Colorado Water Resources Research Institute
Annual Technical Report
FY 2005

Introduction

Water research is more pertinent than ever in Colorado. Whether the project explores the effects of decentralized wastewater treatment systems on water quality, optimal irrigation scheduling, household conservation patterns, the effects of wastewater reuse on turfgrass, the economics of water transfers, or historical and optimal streamflows, water is a critical issue. In a headwaters state where downstream states have a claim on every drop of water not consumed in the state, the quality and quantity of water becomes essential to every discussion of any human activity.

Our charges this year included requests from the legislature and state and federal agencies. Water allocations and agreements and the potential treatment and reuse of industrial water are two examples.

Colorado State Legislature and Department of Natural Resources requested our assistance in engaging researchers and Cooperative Extension in the public discussions of water quantity issues around the state. A series of public meetings in designated water basins elicited input from stakeholders with the goal in mind of creating an interbasin water compact in the state.

The Bureau of Reclamation asked us to help stage a workshop on produced waters those waters resulting from the extraction of coal bed methane and other energy materials. A workshop was scheduled for April 4-6, 2006 in Fort Collins.

The Colorado Water Resources Research Institute serves to connect the water expertise in Colorado's institutions of higher education to the information needs of water managers and users by fostering water research, training students, publishing reports and newsletters and providing outreach to all water organizations and interested citizens in Colorado.

Research Program

Colorado Water Resources Research Institute funded three graduate Fellowships this fiscal year. The Advisory Committee on Water Research Policy selected fellows based on the relevancy of their proposed graduate research to current issues in Colorado.

Kathleen DeJong, CWRRI Fellow at Colorado School of Mines, works with Robert Siegrist. They are exploring the treatment options for onsite wastewater treatment systems in the management of organic wastewater contaminants (OWCs) which result from pharaceuticals and personal care products. DeJong's fellowship work augments an ongoing USGS project on this topic. The study encompasses a variety of sources such as single and multi-family residential systems, commercial systems for restaurants, convenience stores, and retail centers, and institutional systems such as veterinary hospitals, schools, and churches. Some of the management options explored include septic tank options, pre-treatment units such as filters and wetlands, and methods of mitigating percolation through the soil absorption field prior to groundwater discharge.

Julia Keedy, graduate student in Civil Engineering at Colorado State University received a graduate Fellowship to pursue research on the sensitivity of a model of the Colorado River system. Utilizing data from previous studies and naturalized data sets based on tree ring records, Keedy's work is an effort to apply various analytical methods and determine critical reservoir levels, reservoir releases, and shortage and surplus occurrences for the length of the stream. This study is co-sponsored by the Colorado River Water Conservation District.

Jennifer Thorvaldson's graduate project is to analyze the economic impacts on various Colorado communities of a potential reduction in irrigated agriculture. With her advisor, James Pritchett, she will develop a model respresenting the economy and economic interactions within four water basins in Colorado: Arkansas, Republican, Rio Grande, and South Platte. Significant reductions in irrigated agriculture by 2030 are predicted by a variety of experts and state agencies. The model will attempt to quantify the impacts of reduced agricultural production across the entire community, including reduced sales of agriculture related products, retail sales to households, and reduced job opportunities. This project is co-sponsored by the Colorado Agricultural Experiment Station.

Colorado's Evolving Irrigated Agriculture: Economic Accounting Impact Analysis

Basic Information

Title:	Colorado's Evolving Irrigated Agriculture: Economic Accounting Impact Analysis
Project Number:	2005CO115B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	4th
Research Category:	Social Sciences
Focus Category:	Economics, Agriculture, None
Descriptors:	
Principal Investigators:	Robert C. Ward

Publication

Jennifer Thorvaldson

Colorado's water is an important natural resources that contributes to the social, cultural, and economic well-being of the state. Early in Colorado's history, water resources were important to the mining industry. Later, agricultural industries became a primary user of water resources. In the next 25 years, Colorado's population is expected to exceed 7 million people, and additional water will be needed to support growth in cities and towns. Since agriculatural industires are still the primary user of water supplies, representing and estimated 91 percent of all water used in Colorado, any increase in municipal and industrial uses will diminish the water avaialbe for agricultural use.

Agricultural industry is one of Colorado's significant economic sectors. Farming employs roughly 45,000 people in 2000. Seventy-five percent of the total value of Colorado crops is derived from the irrigated sector, highlighting the importance of water resources to these agricultural communities. Colorado's crop production supports livestock, meat-packing and dairy industries. Each primary agricultral industry encourages economic development directly, through purchase of inputs and indirectly through wages and salaries of employees.

In order to analyze the economic impacts of reducing irrigated agriculture in Colorado, this project will develop a model representing the economy and economic interactions within four water basins in Colorado: Arkansas, Republican, Rio Grande, and South Platte. When the economic model is established, the inputs and outputs can be manipulated to predict what the impacts of changes in production in various sectors -- such as reduction in irrigated agriculture -- will have on the remaining economy.

To date, the models for each individual basin have been assembled. These models includ information about local economic interactions known as regional economic accounts, which describe a local economy in terms of the flow of dollars from purchasers to producers within the region. The regional economic accounts are used to construct local-level multipliers. Multipliers describe the response of the economy to an change in that economy, such as a change in demand or production. The multipliers allow us to predict what will happen to the rest of the sectors of the economy when one sector changes.

Additional funding for this project is provided by the Colorado Agricultural Experiment Station. Projected completion date for this model is December 2007.

Occurrence and Fate of Organic Wastewater Contaminants in Onsite Wastewater Systems and Implications for Water Quality Management

Basic Information

Title:	Occurrence and Fate of Organic Wastewater Contaminants in Onsite Wastewater Systems and Implications for Water Quality Management
Project Number:	2005CO117B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	4TH
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Water Quality, Treatment
Descriptors:	
Principal Investigators:	Robert C. Ward

Publication

Organic wastewater contaminants (OWCs) 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 OWCs to the environment, but few have quantified their occurrence in onsite wastewater treatment systems and associated receiving environments. A substantial portion of the wastewater generated in the U.S. is processed by onsite wastewater systems before discharge to the environment. For example, in Colorado there are over 600,000 onsite wastewater treatment systems 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 100 billion liters of wastewater are being processed by onsite wastewater treatment system and then discharged to the environment every year in Colorado alone. A research project was initiated by the Colorado School of Mines in collaboration with the U.S. Geological Survey to determine the occurrence of OWCs in effluents produced from varying sources and by different types of onsite wastewater systems, to assess the fate and transport of OWCs in soil absorption systems prior to groundwater and surface water recharge, and to assess the potential for OWCs to impact receiving waters.

Fellow CSM Ph.D. graduate student Jim McKinley and DeJong sampling septic tank effluent

Thirty onsite wastewater treatment systems, 10 groundwater wells, and 9 surface waters in a Front Range region and Rocky Mountain region of Colorado were selected and sampled for conventional water and wastewater parameters and for a suite of OWCs. The wastewater treatment sites represented a range of sources: residential (single-family and multi-family homes), commercial (restaurants, convenience stores, and retail centers), and institutional (veterinary hospitals, schools, and churches). Ten groundwater wells and 9 surface water sites were selected to be representative of the sampling region and samples were collected in conjunction with the onsite wastewater treatment system sites.

The matrix of each onsite wastewater treatment system effluent, groundwater, and surface water sample collected has been characterized by general water and wastewater parameters. A wide range in concentrations has been measured for onsite system wastewater effluents, as would be expected from the diversity of wastewater sources sampled (e.g. ranging from single-family homes to large commercial and institutional establishments). The median values, though, are comparable to typical values reported for constituents in onsite wastewater treatment system effluents. For example, a typical effluent from an onsite system serving a residential source would be characterized by a carbonaceous biochemical oxygen demand (cBOD5) around 450 mg/L, total nitrogen of 100 mg/L, ammonia of 65 mg/L, and total phosphorus of 47 mg/L.

Each onsite wastewater treatment system effluent, groundwater, and surface water sample collected has also been analyzed for a suite of 25 organic wastewater contaminants. OWCs were identified frequently and at high concentrations in the wastewater effluents. Twenty three of the

25 compounds were identified in one or more of the wastewater effluents in concentrations ranging from less than the reporting level to greater than 1 mg/L. The number of compounds in each wastewater effluent sample ranged from 8 to 19, with the veterinary hospitals and convenience stores having the highest average number of compounds and the residential sources having the lowest average number of compounds. Eight of the most frequently detected compounds are listed in Table 1 with their uses and some common sources.

Surface water site sampled in the study

The occurrence and concentrations of OWCs in onsite wastewater treatment system effluents can be related to the water use distribution at the wastewater source. For example, significantly higher concentrations of cholesterol, 3-β-coprostanol, caffeine, and triclosan were found in both convenience stores as compared to any other wastewater source included in the study. At convenience stores, approximately 90% of the water discharged to the onsite system originates from the public restrooms, i.e. from toilet and urinal flushing and sink faucets, therefore, higher concentrations of human-derived compounds (e.g. cholesterol, 3-β-coprostanol, and caffeine) and ingredients found in hand soaps such as triclosan are be expected in the wastewater effluent. Restaurants and veterinary hospitals that have a higher percentage of wastewater originating from clothes and dish washing reported elevated concentrations of EDTA, 4-methylphenol, and the surfactant metabolite and endocrine disruptor NPEC.

The occurrence of endocrine disruptors such as surfactant metabolites in wastewater raises concerns about their adverse impacts on the environment following recharge of groundwater and potential recharge of surface waters. Concentrations of nonylphenol as low as 10 ug/L have been reported to induce production of the egg yolk precursor vitellogenin, an indicator of endocrine disruption, and significantly decrease the rate of growth of the testes in rainbow trout. In 2003 the U.S. Environmental Protection Agency proposed that the 4-day average concentration of nonylphenol in freshwater should not exceed 5.9 ug/L to ensure aquatic life water quality. Twenty five of the 30 sites included in the study had detectable concentrations of nonylphenol

Table 1. Eight compounds of interest, their uses and sources

Compound	**Use**	**Source**
4-Methylphenol	Disinfectant	Cleaners
3-β-Coprostanol	Animal fecal steroid	Animal
Cholesterol	Animal steroid	Animal
Caffeine	Stimulant	Beverages, drugs
EDTA	Metal-complexing agent	Shampoos, cleaners
Triclosan	Antimicrobial	Soaps, disinfectants, toothpaste
4-Nonylphenol	Surfactant metabolite	Industrial and domestic cleaners
NPEC	Surfactant metabolite	Industrial and domestic cleaners

and approximately half of those exceeded the In the ten groundwater wells, there were more OWCs identified at higher concentrations than in the surface waters. Every groundwater well was contaminated with at least one and at most seven of the 25 OWCs included in this study. Nine of the sites are drinking water wells located up gradient on the same property as an onsite wastewater treatment system included in the study. In the onsite system-reliant developments, contamination of these wells could indicate regional impacts to the groundwater from treated effluent recharge.

Due to the widespread and growing use of onsite wastewater treatment system as an appropriate method of wastewater treatment, understanding the potential impacts on the receiving environments to which they discharge is critical. Results of this study indicate OWCs are present in onsite wastewater treatment system effluent frequently and in variable concentrations. Treatment occurs in the septic tank, in additional pre-treatment units such as filters and wetlands, and during percolation through the soil absorption field prior to groundwater recharge. Controlled laboratory- and field-scale transport studies are underway to investigate the key mechanisms of removal during soil treatment. OWCs have been identified in groundwater wells and, to a much lesser extent, in surface waters located in onsite system-reliant regions. The results from the transport experiments in conjunction with the occurrence findings will aid in defining potential adverse effects to ecosystem and human health due to organic wastewater contaminants discharge from onsite wastewater treatment systems.

Additional funding for this project is provided by Colorado School of Mines. The projected completion date for this study is December 2007.

Development of Characterization Approaches and a Management Tool for the Groundwater-Surface Water System in the Vicinity of Sutherland Reservoir and Gerald Gentlemen Station, Lincoln County, Nebraska

Basic Information

Title:	Development of Characterization Approaches and a Management Tool for the Groundwater-Surface Water System in the Vicinity of Sutherland Reservoir and Gerald Gentlemen Station, Lincoln County, Nebraska
Project Number:	2005CO118G
Start Date:	9/1/2005
End Date:	8/31/2007
Funding Source:	104G
Congressional District:	Colorado 7th
Research Category:	Ground-water Flow and Transport
Focus Category:	Water Quantity, Groundwater, Models
Descriptors:	None
Principal Investigators:	Eileen Poeter, Eileen Poeter

Publication

Problem and Research Objectives

Conflict between competing uses for water (e.g. water for a power plant to generate electricity to run an irrigation pump and water for irrigation) indicates a need for improved management approaches. Effective use of data is essential to resolving this problem. Generally, we, as a society, have not fully tapped the information in available data because of difficulties associated with its integration. The global problem addressed by the research is improving hydrologic system characterization to reduce predictive uncertainty associated with ground water management problems through an iterative process that couples development of alternative conceptual models and data needs assessment. The specific problem to be used as a platform for developing this approach is water management in the vicinity of Sutherland Reservoir and the Gerald Gentlemen Station power plant, which overlies the High Plains (formerly Ogallala) Aquifer in Lincoln County, Nebraska.

This project develops an effective approach to characterization that focuses on reduction of the associated predictive uncertainty. In an iterative process, available data (of varying type) are integrated through modeling that yields predictions (and associated uncertainty) for evaluated scenarios. Analysis of the models indicates the most valuable additional data (type, location, and time) that could be collected and this is incorporated into the field investigations. The resulting data are used to modify the initial set of alternative models. The evolving models facilitate evaluation of the impact of alternative management scenarios on water levels in wells and discharges to the South Platte River.

<u>The Specific Problem that serves as a Platform for Improved Data Fusion</u>

Sutherland Reservoir provides cooling water for the Gerald Gentleman Station (GGS), a 1.4 Gw coal-fired power plant, one of the primary sources of power for Nebraska and surrounding states. Sutherland Reservoir stage has been maintained at or above a critical level since the late 1970s to allow the power plant intakes to receive cooling water for GGS. Over the years, measured and simulated ground-water levels in the underlying High Plains Aquifer indicate that leakage from the reservoir has raised ground water levels in a large, although poorly-defined, region surrounding the reservoir (Nebraska Conservation and Survey Division, 2004). Nearby farms and ranches have come to depend on this ground water for domestic and irrigation use. As of December 2004, nearly every major reservoir in the North Platte River Basin contained less than 30 percent of capacity storage water (Ed Kouma, USBR, personal comm.). The water supply forecast indicates that surface water supplies available to maintain Sutherland Reservoir elevations necessary for operations at GGS will be insufficient by the summer of 2006. To maintain water levels in times of drought, Nebraska Public Power District (NPPD) installed 38 high capacity wells in a 20-square mile area near the reservoir on the Gerald Gentleman Station property in the spring of 2004. These wells will extract water from the High Plains Aquifer and discharge to Sutherland Reservoir. Currently, NPPD project managers plan to utilize the well field starting in the summer of 2006, with a majority of the wells operating daily for up to four months. Pumping rates for these wells range from 1,600 to 2,700 gallons per minute. The same pumping schedule will likely occur during the summers of 2007 and 2008, and if dry climatic conditions persist,

beyond 2008. If necessary, the well field may be used for more than the currently planned four months each year.

Data characterizing the system are sparse and estimates of hydraulic parameters differ in previous studies of the area, and interaction of groundwater within the High Plains Aquifer and water stored in Sutherland Reservoir is not understood. Consequently, the impact of the alternative management scenarios on water levels in wells and discharge to the South Platte River is unknown and a groundwater management model is needed for the study area. The Global Problem Sparse subsurface data cause us to be uncertain of the exact nature of ground water system structure and components. Consequently, it is best, although not always customary, practice to consider multiple representations of the structure of a ground water system before making predictions of system behavior. To the extent possible, items constituting differences in model structure should be automatically adjusted in the calibration process. However, this has been difficult to achieve, thus the need to consider a set of alternative models to some extent. The adjustable parameters of each alternative model must be calibrated (i.e. parameter values adjusted to obtain the best fit to the field data, e.g. using nonlinear regression) before models can be compared (Poeter and Hill 1997). Fortunately, the advent of high speed computing and robust inversion algorithms makes calibration of multiple models feasible. Often, prediction uncertainty is larger across the range of alternative model structures than arises from the misfit and insensitivity of any one optimized model, even to the extent that confidence intervals on predictions from some of the models may not include the values predicted by others. This issue is addressed by weighting the alternative models and calculating model-averaged predictions and intervals (Poeter and Anderson, 2005). If the model averaged predictions are so uncertain that a reasonable decision is untenable, then additional data should be collected to better constrain the range of reasonable models. Hence the iterative process of model development and data collection. The problem involving management of Sutherland Reservoir in Nebraska and predicting its impact on the High Plains aquifer is well suited to the development of a structured approach to iterative alternative model definition and data needs assessment.

Methodology

Task 1: Delineation of the Model Domain

Except for the South Platte River to the north, well defined natural hydraulic boundaries do not occur near the reservoir. Consequently, the model will extend from the Platte River on the north, southward on the order of fifteen miles, with an east-west extent of about 15 miles. The west, south and east boundary will be defined as constant head reflecting the approximate heads in the aquifer at those locations. Simulations of the regional COHYST model will facilitate delineation of boundary conditions and average material properties. The influence of stress on boundary 8 fluxes will be evaluated through out the project and the model domain will be adjusted appropriately.

Task 2: Compilation of available data

Historic data from NPPD, the USGS, and the University of Nebraska Conservation and Survey Division on hydrostratigraphy, hydraulic properties, water levels and flow rates will be coupled with the new lithologic and geophysical borehole data from the well field

installation. These data will be supplemented with pertinent COHYST data for this locale in project databases of various formats (primarily in GIS formats). This database will also be the repository for all USGS hydrochemical data and age dates once it becomes available.

Task 3: Delineation of the hydrostratigraphic framework and associated hydraulic properties Historical interpretation of the hydrostratigraphinc framework (Harza, 1993; Gutentag et al., 1984) will be used as a starting point for further refinement given the hydrostratigraphic data from the newly drilled well field. The surficial geology of the area is dominated by multiple layers of Quaternary loess and fine dune sand deposits that can locally be 50 to 100 feet thick. The base of the reservoir is directly within sand and gravel deposits up to 25 feet thick which facilitate rapid seepage rates. Discontinuous zones of paleosol, a few to several feet thick, presumably the Sangamon, exist below the coarse channel deposits. This sequence of deposits (coarse over fine) creates conditions that enhance horizontal flow of seepage below the reservoir. Fine to medium texture deposits (silts to fine sands up to 40 feet thick) underlie the paleosol. These units lie directly above the Ogallala Group, the primary unit comprising the High Plains Aquifer (up to 350 feet thick). The water table occurs within the upper units. The Ogallala in this area is a mixed sequence of sands and gravels, silts, clays, sandstones, and siltstones, varying substantially over short distances due to the depositional environment. Well yields can be large in this area of the Ogallala with some irrigation wells pumping on the order of 2,000 gallons per minute. The base of the High Plains Aquifer as defined by the USGS High Plains RASA and the Nebraska Platte River Cooperative Hydrology Study (2004) in this area is the Brule Formation, a massive clay- and siltstone (with some coarse deposits locally) within the White River Group (Gutentag and others, 1984).

Task 4: Development of alternative conceptual models Given the hydrostratigrphy and associated uncertainties developed in Task 3, alternative conceptual models will be developed and starting values for hydraulic parameters defined. The simplest geometry consists of continuous horizontal layers from the surface downward of 1) fine loess and sand dunes (50-100 feet), 2) sand and gravel (up to 25 feet thick), 3) paleosol, 4) silts and fine sands (up to 40 feet thick), and 5) the Ogallala, a heterogeneous mix of mixed sequence of sands and gravels, silts, clays, sandstones, and siltstones (up to 350 feet thick). Clearly some of these layers are discontinuous and vary in thickness. Evaluation of the presence, distribution and thickness of these materials will be explored through alternative conceptual models.

Task 5: Construction of numerical models representing the conceptual models Based on the results of tasks 1 through 4, numerical models will be developed using GMS to build the hydrostratigraphy, generate the grid and assign properties. The resulting files will be used for simulation external to GMS (EMRL, 2004) to facilitate manipulation of material zones 9 and inversion with UCODE_2005 and resulting heads and fluxes imported to GMS for visualization. Alternative schemes for finding an optimal zonation of the aquifer zones will be evaluated. Options include the alternatives discussed in a later section titled “Related Research”. The more appropriate methods will be selected once

the general character of the units are identified by analysis of the detailed hydrostratigraphic data recently acquired from drilling the new well field.

Task 6: Calibration of the models using nonlinear regression
The models will be calibrated using nonlinear regression techniques as implemented in UCODE_2005 (Poeter et al., 2005; Poeter and Hill, 1998, Poeter and Hill, 1997), which performs inverse modeling, posed as a parameter-estimation problem, using nonlinear regression. UCODE_2005 is a JUPITER (Joint Parameter IdenTification and Evaluation of Reliability) application (Banta et al., 2005). The JUPITER API is a computer programming environment that includes conventions and software components designed to support the development of computer programs that perform model sensitivity analysis, data needs evaluation, calibration, uncertainty evaluation, and (or) optimization currently under development by the USGS, in coordination with EPA. Statistics generated by UCODE and its post-processor (RESAN_2005) will be used to evaluate the most important parameters in each model as well as the type and location of additional data that would be most useful in reducing parameter and associated predictive uncertainty (Task 7). Evaluation of the important parameters will guide further conceptual model development. In addition, the statistics will be used to compare alternative models and guide development of an improved conceptual model of the region (Tasks 8 and 9).

Task 7: Recommendation of types and locations of data that will improve the model and reduce uncertainty Sensitivities of a model to given types, locations and time of data, as computed by UCODE, are independent of the data value. Increased sensitivity and decreased parameter correlation reduce predictive uncertainty. Consequently various options for data will be considered (at minimal cost) using the calibrated models before the substantial expenditure of field sampling and laboratory analysis. This feedback will be most valuable to the USGS in selecting locations where samples will be collected in 2006 to analyze for the characteristic natural tracers of the reservoir water identified by their work in 2005. The results of their findings in 2006 will be used to further improve the models and reduce prediction uncertainty.

Task 8: Estimation of seepage volume and flow paths
Seepage volume and flow paths will be calculated using the calibrated models and YCINT_2005, a UCODE_2005 post-processor. The values will be model-averaged to generate the best estimate of the volume and paths and the associated uncertainty. This will be accomplished using MMRI (Poeter et al., 2005), a multi-model inference algorithm, and a member of the Jupiter family of codes. MMRI operates on data exchange files from any JUPITER-based inversion algorithm (e.g. UCODE_2005), using them to rank and weight alternative models, then model-averages 10 parameters and predictions (Poeter and Anderson, 2005), using flexible, user-specified algorithms which include the maximum likelihood Bayesian model average (MLBMA) algorithm recommended by Neuman and Weirenga (2003).

Task 9: Prediction of the response of the flow system to various management scenarios

Alternative management scenarios will be defined as the project proceeds. At a minimum they will include steady pumping of all wells in the well field at the distributed rate found necessary to maintain the reservoir at a minimum level given the model calibrations, and some combinations of a subset of wells maintaining minimum levels. Additional scenarios will involve various strategies to recharge the aquifer by raising water levels in the reservoir via canal inflow during wet periods. Further scenarios will be developed as problems are identified (e.g. excessive drawdowns in surrounding wells or low flows in the Platte River) by modeling results. The predictions for each scenario will be averaged for all models using MMRI as discussed in task 8. Their uncertainty will be considered and if the range of uncertainty in predicted conditions is unacceptable recommendations will be made for further data collection to reduce that uncertainty.

Task 10: Preparation of papers delineating the approach, implementation and findings
Two papers will be prepared. One paper will delineate the approach for hydrologic system characterization that reduces predictive uncertainty associated with ground water management problems through an iterative process that couples development of alternative conceptual models, model averaging of predictions, and data needs assessment. The second paper will discuss the implementation of the approach for management of the Sutherland Reservoir and the findings of the project.

Task 11: Preparation and posting of a web page presenting project information
A web site, targeting a multi-level audience, will be developed with graphical displays highlighting project findings, the project report, public domain data, project model input and output files, and directions for their use (see section titled: Information Transfer Plan). Facilities Colorado School of Mines and the International Ground Water Modeling Center have complete computing facilities and software (e.g. Arc/Info, Access, MODFLOW2000, MODPATH, MT3D, GMS, GWV, UCODE among other hydrologic and geologic software) for conducting this work. Students and faculty will write software as necessary to accomplish the tasks. Basic field equipment including pumps, water level sounders, and water quality sampling equipment are available through Colorado School of Mines, but will be supplied by NPPD or their contractors. The USGS will provide geochemical sampling equipment and analysis laboratories.

Principal Findings and Significance

The model domain for the Sutherland Reservoir/ Gerald Gentlemen Station (GGS) investigation was defined as an area of approximately 1,000 square miles with the reservoir located slightly north of the center of the model domain and grid area. This area includes several surface water features and land use types and is sparsely populated.

Several types of pre-project data were compiled for the study. Sources for nearly all of these data include: the Nebraska Department of Natural Resources (NDNR); US Geological Survey (USGS); the University of Nebraska Conservation and Survey Division (CSD); the Nebraska Public Power District (NPPD); and the Platte River Cooperative Hydrology Study (COHYST). The data include historic river flows at several gages on the South Platte River (NDNR, USGS, COHYST), geologic borehole

data (CSD, COHYST, NPPD), evapotranspiration data (COHYST), area well records (NDNR), historic canal diversion and reservoir stage data (NDNR, NPPD), and land use imagery in the last 10 years (COHYST). A considerable effort was expended preparing the data for use in the groundwater model and other software interfaces.

To enhance model calibration, 7 multi-well monitoring nests were installed around the GGS wellfield and Sutherland Reservoir to monitor groundwater levels and identify distinct geochemical signatures of the groundwater at varying locations both vertically and horizontally. Surface water features, including canals, drains, the South Platte River, and Sutherland Reservoir were sampled for water quality. The samples were analyzed by the US Geological Survey. Sampling will continue to evaluate changes after pumping the well field for summer operation of GGS. Flow was, and continues to be measured at six previously unmonitored locations along drains in the model area. It appears that flow at these locations will be important to groundwater model calibration.

A database of geology from boreholes at the GGS site that were installed since 2004 was developed. Pre-project geologic borehole data were incorporated in the data base, such that it now includes over 70 boreholes within an area of less than 60 square miles in the vicinity of GGS. These borehole data have been analyzed in a stratigraphic modeling software interface which allows for three-dimensional modeling of the complex geologic data found at the Sutherland Reservoir/GGS site. These data have been used to generate one of the conceptual models being created for this project. Automated procedures for generating alternative conceptual models are under development.

Currently, four conceptual models with varying hydrostratigraphy at the Sutherland Reservoir/GGS site are being evaluated. These conceptual models include a two-dimensional representation, a three-dimensional two-layer representation, a four-layer representation using previously constructed COHYST data, and a five-layer representation using the new hydrostratigraphy that combines the new geologic borehole data with the COHYST borehole data. Additional conceptual models include alternate hydrostratigraphic representations of the geologic data, and varying representations of boundary conditions based on land-use practices that influence groundwater recharge and evapotranspiration.

Each model has been constructed as a numerical model and calibration has begun. Details of the calibration schemes are under development at this time. Based on preliminary assessments, recommendations have been for additional streamflow data and water quality data that will provide flow paths and mixing ratios for use in model calibration.

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

Basic Information

Title:	Occurrence and Fate of Emerging Organic Chemicals in Onsite Wastewater Systems and Implications on Water Quality Management in the Rocky Mountain Region
Project Number:	2002CO46G
Start Date:	9/1/2002
End Date:	2/28/2006
Funding Source:	104G
Congressional District:	6th
Research Category:	Not Applicable
Focus Category:	Waste Water, Water Quality, Toxic Substances
Descriptors:	
Principal Investigators:	Dr. Robert L. Siegrist, Kathryn S. Lowe, John E. McCray

Publication

1. DeJong, K., 2004, "Occurrence of emerging organic chemicals in wastewater system effluents," presented at the 4th International Conference on Pharmaceuticals and Endocrine Disrupting Compounds in Water, Minneapolis, MN.

Problem and Research Objectives

The Rocky Mountain region has experienced significant development during the past decade, much of which is occurring in suburban fringe and mountain resort settings. In these areas, wastewater management is commonly achieved by onsite wastewater treatment systems (OWS). While for many years, these onsite systems were viewed as temporary solutions until centralized treatment facilities became available, they are now an appropriate and necessary component of the wastewater infrastructure in the U.S. (USEPA 1997). Just like their big-city counterparts (i.e., the centralized, municipal wastewater treatment plants), small onsite systems can, and must, be designed, installed, operated and managed to be protective of public health and environmental quality (Siegrist 2001). At this time, nearly 25% of the U.S. population is served by decentralized wastewater systems and a substantial portion of all new development is being supported by such systems with thousands of new systems being installed each year.

Growth has led to rapid proliferation of onsite wastewater treatment systems throughout Colorado and other Rocky Mountain states. For example, in Colorado there are over 600,000 onsite systems in operation serving about 25% of the State s population and there are 7,000 to10,000 new systems installed each year. On an annual basis this amounts to over 30 billion gallons of wastewater effluent discharged to the environment. In Wyoming, Montana, and Utah, the situation is similar. Issues have been raised regarding potential water quality impacts from onsite systems and the adequacy of current efforts to minimize such impacts. To explore and begin to address these issues in Colorado, in 2001 Ms. Jane Norton, Executive Director of the Colorado Department of Public Health and Environment, established the Individual Sewage Disposal System (ISDS) Steering Committee, comprised of members with a wide range of expertise and interests related to OWS. Findings of this Colorado Committee revealed that water quality impacts are occurring, but the nature and magnitude of resulting problems often has not been verified or rigorously documented (Colorado 2002). Furthermore, the few water quality studies that have been completed have focused on nutrient loading and bacterial levels.

Emerging organic chemicals (EOCs), such as pharmaceuticals and personal care products (PPCPs), have received a great deal of attention in the last decade with several studies indicating the adverse effects of these chemicals on ecosystems and human health. While several studies have pointed to wastewater as a primary contributing source of EOCs in the water environment, only a few studies have quantified their occurrence and fate in wastewater and, most focused on the presence of EOCs in the influents and effluents of large municipal wastewater treatment plants. The results of these studies do not shed much light on the occurrence and fate of EOCs in onsite systems nor the fate of these EOCs during pretreatment operations (e.g., septic tank or sand filter) and percolation through soil before ground water and surface water recharge.

A preliminary literature review was completed at CSM to examine the occurrence and fate of EOCs in wastewater systems in general, and online systems in particular. In

addition, samples of septic tank effluent (STE) were collected from two separate multifamily residential sites in Colorado and analyzed by Dr. Larry Barber (USGS, Boulder) for 48 different EOCs. Some of the key constituents detected were: caffeine (~69000 ng/L), estrone (~355 ng/L), 17-estradiol (~800 ng/L), 17 –ethinylestradiol (~35 ng/L), 4-nonylphenol (~760 ng/L), and bisphenol A (~9000 ng/L). The results of this work were very preliminary, but serve as a motivation for proposing the research outlined herein. Further understanding regarding EOCs in onsite systems is critical to better management and long-term use of these systems. This is particularly true for mountain watersheds where onsite systems may recharge water supplies used as source waters for drinking water. For example, in Summit County, Colorado, over 1000 onsite systems contribute to the Blue River watershed, which feeds Lake Dillon, a surface water that provides 25% of the drinking water supply for the City of Denver. If EOCs are present in onsite wastewater system influents in appreciable concentrations and if they are ineffectively remove during treatment operations and soil percolation, they may reach groundwater and surface waters and present risks for human health and environmental quality.

The overall goal of the proposed research is to determine if EOCs are present in onsite wastewater effluents and to what extent key EOCs of concern are effectively removed during treatment in a septic tank or engineered filter unit (sand or textile filter) and soil percolation prior to release to receiving waters. The specific objectives of the proposed research are to: (1) quantify the occurrence of EOCs in onsite wastewater effluents, (2) evaluate the treatment efficiency of pretreatment units and sandy soil for removal of EOCs, (3) assess the potential for EOCs originating from onsite systems to reach receiving waters, particularly in Rocky Mountain watersheds, (4) educate and train students in experimental methods and scientific research, and (5) transfer the findings to the scientific community and decision-makers in Colorado and the nation.

Methodology

Monitoring efforts follow established protocols and methodologies (APHA 1998, Barber *et al.* 1998, USGS 1999, Van Cuyk *et al.* 2001). To preserve the sample integrity, proper sample handling procedures are employed from the time of sample collection through sample analysis during all monitoring tasks (USGS 1999). During monitoring, all samples are collected in containers of appropriate materials and closures to ensure integrity of the analyses and avoidance of artifacts due to extraneous contamination. Field parameters will be measured in situ or onsite (^{o}C, pH, D.O.). Samples are labeled with permanent, unique numbers and be logged into project notebooks. All samples are placed in coolers and stored at 4¡C until brought to CSM or the USGS laboratory for analysis. Conventional pollutants are analyzed at CSM (alkalinity, solids, TOC, COD, nutrients, anions and cations) using standard methods (APHA 1998). EOCs will be analyzed by CSM students following USGS established methods at Dr. Barber s USGS lab in Boulder, Colorado. On a subset of samples, analyses has been completed for additional analytes at the USGS NWQL following their Schedule 1433 (for 70 EOCs). QA/QC checks of sampling and analysis procedures will consist of field and laboratory

QA/QC samples (~10% of total samples collected). All quality data will be reported from the laboratory as mg or ug per liter (mg/L, ug/L).

Principal Findings and Significance

Thirty OWS, 10 groundwater wells, and 9 surface waters in a Front Range region and Rocky Mountain region of Colorado were selected and sampled for conventional water and wastewater parameters and for a suite of OWCs. The OWS sites represented a range of sources: residential (single-family and multi-family homes), commercial (restaurants, convenience stores, and retail centers), and institutional (veterinary hospitals, schools, and churches). Ten 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.

The matrix of each OWS effluent, groundwater, and surface water sample collected has been characterized by general water and wastewater parameters. A wide range in concentrations has been measured for onsite system wastewater effluents, as would be expected from the diversity of wastewater sources sampled (e.g. ranging from single-family homes to large commercial and institutional establishments). The median values, though, are comparable to typical values reported for constituents in OWS effluents. For example, a typical effluent from an onsite system serving a residential source would be characterized by a carbonaceous biochemical oxygen demand (cBOD5) around 450 mg/L, total nitrogen of 100 mg/L, ammonia of 65 mg/L, and total phosphorus of 47 mg/L.

Each OWS effluent, groundwater, and surface water sample collected has also been analyzed for a suite of 25 organic wastewater contaminants. OWCs were identified frequently and at high concentrations in the wastewater effluents. Twenty three of the 25 compounds were identified in one or more of the wastewater effluents in concentrations ranging from less than the reporting level to greater than 1 mg/L. The number of compounds in each wastewater effluent sample ranged from 8 to 19, with the veterinary hospitals and convenience stores having the highest average number of compounds and the residential sources having the lowest average number of compounds.

The occurrence and concentrations of OWCs in OWS effluents can be related to the water use distribution at the wastewater source. For example, significantly higher concentrations of cholesterol, 3-β-coprostanol, caffeine, and triclosan were found in both convenience stores as compared to any other wastewater source included in the study. At convenience stores, approximately 90% of the water discharged to the onsite system originates from the public restrooms, i.e. from toilet and urinal flushing and sink faucets, therefore, higher concentrations of human-derived compounds (e.g. cholesterol, 3-β-coprostanol, and caffeine) and ingredients found in hand soaps such as triclosan are be expected in the wastewater effluent. Restaurants and veterinary hospitals that have a higher percentage of wastewater originating from clothes and dish washing reported elevated concentrations of EDTA, 4-methylphenol, and the surfactant metabolite and endocrine disruptor NPEC.

The occurrence of endocrine disruptors such as surfactant metabolites in wastewater raises concerns about their adverse impacts on the environment following recharge of groundwater and potential recharge of surface waters. Concentrations of nonylphenol as low as 10 ug/L have been reported to induce production of the egg yolk precursor vitellogenin, an indicator of endocrine disruption, and significantly decrease the rate of growth of the testes in rainbow trout. In 2003 the U.S. Environmental Protection Agency proposed that the 4-day average concentration of nonylphenol in freshwater should not exceed 5.9 ug/L to ensure aquatic life water quality. Twenty five of the 30 sites included in the study had detectable concentrations of nonylphenol and approximately half of those exceeded the proposed value of 5.9 ug/L, some by greater than ten times. The effect from multiple endocrine disruptors, such as the suite of alkylphenolic compounds studied here, is unknown but studies have indicated an additive effect. Significant treatment occurs during infiltration and percolation through the soil absorption system of OWS, though the removal rates and mechanisms of OWCs prior to recharge to the environment are currently unknown. Additionally, there is the potential for treatment failure, by preferential flow through the soil, or from hydraulic failure, such as a storm event, that would send untreated wastewater with pollutant concentrations seen here directly to ground or surface water. Currently, there are no established regulations for these compounds because little is still understood about the long-term reproductive effects of chronic exposure to pharmaceutically-active compounds at low concentrations such as those seen here.

Of the nine surface waters sampled in the study, very few OWCs were identified, and, if present, were in low concentrations. Cholesterol and 4-methylphenol were the only compounds identified in surface waters above the reporting level. The surface water sites are located in regions which rely heavily on OWS for wastewater treatment, but are not directly impacted by wastewater from municipal wastewater treatment plant discharge. Instead, treated OWS effluent percolates through the soil until it reaches the water table and recharges the groundwater which may, in turn, recharge the local surface water. Surface water may also be impacted by runoff from agriculture and development.

In the ten groundwater wells, there were more OWCs identified at higher concentrations than in the surface waters. Every groundwater well was contaminated with at least one and at most seven of the 25 OWCs included in this study. Nine of the sites are drinking water wells located up gradient on the same property as an OWS included in the study. In the OWS-reliant developments, contamination of these wells could indicate regional impacts to the groundwater from treated effluent recharge.

Due to the widespread and growing use of OWS as an appropriate method of wastewater treatment, understanding the potential impacts on the receiving environments to which they discharge is critical. Results of this study indicate OWCs are present in OWS effluent frequently and in variable concentrations. Treatment occurs in the septic tank, in additional pre-treatment units such as filters and wetlands, and during percolation through the soil absorption field prior to groundwater recharge. Controlled laboratory- and field-scale transport studies are underway to investigate the key mechanisms of removal during

soil treatment. OWCs have been identified in groundwater wells and, to a much lesser extent, in surface waters located in OWS-reliant regions. The results from the transport experiments in conjunction with the occurrence findings will aid in defining potential adverse effects to ecosystem and human health due to organic wastewater contaminants discharge from onsite wastewater treatment systems.

Hydrologic Analysis, Forecasting and Simulation of the Upper Colorado River System

Basic Information

Title:	Hydrologic Analysis, Forecasting and Simulation of the Upper Colorado River System
Project Number:	2005CO148B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	4th
Research Category:	Not Applicable
Focus Category:	Hydrology, None, None
Descriptors:	
Principal Investigators:	Robert C. Ward

Publication

Streamflow and basin yield are important issues to water resource management. In an era when water is fully appropriated and water maangers rely on computerized models to help them manage water resources, enhancing and improving the accuracy and sensitivity of models and datasets becomes a vital tool for satisfying all calls on water resources.

Keedy is working with the Colorado River Water Conservation District to enhance the Colorado River System Simulation developed by the Bureau of Reclamation using the RiverWare software program.

Comparison of streamflow data sets with naturalized streamflow data extended backward using stochastic correlation techniques, naturalized streamflows reconstructed from tree ring records spanning from around 1500 to 1999 (the reconstruction has not yet been completed), and generated streamflows based on stochastic techniques will help to test the sensitivity of the model for use in prediction and management decisions. For this purpose, parametric and non-parametric methods will be applied. Steamflow data scenarios will be run to test the sensitivity of the system to varations within the data sets. Key parameters will be used to characterize the response of the basin to various conditions. These parameters include critical reservoir levels (such as dead pool, minimum power pool, top of active conservation, and spillway elevation), reservoir releases, and shortage and surplus occurrences for each state. The parameters will be compared by determining their probabilities of occurrence under each different streamflow scenarios.

Another objective of the study is to determine the safe yield of the upper basin. This task will be accomplished by increasing the demands of the upper basin in order to achieve a given, accepted probability of shortage occurrences. While none of the streamflow data sets are quite ready to be used in the model for the final results of this study, currently available streamflows have been used to run the model so analysis techniques can be developed.

To date, data formatting and input issues have been addressed by creating conversion templates to correlate data from one source to data from another source. Code which allows insertion of many slots of data at one time was obtained, allowing alteration between the data sets.
The model was run simulating the currently accepted streamflow data according to the index-sequential method, a non-parametric technique often used for such purposes. The output of this technique is currently being analyzed to determine the best process to determine variations in the response of the river system to various streamflow simulations.

Goals of the project include the comparison of various methods of analysis, and an exploration of the use of tree ring data to establish historical streamflows and their effects in the absence of human collected streamflow data.

Additional funding for this project is provided by Colorado River Water Conservation District.
The projected completion date for this study is December 2006.

Keedy confers with David Merritt and Dave Kanser at the Colorado River Water Conservation District offices.

Information Transfer Program

Requests from the Colorado legislature to facilitate and inform basin-level discussions of water resources and help develop an interbasin compact for water management purposes emphasized the role Colorado Water Resources Research Institute plays in providing a nexus of information. Some major technology transfer efforts this year include:

- Provide training for Cooperative Extension staff in various water basins to help facilitate discussions of water resources
- Encourage interaction and discussion of issues between water managers, policy makers, legislators, and researchers at Water Dialogue one-day conference
- Publication of the bi-monthly newsletter which emphasizes water research, current water issues
- Posting of all previously published CWRRI reports to the web for easier access
- Working with Colorado Institute for Public Policy to develop a charter for the state Interbasin Compact Commisson

Technology Transfer and Information Dissemination

Basic Information

Title:	Technology Transfer and Information Dissemination
Project Number:	2005CO116B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	4th
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Robert C. Ward

Publication

1. Laflin, Rose, 2005, Irrigation, Settlement, and Change on the Cache La Poudre River, Special Report 15, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, 204 pp.

Colorado Water, bi-monthly newsletter of CWRRI and Colorado State University Water Center, provided research updates, meeting briefs, and other water resources news on topics such as conjunctive use, water basin roundtable process initiated by the Colorado State Legislature, river restoration, and the water-energy nexus. Archived newsletters are available from our web page www.cwrri.colostate.edu .

Web pages for the center were updated to include immediate access to the documents published by CWRRI. More than 300 reports were scanned, saved as .pdf files, and uploaded to the webpage this year. Reports are available from our web page at www.cwrri.colostate.edu.

Produced Waters Workshop

Basic Information

Title:	Produced Waters Workshop
Project Number:	2005CO147S
Start Date:	9/26/2005
End Date:	6/30/2002
Funding Source:	Supplemental
Congressional District:	
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Robert C. Ward

Publication

Produced Waters Workshop

April 4-5 2006

Purpose of Workshop: ***What is the potential opportunity for beneficial use of produced waters and how can we make it happen?***

This workshop is to encourage discussion and enhance understanding of the potential opportunities and barriers for putting produced water to beneficial use. Water that is brought to the surface during oil and gas production is commonly known as 'produced waters'. Prior to the recent large-scale development of coal bed natural gas (or coal bed methane), this water largely escaped our notice or was considered of insufficient quality to be used beneficially. Hence, energy companies have developed methods to reinject or otherwise dispose of this by-product as efficiently and cheaply as possible.

What has changed to make us reconsider produced waters? First and foremost, the pace of coal bed natural gas development in the West has been frenzied due to current energy prices and policies. These coal formations act as aquifers that must be dewatered to allow gas extraction. Produced water must be dealt with, but traditional methods of disposal usually result in these waters being lost for further human use; in some cases creating problems for downstream landowners. The droughts and water shortages of recent years have prompted many to ask if we are wise to sacrifice one vital resource in order to gain another.

Technology exists today to treat impaired waters to meet beneficial-use standards. In some cases, there appear to be favorable economic trade-offs between water disposal costs and treatment for resale. However, to make produced water a viable and reliable source of water, the energy industry, water industry, water-user interests, environmental interests, as well as Federal, State and local governments must come together to overcome the constraints hindering development of this resource. The various parties must reach common definitions of terms, agree on the issues at stake, and collaborate to overcome the legal impediments to simultaneously developing energy and water.

Water and energy businesses operate within different markets and, consequently, within very different incentive structures and time frames. Oil and gas producers react quickly to swings in the energy market, while water suppliers enjoy a more steady market without large swings in price (except in periods of drought). As a result, energy companies work quickly in accessing their non-renewable supplies, while raw water suppliers (generally government organizations) work over long time frames in planning new water projects. Energy companies often work with high risk, while water utilities/districts try to reduce risk to the lowest possible levels. Energy and water are two very different cultures, a point which was apparent many times during the workshop. The Department of Interior's current emphasis on rapid energy development conflicts with the longer time frame needed to plan and implement water projects.

The Workshop Will:

- Identify the key opportunities and capabilities of state-of-the-art treatment technologies for produced waters;

- Initiate discussions regarding public policies to facilitate the development of this valuable resource; and,
- Define a course of action to further evaluate and pursue these opportunities.

Partial List of Presenters:
- Mark Limbaugh, Assistant Secretary for Water and Science, Department of the Interior
- Lynn Takaichi, Vice President, Kennedy/Jenks Consultants
- Harold Bergman, Director, William D. Ruckelshaus Institute
- Pat O'Toole, President, Family Farm Alliance

Optional Tour on April 6: Optional tour on the morning of April 6. Travel to Wellington, Colorado to visit a local produced water treatment facility. Space is limited. Must register for tour. First come, first served.

Anticipated Audience: Legislators, energy producers, water users, water supply planners, government agency staff, researchers, and industry representatives.

Co-Sponsors:
- Bureau of Reclamation
- Family Farm Alliance
- National Institutes for Water Resources
- Ruckelshaus Institute of Environment and Natural Resources
- U.S. Geological Survey

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	4	2	0	0	6
Masters	2	0	0	0	2
Ph.D.	1	1	0	0	2
Post-Doc.	0	0	0	0	0
Total	7	3	0	0	10

Notable Awards and Achievements

Neil Grigg received the Distinguished Faculty Award from the Colorado State University Alumni Association. His research in water resource planning and management, public works infrastructure management, water law, urban water systems, and disaster preparedness includes multiple Colorado Water Resources Research Institute projects. He served as institute Director for many years.

Enrique Triana, PhD student in the Department of Civil Engineering at Colorado State Universtiy, was awarded the Rich Herbet Scholarship by the American Water Resources Association Colorado section. He has been working on enhancements to the MODSIM River Reservoir Operation Model with his advisor, Dr. John Labadie. Their goal is to develop the graphical user interface and increase the capacity of the system to deal with water allocations in shorter time intervals. Triana has also been engaged in water management studies in the Arkansas River Basin headed by Tim Gates and funded by USGS grant monies.

Publications from Prior Projects

1. 2004CO105B ("Determination of Ecosystem Response Thresholds to Nutrient of Flowing Waters in Montane Colorado") - Water Resources Research Institute Reports - Lewis, Willam M., Jr., 2005, Determination of Ecosystem Response Thresholds to Nutrient Enrichment of Flowing Waters in Montaine Colorado, Completion Report 201, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, 13 pp.
2. 2002CO4B ("Quantifying the Effectiveness of Best Management Practices (BMPs) in Controlling Non-Point Source Pollution From Forestland Uses") - Water Resources Research Institute Reports - Teves, Nani B., and John D. Stednick, 2005, Effectivenss of Forestry Related Best Management Practices in the Trout Creek Watershed, Colorado, Completion Report 202, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado, 121 pp.