Bent counties during summer 1999 (the ten fields surveyed in Bent County were not equipped with monitoring wells in 1999), in 77 fields over summer 2000, in 80 fields over summer 2001, and in 80 fields over summer 2002. Global positioning system (GPS) receivers were used to accurately locate sampling sites, land topography, and hydrography, for use in a geographic information system (GIS). Slug tests, for estimating hydraulic conductivity, have been conducted at 95 locations within the study subregion. Thousands of samples have been collected for estimating soil texture with depth. Crop yield losses are being estimated through harvest records on many of the fields that have been studied.

Contour plots in Figure 4 reveal substantially high water tables averaged over the 1999, 2000, and 2001 irrigation seasons. The portion of cultivated area with water table depth less than 2.5 m below ground surface was about 44% in 1999, 27% in 2000, and 25% in 2001. The average measured salinity (as electrical conductivity, EC) of the water table in the study region was about 3.5 dS/m (3100 mg/l) in 1999 (Figure 5a), 3.2 dS/m (2850 mg/l) in 2000 (Figure 5b), and 3.1 dS/m in 2001 (Figure 5c). Surface-water salinity was measured weekly throughout most of the season at more than 170 locations, including points in the Arkansas River, in six major canals, in twelve drainages, and in two reservoirs. The average salinity of the water in the irrigation canals was 0.93 dS/m (812 mg/l) in 1999 and 1.12 dS/m (978 mg/l) in 2000, and 1.03 dS/m (899 mg/l) in 2001, indicating low to moderate restriction in use for irrigation. Global positioning equipment was used to accurately locate each of the groundwater and surface-water sampling sites for use in a geographic information system.

Estimates of irrigation efficiency (product of conveyance and application efficiencies) and salt loading, based on flow and salinity measurements, ranged from 25% to 40% and from 10,300 kg/ha to 17,900 kg/ha, respectively, over the subregion. Data collected in 2001 are still being analyzed.

Soil salinity (to a depth of about 1 m) was measured in early June and in mid August on 68 different fields in 1999, on 77 fields in 2000, on 80 fields in 2001, and on 80 fields in 2002. Data collected in 2002 have not yet been analyzed. On each field, soil salinity (as electrical conductivity of saturated extract,  $EC_e$ ) was estimated from measurements using electromagnetic



induction probes at an average of about 62 locations (about 1 to 10 locations per acre) for each sampling. In addition, more than 5,000 soil samples were collected for use in calibrating the electromagnetic probes. Soil salinity measured in overlying fields varied from benign to extreme, tending to exceed threshold tolerances for crops when the depth to the saline water table was less than about 3 m. The overall average soil salinity was estimated as 2.9 dS/m (2560 mg/l) in 1999, 2.0 dS/m (1730 mg/l) in 2000, and 2.6 dS/m (2290 mg/L) in 2001. For the late-season readings in 1999, about 70% of fields had at least 25% of measured points above the salinity threshold (level above which crop yield reductions are expected), indicating significant soil degradation and declining yield. Crop yield reduction due to salinization was estimated to range between 0 and 75% on fields spread over the subregion, averaging about 10%. This indicates a total revenue loss ranging \$0/ha - \$750/ha among the fields, and averaging \$70/ha - \$100/ha over the study subregion, based on 1999 crop prices. Additional losses are likely occurring due to waterlogging. Data collected in 2000 and 2001 are currently under analysis.

**Investigator's qualifications:**

Resumes for the principal investigators Dr. Timothy K. Gates and Dr. John W. Labadie, and for the co-principal investigators, Dr. Marshall Frasier and Dr. Grant E. Cardon, are attached. These investigators have extensive experience in the physical and economic analysis of water resources, salinization, irrigation, and drainage, both in the U.S. and abroad.

**Training potential:**

The project will provide partial support for one MS graduate student in Civil Engineering and for one PhD student in Agricultural and Natural Resources Economics. The students will prepare theses and two or more refereed journal articles based upon the project results. Two undergraduate students also will be partially supported by the project. The project will afford an excellent opportunity for the students to develop analytical expertise in the diagnosis and solution of salinity and drainage problems.

Various education and information programs will be instituted for farmers and other water users in the Valley under the project. This will include seminars and meetings describing modeling approaches and soliciting input in the development and evaluation of solution strategies.

# Urban Landscape Irrigation with Reclaimed Wastewater: Water Quality Assessment and Community Experience

## Basic Information

<b>Title:</b>	Urban Landscape Irrigation with Reclaimed Wastewater: Water Quality Assessment and Community Experience
<b>Project Number:</b>	2003CO71B
<b>Start Date:</b>	3/1/2003
<b>End Date:</b>	2/28/2004
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	
<b>Research Category:</b>	None
<b>Focus Category:</b>	Irrigation, Waste Water, Water Supply
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Yaling Qian, Yaling Qian

## Publication

1. Qian, Y.L., 2004, Urban Landscape Irrigation With Recycled Wastewater: Preliminary Findings. Colorado Water Resources Research Insitute, Colorado State University, Colorado Water, 21(1), pp. 7-11.
2. Qian, Y.L., 2003, Urban Landscape Irrigation With Reclaimed Wastewater: Opportunities and Potential Problems, in 2003 Water Reuse Workshop: Reuse It or Lose It!, Co-Sponsored by Rocky Mountain Water Environmental Association, AWWA Rocky Mountain Section, and Water Reuse Association, Golden, CO.
3. Gejer, Melinda, 2003, Long Term Effects of Effluent Water Irrigation on Soil Nitrate and Phosphorus Profiles Under Turfgrass, Presented in the 2003 Research Experiences for Undergraduates Program in Water Research, Colorado State University, Fort Collins, CO.
4. Qian, Y.L., 2003, Urban landscape Irrigation With Reclaimed Wastewater: Preliminary Findings, Presented in the 50th Rocky Mountain Regional Turfgrass Conference, Denver, CO.

## Problem and research objectives

Growing concerns of our future water supply and more stringent wastewater discharge standards to surface water bodies have contributed to increasing interest in using recycled wastewater for urban landscape irrigation. Increasing numbers of landscape facilities and development areas have been switched to or plan to use recycled wastewater for irrigation in the western states.

Recycled wastewater (i.e. reclaimed wastewater) is treated wastewater from the community to meet a permit issued through Federal or State Water Acts. During treatment, suspended solids are removed, pathogens are disinfected, and partial to substantial reduction in nutrients occurs, depending on the level of treatment. However, recycled water may still contain different levels of dissolved solids, ions, nutrients (N and P), and other elements.

The growth in water reuse has created the needs to provide information on the chemical and biological properties of effluent water and to determine the effects of recycled wastewater irrigation on urban landscape soils, plants, and the ecosystem as a whole.

The primary objectives of the project are to:

- 1) To assess chemical properties of recycled wastewater for urban landscape irrigation; and
- 2) To evaluate landscape plants and soils that are currently under recycled wastewater irrigation.

## Methodology

The procedures and methodology of the project involved:

- 1) Preparing and sending surveys to the wastewater treatment plants that are currently supplying recycled wastewater for urban landscapes along the Front Range of Colorado. Requesting data on effluent water analysis from wastewater treatment facilities, which include total suspended solids, turbidity, biological oxygen demand, chemical oxygen demand, E-coli, and other basic chemical characteristics.
- 2) Collecting water samples from irrigation ponds and irrigation sprinkler outlets on reuse sites to test salinity, individual mineral concentrations, and bicarbonate content.
- 3) Collecting and analyzing soil samples from reuse sites vs. landscape sites that have not used recycled wastewater.
- 4) Visual evaluations of the health of landscape plants on reuse sites.

## Principal findings and significance

1) Golf courses are the earliest and leading urban landscape users of recycled wastewater in Colorado. Recently, the reuse practice has been extended to include some of the large parks, open spaces, and greenbelts. Survey data indicated that cost savings was not the main reason for using recycled wastewater for irrigation. Rather the availability and reliability of the water were the driving force for using recycled wastewater for irrigation.

2) Data from five advanced wastewater treatment plants in the Front Range of Colorado revealed that, although there were variations in water quality between wastewater treatment facilities, in all cases, the water quality of effluent exceeded the regulations in the terms of E-coli count, turbidity, and suspended solid.

3) The chemical constituent of recycled wastewater is dominated by sulfate, bicarbonate, chloride, and sodium. These 4 ions comprise of about 70% of total dissolved salts. The average electrical conductivity (EC) of 37 recycled wastewater samples from 6 reuse sites was 0.84 dS/m and the range was 0.47 to 1.32 dS/m. An electrical conductivity higher than 0.75 dS/m indicates the water may impose negative effects on salt sensitive plants. Periodic leaching of salts is required to mitigate the potential salinity problem. Adjusted sodium absorption ratio (SAR) of recycled wastewater from reuse sites ranged from 1.6 to 8.3. Based on the interactive effect of salinity and sodicity on soil infiltration and percolation, 90% of the water samples collected showed slight to moderate effects on soil infiltration and permeability. The average sodium and chloride concentrations of 37 water samples collected were 99 mg/L and 95 mg/L, respectively. Previous literature suggests that, with sprinkler irrigation, sodium and chloride toxicity could occur on sensitive plants when their concentrations exceed 70 and 100 mg/L, respectively. Therefore, sodium toxicity would likely to occur to sensitive landscape plants under long-term recycled wastewater irrigation. For sites with poor drainage and/or have a shallow water table present, chloride applied over time may also accumulate to a toxic level.

4) Although, typically the wastewater treatment systems have continuously evolved in response to the growth and regulatory requirements, our results indicated that soils from sites where recycled wastewater was used for prolonged time exhibited higher concentration of sodium, chloride, boron, and phosphorous than sites with surface water irrigation. However, the cation exchange sites occupied by magnesium and potassium were lower. Comparison of soil chemical properties before and 5 years after recycled wastewater irrigation on 2 golf courses also revealed the following findings: a) increased sodium content and sodium exchange percentage; b) increased boron content; and c) increased phosphorous content at the surface depth.

5) Quality decline of some conifer trees was often observed on golf courses with recycled wastewater for irrigation. Landscape managers also revealed that turf became more susceptible to drought stress after years of recycled wastewater irrigation. It is difficult to draw conclusions about the causes of the decline, although the degree of decline appeared to relate to water quality, species, soil texture, irrigation methods, and drainage effectiveness. More research is needed to define the causes of the decline and to study

the tolerance of different landscape plants to recycled wastewater irrigation.

From our initial study we found that, while recycled wastewater irrigation in urban landscapes is a powerful means of water conservation and nutrient recycling, potential problems associated with recycled wastewater irrigation do exist. These problems include a relatively high sodium concentration and the resulting changes in soil physical and chemical properties after long-term application of recycled wastewater. As landscape facilities and development areas plan to switch to recycled wastewater for irrigation, landscape managers must be prepared to face new challenges associated with the use of recycled wastewater. City landscape planners and managers need to understand the hidden costs in managing these landscapes to mitigate problems, such as higher water use for leaching; the need of frequent aerifications to maintain infiltration, percolation, and drainage; application of soil amendments to reduce sodium problems; soil and plant monitoring, etc.

# Canal Modernization for Addressing Salinity Issues in the Arkansas Valley, Colorado

## Basic Information

<b>Title:</b>	Canal Modernization for Addressing Salinity Issues in the Arkansas Valley, Colorado
<b>Project Number:</b>	2003CO72B
<b>Start Date:</b>	3/1/2003
<b>End Date:</b>	2/28/2004
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	
<b>Research Category:</b>	None
<b>Focus Category:</b>	Irrigation, Water Quality, Management and Planning
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	John Reese Wilkins-Wells, Ramchand Oad

## Publication

1. DeJong, Kathleen E., 2004, Occurrence of Emerging Organic Chemicals in Wastewater System Effluents, Presentation at the 1st WEF/AWWA Student Conference, Rocky Mountain Region, May 18, 2004, Colorado School of Mines, Golden, CO.
2. DeJong, Kathleen E., Robert L. Siegrist, Larry B. Barber, and Abigail L. Wren, 2004, Occurrence of Emerging Organic Chemicals in Wastewater Effluents from Onsite Systems, In: Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, Sacramento, California, p. 400-407.
3. Siegrist, Robert L., 2002, Water Quality Protection Provided by Onsite Wastewater Systems, in Proceedings of the 13th Annual South Platte Forum, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, Information Series No. 94, p. 16-17.

### Problem and research objectives:

The problem was to identify methods to assist canal companies in the Arkansas Valley to modernize their canal infrastructure, and to better understand factors influencing the desire to invest in further agricultural production, by way of improvements in canal systems. Canal modernization is needed to address both water conservation and salinity problems in the valley.

Research objectives included organizing workshops, study tours and feasibility studies on various approaches to canal modernization. In addition, several discussions were conducted with growers throughout the Arkansas Valley.

Utilizing the grant, the researchers were able to interest one city with two large irrigation canal companies passing through its annexed area to apply for a grant from the Colorado Water Conservation Board to conduct a feasibility study on modernizing these two canals while developing a pressurized secondary water system for the city, using shares of stock the city owned in the two canal companies. The researchers then collaborated with a private sector firm, Aqua Engineering, Inc., of Fort Collins, Colorado to conduct the feasibility study (see listed publication below).

In addition, the researchers were able to conceptualize the issues surrounding canal modernization by hypothesizing a set of key factors influencing the desire to continue farming in the Arkansas Valley. This hypothetical model is discussed below.

### Methodology

Formal presentations on canal modernization:

- City of Lamar Water Board, Colorado 5/1/03
- Catlin Canal Board of Director, Colorado 5/12/03
- The Town of Swink, Colorado 5/12/03
- City of Lamar Water Board, Colorado 5/22/03
- Catlin Canal Board of Directors, Colorado 6/9/03

Organized study tours:

- City of Lamar Water Board – visit to canal companies in Utah undergoing modernization 10/3/03 to 10/5/03

### Principal findings and significance

There are many economically viable opportunities for canal companies in the Arkansas Valley to improve their water delivery systems. These include improved water delivery recordkeeping through greater use of computers, including the use of computerized accounting of well augmentation plans within the service areas of canal systems; improvements in canal structures, such as canal check structures, gates, flumes and weirs; the use of SCADA (automated supervisory control and data acquisition) for both

monitoring of water supplies and for controlling structures, and; canal modernization through the provision of secondary water for lawns and gardens to surrounding rural communities and rural subdivisions. The presentations given at meetings on these technologies, as well as the study tour organized to visit canal modernization in Utah involving the use of technologies, were favorably received by those attending the sessions.

However, major constraints to the adoption of these technologies include insufficient income from farming, and the increased opportunity costs of farming due to the rapidly rising value of farm assets (i.e., land and water) for urban uses. Urbanization in the region, and the impact this urbanization is having on the value of water in the Arkansas Valley for uses other than for farming, appears to be resulting in a growing feeling of impermanence about future opportunities in agriculture. The continued desire to farm in the area appears to be primarily affected by the following key factors:

### Modeling the Desire to Farm Under the Influence of Urbanization

$$C_d = f(W_s, Y_p, Y_f, L_p, G_{al}, I_s) + t$$

Where:

$C_d$  = farm household desire to farm

$W_s$  = water right

$Y_p$  = present income (combined on-farm and off-farm)

$Y_f$  = anticipated future income

$L_p$  = price of land for non-agricultural uses

$G_{al}$  = farm household pursuit of alternative lifestyles

$I_s$  = feeling of impermanence

$t$  = technology (affordability, rate of adoption)

These factors are believed essential to understanding the process of technology transfer in agriculture as well, whether the issue is improvements in methods of farming, the exploration of new commodity markets, or the use of climate data for production purposes. The opportunity costs of continuing to farm in the Arkansas Valley have increased dramatically in recent years with the demand for agricultural water for out-of-basin urban uses. This demand has coincided with efforts to interest farmers in water banking, forbearance contracts, and other market mechanisms designed primarily to divert water from agricultural use.

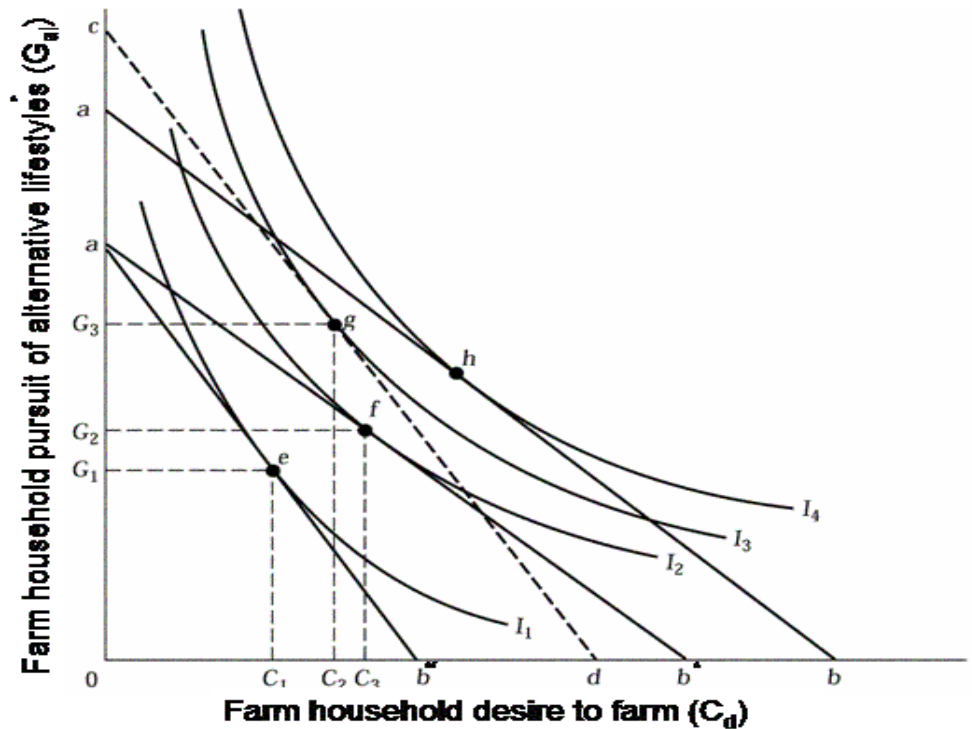
Additional research is needed to arrive at a better understanding of important social trends in agriculture and how these new institutional market mechanisms may affect the overall production decision-making and rate of technology adoption by growers, whether for on-farm production needs or for canal modernization. The following is an initial conceptualization of the relationship between market demands for land and water for uses other than for agriculture. This conceptualization is based on discussions with growers, the presentations on canal modernization and the Utah study tour.



Figure 1 provides a simple portrayal of the influence of urbanization on the desire to farm, expressed through indifference curves or isoquants for all possible combinations of (1) the household desire to farm,  $C_d$ , on the horizontal axis, and (2) the pursuit of alternative lifestyles,  $G_{al}$ , on the vertical axis. The farm household desire to farm is represented by the cost of purchasing goods and technologies for farming, while the farm household's pursuit of alternative lifestyles is represented by the cost of purchasing non-farming related consumer goods.

The farm household's ability to select combinations of alternative lifestyles and/or continuing in farming is shown by the farm budget constraint line,  $ab$ . All combinations on or below line  $ab$  (within the triangle area  $0ab$ ) would be financially attainable by the farm household, based on its perceived income prospects represented by the slope of the  $ab$  budget constraint. Also, the steeper the slope of the budget line, the higher the cost of farming relative to the cost of competing alternative lifestyles (i.e.,  $ab''$ ).

**Figure 1 – Theoretical Options to Continue Irrigation Farming Under the Influence of Urbanization**



According to this hypothesized demand-based theory of irrigation farming while under the influence of urbanization, the farm household chooses from among all attainable combinations the one combination of alternative lifestyle costs and farming costs that maximizes household satisfaction. Diagrammatically, this optimal combination is represented by point  $f$ , the tangency point between the budget constraint,  $ab$ , and indifference curve  $I_2$ .

A rise in farm household income, represented by the outward shift of the budget line from  $ab$  to  $a'b'$ , would enable the farm household to attain a higher level of satisfaction (point  $h$  on curve  $I_4$ ); this higher satisfaction represented by consuming more of both alternative lifestyle goods and farming goods.

An increase in the cost of farming goods, or increased opportunity costs of farming resulting from dramatically increased values of farm assets (i.e., land and water) resulting from urbanization, relative to the pursuit of alternative lifestyles, will cause farm households to substitute the pursuit of these alternative lifestyle costs for the desire to farm costs. In other words, other factors being constant, a rise in the relative cost (or opportunity cost) of farming causes the household utility-maximizing consumption combination to occur on a lower indifference curve, as shown by the movement of the equilibrium point from  $f$  to  $e$  when the budget line rotates around point  $a$  to  $ab''$ .

Another scenario is a simultaneous increase in household income and farming as a result of, say, expanded off-farm employment opportunities, along with perhaps increased liabilities associated with farming on the urban fringe. In this case, there would be both an outward shift and downward rotation of the budget constraint line to the dashed line  $cd$ . This represents a shift to a new utility-maximizing combination with the relative increase in the cost of farming (whether brought about directly by liability issues or indirectly by increased feelings of impermanence).

The importance of this theoretical model is to show the potential relationship between (1) the effect of the current popular public policy of looking to agriculture for urban water supplies and (2) potential changes in the economic assessment of growers toward farming in general. The market for water in conjunction with urbanization, represented through new institutional mechanisms, such as water banking and forbearance contracts, has unleashed a tremendous and compelling force on the grower not to continue farming, due to increased value of key farm assets (land and water) and associated opportunity costs of farming, given current levels of farm income.

In addition, this may be leading to a greater feeling of impermanence regarding the future of farming in the region, and may make the adoption of new technologies for farm improvements and water conservation of minimal value to the producer, particularly when future income anticipated from these improvements is perceived by the grower to be unlikely, given increasing economic pressures to sell the land and water assets of the farm.

Relative to issues surrounding canal modernization, based on recent studies of what is occurring in other areas of the Rocky Mountain region, it is believed that canal companies being affected by land and water sales should explore new profit centers, such as providing pressurized secondary water for rural community and rural subdivision landscape use. This involves the canal company purchasing canal company stock when it is placed on the market by growers, transferring that stock to traditional canal treasury stock, and then utilizing this water in a pressurized secondary system for residential outdoor use (i.e. for rural communities and rural subdivisions). This would provide canal

companies with some new revenue sources to help modernize their irrigation infrastructure, while ensuring that the water decree of the canal company has at least a fighting chance of remaining viable and attached to the local area. Further research is needed to assess these strategies.

# Use of Low-Cost Data to Simulate Fractured-Aquifer Watersheds for Management of Water Quality and Quantity

## Basic Information

<b>Title:</b>	Use of Low-Cost Data to Simulate Fractured-Aquifer Watersheds for Management of Water Quality and Quantity
<b>Project Number:</b>	2001CO261G
<b>Start Date:</b>	9/1/2001
<b>End Date:</b>	1/31/2004
<b>Funding Source:</b>	104G
<b>Congressional District:</b>	6th District
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Water Quality, Geochemical Processes, Non Point Pollution
<b>Descriptors:</b>	Water quality, Water quantity, Fractured-aquifer watersheds
<b>Principal Investigators:</b>	Eileen Poeter

## Publication

1. Poeter, E., G. Thyne, J. McCray, J. Lee and G. VanderBeek, 2002, Low-Cost Data for Characterization and Management of Fractured-Crystalline Aquifers, Proceedings of Fractured Rock Aquifers 2002, National Ground Water Association.
2. Day, S., G. Thyne and E. Poeter, 2003, Using statistical analyses to characterize effects of population growth on water quality, Geol. Soc. Amer., Abstracts with Programs, 35(5), p. 30.
3. Day, S., G. Thyne, E. Poeter, and J.E. McCray, 2002, Effects of population growth on water quality in a mountain watershed, Geol. Soc. Amer. Abstracts with Programs, 34(6).
4. Day, Sharon, Geoff Thyne, John McCray, and Eileen Poeter, 2002, Evaluation of the effects of population growth on water quality in a mountainous watershed, Geol. Soc. Amer. Abstracts with Programs, 33(4).
5. Guler, C., and G. Thyne, 2002, Hydrochemical evolution model and characterization of flow in a fractured crystalline rock aquifer, Turkey Creek, Colorado, Geol. Soc. Amer. Abstracts with Programs, 34(6).
6. Thyne, G., S. Day, J.E. McCray, and E. Poeter, 2002, Evaluation of the effects of population growth in mountain watershed water quality, EPA Fractured Rock Aquifers 2002 Focus Conference, Denver, Colorado.
7. VanderBeek, Greg and Eileen Poeter, 2004, Water Resource Evaluation in Fractured Rock Aquifers

Using Low-Cost Data, in preparation for Ground Water.

8. Wellman, Tristan and Eileen Poeter, 2004, Estimating Spatially Variable Representative Elementary Scales in Fractured Architecture Using Hydraulic Head Observations, in review at Water Resources Research.
9. Thyne, G. D., C. Guler, and Poeter, E., 2004, in press for Ground Water Sequential Analysis of Hydrochemical Data for Watershed Characterization, Ground Water.
10. Poeter, E., G. Thyne, G. VanderBeek, and C. Güler, 2003, Ground water in the Turkey Creek Basin of the Rocky Mountain Front Range in Colorado, in press in Engineering Geology in Colorado: Contributions, Trends, and Case Histories, ed. Douglas Boyer, Paul Santi, and Pat Rogers, Association of Engineering Geologists Special Publication 15 and Colorado Geological Survey Special Publication 55.
11. Wellman, Tristan and Eileen Poeter, 2004 in press, Optimizing the Predictive Accuracy of Hydraulic Head Observations to Delineate Continuum Scales in Phreatic Fractured Rock Aquifers, The Finite-Element Models, MODFLOW, and More 2004 conference, Carlsbad, Czech Republic.
12. Wellman, T. and E. Poeter, 2004, Evaluating Hydraulic Head Data as an Estimator for Spatially Variable Equivalent Continuum Scales in Fractured Architecture Using Discrete Feature Analysis, Dynamics of Fluids in Fractured Rock Conference, Sponsored by Lawrence Berkeley National Laboratory, February.
13. Wellman, TP and EP Poeter, 2003, Estimating Equivalent Continuum Scales in Fractured Aquifer Watersheds Using Discrete Feature Network Simulation, Fall AGU Meeting, Eos, 84 (46) abstract H42B-1071.
14. VanderBeek, G., Poeter, E.P., Thyne, G.D., and McCray, J.E., 2003. Ground-water availability in Turkey Creek Basin, Colorado, Geol. Soc. Amer., Abstracts with Programs, 35(5).
15. Dano, K., Poeter, E. and Thyne G., 2002, Geochemical and geophysical determination of the fate of septic tank effluent in a mountain watershed. Colorado. Geol. Soc. Am. Abstracts with Programs, 34(6).
16. VanderBeek G, Poeter E, Thyne G, McCray J.E., 2002, Ground-water Availability in Turkey Creek Basin, CO. GSA Abstracts with Programs, 33(4).

## Problem and research objectives

Mountain watersheds are primary water resources in the western United States, but we lack a scientific basis for making credible decisions regarding mountain land use. The rapid growth of population and development in mountain watersheds caused Jefferson County of Colorado to begin collecting data in a pilot study of ground-water resources in the Turkey Creek Watershed, a fractured-crystalline rock aquifer, typical of those that support individual domestic wells and sewage disposal systems for residents of the county and similar areas throughout Rocky Mountains, United States, and the world. A number of agencies funded data collection in the watershed, but the data are in different forms at many locations and have not been integrated into a model for a management tool. Although a ground-water model of the watershed is not expected to predict conditions in a particular well, it can provide information about future conditions in specific areas of the watershed. The proposed research utilizes a rare database from the watershed to complement and extend the work of the USGS by integrating data from many sources and developing models to: 1) better understand the flow system, 2) determine which low-cost data are instrumental in describing the system and which data reduce uncertainty, and 3) simulate the impacts of alternative development scenarios on ground-water levels, quality, and its to the total maximum daily load in streams. The value of the low-cost data will be confirmed using the more unusual data. The methods developed in this research will be useful for assessing the effects of population growth and development in other fractured-aquifer watersheds. The most difficult portion of this task is evaluating the fracture character of the aquifer. At this time, society cannot afford to characterize every detail of the subsurface water-bearing fractures to manage ground water. This project will use an elaborate database to determine the value of low-cost, holistic measures for evaluating the character of three-dimensional fracture flow and the scale at which equivalent porous media models can be used to predict impacts of management scenarios. Before collecting additional field data, modeling studies can glean information from existing data and determine which data will decrease uncertainty.

## Methodology

Task 1) compile and organize available data in a manner that will facilitate its dissemination;

Task 2) evaluate the data by viewing their distribution from a variety of perspectives;

Task 3) utilize the data to develop representative synthetic equivalent-porous-media and fracture flow models, with characteristics similar to that of Turkey Creek Watershed, to evaluate attributes generally believed to differentiate porous media and fracture flow systems and compare the character of hydraulic head and water quality observed in Turkey Creek Watershed to synthetic model behavior to estimate the scale at which Turkey Creek Watershed can be represented as equivalent porous media;

Task 4) use results of task 3 to generate models of Turkey Creek Watershed applicable to the management scale, calibrate the models using multiple regression techniques, and identify the data that are instrumental in describing the flow system, as well as, the type

and location of new data that will improve the calibration or confirm the value of the low-cost data

Task 5) collect data identified in task 4 and incorporate the data into the model calibration to modify and improve the representative models;

Task 6) use the representative models to predict the impact, and associated uncertainty, of increased development on the quantity and quality of water resources;

Task 7) identify the data that are instrumental in making accurate predictions and evaluate the type and location of new data that would reduce prediction uncertainty or confirm the value of the low cost data;

Task 8) prepare a report and provide project findings to the public; and

Task 9) train future geological engineers while accomplishing the previous objectives.

### Principal findings and significance

Evaluation of front-range aquifers is only beginning and this project will continue to refine conceptual models and limit the possible range of interpretation through data mining, data collection, and analysis. Current analysis of the available data reveals:

- Water bearing fracture frequency is fairly uniform among rock types (~0.01 water-bearing fractures per foot) but fault zones and coarse granitic rocks have higher yields per fracture, thus are likely to have larger apertures and/or better connectivity.
- Fracture frequency (and yield) is uniform between 100 and 700 feet below ground surface.
- Well yields are higher in the fault zones and coarse granite, which occupy limited area in the upper portion of the basin.
- Depth to water averages less than 100 feet (30m).
- Water levels in wells mimic the topography, with coincident surface and ground-water divides.
- Water levels are responsive to spring recharge and generally exhibit a recession each water year.
- Precipitation is on the order of 20 in/yr (508 mm/yr) while evapotranspiration is on the order of 18 in/yr (457 mm/yr). Both are variable and known from a short period of limited spatial distribution, and thus introduce much uncertainty in the water budget.
- Water levels are declining.
- Storage in the basin is poorly characterized.
- Volume of annual recharge is uncertain but is currently estimated on the order of an inch per year, with 75% pumped, but only 7% consumed because of ISDS recharge.
- Estimates of recharge are uncertain due to the short period of record and limited spatial distribution, consequently the estimate may be somewhat more or substantially less.

- The uncertainty associated with the water budget renders assessment of the sustainable population difficult.
- Surface water chemistry appears to have been adversely impacted by population growth during and after the 1970s.
- Ground-water chemistry has been impacted by anthropogenic effects that include high nitrate and chloride and lower pH, primarily in areas of high population density.
- Limited duration and spatial distribution of data prevents determination of whether the system has reached equilibrium concentrations.
- Ongoing studies will reduce current uncertainties.
- Hydrochemical data, water levels, and response of wells to recharge suggest an equivalent porous medium can represent the watershed for large-scale evaluations.
- Equivalent porous media models can be used to integrate the data, design further data collection and provide predictions of the hydrologic response to further development with ever decreasing uncertainty as additional data are accumulated.

Uncertainty associated with the Turkey Creek Basin water budget is large, making it difficult to determine the population that can be reasonably supported in the basin. Short-term records can be misleading, and must be used with caution. Water quality has been impacted by development, but the limited period of record prevents us from knowing whether concentrations have reached a steady condition or are reflecting only the beginning of a long-term increase. Continued collection of hydrologic records and assessment modeling is necessary to reduce uncertainty.

#### **Update based on project work from March 2003 through February 2004:**

**Modeling of the Turkey Creek Basin was conducted** and a manuscript is in preparation for the journal Ground Water. This will be submitted to CWRI when it is complete. **A summary of the findings follows.**

Low-cost data are useful for characterizing the spatial distribution and magnitude of recharge, hydraulic conductivity, storage, and water consumption, in support of sustainability evaluation. For a system to be sustainable, long term recharge to the system must exceed long term consumption, and storage volume must be sufficient and its rate of decline slow enough to provide water during times of drought when use exceeds recharge.

In TCB, water use and return flow fractions are uncertain yielding a broad range of possible consumption on the order of 113,000 to 670,000 m<sup>3</sup>/yr, with a likely value on the order of 340,000 m<sup>3</sup>/yr (~90, 275, and 550 AFY for low, intermediate and high consumption rates). Recharge varies with location with a long-term spatially average rate between 0.3 in/yr and 2+ in/yr (750 to 5664 AFY), but is likely less than 1 in/yr and closer to the lower value. Hydraulic conductivity in TCB is low, ranging from 0.0001 to 0.003 ft/day. Consequently, drainage from the basin will be relatively slow, which should enhance sustainability through droughts. This is confirmed by the slow decline of water levels during the drought of 2001. Although different approaches to estimating specific yield produce wide variation, overall system behavior, given aquifer tests and water level declines during drought, suggest a specific yield is on the order of 0.6%. However this may reflect shallow conditions and specific yield may decrease with depth,



which may cause the level of sustainability during droughts to decrease if averages use increases and lowers regional water levels.

Water use ranges from 100 to 200 AFY, assuming a 90% return, or from 300 AFY to 600 AFY for a 70% return. The long-term average recharge rate in the Turkey Creek Basin is expected to exceed 0.3 in/yr (~750 AFY), thus current water use in TCB appears to be sustainable on average. However, if the high estimate of use is more representative of current use, then sustainability of further growth is questionable. Additional monitoring of pumpage and return flow is warranted to obtain a better representation of consumptive water use.

Given that the current use is likely near the low estimate of the possible range of recharge to TCB, the long-term water level declines likely reflect a transition to a new equilibrium condition. In a fractured environment this may result in individual wells going dry (well yield below sustainable use), but deepening or relocating wells should yield a sufficient supply once a well-connected fracture is tapped by the well. Given that 1) the long-term average recharge is likely greater than average water consumption in TCB, and 2) available storage relatively high and declines slowly (for a fractured rock aquifer), the current population of TCB is expected to be sustainable. However, specific yield is likely to decrease as water levels decline, and the maximum estimated current water use exceeds the minimum estimated recharge, thus continued refinement of these estimates is prudent.

**Theoretical development of a method for estimating spatially variable representative elementary scale (RES) from low-cost data** for the purpose of estimating the potential minimum scale of water resource management in a fractured aquifer led us to the following conclusions:

1. Porous media theory requires that the minimum scale of RES is constant in geometry and magnitude throughout a model domain. In naturally fractured media there is wide variation of connectivity, which we argue must lead to spatially variable RES. We have developed the HYRES approach to estimate spatially variable RES using readily-available low-cost field data.
2. Requiring absolute scale invariance of a parameter to define RES likely is not reasonable and arguably impossible for many fractured aquifers. We use scale derivatives of effective hydraulic head to estimate an appropriate tolerance, which we determine by dividing the global head gradient by the model area. Other tolerances may be appropriate and can be evaluated by plotting scale derivatives as a function of sampling area, in the manner described above. In practice an appropriate tolerance should be determined for each fractured aquifer.
3. We demonstrate the utility of estimating spatially variable RES using hydraulic head observations. HYRES is consistent with hydraulic head contours and fracture structure. Rather than analyzing structural behavior as a function of sampling volume, HYRES measures the variability of volume-normalized fluid energy. We argue HYRES is a more direct measure of flow behavior.
4. RES estimated via porosity indicates major regions where fractures have become disconnected, but exhibits significant noise in regions which are relatively homogeneous, as

indicated by head contours and fracture structure. While RES determined from porosity can sense the structure of a discontinuity it does not account for fluid diversion around impermeable or low conductivity regions.

5. There is strong agreement between RES predicted by hydraulic conductivity and HYRES. Difficulty with using effective hydraulic conductivity results from its scale dependency, spatial variability, and the difficulty of measuring hydraulic conductivity relative to measure hydraulic head. Our analysis cannot distinguish which predictor is more accurate.
6. HYRES distinguishes disconnected regions with improved accuracy for larger data sets.
7. HYRES distinguishes clustered regions via varying tolerances. Varying tolerances in an iterative manner can identify clustering and regions with similar permeability. Regardless of the tolerance used for evaluating clustering, an appropriate tolerance should be employed for the HYRES analysis.
8. Varying hydraulic gradient does not affect HYRES. RES in a fracture flow system is independent of the fluid energy gradient, but dependent on spatial variability of fluid energy.
9. Varying flow direction causes a significant difference in predicted RES. These results do not contradict porous media theory but highlight the fact that discretely fractured systems will seldom, if ever, approach theoretical porous media behavior. Subsequently a structural measure of continuum for fractured aquifers may not be appropriate, at least with respect to a flow continuum.
10. Multiple realizations are conducted using different numbers of observations. Accuracy and consistency of RES estimations improve with increasing number of observations.

We cannot determine nor numerically honor the true fracture architecture over large scales. Therefore determining a direct relation between complex, spatially variable fracture structure and RES may not be possible. We hypothesize RES can be determined by examining fluid behavior in an unknown fracture network by spatially analyzing hydraulic head observations. Our analyses compare HYRES to structural indicators of RES, and HYRES behavior under varying boundary conditions and fracture architecture. Our results indicate HYRES is an appropriate fluid-based approach to estimate spatially variable RES.

HYRES is an estimation of RES for fluid flow and provides some indication of subsurface structure, which may not completely coincide with transport RES. HYRES maps indicate areas with low fracture connectivity, thereby delineating zones where flow is channeled. In these regions it is reasonable to expect that transport is also channeled, possibly with a stronger control by the fracture network geometry. Therefore, HYRES maps provide some understanding of subsurface structure which is most pertinent to flow continuum but may have some first order applicability for transport.

HYRES improves with increasing data observations, in accordance with most analyses involving spatial data. Hydraulic head measurements are optimal because they are readily available and relatively inexpensive to collect. HYRES accuracy is likely a function of the number of data observations, the distribution of these points, and fracture architecture. In systems that are essentially homogeneous few points may characterize continuum behavior, whereas in highly heterogeneous zones more points may be required to adequately constrain spatially variable RES.

We argue that because HYRES analyzes variability of fluid energy it is a direct measure of flow behavior. Analyses support our hypothesis, indicating HYRES may provide the best estimation of large-scale flow continuum in fracture aquifers.

We have submitted the HYRES methodology to estimate spatially variable RES in fractured architecture for review for publication in Water Resources Research.

# Occurrence and Fate of Emerging Organic Chemicals in Onsite Wastewater Systems and Implications on Water Quality Management in the Rocky Mountain Region

## Basic Information

<b>Title:</b>	Occurrence and Fate of Emerging Organic Chemicals in Onsite Wastewater Systems and Implications on Water Quality Management in the Rocky Mountain Region
<b>Project Number:</b>	2002CO46G
<b>Start Date:</b>	9/1/2002
<b>End Date:</b>	8/30/2004
<b>Funding Source:</b>	104G
<b>Congressional District:</b>	6th
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Treatment, Water Quality, Toxic Substances
<b>Descriptors:</b>	Contamination transport, Health effects, Septic tanks, Organics, Wastewater treatment, Water quality monitoring
<b>Principal Investigators:</b>	Dr. Robert L. Siegrist, Kathryn S. Lowe, John E. McCray

## Publication

1. DeJong, Kathy, Robert L. Siegrist, Abigail Wren, and Larry B. Barber, 2004, Occurrence of Emerging Organic Chemicals in Wastewater Effluents from Onsite Systems, accepted for platform presentation at the Tenth National Symposium on Individual and Small Community Sewage Systems, March 21-24, 2004, Sacramento, California, Am. Soc. of Agric. Engrs.
2. Siegrist, Robert, 2002, Water Quality Protection Provided by Onsite Wastewater Systems, in Proceedings of the 13th Annual South Platte Forum, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, Information Series No. 94, p. 16-17.
3. Siegrist, Robert L., 2003, Advancing the Science and Engineering of Decentralized Wastewater Systems, Colorado Water Resources Research Institute, Colorado State University, February, pp. 22-27.
4. VanderBeek, G., E. Poeter, G.D. Thyne, and J.E. McCray, 2003, Ground-water Availability in Turkey Creek Basin, Colorado, Geol. Soc. Amer., Abstracts with Programs, 35(5).
5. Wellman, Tristan, Eileen Poeter, and Sebastian Trivisani, 2003, Estimating Recharge And Storage

- Coefficient In A Fractured Rock Aquifer Using MODFLOW, Proceedings of MODFLOW and More 2003: Understanding Through Modeling, IGWMC.
6. VanderBeek, Greg, Eileen P. Poeter, and John E. McCray, 2003, Estimating Spatially Variable Ground-Water Recharge Rates Using GIS, Proceedings of MODFLOW and More 2003: Understanding Through Modeling, IGWMC.
  7. Wellman, T.P. and E.P. Poeter, 2003, Estimating Equivalent Continuum Scales in Fractured Aquifer Watersheds Using Discrete Feature Network Simulation, Fall AGU Meeting, Eos, 84(46) abstract H42B-1071.
  8. Thyne, G.D., Guler, C. and Poeter, E., 2004, Sequential Analysis of Hydrochemical Data for Watershed Characterization, in press, Ground Water.
  9. Wellman, T. and E. Poeter, 2004,(in press) Evaluating Hydraulic Head Data as an Estimator for Spatially Variable Equivalent Continuum Scales in Fractured Architecture Using Discrete Feature Analysis, Dynamics of Fluids in Fractured Rock conference, Sponsored by Lawrence Berkeley National Laboratory, February.
  10. DeJong, Kathleen E., 2004, Occurrence of Emerging Organic Chemicals in Wastewater System Effluents. Presentation at the 1st WEF/AWWA Student Conference, Rocky Mountain Region, May 18, 2004, Colorado School of Mines, Golden, CO.
  11. DeJong, Kathleen E., Robert L. Siegrist, Larry B. Barber and Abigail L. Wren, 2004, Occurrence of Emerging Organic Chemicals in Wastewater Effluents from Onsite Systems In: Proceedings of the Tenth National Symposium on Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, Sacramento, California, p. 400-407.
  12. Siegrist, Robert L., 2002, Water Quality Protection Provided by Onsite Wastewater Systems, in Proceedings of the 13th Annual South Platte Forum, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, Information Series No. 94, p. 16-17.

### Problem and research objectives:

Emerging organic chemicals (EOCs) such as pharmaceuticals and personal care products have received increasing attention in the last decade due to their possible adverse effects on ecosystems and human health. Several studies have identified wastewater as a primary contributing source of EOCs to the environment, but few have quantified their occurrence, especially in onsite wastewater treatment systems and associated receiving environments. To enhance the current understanding, this research project was initiated by the Colorado School of Mines in collaboration with the U.S. Geological Survey to determine the occurrence of EOCs in effluents produced from varying sources and by different types of onsite wastewater systems (OWS), to assess the fate and transport of EOCs in soil absorption systems prior to groundwater and surface water recharge, and to assess the potential for EOCs to impact receiving waters.

In Colorado and elsewhere in the U.S., interest in improved understanding of if and how EOCs are being released to the environment from OWS is needed since a substantial portion of the wastewater generated in the U.S. is processed by OWS before discharge to the environment. For example, in Colorado there are over 600,000 OWS in operation serving approximately 25% of the State's population and 7,000 to 10,000 new systems are being installed each year. As a result, over 30 billion gallons of wastewater are being processed by OWS and then discharged to the environment each year.

### Methodology:

Fifty sites including 30 OWS, 11 groundwater wells, and 9 surface waters in Jefferson and Summit Counties, Colorado, were selected for sampling. The OWS sites were chosen as a representative subset of the types of systems in the region, providing a range of influent sources and system operation types. Influent was from three types of sources: domestic (19 of 30), commercial (9 of 30), and institutional (2 of 30), targeting sources most likely to contain EOCs in their effluent. The type of onsite treatment operation also varied- 22 were conventional systems, with a tank or series of tanks discharging to a soil absorption field, 7 were equipped with textile filter units designed to recycle the wastewater through the septic tank before discharge, and one system utilized a constructed wetland. Eleven groundwater wells and 9 surface water sites were selected to be representative of the sampling region and samples were collected in conjunction with the OWS sites. All sites were sampled during two distinct hydrologic seasons: Fall 2003 and Spring 2004.

Several parameters useful in matrix characterization were measured. Air and water temperature, pH, specific conductance, carbonaceous biochemical oxygen demand (cBOD<sub>5</sub>), total suspended solids (TSS), total dissolved solids (TDS), total organic carbon (TOC), dissolved organic carbon (DOC), and ultraviolet light absorption were measured for all samples collected in both the fall and the spring. In addition, total phosphorus, total nitrogen, ammonia, and nitrate were measured for all samples collected in Spring 2004.

Six compounds- ethylenediaminetetracetic acid (EDTA), nitrilotriacetic acid (NTA), and four nonyphenolethoxycarboxylates (NP1-4EC)- required derivatization to be analyzed by GC/MS. A 100-mL formalin-preserved sample was spiked with surrogate standards and evaporated to dryness. Formic acid was added and the sample was vacuum evaporated to dryness. The residue was reacted with a derivatizing agent, a mixture of propanol and acetyl chloride, to form the propyl esters of NPEC, NTA, and EDTA. The esters were extracted into chloroform, the chloroform was evaporated, the residue was dissolved in toluene, and the extract was analyzed by capillary column GC/MS.

To determine the occurrence of a suite of over 50 EOCs such as caffeine and triclosan, one-liter unfiltered raw samples were extracted using continuous liquid-liquid extraction with methylene chloride. Prior to extraction, samples were spiked with a surrogate standard mix, the ionic strength of the sample was increased by adding sodium chloride, and the pH was dropped below 3 by adding sulfuric acid. Samples were extracted for 7-8 hours, during which time distilled solvent was recycled through a microdroplet dispersing frit to improve extraction efficiency. The extract was concentrated under nitrogen gas and analyzed by capillary column GC/MS.

In Fall 2004, controlled experimentation at the laboratory- and field-scale (CSM and USGS labs and the Mines Park Test site on the CSM campus) will be initiated. The purpose of this work is to elucidate the fate and transport of key EOCs in soil and ground water systems, which are the receiving environments to which OWS discharge their effluents.

#### Principal findings and significance:

The matrix of each OWS effluent, groundwater, and surface water sample collected in Fall 2003 has been characterized by general water and wastewater parameters. Air and water temperatures were, on average, lower in the mountainous Summit County as compared to Jefferson County, which is located in the foothills and plains (ranging from 4-12°C and 11-32°C for air and 5-13°C and 10-30°C for water, respectively). Specific conductance values ranged from 88.9 uS in surface water to 11,050 uS in a constructed wetland. All pH values were within 2 units of 7.0, ranging from 5.24 (a groundwater) to 8.69 (an OWS), with one exception. A pH of 4.92 was recorded in a septic tank receiving influent from a bakery, possibly due to a high flour and yeast content of the wastewater. Alkalinity values ranged from 8-232 mg/L as CaCO<sub>3</sub> in ground and surface water (average values were 83 and 41 mg/L as CaCO<sub>3</sub>, respectively). The alkalinity values were much higher in OWS, ranging from 20-1036 mg/L as CaCO<sub>3</sub> with an average of 342. The highest alkalinity value of 1036 mg/L as CaCO<sub>3</sub> was recorded in the final septic tank serving a large restaurant. Total dissolved solids ranged from 75-375 mg/L (average of 171 mg/L) in surface water, 170-6350 mg/L (average of 543 mg/L) in groundwater, and 380-6615 mg/L (average of 985 mg/L) in OWS. The maximum value in groundwater, 6350 mg/L, was an outlier in the data set and was recorded from a well that is currently being tested by the county to determine the extent of contamination from nearby development. Total suspended solids followed the same trend, with values of <1-10 mg/L (average of 2 mg/L) in surface water, <1-185 mg/L (average of 22 mg/L) in groundwater, and <1-1030 mg/L (average of 149 mg/L) in OWS. Values from the Spring 2004 sampling round are currently being compiled and the complete results will provide a characterization of each site matrix by general water and wastewater quality parameters.

Values for the total organic carbon (TOC) and dissolved organic carbon (DOC) of eleven of the samples collected in Fall 2003 have been compared and an increasing trend in values was seen from groundwater to surface water to OWS. Groundwater TOC and DOC values were less than 1 mg/L, surface waters ranged between 0.4 and 1.7 mg/L, and OWS effluent samples ranged from 8.1 to 69.1 mg/L. There was a decrease in TOC and DOC from the influent sample to the effluent sample in all three multi-tank OWS, as would be expected as the wastewater moves through the treatment system.

All samples collected in Fall 2003 have been analyzed for EDTA, a ubiquitous metal-chelating agent found in household cleaners and shampoos, and total NPEC, representing the sum of four compounds (NP1-4EC), that are known endocrine disruptors. These are degradation products of a group of non-ionic surfactants used in household and industrial detergents. EDTA and NPEC were identified in all 30 OWS, with EDTA values ranging from 2-2000 µg/L and NPEC values ranging from less than the reporting limit (0.25 µg/L) to approximately 20 µg/L. Both institutional sources, which are veterinary hospitals, recorded very high concentrations of EDTA, 1175 and 2500 µg/L, while the average values for commercial and domestic systems were approximately 90 µg/L and 50 µg/L, respectively. A convenience store located along a busy highway recorded the highest concentration of NPEC, 19 µg/L, raising the average in commercial systems to 5.4 µg/L, while average values in institutional and domestic sources were 3.8 and 2.1 µg/L, respectively. While EDTA and NPEC were present in some of the ground and surface waters, the median values for both compounds were below the reporting limits of 0.5 µg/L for EDTA and 0.25 µg/L for NPEC.

The occurrence of a broader suite of EOCs is presently being determined and will be compiled with the current EDTA, NPEC, TOC, DOC, and general water and wastewater parameter data. The results will characterize OWS by source and operational system type in terms of potential impact to receiving environments. EOCs will be identified by presence or absence, concentration, frequency of occurrence, co-occurrence with similar or unrelated EOCs, and relative potential adverse effects. This will provide a basis for designing controlled fate and transport experimentation at the laboratory- and field-scale. Together, the results will aid in defining the potential risks to ecosystems and human health due to EOCs discharged in OWS effluents.



# Microbe Transport in Saturated Filter Sand and Karst Media (2002CO300)

## Basic Information

<b>Title:</b>	Microbe Transport in Saturated Filter Sand and Karst Media (2002CO300)
<b>Project Number:</b>	2003CO310
<b>Start Date:</b>	1/1/2002
<b>End Date:</b>	1/1/2003
<b>Funding Source:</b>	Other
<b>Congressional District:</b>	4th
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Groundwater, Water Supply, None
<b>Descriptors:</b>	Water quality, Aquifer recharge, Ground water, Wastewater, Karst aquifers
<b>Principal Investigators:</b>	Joseph N. Ryan

## Publication

# **Information Transfer Program**

# Technology Transfer/Information Dissemination

## Basic Information

<b>Title:</b>	Technology Transfer/Information Dissemination
<b>Project Number:</b>	2002CO8B
<b>Start Date:</b>	3/1/2003
<b>End Date:</b>	2/28/2004
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	4th
<b>Research Category:</b>	None
<b>Focus Category:</b>	None, None, None
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Robert C. Ward

## Publication

1. Ward, Robert C. (editor), 2003, Proceedings of the Colorado Drought conference, December 4, 2002, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, 230 pp.

## **Information Transfer Activities**

CWRRI provides Colorado water users with the latest water information and research results through its information and technology transfer program including the CWRRI newsletter, COLORADO WATER, the CWRRI websites, water conferences, seminars, and publications series.

### ***Web sites***

The CWRRI web page is at <http://cwri.colostate.edu> and contains links to the following information:

#### About CWRRI

- History and Mission
- Contact us

#### Current Events

- Drought Related Publications and Links
- Calendar of Events
- Water Resources Seminar (GS592)
- Stretching Urban Water Supplies in Colorado – Strategies for Landscape Water

#### Conservation

- Evapotranspiration
- Justice Hobbs' April Newsletter Article Appendix
- Research Projects and Publications
- Water Research Projects
- Water in the Balance
- Report Series
- Additional Publications

#### New Reports

- CR196: Forest and Water
- Colorado Drought Conference Proceedings

#### Colorado Water Newsletter

- June 2004
- Back Issues
- Index of Newsletters

#### Water Education and Outreach

- Cooperative Extension Water Specialists
- Water Courses at Colorado Universities

#### Water Research Expertise

- Academic Faculty
- Federal Agency Contacts

#### Additional Resources

- Colorado Water Concerns
- Kids Zone
- Jobs in Water
- Useful Water Links
- Water Resources Archives

The Water Center web site is <http://watercenter.colostate.edu> and provides the following links:

Information on the Water Center

What is the Water Center?

Overview of Programs

People Involved

Computer Modeling

MODSIM-DSS

Professional Development

Jobs in Water Resources

Meetings/Seminars & Conferences

Educational Opportunities

Water Related Courses at Colorado Universities

Fellowships

Scholarships

Study of Water at CSU – Undergraduate

Educational Opportunities

List of Departments

Undergraduate Water Minor

Research Experiences for Undergraduates in Water

Study Water at CSU – Graduate

Water Information for New CSU Graduate Students

Graduate School at Colorado State University

List of Departments

The Colorado Water Knowledge web site is at <http://waterknowledge.colostate.edu> .

From this page, you can link to:

- Cool Water Facts: A huge list of water facts!
- Overview: A description of stream processes and an overview of Colorado's geology, water history and climate. Links to water related definitions are also provided.
- Sources, Uses, Management and Conservation: A description of Colorado's major river basins and aquifers, how the water from these sources is used and managed, and methods for conserving Colorado's water.
- Aquatic Life, Wetlands, Water Quality and Environmental Law: A description of the fish and aquatic insects present in Colorado's waters, wetlands, water quality, and links to environmental laws.
- Water Administration: A description of transmountain diversions, interstate compacts, Colorado water rights law, and federal, state, and local administrative agencies.
- Frequently Asked Questions: A list of frequently asked questions and answers about Colorado water.
- The Incredible Journey of the Greenback Cutthroat: Information about this recovering species.
- Colorado Watershed Assembly: Committed to protecting and restoring Colorado's watersheds

- Other Colorado Watershed Protection Efforts
- CWRRI WWWater information for kids page: links to water information and the water quiz
- National Drinking Water Clearinghouse “Drinking Water Kids” page with drinking water information for children
- USA Today Hydrology page: with more links to changing hydrologic information.
- USGS “Water Science for Schools” page with water information for students and teachers
- River of Words: an environmental art and poetry program created to promote watershed awareness, literacy, and the arts.

The Hydrology Days web site at <http://HydrologyDays.colostate.edu> contains information about the upcoming (or most recent) Hydrology Days, an annual event. The listing of speakers is posted prior to the event, and a link to the proceedings is available after the event.

Colorado Water Quality Monitoring Council web site is at <http://cwqmc.colostate.edu/>

# Colorado Water Quality Monitoring Council

About the Council

Meetings Agendas Minutes

Monitoring Tools

Monitoring Plans and Methods

Database Management

Colorado Water Quality Monitoring Locations

Water-Quality Related Groups and Events

Other Useful Links

Water-Quality Related Grants

## Purpose

The *Colorado Water Quality Monitoring Council* will serve as a statewide collaborative body, open to all, to help achieve effective collection, analysis and dissemination of water quality data, and monitoring information. The Council seeks to improve the linkage between information needs of policy and decision makers with efforts to collect and assess data. The Council promotes effective monitoring programs that include the components of goal identification, data collection, analysis, storage, retrieval, and reporting/dissemination of information. The Council shall address the full range of water quality information, including chemical, biological, and physical characteristics of surface and ground waters. The Council is a non-voting body that operates through consensus.

- Provide a forum for effective communication, cooperation, collaboration, and documentation among individuals and organizations involved in monitoring.
- Promote the development of collaborative and cost effective watershed-based monitoring strategies.

- Promote the use of quality assurance procedures and protocols related to sample collection, analytical methods, assessment, data management, and dissemination
- Provide strategic direction for a statewide structure for the acquisition, analysis, archiving, and dissemination of water-quality information

**For more information about CWQMC contact:**

**Vic Lucero, 2003 Co-Chair**  
[vic.lucero@cityofthornton.net](mailto:vic.lucero@cityofthornton.net)

**Jill Minter, 2003 Co-Chair**  
[minter.jill@epamail.epa.gov](mailto:minter.jill@epamail.epa.gov)

## ***Publications***

CWRRRI publishes and distributes water research information via the following publications:

**WATER IN THE BALANCE:** a user-friendly publication series that provides a condensed version of research completion reports giving water users a 16-24 page review and analysis of the results of research conducted under the auspices of the State Water Institute Program.

**COMPLETION REPORTS:** These reports contain information about completed research and include details of procedure, analysis of data and conclusions reached.

**TECHNICAL REPORTS:** CWRRRI provides technical information of interest to water resource professionals through this series.

**INFORMATION SERIES:** These reports provide information of general public interest on water-related subjects including conferences and symposia.

**OPEN-FILE REPORTS:** CWRRRI provides complete reports of research (at cost) upon request. These reports consist primarily of theses and dissertations from CWRRRI-funded projects.

CWRRRI is working to make the newest and the most requested older documents available on the World Wide Web, accessible from the CWRRRI home page at <http://cwrrri.colostate.edu>.

## ***Meetings***

### **Watering Your Future: 10<sup>th</sup> Annual Arkansas River Basin Forum**

The 10<sup>th</sup> Annual Arkansas River Basin Water Forum was held on March 29 – 30 in Pueblo on the University of Southern Colorado campus. Approximately 165 water users, water managers and other interested parties in attendance were treated to keynote addresses by former Senator Hank Brown and Mr. Alan Hamel addressing the challenges of weather and politics that buffeted Colorado and the Southeastern Colorado Water Conservancy District in the past year. Discussions centered around water banking, the Kansas-Colorado lawsuit and compact, the newly created Lower Arkansas River Conservancy District, well augmentation, and drought. Julie Scalpo, a member of Pueblo Board of Water Works, was introduced as the newly appointed general manager of the Lower Arkansas Valley Water Conservancy District, which was created last November by voters in five Southeast Colorado counties. James Broderick, newly appointed General Manager of the Southeast Colorado Water Conservancy District, addressed the Forum and discussed ways the District serves the Arkansas River Basin. Local students



were honored for their submissions of art, poetry and prose on the value and beauty of the river. CWRRI is a cosponsor of this annual event.

### **Stretching Agricultural Water Supplies**

The Science and Technology Program, in collaboration with the Northern Colorado Water Conservancy District and the U.S. Department of Agriculture, sponsored a workshop for northern Colorado's agricultural community entitled "Stretching Agricultural Water Supplies" in Greeley, Colorado on February 19, 2003. The workshop explored ways to stretch limited water supplies. Sessions included water management issues from local, state and federal perspectives; new technology and funding sources to help irrigators conserve water; and opportunities to cooperate and share resources. The benefits of the workshop were to engage end users of research in learning about and discussing challenges, looking at new and emerging water management tools and solutions, ensuring that irrigation districts and farmers can remain profitable and viable, and discussing what needs to be done in the future toward developing and implementing solutions that can help make a difference. CWRRI Director Robert Ward and Water Resources Specialist Reagan Waskom helped line up the program and participated in workshop panels.

### **Colorado Streamgaging Symposium 2003**

Snow greeted the flow data collectors and users at the Beaver Run Resort on May 8, 2003, as they arrived for the Second Colorado Streamgaging Symposium. The symposium is a joint effort of state, federal and university organizations. Co-sponsors of the 2003 symposium were: the Colorado Water Conservation Board, the Division of Water Resources, the U.S. Geological Survey, and the Colorado Water Resources Research Institute.

The streamgaging symposium shared information about:

- The major streamgaging programs in Colorado.
- The uses of flow data – current and proposed.
- Coverages of flow gages, and thus, flow data availability.

Organizations that collect flow data in Colorado operate more than 700 gages, most of which now transmit data via satellite. Increasingly, this data is readily available via the Internet and supports the ability of Colorado citizens from a wide array of economic endeavors to share benefits from multiple uses of Colorado's water resources. Since the first Streamgaging Symposium in 2001, a number of gages in critical stretches of Colorado rivers have been "hardened" against flood flows. This means the gages are better able to record high flows without damage. New satellite telemetry is being installed to speed up the data transmission rates. Studies aimed at reducing redundancy in gaging efforts and increasing the accuracy of winter flow measurements were reported. Post-fire burn measurements, as well as debris flow studies, were described. Many of the above efforts to improve flow data acquisition represent enhanced collaboration among water organizations in Colorado. During an open discussion session at the end of the meeting, the use of flow data in water-quality management decision-making (e.g.,

discharge permit and TMDL calculations) as well as the increasing use of water quality data in water exchange agreements, were noted as representing increasingly important water data interfaces in Colorado. With strong pushes toward efficiency and accuracy in water data collection and use, there appears to be a growing desire to further enhance the ability to readily share water data among organizations and individuals. This need, in turn, suggests development of a water “data commons” where organizations and individuals can readily determine what data exists – thus greatly increasing the efficiency of water data acquisition funds. It was noted that this is a topic needing additional discussion and, in particular, a national dialogue among those collecting water data and those using the data, as it is not clear who would be responsible for creating and maintaining a water ‘data commons.’

### **‘Can Do’ Landscape Drought Conference**

On April 15, 2003, an overflow crowd gathered in the Hall of Education at the National Western Stock Show to hear speakers discuss the impact of drought watering restrictions on Colorado’s landscape industry and possible options for stretching urban water supplies in the future. The conference theme was “Dealing with Drought: Saving Water Now, Planning for the Future.”

Attorney General Ken Salazar stressed the need for water efficiency and outlined ways to stretch Colorado’s urban water supplies: additional water management flexibility during times of drought; increased use of reclaimed water; enhanced water education; ‘retrofitting’ old water systems; and evaluation of new water pricing structures. Other speakers addressed the variability of Colorado’s precipitation; stressed the need to plan for the invariable uncertainty present in Colorado’s weather; presented examples of urban water conservation efforts in other states; stressed the need for better data on urban water use; and provided examples on how Colorado’s landscape industry is addressing the need to make landscapes more drought-resistant.

The conference was organized by Colorado State University’s Department of Horticulture and Landscape Architecture; College of Agricultural Sciences; and Cooperative Extension in collaboration with CSU’s Water Center, CWRRI, and the Green Industries of Colorado.

This conference resulted in the CWRRI special report 13 “Stretching Urban Water Supplies in Colorado, *Strategies for Landscape Water Conservation*” by Rachel Barta, a former Graduate Research Assistant in the Department of Engineering. Furthermore, a follow-up conference is scheduled for Fall 2004.

### **Drought Impacts on South Platte Aquatic Ecosystems and Water Quality Discussed at CSU Conference**

Over 100 scientists, water managers, public officials, students, and the public met on the CSU campus April 3-4, 2003, to examine the impacts of drought on aquatic ecosystems and water quality in the South Platte River. The conference was sponsored by the U.S. Environmental Protection Agency’s Office of Global Change. CWRRI was a cosponsor.

The objectives of the conference organizers, Jill Baron (USGS and CSU) and Alan Covich (CSU), were to share scientific understanding of the consequences of severe drought, develop awareness and possibly preparedness for future drought, and build collaboration and trust among participants. Judging from the liveliness of the discussion and debate, the conference readily met its objectives.

A broad range of presentations explored direct and indirect effects of drought on species, ecosystems, and water quality, and the social and economic ramifications of drought to communities. A number of innovative planning and modeling tools were presented as ways to explore the consequences of different management approaches on municipal, agricultural, and environmental parameters. Several talks on managed groundwater recharge, termed “smart storage” by one speaker, were presented to illustrate innovative partnerships that can enhance instream flow, wildlife habitat, while meeting water rights obligations.

Issues of current concern mentioned during the meeting include the impact of tributary groundwater pumping on stream flows, the continued movement of water from agriculture to cities, the search for additional trans-basin diversions, the ‘Big Straw,’ (a proposal to divert water from the Colorado River) and growing pressure to pursue significant water conservation measures. Water quality and environmental issues were noted as often viewed as constraints limiting water development and management options, not as having value as sources of important environmental goods and services. Ultimately, the greatest environmental impact of drought may be in how it influences the political environment, and the long-term, statewide legacy of decisions made during periods of crisis.

### **Hydrology Days - 2003**

The 23<sup>rd</sup> annual Hydrology Days was celebrated March 31-April 2 on the CSU campus. Besides annually honoring an outstanding hydrologist, a new Borland Lecture Series was initiated as part of the Hydrology Days program. The Borland Lecture Series, endowed by Whitney Borland, brings nationally and internationally recognized hydrology-related speakers to Hydrology Days.

Seventy-one oral and 25 poster presentations were authored by scientists and students from around the world and across the United States, in addition to numerous faculty and students from Colorado State University, the Colorado School of Mines, University of Northern Colorado, and the University of Colorado at Boulder. Sessions addressed a wide range of topics including ‘Drought, Fire, and Forests’; ‘Advances in Stream Restoration’; ‘Snow Hydrology’ and ‘Ground Water’

The 2003 Borland Lectures were presented by Prof. Jose Salas from Colorado State University and Prof. John Dracup from the University of California at Berkeley. Prof. Salas presented a lecture entitled “Characterizing the Dynamics of Drought”. Prof. Dracup presented a lecture entitled “Linking drought research to water resource management actions”.

Prof. Jose Salas was designated the 2003 Hydrology Days honoree for his contributions to flood and drought risk assessment calculations as well as modeling and simulation of stochastic hydrologic processes.

Whitney Borland, an employee of the Bureau of Reclamation from 1930 to 1972, worked on many of the Bureau's major water projects, including the building of Hoover Dam, Grand Coulee Dam and the Colorado-Big-Thompson Project. He specialized in sedimentation issues surrounding the large projects. He began his Bureau career performing sedimentation studies at the hydraulics lab on the campus of Colorado State University. During WWII, Mr. Borland served as a lieutenant colonel in the Army's 10<sup>th</sup> Mountain Division. Mr. Borland died October 2, 2001.

### **Colorado Water Workshop's 2003: Drought, Water Allocation And Supply Limits**

Western water scarcity in the face of increasing demand has been a recurring topic of discussion at previous editions of the Colorado Water Workshop, held annually on the campus of Western State College in Gunnison, Colorado. With certain areas of Colorado and other western states still affected by the drought, the 2003 workshop, held July 23 to 25, focused entirely on issues related to water allocation and use when drought imposes even greater limits on normally scarce water supplies. Under the theme of "In Hard Times: Collaboration or Contention?" water managers, consultants, representatives of environmental organizations, and government officials presented various perspectives on how the West can cope with the combined opposing stresses of increasing demands and decreasing supply.

The first day of the workshop provided an overview of various strategies for coping with severe water shortages. Doug Kenney of the CU Natural Resources Law Center presented a summary of the Colorado General Assembly's activity during the 2003 session in response to the drought. A highlight of this day was a special presentation by Colorado Governor Bill Owens on legislative initiative and the "Big Straw Project."

Dan Luecke, environmental consultant, presented an analysis commissioned by the Sustainable Water Caucus of the feasibility of new water storage projects. He concluded that new storage projects are less efficient economically in meeting increased demand for water and suggested alternative strategies such as conservation, cooperative arrangements between cities and farmers, expansion of existing facilities, and better overall management of existing supplies. These arguments were echoed by John Keys III, Commissioner of Reclamation, who presented a summary of Reclamation's Water 2025 initiative, which emphasizes conservation and better management of existing supplies to meet future water demand in the West.

The second day of the program started with an update on the recent agreement that quantifies the federal reserved water right for the Black Canyon of the Gunnison between the Colorado Water Conservation Board and the National Park Service. The remainder of the morning program was devoted to further review of 2003 legislation, particularly those elements that produced institutional changes in water administration. This review

was prefaced by a presentation from Colorado Supreme Court Justice Greg Hobbs on the historical evolution of water law in Colorado, with particular emphasis on the influence the drought has on water law. The afternoon program was devoted entirely to presentations illustrating the value of collaboration among existing, sometimes even competing, water interests in producing solutions to problems resulting from limited water supplies. Presentations were made by representatives of a diverse array of government agencies, water suppliers, conservancy districts, and conservation districts.

The general session on the morning of the final day was devoted to a review of the Colorado River Compact in light of the current extended drought. David Getches, Dean of the CU Natural Resources Law Center, presented an overview of the Law of the River in relation to historic development within the basin, the various competing demands, and the changes in supply-demand balance over time. His presentation was followed by speakers representing four different interests within the basin, each providing an overview of various water supply issues. Paul Davidson, Bureau of Reclamation, provided an overview of historic basin streamflows and projections of future supplies based on various assumptions. Gerald Zimmerman, Executive Director of the Colorado River Board of California, presented a summary of the proposed quantification settlement agreement between the Department of Interior and the state of California. A review of current conflicts between Navajo Nation reserved water rights and the Law of the River, along with suggestions for their resolution, was given by Stanley Pollack, Water Rights Counsel of the Navajo Nation. Scott Balcomb, Colorado's Commissioner to the Upper Colorado River Commission, presented an overview of Colorado's interests in relation to the other upper basin states and the lower basin. The workshop concluded with a luncheon presentation by Rita Schmidt-Sudman, Director, Water Education Foundation, on California's water wars. CWRRI was cosponsor for the event.

#### **Institute for K-12 Teachers spotlights Western Water History**

"The West of John Wesley Powell" was the topic of conversation and study at a June 2003 Colorado Endowment for the Humanities Teacher Institute and Public Program held on the CSU campus. The five-day Institute, developed especially for K-12 teachers, focused on the Colorado River, geology of the western landscape, Native American ethnology and linguistics, and western water history. The Institute was directed by Clay S. Jenkinson, one of the nation's leading public humanities scholars, and participated in by other distinguished environmental and water historians.

Topping off the week was a free public program, Water in the West: Multiple Visions 1866-2003 at the Morgan Library featuring a Chautauqua presentation of John Wesley Powell by Clay Jenkinson and a humanities-style discussion of water in the West. Discussion panelists included Colorado State Supreme Court Justice Greg Hobbs, Reclamation historian Brit Storey, and environmental historian Mark Fiege. Added events included a reception, a tour of the Library's Water Resources Archive, and an exhibit, Moving Waters: The Colorado River and the West.

Children were not left out of the evening's activities. Storyteller Beverly Brayden told water stories to youngsters while the Museum of Nature and Science challenged an older

group to some fun scientific experiments . . . all water related of course! CWRRI Director Robert C. Ward helped plan the program.

### **NPS Forum Participants Learn About “Tools For Your ‘Shed”**

The third annual Colorado Nonpoint Source Forum, "Tools for Your 'Shed," was held Sept.10 in Glenwood Springs, Colo. The forum brought together 60 participants for an afternoon of presentations designed to spotlight effective watershed efforts and NPS strategies.

Gene Schleiger, co-chair of the Colorado Nonpoint Source Council, welcomed the group and set the tone for the presentations. He mentioned that this year's forum was being held in conjunction with the Colorado Watershed Assembly Conference, which provided added value to participants. CWRRI Water Resources specialist Reagan Waskom was a member of the Watershed Assembly's founding committee.

### **Bureau of Reclamation Examines New Developments In Water Management**

The Bureau of Reclamation's Technical Service Center hosted a Workshop on River Systems Management, November 4-6, 2003, at the University Park Holiday Inn in Fort Collins. The workshop, the eighth in a series held at intervals of one to-two years, focused on priorities and new developments that affect how Reclamation manages water resources. This year, specifically, the focus was on how to reduce conflict in water resources management.

Over 100 Reclamation managers, technical staff and invited speakers from other government agencies, universities, stakeholder organizations and the private sector participated in both technical sessions and breakout workshops on such topics as water resources modeling and optimization; collaboration in water data collection and sharing; legal issues impacting water allocations; ecologically based system developments; and real-time flow forecast modeling.

### **South Platte Forum 2003: Planning for Uncertainty**

The current drought in Colorado reminds us all that we live in a semi-arid climate with all the water supply uncertainties associated with such climates. The 2003 South Platte Forum, held October 22-23 in Longmont, Colorado, examined the implications of water supply uncertainty, paying particular attention to current efforts to plan for uncertainty. Rod Kuharich, Director of the Colorado Water Conservation Board, updated the 120 attendees on the Statewide Water Supply Initiative currently underway.

Attorney General Ken Salazar updated the audience on efforts to better integrate ground and surface water management in Colorado. Dennis Montgomery, Hill and Robbins, Described lessons learned in resolving interstate water disputes, including developing scientifically sound water use data. Peter Binney, City of Aurora, summarized efforts of a Front Range municipality to meet its growing need for water.

Other topics addressed dealt with the economic impacts on rural economies of water transfers from agriculture, biological responses to water development, the interface

between aggregate mining and water management, landscape industry plans to prepare for future droughts, the emerging role of water banks, and an examination of future trends in water management in the South Platte Basin.

### **Ogallala Aquifer Symposium – 2004**

#### **Water Conservation – Saving Water Today for Tomorrow**

The symposium was held February 23, 2004 at Wray High School Auditorium in Wray, Colorado. The organizing committee included staff from private industry, Colorado state engineers office, Colorado State University Cooperative Extension, and Natural Resources Conservation Service. Troy Bauder, water specialist for Colorado State University Cooperative Extension, presented information about the advantages and disadvantages of ET-Based Irrigation Scheduling as part of a session on conservation programs during the symposium. Other presenters in the session included Freddie Lamm (professor, Kansas State University) talking about subsurface drip irrigation and Dennis Alexander (assistant state conservationist, Colorado Natural Resources Conservation Service) discussing Farm Bill Financial assistance programs for irrigation practices. The symposium also included sessions entitled “Water Supply Update,” “Republican River Litigation – Update,” “Water Legislation Update,” and “Water Savings Panel,”

#### ***Awards***

##### **Chuck Howe Receives the 2003 Warren A. Hall Medal**

Chuck Howe, Professor Emeritus of Economics and former Director of the Environment and Behavior Program, Institute of Behavioral Science at the University of Colorado, received the 2003 Warren A. Hall Medal at the annual UCOWR meeting in August, 2003. The medal is presented by the Universities Council on Water Resources to recognize distinguished achievements of an individual in the field of water resources. Dr. Warren A. Hall, known worldwide for his active involvement in water resources research, was a founder in 1962 of the Universities Council on Water Resources. Dr. Hall pioneered the introduction of systems analysis and multi-objective tradeoff analysis in water-resources planning and management. He taught at Colorado State University from 1975 to his retirement in 1985.

Dr. Howe has had a distinguished and unique career in water resources activities at the university, state, federal and international levels. He served as chairman of the Department of Economics at the University of Colorado from 1972 to 1976. In 1986 he became Director of the Environment and Behavior Program, Institute of Behavioral Science at CU. He was Chair of the Governor’s Science and Technology Advisory Council, State of Colorado (1983-1987) Dr. Howe’s federal appointments include Director of the Water Resources Program, Resources for the Future, Inc., Washington, D.C. (1965-1970); Chair of the Committee on Privatization of Water Services in the United States, Water Science and Technology Board, National Research Council (1999-2002); and Lead Author on Water Resources for the Intergovernmental Panel on Climate Change (IPCC) (1998-2001). He served on other WSTB//NRC panels that evaluated climate impacts, irrigation-induced water quality problems, and international

development. He was a member of the National Panel for the Evaluation of the State Water Resources Research Institutes by the U.S. Geological Survey in 1994.

Dr. Howe has been a Visiting Professor at the Universities of York (UK) and Montpellier (France), University of Wageningen (Netherlands), and Gadjah Mada University (Indonesia). He has served as a consultant on water issues for the United Nations, the Agency for International Development, World Bank and the Ford Foundation in Senegal, Botswana, Kenya, Ghana, and Mexico.

Currently, Dr. Howe serves as General Editor of the Edward Elgar Publisher Series on Water Resources.



## Student Support

Student Support					
Category	Section 104 Base Grant	Section 104 RCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	12	1	0	0	13
Masters	3	4	0	0	7
Ph.D.	2	2	0	0	4
Post-Doc.	1	2	0	0	3
<b>Total</b>	18	9	0	0	27

## Notable Awards and Achievements

### Publications from Prior Projects

- 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Michelson, A.M. and R.G. Taylor, 1999, Endangered Species Recovery and River Basin Policy: Contribution of Economic Analysis, American Journal of Agricultural Economics, 81(5):1250-1251.
- 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Huffaker, R., A.M. Michelsen, J. Hamilton and M. Frasier, 2001, Western Water Allocation Issues Arising from the Hierarchy of International, Federal, State and Local Laws Regulating Water Transfer, Complexities With Transboundary Water Resource Management, Water Resources Update 118:3-10.
- 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Frasier, M., A. M. Michelsen, R. Huffaker and R.G. Taylor, 1999, Economic and Institutional Alternatives for Meeting Interstate ESA Instream Flow Requirements in the Platte River Basin, American Journal of Agricultural Economics, 81(5):1257-1261.
- 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Michaelson, A. M., 1999, Water Management Alternatives for Meeting Endangered Species Water Requirements on the Platte River, University of Wyoming and Casper College, Casper, WY, October 7, 1999. Invited Presentation.
- 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Conference Proceedings - Michelsen, A. M., J.F. Booker and M. Frasier, 1999, "Feasibility of Alternatives to Manage Platte River Instream Flows to Accommodate Endangered Species" in Water: World Lessons, Proceedings of the Joint Meeting of the Universities Council on Water Resources, International Water Resources Association and International Water and Resource Economics Consirtium, Kamuela, Hawaii, June 20-July 2, 1999.
- 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated

- Multi-State River Basin") - Conference Proceedings - Michelsen, A.M. and R. Huffaker, 2000, "Federal Intervention in State Water Laws and Strategies to Restrict Interstate Reallocation" in Living Downstream in the Next Millennium: Reconciling Watershed Concerns With Basin Management, Proceedings of the Universities Council on Water Resources Meeting, New Orleans, LA, August 1-4, 2000.
7. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R., A. M. Michelsen, J. Hamilton and M. Frasier, 2000, The Uneasy Hierarchy of federal and State Water Laws and Policies, Presentation, 2000 Annual Meeting of Western Agricultural Economic Association, Vancouver, B.C., June 2000.
  8. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Conference Proceedings - Booker, J.F., W.M. Frasier, E. Houk, A.M. Michelsen and R.B. Taylor, 2001, Foregone Benefits in Supplying Water for Endangered Species Recovery, Proceedings, Decision Support systems for Water Resources Management, American Water Resources Association and Universities Council on Water Resources Annual Conference, Snowbird, Utah, June 27-30, 2001.
  9. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Huffaker, R.G., and N. Whittlesey, 2003, A Theoretical Analysis of Economic Incentive Policies Encouraging Agricultural Water conservation, International Journal of Water Resources Development, March 2003, 37-53.
  10. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Huffaker, R.G., A. Michelsen, J. Hamilton, and M. Frasier, 2001, The Uneasy Hierarchy of Federal and State Water Laws and Policies, Water Resources Update, January 2001, 3-10.
  11. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Huffaker, R.G. and N.K. Whittlesey, 2000, The Allocative Efficiency and conservation Potential of Water Laws Encouraging Investments in On-Farm Irrigation Technology, Agricultural Economics, 24(2000):47-60.
  12. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Huffaker, R.G., N.K. Whittlesey and J. Hamilton, 2000, The Role of Prior Appropriation in Allocating Water Resources into the 21st Century, International Journal of Water Resources Development, June 2000:265-275.
  13. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Huffaker, R.G., M. Frasier and J. Hamilton, 2000, The Intrastate-Trade-Restriction defense in Commerce-Clause Challenges of State-Imposed Restrictions on Water Exports to Neighboring States, International Journal of Water Resources Development, June 2000:275-279.
  14. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Articles in Refereed Scientific Journals - Michelsen, A., R.G. Taylor, R.G. Huffaker and T. McGuckin, 1999, Emerging Price conservation Programs in Agricultural Water Use, Journal of Agriculture and Resource Economics, July 1999:222-238.
  15. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Book Chapters - Huffaker, R.G., In Press, Finding a Modern Role for the Prior Appropriation Doctrine in the American West, "in" NEED EDITOR'S NAME, Water Resources Management - Structure, Evolution, and Performance of Water Institutions, NEED CITY, Springer-Verlag (NEED PAGE NUMBERS).
  16. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated

- Multi-State River Basin") - Other Publications - Huffaker, R.G., and J. Hamilton, In Press, Conflict in U.S. Irrigation, Irrigation of Agricultural Crops Monograph, Editors R. Lascano and R. Sojka, USDA-ARS (NEED NUMBER OF PAGES).
17. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R.G., N. Whittlesey and J. Hamilton, 2003, Irrigated Agriculture and Endangered Species Policy, Encyclopedia of Water Science, Marcel Dekker, Inc. 2003.
  18. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R.G., 2003, The Linkage Between Irrigation Effectiveness and Water Conservation: What New Water Managers Shold Know, Invited presentation to the Water REsources Seminar: Hazards of Practicing Your Trade: Tips for New water Managers, Colorado State University, October 2003.
  19. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R. G., 2003, The Agricultural Water Conservation Morass, Principle paper session, Western Agricultural Economics Association annual meetings, July 2003.
  20. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R.G., 2002, Equating Increased Irrigation Efficiency with Agricultural Water conservation, Invited presentation to the Seattle Economists Club, Audience: Private and government sector economists, October 2002.
  21. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R.G., 2001, Agricultural Water Conservation Laws Designed to Increase Water Levels in the Ogallala Aquifer, Keynote address to the Water and Future of Kansas Conference, Manhattan, KS, March 2001.
  22. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R.G., 2001, Sustainable Management of Global Water Supplies, Invited presentation to the world Bank, Washington D.C., June 2001.
  23. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Other Publications - Huffaker, R.G., 2001, The Role of Prior Appropriation in Allocating Water Resources into the 21st Century, Invited presentation to USDA-ERS, Washington D.C., June 2001.
  24. 1998CO0017G ("Meeting Time Dependent Instream Flow Requirements in a Fully appropriated Multi-State River Basin") - Dissertations - Butt, Tanveer Akhtar, 2002, The Economic and Food Seurity Implications of Population, Climate Change, and Tchnology, Agriuctlural Economics, Texas A&M University, Evans Library Stacks, Call No 2002 Dissertation B95.
  25. 2000CO7B ("Water Quality Monitoring Effectiveness: Denver Water Case Study") - Other Publications - Twenter, Justin C., 2002, Design of a Water Quality Information System for Source Water Assessment: a Denver Water Case Study, Denver, Colorado, MS Thesis, Department of Civil Engineering, Colorado State University, Morgan Library, Colorado State University, Call number I 19 42/4:85-4110.
  26. 2000CO7B ("Water Quality Monitoring Effectiveness: Denver Water Case Study") - Other Publications - Twenter, Justic C., 2002, Design of Water Quality Information systems for Source Water Assessment: A Denver Water Case Study, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Colorado Water, October, pp. 9-13.
  27. 2000CO7B ("Water Quality Monitoring Effectiveness: Denver Water Case Study") - Water Resources Research Institute Reports - Twenter, Justin C., and Jim C. Loftis, 2003, Design of a Denver Water Quality Information System, Colorado Water Resources Research Institute, Colorado State

- University, Fort collins, Colorado, Completion Report No. 197.
28. 2002CO4B ("Quantifying the Effectiveness of Best Management Practices (BMPs) in Controlling Non-Point Source Pollution From Forestland Uses") - Other Publications - Hall, E.B. and J.D. Stednick, 2002, Nutrients and Trophic Status in Off-channel Storage Reservoirs of the South Platte River, Colorado, Colorado State University, Fort Collins, Colorado, Colorado Water, December, pp.7-11.
  29. 2002CO4B ("Quantifying the Effectiveness of Best Management Practices (BMPs) in Controlling Non-Point Source Pollution From Forestland Uses") - Water Resources Research Institute Reports - Stednick, John D. and Emile Hall, 2003, Applicability of Trophic Status Indicators to Colorado Plains Reservoirs, Colorado Water Resources Research Institute, Colorado State University, Fort collins, Colorado, Completion Report No. 195.
  30. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Other Publications - Fausch, Kurt D. and Kevin R. Bestgen, 1999, Why and How to Collect High-Quality Data on Plains Stream Fishes, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, Colorado Water, February, pp. 19-22.
  31. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Other Publications - Scheurer, J. A. and K. D. Fausch, 2001, "Stream fish persistence at landscape scales: extinction-recolonization dynamics of brassy minnow in an intermittent Great Plains watershed," Oral presentation at: Student Ecology Symposium, March, Colorado State University, Fort Collins, CO.
  32. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Other Publications - Scheurer, J. A. and K. D. Fausch, 2001, "Stream fish persistence at landscape scales: extinction-recolonization dynamics of brassy minnow in an intermittent Great Plains watershed," Oral presentation at: Colorado/Wyoming Chapter of The American Fisheries Society Annual Meeting, March, Cheyenne, WY.
  33. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Other Publications - Scheurer, J. A. and K. D. Fausch, 2001, "Stream fish persistence at landscape scales: extinction-recolonization dynamics of brassy minnow in an intermittent Great Plains watershed," Oral presentation at: North American Benthological Society Meeting, June, La Crosse, WI.
  34. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Other Publications - Scheurer, Julie A. and Kurt D. Fausch, 2002, The Identification, Historical Distribution, and Habitat Requirements of Brassy Minnow in Colorado Plains Streams, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Colorado Water, April, pp. 8-11.
  35. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Water Resources Research Institute Reports - Scheurer, Julie A. and Kurt D. Fausch, 2003, Brassy Minnow in Colorado Plains Streams: Identification, Historical Distribution, and Habitat Requirements at Multiple Scales, Colorado Water Resources Research Instiute, Colorado State University, Fort Collins, CO, Completion Report No. 198.
  36. 2001CO882B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Articles in Refereed Scientific Journals - Fausch, Kurt, Christian E. Torgersen, Colden V. Baxter, and Hiram W. Li, 2002, Landscapes to Riverscapes: Bridging the Gap Between Research and Conservation of Stream Fishes, in *Bioscience*, Vol. 52, Issue 6 (June) pp. 1-16.
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Transactions of the American Fisheries Society, 132:840-855.

38. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Articles in Refereed Scientific Journals - Scheurer, Julie A., Kevin R. Bestgen, and Kurt D. Fausch, 2003, Resolving Taxonomy and Historic Distribution for Conservation of Rare Great Plains Fishes: *Hybognathus* (Teleostei: Cyprinidae) in Eastern Colorado Basins, *Copeia* 2003(1), pp. 1-12.
39. 2000CO18B ("Distribution, Habitat, and Life History of Brassy Minnow (*Hybognathus hankinsoni*) in Eastern Colorado Streams") - Other Publications - Scheurer, Julie A., 2002, Systematics and Ecology of Brassy Minnow (*Hybognathus hankinsoni*) in Colorado, MS Thesis, Department of Fishery and Wildlife Biology, Morgan Library, Colorado State University, Call No QL638.C94 S35 2002, 133 pp.
40. 2001CO861B ("Eutrophication of Reservoirs on the Colorado Front Range") - Other Publications - Loftis, Jim C., 2002, Eutrophication of Drinking Water Reservoirs on the Colorado Front Range, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Colorado Water, December, pp. 6-7.
41. 2001CO861B ("Eutrophication of Reservoirs on the Colorado Front Range") - Other Publications - Gelder, Brian Keith, 2002, Colorado's Front Range Reservoirs: A Regional Investigation of Eutrophication Modeling, MS Thesis, Department of Civil Engineering, Colorado State University, Morgan Library, Colorado State University, Call No. TD224.C6 G365 2002.
42. 1999CO101B ("Determination of High Quality Aquifers in Colorado") - Other Publications - O'Keefe, Nancy Ann, 2002, High Quality Aquifers and Associated Demographic Information in the State of Colorado, MS Thesis, Department of Soil and Crop Sciences, Morgan Library, Colorado State University, Fort Collins, CO.
43. 1999CO101B ("Determination of High Quality Aquifers in Colorado") - Water Resources Research Institute Reports - O'Keefe, Nancy Ann and Grant Cardon, 2002, Protocol for a Statewide Ground Water Quality Monitoring Program and Establishment of a Ground Water Quality Data Clearinghouse, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Completion Report No. 199.
44. 2000CO8B ("Forest Management, Water Yield, and Water Quality: A State-of-the-Art Assessment") - Other Publications - Huffman, Edward Louis, 2001, Fire-Induced Soil Hydrophobicity Under Ponderosa and Lodgepole Pine, Colorado Front Range, M.S. Thesis, Morgan Library, Colorado State University, Fort Collins, CO, Call No. S593-H84 2001, 186 pp.
45. 2000CO8B ("Forest Management, Water Yield, and Water Quality: A State-of-the-Art Assessment") - Other Publications - MacDonald Lee H., 2002, Effects of Changes in Colorado's Forests on Water Yields and Water Quality, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Colorado Water, October, pp. 6-8.
46. 2000CO8B ("Forest Management, Water Yield, and Water Quality: A State-of-the-Art Assessment") - Water Resources Research Institute Reports - MacDonald, Lee H. and John D. Stednick, 2003, Forests and Water: A State-of-the-Art Review for Colorado, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO, Completion Report No. 196, 65 pp.
47. 2002CO5B ("Determining the Fate of Non-source Pollution from Septic Tanks in Turkey Creek Basin, Colorado, and Delineating Improved Management Practices") - Articles in Refereed Scientific Journals - Dano, K., E. Poeter, and G. Thyne, 2002, Geochemical and geophysical determination of the fate of septic tank effluent in a mountain watershed, Colorado, *Geol. Soc. Am. Abstracts with Programs*, 34(6).