Colorado Water Institute
Annual Technical Report
FY 2013

Introduction

Water research is more important 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.

The Colorado Water Institute (CWI), an affiliate of Colorado State University (CSU), exists for the express purpose of focusing the water expertise of higher education on the evolving water concerns and problems being faced by Colorado citizens. We are housed on the campus of CSU but work with all public institutions of higher education in Colorado. CWI coordinates research efforts with local, state, and national agencies and organizations. State funding currently allows CWI to fund research projects at CSU, the University of Colorado, University of Northern Colorado, and Colorado School of Mines.

Our charges this year included requests from the legislature and state and federal agencies. The Colorado Legislature passed House Bill 12-1278, requiring the Colorado Water Institute to conduct a comprehensive study of groundwater utilization in the South Platte River Basin. The Colorado Department of Natural Resources requested our assistance in engaging researchers and Extension in the public discussions of water quantity issues around the state. Water Roundtables in designated water basins elicited input from stakeholders with the goal in mind of creating an environment for water sharing arrangements in the state. In addition, CWI and the Colorado Department of Agriculture are co-chairing the State's agricultural drought impact task force.

CWI 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 Introduction

The Colorado Water Institute funded 2 faculty research projects, 1 student research projects, and 3 internships this fiscal year. The Advisory Committee on Water Research Policy selected these projects based on the relevancy of their proposed research to current issues in Colorado.

Under Section 104(b) of the Water Resources Research Act, CWI is to plan, conduct, or otherwise arrange for competent research that fosters the entry of new scientists into water resources fields, expands understanding of water and water-related phenomena (or the preliminary exploration of new ideas that address water problems), and disseminates research results to water managers and the public. The research program is open to faculty in any institution of higher education in Colorado that has demonstrated capabilities for research, information dissemination, and graduate training to resolve State and regional water and related land problems. The general criteria used for proposal evaluation included: (1) scientific merit, (2) responsiveness to RFP, (3) qualifications of investigators, (4) originality of approach, (5) budget, and (6) extent to which Colorado water managers and users are collaborating.

Active NIWR projects and investigators are listed below:

Faculty Research

1. Assessing the Agronomic Feasibility of Partial and Full Season Hay Fallowing as Part of a Western Slope Water Bank, Joe Brummer, Colorado State University, $20,00 (104b)
2. Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts, John McCray, Colorado State University, $140,162 (104g)

Student Research (Faculty advisor in parenthesis)

1. Social Network Analysis Technique for Water Resources Management Workshop, Margaret Herzog (Labadie), Colorado State University, $4,500 (104b)

Internships

1. MOWS - Modeling of Watershed Systems, Steve Regan, USGS, $20,000, Michael Sanders (University of Colorado), Andrew Reimanis (Colorado State University)
2. WEBB – Water, Energy, and Biogeochemical Budgets, $40,219, Sydney Wilson (Colorado School of Mines)
3. CWCB Interns – Craig Godbout (Colorado State University), Elizabeth Mahon (Olin College of Engineering)

For more information on any of these projects, contact the PI or Reagan Waskom at CWI. Special appreciation is extended to the many individuals who provided peer reviews of the project proposals.

Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts

Basic Information

Title:	Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts
Project Number:	2011CO245G
Start Date:	9/1/2011
End Date:	8/31/2014
Funding Source:	104G
Congressional District:	D-CO7
Research Category:	Water Quality
Focus Category:	Water Quality, Hydrogeochemistry, Treatment
Descriptors:	None
Principal Investigators:	John E. McCray, Reed Maxwell

Publication

1. McCray, John, 2011, Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts, Colorado Water Institute Proposal, 38 pages.

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Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts

The following report summarizes the work performed under Subaward Number G-2914-1; PI: Dr. John E. McCray for the reporting period ending 14 March 2014.

1. *Research: Project Synopsis*
   The goal of the research funded under this subaward, is to understand the potential for disinfection byproduct formation and metal mobilization resulting from perturbations to the water and nutrient cycles in forested watersheds currently experiencing a severe mountain pine beetle epidemic. The subaward provides the means to add these analyses to the existing USGS research project being conducted in Rocky Mountain National Park, under the supervision of Dr. Dave Clow.

   During this reporting period, the following tasks were completed: (a) performed modeling of changes in metal mobility to supplement previous sequential extractions; (b) completed hydrologic flow path analysis using 2012 isotope data; (c) continued coordination and field sampling with Dr. Clow (USGS) and his field team; (d) began preliminary modeling of changing flow paths in impacted watersheds. The goal of the current analyses is to improve our understanding of the flow paths transporting carbon and metals to the streams, and if the MPB is impacting water sources and residence times in these high mountain systems. All anticipated fieldwork is completed for this project. The main focus of our research over the remainder of the project is to complete any isotope analysis and use hydrologic models to provide additional interpretation of the isotope results.

2. *Publications*
   Two papers first authored by Lindsay A. Bearup (funded by this subaward) were submitted during this reporting period. The first was accepted to *Nature Climate Change* and the second is currently in review at *Science of the Total Environment*. One additional paper on metal mobility was also second-authored by Lindsay Bearup, who contributed to analysis and writing. In addition, four conference presentations by PhD student Lindsay Bearup were published as abstracts. Finally, Professor McCray gave one invited talk (not published) to the Fulbright Commission and the US State Department in Chile last spring related to this project. The citations for these activities are provided below.

   <u>Journal papers</u>

   Bearup, LA, KM Mikkelson, JF Wiley, AK Navarre-Sitchler, RM Maxwell, JE McCray. Metal fate and partitioning in soils under bark beetle killed trees. *In review at Science of the Total Environment.*

Bearup, LA, RM Maxwell, DW Clow, JE McCray. (2014). Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. *Nature Climate Change*. doi: 10.1038/nclimate2198

Mikkelson, KM, LA Bearup, AK Navarre-Sitchler, JE McCray, JO Sharp. (2014) Changes in metal mobility associated with bark beetle-induced tree mortality. *Environmental Science: Processes & Impacts*. doi: 10.1039/C3EM00632H

Conference Presentations

Bearup, LA, RM Maxwell, C Penn, DW Clow, JE McCray. Connecting increased groundwater contributions to transpiration losses in bark beetle infested watersheds. Presented at AGU Fall Meeting; San Francisco, California, 9-13 December 2013.

Bearup, LA, KM Mikkelson, AK Navarre-Sitchler, RM Maxwell, JE McCray, JO Sharp. Metal Mobility in Bark Beetle-Infested Forests. Presented at GSA Annual Meeting; Denver, Colorado, 27-30 October 2013.

Bearup, LA, C Penn, RM Maxwell, DW Clow, JE McCray, JO Sharp. Unraveling the interconnection between hydrology and geochemistry in mountain pine beetle infested watersheds using stable isotopes and modeling. Presented at ModFlow and More; Golden, Colorado, 2-5 June 2013.

Bearup, LA, RM Maxwell, DW Clow, JE McCray, JO Sharp. Interpreting watershed scale hydrological alterations from widespread mountain pine beetle infestation using stable isotopes. Presented at Hydrology Days; Fort Collins, Colorado, 25-27 March 2013.

McCray, J.E., Bearup, L.A., Mikkelson, K.M., Maxwell, R.M., 2013. Water quality and quantity impacts of the mountain pine beetle infestation in the Rocky Mountain West, Presented at the Fulbright Commission to Chile and the U.S. State Department, Santiago Chile, March 2013, (*Invited*).

3. *Information Transfer Program*
   Lindsay Bearup participated in and helped conduct a workshop to communicate science findings related to MPB impacts on water resources to stakeholders and identify stakehold priorities at the 2013 RMSAWWA/RMWEA joint annual conference. Also see journal papers and public presentations listed above.

4. *Student Support*
   This subaward provided funding for one PhD student during this reporting period.

5. *Student Internship Program* – N/A

6. *Notable Achievements and Awards –*

    a. Isotope analysis of flow path perturbation paper accepted for publication.
    b. Metals paper submitted and under review.
    c. 4 conference abstracts published at national conferences
    d. Professor McCray gave an invited talks using material from this project to the Fulbright Commission of Chile and the U.S. State Department, in Santiago Chile in March 2013.
    e. Professor McCray earns Fulbright Technical Specialist Award to visit Universidad de Concepcion in Chile for his expertise in mountain hydrology and water quality.
    f. 2013 Field Season completed with water samples collected for analysis.
    g. Completed hydrologic flow path analysis based on mixing models from 2012 isotope data.

Reconstructing a Water Balance for the San Luis Valley: Streamflow Variability, Change, and Extremes in a Snowmelt Dominated Internal Drainage Basin

Basic Information

Title:	Reconstructing a Water Balance for the San Luis Valley: Streamflow Variability, Change, and Extremes in a Snowmelt Dominated Internal Drainage Basin
Project Number:	2012CO262B
Start Date:	3/1/2012
End Date:	8/31/2013
Funding Source:	104B
Congressional District:	4th
Research Category:	Climate and Hydrologic Processes
Focus Category:	Irrigation, Surface Water, None
Descriptors:	
Principal Investigators:	Steven Fassnacht

Publication

1. Venable, Niah B. H., Reconstructing a Water Balance for North Crestone Creek: Streamflow Variability and Extremes in a Snowmelt Dominated Internal Drainage Basin. Colorado Water Newsletter, Volume 30 - Issue 5 (September/October 2013), Colorado Water Institute, Colorado State University, Fort Collins, CO, 5 pages.

Reconstructing a Water Balance for the San Luis Valley: Streamflow Variability, Change, and Extremes in a Snowmelt Dominated Internal Drainage Basin

Niah Venable, PhD Student, Watershed Science, Colorado State University

Faculty Advisor: Steven Fassnacht

This report summarizes work to date on the CWI/NIWR State Program Project Award 2012CO262B. The project PI is Dr. Steven Fassnacht, Associate Professor of Snow Hydrology, and the student researcher is Niah Venable, a PhD student in the Watershed Science program at Colorado State University. The project originally began on March 1, 2012, with a completion date of March 1, 2013, but due to ACMS field research fellowship duties in Mongolia and fall semester GEOL 122 instructor commitments for Venable, the completion date was extended to August 1, 2013.

Research Project Objectives:

- Assess the natural variability, extremes, and changes in streamflow to examine how natural systems in a closed basin function over longer periods and provide insight into the sustainability and further development of dry regions and to help define possible impacts of future change.

- Compare a modern water balance and streamflow of a catchment draining into the basin with that reconstructed from paleo-climatic data derived from tree-rings.

Tasks Completed:

- Preliminary project work was initiated in Fall of 2012. Additional references and data sources were identified and the research plan for the first half of the project was finalized.

- In the Spring semester of 2013, tree-ring records from the International Tree-Ring Data Bank (ITRDB) were screened for suitability and 9 sites within about 100 km of Crestone Creek in the San Luis Valley were selected for analysis.

- The residual site chronologies were used as potential predictors of streamflow over a period 300 years longer than the observed flow record at that creek. Stepwise regression was used to develop the model. Three chronologies located to the south and east of the watershed and extending from years 1636 to 2000 provided a best fit to the streamflow record, with a final model R^2 of 0.69. Other statistical tests also confirmed the robust nature of the reconstruction.

- The results of the analysis compare favorably to previous analyses performed by Woodhouse *et al*., (2004). Her reconstructions of flow in Saguache Creek, and the Rio Grande at Del Norte, both in the San Luis Valley show similar trends in wet and dry conditions and have similar statistical results and model fits.

Student Support:

This award provided support for the PhD student Venable, and will continue to provide critical support for her to complete project work over the next few months.

Publications:

Venable, N. B. H., Brown, P.M., Fassnacht, S. R., "Streamflow to Nowhere: Long-term Variability of Flow Into the San Luis Closed Basin, CO, USA."Poster Presentation, 33rd Annual American Geophysical Union Hydrology Days, Colorado State University, Fort Collins, CO, March 27th, 2013.

Talk prepared for the Spring Geosciences Advisory Council Student Presentations which were postponed to the Fall semester 2013 due to poor weather conditions and other departmental schedule changes.

Remaining Work Plan (subject to revision):

- Further examine flow regimes, extremes and long-term variability at Crestone Creek via completed flow reconstruction(s).

- Better characterize Crestone Creek area through field investigations of flow conditions, land use/land cover, etc.

- Analyze data and create modern water balance (Thornthwaite model) using PRISM inputs and observed flow (WY 1948-2012).

- Reconstruct precipitation for Crestone watershed using stepwise regression process on original pool of tree-ring chronologies. PRISM data will be used for calibration of the model.

- Examine feasibility/create a paleo-water balance using reconstructed precipitation and possibly temperatures (NOAA/ITRDB products).

- Compare results to other modeling efforts and basin analyses as appropriate.

Project Timeline (details subject to revision):

- Fieldwork, May 10th-13th, 2013.
- Modern water balance modeling, May 22nd-25th.
- Precipitation reconstruction, May 27th-May 31st.
- Paleo- water balance modeling, June 1st-6th.
- Reporting draft, June 9th-11th.
- Meet with Fassnacht to discuss draft and further project work, June 12th-14th.
- Final project report (draft), July 1st. Submission to CWI soon after?!
- Further incorporation of additional project work and results to conference proceedings/papers/dissertation proposal through end of 2013.

Reference: Woodhouse, C.A., et al. (2004) TreeFlow Colorado Streamflow Reconstructions. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2004-029. NOAA/NGDC Paleoclimatology Program, Boulder CO, URL http://treeflow.info/index.html

Assessing the agronomic feasibility of partial and full season hay fallowing as part of a Western Slope Water Bank

Basic Information

Title:	Assessing the agronomic feasibility of partial and full season hay fallowing as part of a Western Slope Water Bank
Project Number:	2013CO290B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	2nd
Research Category:	Biological Sciences
Focus Category:	Agriculture, Conservation, Irrigation
Descriptors:	None
Principal Investigators:	Joe Brummer

Publications

There are no publications.

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Assessing the Agronomic Feasibility of Partial and Full Season Hay Fallowing as Part of a Western Slope Water Bank

The following report summarizes the work performed under Project Number 2013CO290B; PI: Dr. Joe Brummer for the reporting period ending 9 May 2014.

1. *Research Project Synopsis*

   The Colorado River is managed under several acts and federal laws dating back to The Colorado River Compact of 1922. Over the years, numerous acts, agreements, and treaties have altered the way the river is managed. The act of 1922 separated the seven states involved into the upper basin and lower basin. Each basin is allowed 7.5 million-acre feet (MAF) of the river's annual flow. In 1944, a treaty stated that Mexico was also entitled to receive 1.5 MAF. Colorado legally utilizes just over 50% of the 7.5 MAF allocated to the upper basin. The western slope of Colorado alone, accounts for close to 1.3 MAF of the rivers annual flow. Although insufficient amounts of water were not a critical factor in the past, in recent years, a combination of drought, increased development, and growing populations have increased pressure on river resources. Since the upper basin must legally send 7.5 MAF of water to the lower basin, water shortages are a growing concern. One possible approach to this issue that is gaining interest is a water banking system where water would be taken out of agricultural production to free up water to meet compact obligations and/or be leased for other uses.

   The objective of this project is to assess the agronomic feasibility of partial and full season fallowing of hayfields on the Western Slope of Colorado. The goal is to provide enough information for local hay producers to confirm if this water banking approach is worth pursuing. More specifically, this project is intended to determine the impacts to forage yield, quality, and associated recovery period for fallowed and partially fallowed hayfields on the Western Slope.

   During the spring of 2013, three alfalfa and four grass hayfields were located throughout the Western Slope including the Yampa River basin, the Upper Gunnison River basin, the Upper and Lower Colorado River basins, and the San Juan/Dolores River basin. Alfalfa sites were located at the Kehmeier Farm near Eckert, CO, the Western CO Research Center near Fruita, CO, and the Southwestern CO Research Center near Yellow Jacket, CO. Grass sites were located at the Carpenter Ranch near Hayden, CO, the Fetcher Ranch near Steamboat Lake, CO, the Trampe Ranch near Gunnison, CO, and the Blue Valley Ranch near Kremmling, CO. Treatments on the alfalfa sites consisted of fully irrigated (control), stop irrigating after the first cutting, and stop irrigating after the second cutting. One alfalfa site also included a complete fallow (no irrigation) treatment. Only 2 treatments were implemented at the grass sites: fully irrigated (control) paired with a full season fallow, or non-irrigated treatment.

Yield reductions at the season-long fallowed grass sites ranged from 24% to 70%. Potential crop ET for the season ranged from 16.5 to 25.6 inches and precipitation ranged from 3.22 to 6.74 inches. Yield reductions at the alfalfa sites for the treatment where irrigation was stopped after the second irrigation ranged from 0% to 54%, while in the areas where irrigation was stopped after the first irrigation, reductions ranged from 42% to 71%. The complete fallow treatment, only implemented at the Yellow Jacket site, showed a 77% yield reduction. Potential crop ET at the alfalfa sites was between 38.3 to 41.6 inches and precipitation ranged from 3.93 to 9.28 inches.

In 2014, grass plots that were fallowed will be returned to normal irrigation while the alfalfa plots will receive the same partial irrigation treatments. Identical data will be collected and analyzed to determine the effects of the previous year's treatments on the hay crops and soils. Effects to hay crop yields, quality, possible recovery period, increase in weeds, decrease in desirable forages or plant density, and changes in soil nutrients will all be analyzed to help determine if using water from hayfields for a water banking system has potential for hay producers on the Western Slope.

2. *Publications*

Jones, L.P., J.E. Brummer, C.H. Pearson, and A.F. Berrada. 2013. Agronomic responses to partial and full season fallowing of alfalfa and grass hayfields. Western PhytoWorks (Calvin H. Pearson, ed.), Newsletter (winter edition) of the Western Colorado Research Center, Agricultural Experiment Station, Colorado State University, Fort Collins, CO. 2p.

3. *Information Transfer/Outreach*

An update presentation entitled "Agronomic Responses to Partial and Full Season Fallowing of Alfalfa and Grass Hayfields" was given at the following meetings and workshops in 2013: Routt County Hay Days (July 10), Compact Water Bank Meeting sponsored by the Colorado River District (Oct. 11), Colorado Water Institute Advisory Board Meeting (Nov. 15), and the Water Bank Working Group Meeting (Dec. 3).

4. *Student Support*

Funding from this project supported one master's level student (Lyndsay Jones) during this reporting period.

5. *Notable Achievements*

   a. Three alfalfa and four grass sites were selected for study.
   b. Soil, plant, and evapotranspiration data were collected for the 2013 field season.
   c. Soil and plant yield data has been analyzed. Forage quality analyses are ongoing.
   d. One newsletter article was published to let producers on the Western Slope know of this project and its potential benefits.
   e. Four presentations were given in 2013 to update interested parties as to the objectives and preliminary results of this project.

Information Transfer Program Introduction

Requests from the Colorado legislature and key water agencies to facilitate and inform basin-level discussions of water resources and the state water plan emphasized the role Colorado Water Institute plays in providing a nexus of information. Some major technology transfer efforts this year include:

- Providing training for Extension staff in various water basins to help facilitate discussions of water resources
- Encouraging interaction and discussion of issues between water managers, policy makers, legislators, and researchers at conferences and workshops
- Publishing the bi-monthly newsletter, which emphasizes water research and current water issues
- Posting and distributing all previously published CWI reports to the web for easier access
- Working with land grant universities and water institutes in the intermountain West to connect university research with information needs of Western Water Council, Family Farm Alliance, and other stakeholder groups
- Working closely with the Colorado Water Congress, Colorado Foundation for Water Education, USDA-NIFA funded National Water Program to provide educational programs to address identified needs

Social Network Anlysis Technique for Water Resources Management Workshop

Basic Information

Title:	Social Network Anlysis Technique for Water Resources Management Workshop
Project Number:	2013CO289B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	4th
Research Category:	Social Sciences
Focus Category:	Education, None, None
Descriptors:	None
Principal Investigators:	John W. Labadie

Publications

There are no publications.

Social Network Analysis Techniques for Water Resources Management Workshop

Margaret T. Herzog, Department of Civil and Environmental Engineering, Colorado State University
Faculty Advisor: John W. Labadie
Co-Advisor: Neil S. Grigg

Shared Learning Environment at CSU. Photo by Kim Hudson

Study: Develop an introductory workshop in social network analysis techniques employed in water resources management and research.

Methods: Create SNA workshop materials to teach diverse participants in various formats to test effectiveness.

Results: The SNA workshop should be expanded into a semester-long course to support more complex, multi-dimensional problem-solving.

The Problem

Water resources issues today rarely have a clear technical solution. Competing water demands, water quality regulatory compliance, environmental flow needs, and sediment transport all contribute to the complexity of water problems. Fragmented rule-making authority spans federal, state, county, and local jurisdictions. Public, private, and leased lands intermingle, making landscape-scale wildfire, flood, and drought mitigation planning more challenging. Uncertainty in pollutant sources and their fate and transport makes it difficult to determine the most appropriate technical measures to improve water quality. Even when pollution sources and pathways are generally known, competing science and contrasting results may lead to disagreement over which corrective measures to employ.

How SNA Training Can Help

Social network analysis (SNA) is a method for studying relationships and transactions between people, organizations, or other entities. By helping to analyze stakeholders involved in water and landuse decisions, their competing interests, and underlying values, SNA may help resolve complex water issues. SNA can be used to plan stakeholder engagement processes to work towards shared understanding. Robust coalitions may then be built to address complex issues as a team. Knowledge, resources, and funds can be pooled toward more creative, longer-term solutions than any one group could accomplish on its own. Regulatory effects may also be better

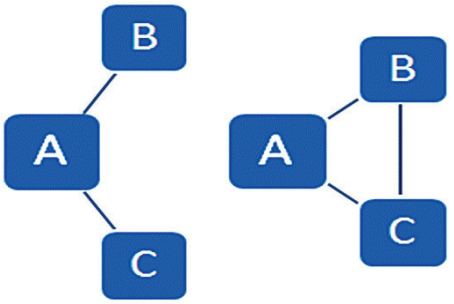

Figure 1. *Triadic closure: Friend A introduces Friends B & C, creating a relationship triad.*

aligned to reduce the economic cost of compliance.

SNA simplifies study of relationships as nodes (entities) connected with links (relationships). Software has been developed to manage data in a matrix format to permit statistical analysis of social network structural characteristics. This helps determine which nodes are the most important ones in each cluster, which nodes serve as brokers between clusters, and where gaps exist that may need to be bridged.

For example, one of the simplest social network concepts is the relationship that often develops among three friends. One friend may be friends with two others, who don't know each other yet. However, over time it's likely they'll be introduced and become acquainted, and maybe even start doing things all together.

This happens often in reality because friends typically have much in common, so their friends tend to be similar, too. This makes it easy to create a group of likeminded individuals. At the group level, different environmental groups may have a lot in common, so they may also meet together at annual events or through community volunteer efforts. Oil and gas companies, though competitors, may also get together at trade shows and professional events. However, oil industry and environmental groups often have opposing interests and tend to avoid one another, unless facing off in a courtroom or other public proceedings. This tendency to conglomerate in groups of like-minded community and business interests further complicates the issue of fragmented regulation and land management. In contrast, brokers that can bridge these different interests toward mutual benefit can create more dynamic structures. As more groups bridge the divides, information and resources have more ways to flow, and transactions can be executed with fewer intermediaries. Stronger, community-wide relationships may also permit more rapid, coordinated response to unexpected events. By creating more cohesive groups more strongly tied to a wider variety of other organizations, such improved core-periphery social structure can support more effective water and natural resource management. Consciously focusing on this goal is difficult without formal analytical methods, which SNA provides. By training more technical professionals in SNA techniques, they may be able to more systematically foster the antecedents necessary for more effective, joint decision making. Technical professionals will also learn that actively seeking a diversity of knowledge about complex social-ecological systems from community members will improve their own ability to plan and design civil projects for systems-wide improvement.

Methods

To achieve improved cooperation, it is important for technical disciplines to learn new strategies like SNA. However, no CSU course in engineering, agriculture, or natural resources includes SNA methods. Therefore, after extensive SNA methods research, the utility of SNA was tested in a watershed-scale nutrient management case study. Then results were used to create a half-day workshop with support of CSU TILT instructional designers and research-based instructional methods. In the fall of 2013, two offerings of the SNA workshop were provided to interested Colorado State University (CSU) students, faculty, and community members. A few experts in SNA-related application were invited to each session to provide more real world insight. In the spring of 2014, SNA training techniques were further tested in three additional formats. First, SNA results were provided in a 20-minute segment of a three-person expert panel on SNA applications. Next, a shorter version of the half-day workshop was presented during one class period of a communications course for Metro Denver, One World-One Water (OWOW) undergraduate students. Finally, a full-day introduction to SNA software methods was provided to CSU Natural Resources, Conservation Leadership through Learning (CLTL) program students.

Results

About 30 participants attended the two, four-hour fall seminars rather evenly divided among engineering, agriculture, natural resources, and other technical disciplines. Twenty people attended the spring panel, and 11 OWOW and 19 CLTL students attended their sessions. Thus, over 80 people received training through this study grant. Most came to solve work-related or community participation problems or for research or personal interests.

Having the fall workshops set around a large, oval table was more conducive to shared learning than the spring classroom sessions. Attendees enjoyed high interaction, guest speakers, and developing greater consciousness of sociology concepts and social network features. Two common takeaways were focusing on bridging groups and encouraging constant, incremental structural improvement in practice.

One frequent comment was a desire to learn SNA software, which could not be introduced in the half-day session. Therefore, the SNA workshop was expanded to a full-day session for CSU CLTL students to try to include software training. Students could select from one of four demos to explore for each collaborative they had studied in class in previous weeks. Although the software introduction was not as effective as hoped, lessons learned by the group can be applied to make future software sessions more effective.

Discussion

As an initial SNA introduction, a small group session format was quite successful. Conducting the SNA introduction around a central meeting table and including a shared meal seemed to be the most effective shared learning environment.

SNA workshop participants agreed that SNA was a useful framework to improve management of complex social-ecological systems. However, there was less agreement that employing SNA software to more systematically analyze relationships and transactions would be worth the learning curve. Perhaps, if training were provided in shorter sessions throughout a college semester, students could more easily digest each new concept. SNA software could then be introduced in a more stepwise fashion as each new SNA concept was introduced.

To Learn More About SNA

If you are interested in SNA, please visit the SNA workshop companion website at sna.wateractionnetwork.org for online software, textbooks, and course links, or to schedule an SNA workshop for your class, organization, or community group.

Above Figure: *Student facilitator teaching SNA workshop at CSU, October 29, 2013.*
Photo by Kim Hudson
Right Figure: *Example Resource Coalition exhibiting mature core-periphery network structure.*

Technology Transfer and Information Dissemination

Basic Information

Title:	Technology Transfer and Information Dissemination
Project Number:	2013CO292B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	4th
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Reagan M. Waskom

Publications

1. Colorado Water Newsletter, Volume 30 - Issue 2 (March/April 2013), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 33 pages.
2. Colorado Water Newsletter, Volume 30 - Issue 3 (May/June 2013), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 41 pages.
3. Colorado Water Newsletter, Volume 30 - Issue 4 (July/August 2013), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 37 pages.
4. Colorado Water Newsletter, Volume 30 - Issue 5 (September/October 2013), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 33 pages.
5. Colorado Water Newsletter, Volume 30 - Issue 6 (November/December 2013), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 37 pages.
6. Colorado Water Newsletter, Volume 31 - Issue 1 (January/February 2014), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 41 pages.
7. Neupauer, Roseanna M., November 2013. Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping. Colorado Water Institue, Colorado State University, Fort Collins, CO. 16 pages. www.cwi.colostate.edu/publications/CR/225.pdf
8. Waskom, Reagan M., December 2013. HB12-1278 Study of the South Platte River Alluvial Aquifer. Colorado Water Institute, Colorado State University, Fort Collins, CO. 207 pages. www.cwi.colostate.edu/southplatte/files/report/HB1278%20Final%20Report.pdf
9. Brown, Jennifer, Ed., October 2013. Proceedings, South Platte Forum 24th Annual, "The Ins and Outs of the South Platte Basin". Colorado Water Institute, Colorado State University, Fort Collins, CO. 24 pages. www.cwi.colostate.edu/publications/IS/115.pdf

Colorado Water Institute Activities

- Water Tables 2014, The Colorado Water Doctrine, January 30, 2014
- Dialogue instead of Debate, Setting the Tone Through HB12-1278 Community Meetings and Website Input, Colorado Water Institute, October 2012
- Advances in Water Research, Interdisciplinary Water Resources Seminar, Spring 2013
- *Colorado Water*, Colorado Water Institute, March 2013-February 2014

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SAVE THE DATE

Water Tables 2014

January 30, 2014

David Schorr, Tel Aviv University Faculty of Law
Author of: *The Colorado Water Doctrine*
Water Rights, Corporations, and Distributive Justice on the American Frontier

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Dialogue instead of Debate

Setting the Tone Through HB12-1278 Community Meetings and Website Input

MaryLou Smith, Policy and Collaboration Specialist, Colorado Water Institute

Community meetings and a dedicated HB12-1278 website allow for community input and interaction with study findings.

Can thoughtful dialogue take precedent over polarized debate on a subject as contentious as the operation of alluvial wells in conjunction with surface water on the South Platte River? Believing that it could, the Colorado Water Institute (CWI) at Colorado State University set about to provide such an opportunity through community meetings and a process for website input as part of its HB12-1278 study.

Colorado House Bill 12-1278 was passed in 2012, authorizing the first comprehensive groundwater study in the state since the landmark study of 1968 that preceded the "Water Right Determination and Administration Act of 1969." The 1969 act was Colorado's attempt to bring groundwater under the same prior appropriation system as surface water rights. The HB12-1278 study was authorized by the legislature, in part, to shed light on whether the strict augmentation of water supplies now required of those who use wells is actually over-augmenting the alluvial aquifer, causing damage from high water tables.

Knowing that the issue is contentious and polarizing, CWI set about to design and implement a process to inform stakeholders and the public about its study and to encourage them to bring creative thinking to the issue through two means—community meetings and an opportunity for input via a dedicated HB12-1278 website.

Community Meetings

January meetings in the communities of Longmont, Gilcrest, and Sterling drew significant audiences. Basic information about the HB12-1278 study and how it is being conducted was followed by a well-received animated human history of the South Platte River and its alluvial aquifer, and the events that led up to the current issues under study. Joe Frank and Robert Sakata, two state water leaders often seen to be on opposite sides of the issue, engaged in a facilitated-dialogue highlighting their respective views, as a means of modeling for the audience the difference in dialogue and debate. Their tone—listening to and exhibiting curiosity about the other's views—set the tone for the public input part of the program. The use of cards with lead statements for members of the audience to complete ahead of speaking, assisted in promoting thoughtful expression of values and beliefs. Those statements included such leads as "I am concerned that…", "I need more information to help me understand," and "We need to preserve…." Different perspectives were shared, but the technique did not lend itself to diatribes and accusations; instead, it allowed for an even-handed expression of various interests.

On a South Platte tour in October, 2012, Governor Hickenlooper said we need more knowledge of the aquifer, and cooperation on all sides moving forward. He said "Smart people willing to compromise can figure this stuff out."
Courtesy of The Greeley Tribune

Stakeholder Input on the Website

In addition to the opportunity to share views at the January community meetings, stakeholders were given the means for sharing their views anonymously via the HB12-1278 website. More than 300 individual statements were contributed and can be viewed online at http://www.cwi.colostate.edu/southplatte/dialogue.shtml. The website also gave those who have experienced adverse effects from high groundwater levels the opportunity to register the specifics of their experience as a means of input to the study team.

Reagan Waskom, director of the Colorado Water Institute and the HB12-1278 study, expressed that the hope of the approach taken with the community meetings and

the website stakeholder input was to "raise the level of conversation from contentious debate to respectful dialogue—an important role of a land-grant university."

Website as an Educational Tool

The HB12-1278 website also serves as a means to educate the public about the multitude of issues surrounding the South Platte River and its alluvial aquifer as well as the experiences of other places with similar issues.

- A resources page includes presentations made at a conference on the South Platte issues in November 2012 as well as a number of previous studies, including the 1967 Bittinger-Wright study leading up to the 1969 Act.
- Links to other pertinent websites are provided, including a link to the Colorado Division of Water Resource's groundwater page and the Groundwater Atlas of Colorado by the Colorado Geological Survey.
- A Google Earth flyover of the South Platte River gives the public a chance to take a virtual trip down the South Platte with commentary pointing out major canals and diversions, stream gages, recharge structures, and more.
- A You-Tube video can be accessed on the website. This animation is called Working the Waters: A Brief Human History of the South Platte River and its Alluvial Aquifer, and gives viewers a practical guide to understanding the background of today's issues.
- At the conclusion of the study, the website houses the report to the legislature (the full report as well as an executive summary version) and all the appendices provided as a part of the report.

John Stulp, Reagan Waskom, and Bob Sakata listen as Glenn Fritzler, agricultural producer near LaSalle, shares his thoughts on the South Platte groundwater issue at one of three HB1278 Community meetings.
Photo by Stephen Smith

Aerial view of the South Platte River northeast of Kersey, Colorado.
Photo by Bill Cotton

Spring 2013
Interdisciplinary Water Resources Seminar

Sponsored by: CSU Water Center, USDA-ARS, Civil and Environmental Engineering, Forest and Rangeland Stewardship, and the School for Global Environmental Sustainability

Theme: Advances in Water Research

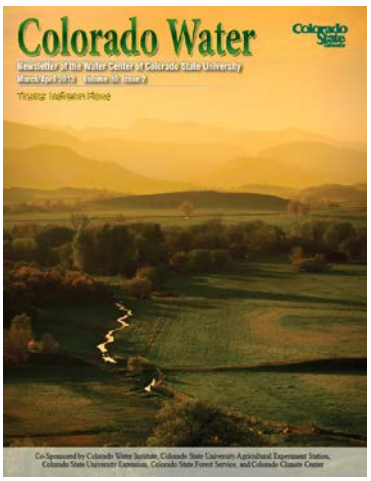
Wednesdays From 12:00 to 1:00 PM

February 6 **LSC Room 208**	**Joe Ryan & Mark Williams - University of Colorado** **Economic and Environmental Trade-Offs of Unconventional Oil and Gas Extraction**
February 13 **LSC Room 226**	**Holly Barnard - University of Colorado** **Ecohydrology of Forested Catchments: Investigations of Transpiration and Subsurface Hydrology**
February 20 **LSC Room 208**	**Suzanne Pashke - U.S. Geological Survey** **Simulation of Groundwater Movement in the Denver Basin Aquifer System**
February 27 **LSC Room 208**	**Thijs Kelleners - University of Wyoming** **Measurement and Modeling of Soil-Plant-Atmosphere Water, Heat, and Carbon Fluxes in Cold Regions**
March 6 **LSC Room 208**	**Dave Williams & Scott Miller - University of Wyoming** **Hydrological Consequences of Woody Plant Encroachment into Floodplain Grasslands**
March 13 **LSC Room 208**	**Levi Brekke - U.S. Bureau of Reclamation** **Evaluating the Relevance, Reliability, and Applicability of CMIP5 Climate Projections for Water Resources and Environmental Planning**
March 20	**No Seminar** **Spring Break**
March 27	**No Seminar** **Hydrology Days Mar. 25-27; www.hydrologydays.colostate.edu**
April 3 **LSC Room 208**	**Stephen Burges - University of Washington** **Hydrological Variability, Reservoir Storage, and Water Supply Reliability**
April 10 **LSC Room 208**	**Michael Ronayne - Colorado State University** **Modeling Coupled Conduit and Matrix Flow in Karst Aquifers**
April 17 **LSC Room 211E**	**Mark Eiswerth - University of Northern Colorado** **The Joint Impact of Drought Conditions and Media Coverage on the Colorado Rafting Industry**
April 24 **LSC Room 228**	**Lee Sommers - CSU Agriculture Experiment Station** **Reflections on Water Research**
May 1 **LSC Room 208**	**Reed Maxwell - Colorado School of Mines** **Towards a Complete Description of the Hydrologic Cycle: Large Scale Simulations with Parallel Integrated Models**

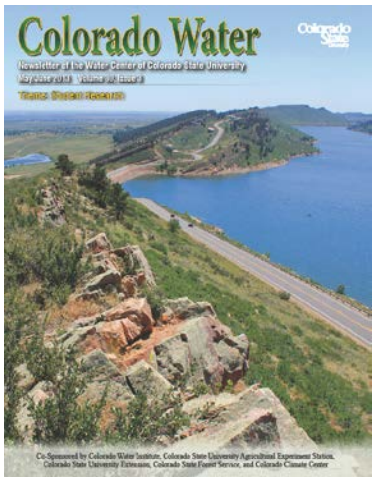
* Room may be changed if needed. Check weekly announcements.

All interested faculty, students, and guests are encouraged to attend.

For more information, contact Reagan Waskom at reagan.waskom@colostate.edu or visit the CWI web site.



Colorado Water
Volume 30, Issue 2
Instream Flows



Colorado Water
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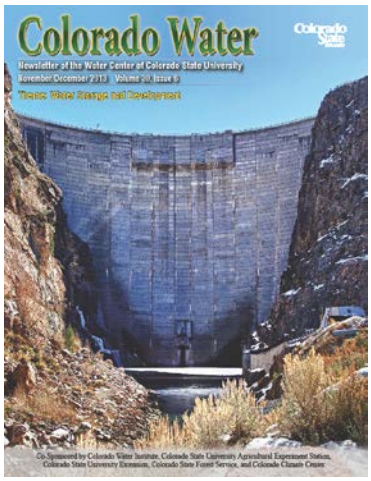
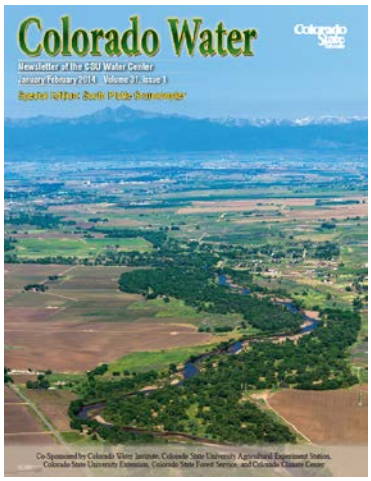
Student Research

Colorado Water
Volume 30, Issue 4
Agricultural Water

Colorado Water
Volume 30, Issue 5
Water Technology and Innovations



Colorado Water
Volume 30, Issue 6
Water Storage and Development



Colorado Water
Volume 31, Issue 1
South Platte Groundwater

Other Colorado Water Institute Research and Activity Reports

- Modeling the Influence of Conjunctive Water Use on Flow Regimes in the South Platte River Basin Using the SPDSS Groundwater Flow Model, Domenico Baú, CWCB

- Determination of Consumptive Water Use of Corn in the Arkansas Valley of Colorado, A. A. Andales, CWCB

- Investigation of the Effects of Whitewater Parks on Aquatic Resources in Colorado, Brian P. Bledsoe, CWCB

- Agricultural Economics and Water Resources: Methods, Metrics and Models-A Specialty Workshop, Perry Cabot, CWCB

Modeling the Influence of Conjunctive Water Use on Flow Regimes in the South Platte River Basin Using the SPDSS Groundwater Flow Model

Domenico Baú, Department of Civil & Environmental Engineering, Colorado State University

Using the South Platte Decision Support System groundwater flow model, researchers modeled 2,500 square miles of the South Platte basin with the long-term goal of evaluating the model for capabilities, strengths, and weaknesses.

The South Platte Decision Support System (SPDSS) Alluvial Groundwater Model was developed by CDM Smith on behalf of the Colorado Water Conservation Board (CWCB) during the period 2003-2013. Its main objectives included improving our understanding of the regional flow regime and providing a tool that may assist stakeholders in the evaluation and planning of water resources of the regional aquifer system. The SPDSS modeled area is around 2,500 sq. miles, and the simulation period spans from 1950 to 2006. A modified version of MODFLOW, a widely used U.S. Geological Survey finite-difference groundwater flow model, was developed by CDM Smith to simulate historical fluxes into and out of the South Platte groundwater system.

The long-term goal of this project is to provide the CWCB with an independent evaluation of the SPDSS groundwater flow model, highlighting model capabilities, strengths, and weaknesses. The activities carried out at CSU during the first year consisted of a thorough examination and visualization of the data included in the input files developed to construct the aquifer model, with comments regarding the functioning of the model. In addition, preliminary model runs were performed to gain insight into the tool and assess its general capabilities. In these runs, the model was used to simulate some hypothetical scenarios, in which historical well extractions and injections are reduced and increased in order to verify the responses of the models for water levels, stream-aquifer intra-flux, and evapotranspiration. The goal of these preliminary runs was to assess the numerical robustness and stability of the model, as well as create expertise and provide training opportunities to improve the human capital and skills required for using the SPDSS groundwater model.

Model Input Files

Table 1 lists 14 MOFLOW input files that describe structural, parametric, and mass fluxes of the simulated region. The structural input files include the domain discretization, temporal discretization, time steps, boundary conditions, and initial boundary conditions. The input files also include information about the geometry of the aquifer (ground surface and bedrock elevations) and hydrogeological parameters (conductivity, specific storage, etc.). Water fluxes in and out of the alluvial aquifer are described by the well, stream, recharge, evapotranspiration packages.

Figure 1 shows the locations of the wells used in the model. While several wells represent actual groundwater pumping, a large portion of them is used to represent inflow or outflow from the Denver Basin aquifers that constitute the bedrock base for the alluvium. Another relatively large number of wells is also used to represent prescribed lateral-flow boundary conditions.

The total number of wells activated varies over stress periods, but remains relatively constant. For example, the number of wells activated for the last stress period (December 2006) is equal to 52,363.

While lumping together actual groundwater well pumping, flux exchange across the bedrock, and lateral flow boundary conditions does not affect the accuracy of the model, it may limit the ability of other users to modify the input files, for example to simulate different management scenarios of well pumping. In addition, such a practice makes it difficult to interpret mass balance results.

The map presented in Figure 2 shows the location of injection, extraction, and inactive wells in the month of June 2006. From Figure 2, it possible to observe that the Denver aquifer withdraws water from the alluvium, while water is provided to it through most of the lateral boundary. Figure 3 provides a map of the basin with the location of the monitoring wells mentioned above.

Output Files

Table 2 lists six MODFLOW output files that describe the SPDSS groundwater model results, which include spatial-temporal groundwater level distributions, cell-to-cell water budget and mass fluxes in and out of the region, and stream stage at each reach. A post-processing step is required to analyze the cell-to-cell budget file in order to summarize system mass balance at each time step. The prescription of the output data to be printed out is controlled using the P5_tr.oc file. In particular, this file specifies the times at which the output

is saved and the format, either binary or ASCII, with which it is produced.

Simulated Mass Balance

The model output provides a cell-to-cell flow budget for all prescribed stress periods. These results demonstrate that the numerical solution obtained by MODFLOW is globally accurate. The most important observation that can be made from the mass balance output relates to the components of aquifer recharge, aquifer discharge into the stream network, and extraction wells. In general, aquifer recharge progressively increases through the growing season, and aquifer discharge into streams is shown to decrease until the month of June and increase in the second half of the year. These results can be explained by observing that there is a gradual increase in well extraction rates during the growing season. However, this is a qualitative conclusion, since well extraction accounts not only for groundwater pumping, but also for exchange flows of water with the aquifer across the lateral boundary and the portion of the lower boundary where it connects with Denver Basin's bedrock aquifers.

Data included in the file P5_tr06.ccf have been used to derive time-series profiles for the period 1950-2006 on the water budget components. These "hydrographs" are compared to the corresponding results obtained under different conditions of well pumping.

Scenarios for Modified Well Pumping Conditions

To test the numerical stability and robustness of the SPDSS groundwater model and, at the same time, gain insight into its ability to simulate changes in hydrological and anthropogenic stress conditions, a number of additional hypothetical simulation scenarios are considered. In these scenarios well injection and extraction rates as prescribed in the baseline simulation are modified by: reducing extraction rates by 20 percent (Scenario 1); increasing extraction rate by 20 percent (Scenario 2); reducing injection rates by 20 percent (Scenario 3); and increasing injection rates by 20 percent (Scenario 4). These hypothetical scenarios are thus compared to the baseline conditions. In Scenario 1, where well extraction rates are reduced by 20 percent (see the green-line profiles), there is an overall increase in aquifer storage, along with an increased flow out of the aquifer across general boundary condition grid cells. Recharge volumes do not change since in these simulations, recharge conditions are left unchanged and therefore are not affected by varied conditions of pumping. The volume of water discharged from the aquifer in the stream network is decreased.

Table 1. *Input Files for the SPDD groundwater model*

No.	File Type	File Name	Description
1	DIS	P5_tr_mod_20100729.dis	Discretization package
2	HED	P5_tr06_stable.hed	Initial head file
3	BA6	P5_tr.ba6	Basic package
4	LPF	P5_tr_run.lpf	Layer property flow package
5	SFR	sfr_output_tr_por_20110608_90ke.sfr	Stream flow package
6	WEL	P5_SPDSS_TR_WEL_MODFLOW_20100812_por_mask_s5.wel	Well package
7	OC	P5_tr.oc	Output control package
8	RCH	RCH_Full_POR_20090428.rch	Recharge package
9	PCG	P5_tr.pcg	Preconditioned conjugate gradient solver
10	GMG	p5.gmg	Geometric multigrid solver
11	GHB	P5_tr_20110616.ghb	General head boundary package
12	ETS	output_ets_50_to_06_20111219.ets	Evapotransportation package
13	GGE	gage_20100521.gge	Stream gage locations
14	HOB	HOB_clean_valid20110606.hob	Head observation package

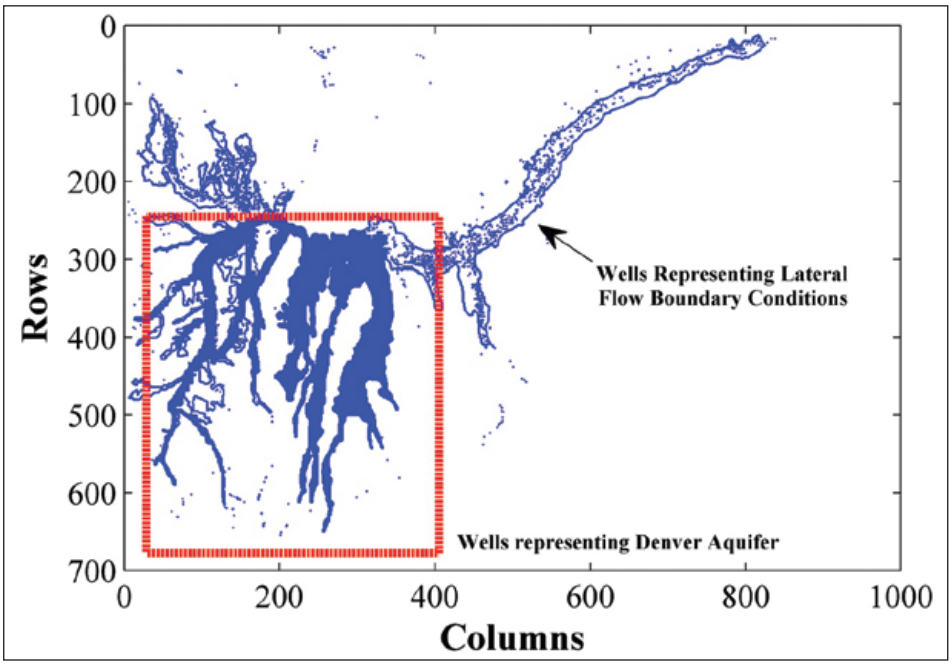


Figure 1. *Wells Locations and Boundary Conditions*

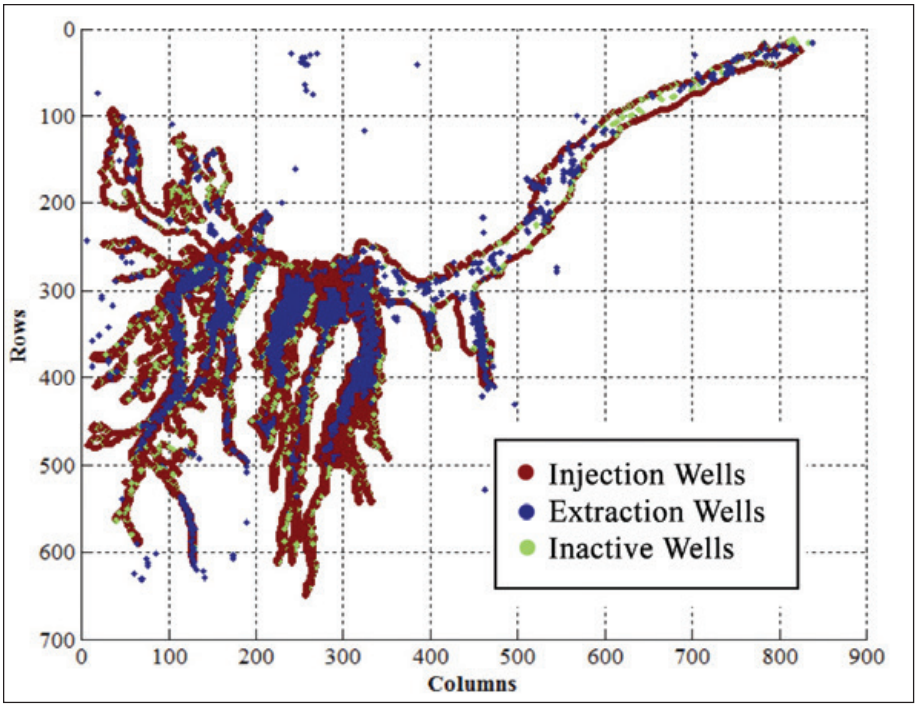


Figure 2. *Location of injection, extraction, and inactive wells as of June 2006*

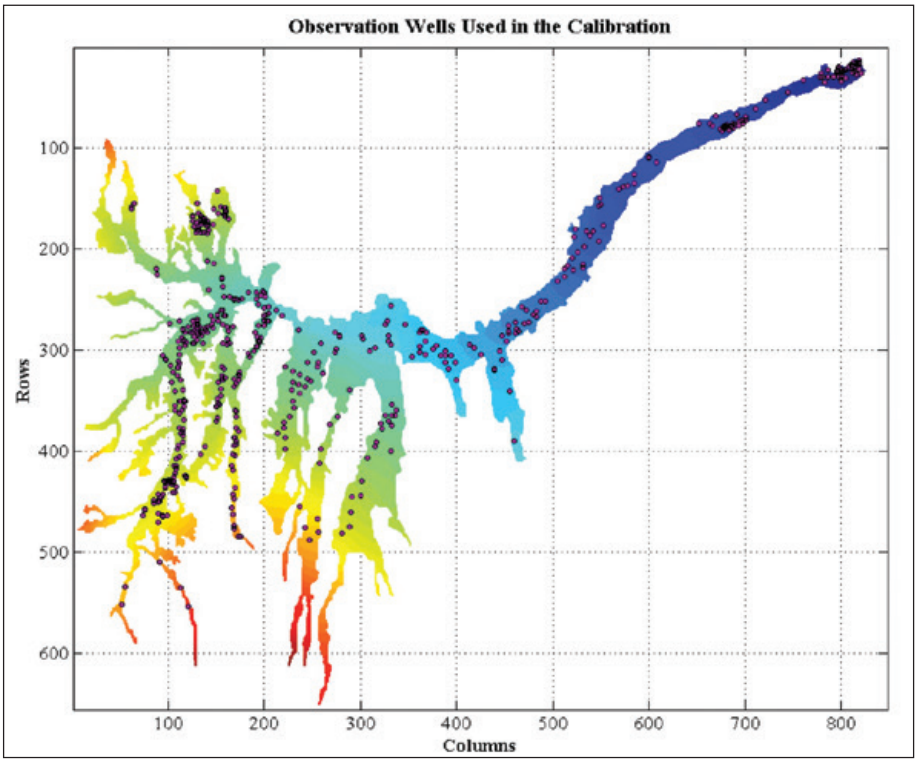


Figure 3. *Location of observation wells used in the calibration*

Table 2. *Output Files produced by the SPDD groundwater model*

No.	File Type	File Name	Description
1	GLO	P5_tr06.glo	Global file
2	HED	P5_tr06.hed	Simulated head
3	CCF	P5_tr06.ccf	Cell to cell budget
4	DAT	P5_tr06_stream.dat	Stream flow output
5	SG1	gage_tr06_out.sg1	Stream flow downstream end
6	SG2	divert_tr06_out.sg2	Stream flow downstream end

Evapotranspiration volumes increase slightly with respect to the baseline conditions (blue-line profiles). Most of these results can be explained in terms of an average increase of the water table elevations. Only the decrease in the water globally discharged from the aquifer into streams network is difficult to justify. In this case, a more thorough spatial analysis of the components of the mass balance is necessary and likely to explain these results.

When compared to the baseline condition, Scenario 2, which is characterized by well extraction rates increased by 20 percent (see the green-line profiles), shows results that are substantially opposite to Scenario 1.

In Scenario 3, where well "injection rates" are reduced by 20 percent (see the pink-line profiles), the overall volume extracted through pumping units (actual wells, lateral boundaries, and bedrock aquifers) is highly reduced. Globally this produced a small decrease in groundwater storage. The volume of water lost through general boundary condition grid cells is decreased. The volume of water discharging form the aquifer into streams decreases significantly, and evapotranspiration losses are reduced. These results can be explained in terms of an average decrease of the water table elevations. When compared to the baseline condition, Scenario 4, which is characterized by well "injection" rates increased by 20 percent (see the black-line profiles), shows results that are opposite to Scenario 3.

The purpose of these simulations is to gain familiarity with the SPDSS groundwater model and verify its capabilities in terms of providing results that can be well understood and foreseen, from a perspective of global mass balance. It is however important to emphasize that the results presented in the above scenarios are valid only within the context of groundwater model. In reality, changing the well flow rates cannot be done without affecting the conditions of aquifer recharge, since usage of water resources is

highly dependent on water availability and strictly regulated by water rights.

Overall, the results obtained from this set of simulations with modified pumping scenarios indicate that the SPDSS groundwater model is numerically robust and provides results that can be explained in terms of a basic application of the mass balance equations.

Model Calibration

Based on information provided by CDM-Smith, the SPDSS groundwater model was initially calibrated under steady-state conditions using field observations available for the period 1991-1994. The calibration was then refined under transient-state conditions using field data collected between 1999-2005. In both phases, calibration was performed automatically by combining the MODFLOW code with the optimization package PEST. Finally, the model calibration was fine-tuned manually to resolve numerical issues associated with the occurrence of dry cell conditions and ultimately provide a better matching between simulated variables and observed variables. Field data used in the calibration included head observations, stream gauge readings, and remote sensing based estimations of ET. Based on the SPDSS model files, it was possible to retrieve the head observations (file HOB_clean_valid20110606.hob), as well as stream flow data at the downstream end of the SPDSS groundwater model domain (files gage_tr06_out.sg1 and divert_tr06_out.sg2). ET satellite data were not made available in the files.

The parameters that were calibrated included the hydraulic conductivity field and the bed conductance spatial distribution. Since the number of active cells is large, it is computationally prohibitive to calibrate the conductivity field directly. Therefore a pilot method was used, in which the hydraulic conductivities at 270 points were used as the target parameters of the calibration. The hydraulic conductivity field was then estimated by spatial interpolation of the pilot point conductivity values. In this interpolation, only points within a specified zone were used. For this purpose, the aquifer domain was subdivided into 16 zones. It is not possible to make any conclusions on this approach since it was not specified how these zones were delineated.

All together, the calibration process required the estimation of a total number of at least 270 parameters. Although the range of variability of each parameter was somewhat constrained using the interpolation technique mentioned above, the number of parameters seems quite large. In these conditions of over parameterization, the calibration procedure is typically affected by problems of non-uniqueness of the solution. Such calibration procedures are widely accepted and used in the standard practice. However, they do not exclude the existence of other parameter sets that can make the model reproduce the observed data with the same accuracy.

What Knowledge Can Be Gained?

It is very important to highlight that the SPDSS groundwater model simulates water flow over a very large area and over a particularly long period of time. A regional model of this size is rarely found in the literature. In our opinion, the size of the grid cell that forms the SPDSS model is such that it cannot be used to represent water flows at the local scale with accuracy, but can be fundamental to gaining insight into the water regimes and balances at the regional scale. While imitating reality for small-scale models is also difficult, the predictive ability of large-scale models is influenced by uncertainties due to the high degree of heterogeneity and complexity of the systems and the hydrological processes. Ideally, the principle of parsimony is in favor of simplified models, in which the majority of systems' uncertainty can be attributed to few parameters. However, oversimplified models are also limited in their ability to give reasonable answers. In summary, we consider the SPDSS groundwater model an important start for a continuous effort toward effective management of water resources in the South Platte.

A realistic approach to construct reliable regional groundwater models is to deal with them as evolving tools that simulate and explain the dynamics of the hydrologic system. These tools should be flexible enough to receive continuous updates and improvements to cope up with new data and observations and reduce model uncertainties. In our opinion, the SPDSS groundwater model is a valuable tool for regional water management but will need constant upgrading as new data are collected and made available. These data should be adequate for the scale of the model. For example, an interesting approach for further validation of the SPDSS model would be to integrate in it remote sensing measurements, such as GRACE data, which can provide monthly estimates of regional changes in subsurface water storage.

One another possible application of the SPDSS model is to provide a base for the development of "child" models, that is, local models characterized by a much higher level of resolution that can be used to understand with more detail the interrelations between water use, groundwater storage and stream flows in any particular area of interest within the SP River Basin. These child models, which would not be any less complex than the full-scale model, could be coupled to the regional SPDSS groundwater model and together would form a modeling framework that could be used to manage groundwater resources both at the regional level and at the local level.

Research Team Members

1) Domenico Baú, PhD, Project PI; 2) Ayman Alzraiee, PhD, Post-doc Fellow; 3) Armin Afifi Sabet, PhD Student.

DETERMINATION OF CONSUMPTIVE WATER USE OF CORN IN THE ARKANSAS VALLEY OF COLORADO

A. A. Andales, D. Straw, L. H. Simmons, M. E. Bartolo

The authors are **Allan A. Andales,** Associate Professor, Department of Soil and Crop Sciences, Colorado State University, Fort Collins, Colorado; **Dale Straw**, Engineer (Retired), Colorado Division of Water Resources, Denver, Colorado; **Lane H. Simmons**, Research Associate, Arkansas Valley Research Center, Colorado State University, Rocky Ford, Colorado; **Michael E. Bartolo,** Manager/Research Scientist, Arkansas Valley Research Center, Colorado State University, Rocky Ford, Colorado **Corresponding author:** Allan A. Andales, Department of Soil and Crop Sciences, 1170 Campus Delivery, Fort Collins, CO 80523-1170; phone: 970-491-6516; e-mail: Allan.Andales@colostate.edu.

Abstract. *Accurate calculations of crop consumptive water use or crop evapotranspiration (ET_c) of irrigated corn (Zea mays) are needed in the Arkansas Valley of Colorado. A locally-derived crop coefficient (K_{cr}) curve for corn is needed to convert alfalfa reference crop ET_{rs} calculated from the ASCE standardized equation to non-stressed corn ET_c at different stages of crop development. The objective of this study was to measure the seasonal ET_c of corn and develop a preliminary K_{cr} curve using data collected in 2013. A precision weighing lysimeter at Rocky Ford, Colorado was used to measure daily ET_c of furrow-irrigated corn grown under local weather and environmental conditions. The mass of an undisturbed soil monolith with an actively-growing corn crop contained in a steel tank (3 m x 3 m area; 2.4 m deep) was continuously monitored with a calibrated load cell to determine corn ET_c. Corn (Fontanelle 8A818RBC variety) was planted on the monolith and surrounding field (4 ha) on 5/7/2013. Crop height and soil water content were monitored weekly during the growing season. Hourly measurements of solar radiation, air temperature, wind speed, and humidity were used to calculate hourly and daily ASCE standardized ET_{rs} values. Daily K_{cr} values for corn were calculated as ET_c / ET_{rs}. Total season corn ET_c (5/6/2013 – 10/17/2013) was 817.68 mm. Average daily ET_c was 5.0 mm d^{-1}. The seasonal corn K_{cr} curve in 2013 had an initial value of $K_{cr\ ini}$ = 0.12 (1 – 25 days after planting (DAP)), a mid-season value ($K_{cr\ mid}$) of 1.08 (58 – 106 DAP), and an ending value ($K_{cr\ end}$) of 0.10 (160 DAP). Corn grain water use efficiency (WUE) was 1.66 kg m^{-3}, which was comparable to published values for the High Plains.*

INVESTIGATION OF THE EFFECTS OF WHITEWATER PARKS ON AQUATIC RESOURCES IN COLORADO

Prepared for the

Colorado Water Conservation Board

Prepared by

Brian P. Bledsoe, E. Kolden, B. Fox, and T. Stephens

September 2013

Colorado State University
Daryl B. Simons Building *at the*
Engineering Research Center
Fort Collins, Colorado 80523

Colorado State University

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EXECUTIVE SUMMARY

Whitewater parks (WWPs) have become a popular recreational amenity in cities across the United States with Colorado being the epicenter of WWP design and construction. Whitewater parks consist of one or more in-stream structures that create a hydraulic wave for recreational purposes. A wave is typically created by constricting flow into a steep chute, creating a hydraulic jump as it flows into a large downstream pool. There is a paucity of research that surveys on-the-ground biological or ecological conditions to evaluate the actual impacts of WWPs. Consequently, the effects of WWPs on aquatic habitat and fish passage are poorly understood. This lack of information creates a problem for state wildlife agency personnel, who are asked to comment on the Section 404 permits required for WWP construction. They must provide their expert opinion without having any concrete studies to inform that opinion. This report provides a brief summary of research examining the complex hydraulic conditions present in WWPs and the effects of WWPs on aquatic habitat and fish passage. The two major sections of this report provide condensed versions of two complementary theses focused on the effects of WWPs on aquatic resources in Colorado.

The objectives of the study conducted by Kolden (2013) were to:

- describe and compare fish habitat quality in WWPs and natural reaches using a traditional method based on two-dimensional (2-D) hydraulic modeling and habitat suitability criteria;
- compare predicted fish habitat quality to results from field surveys that provide preliminary estimates of fish biomass;
- use three-dimensional (3-D) modeling to describe and compare ecologically-relevant hydraulic descriptors in WWPs vs. natural reaches; and
- compare 2-D and 3-D hydraulic and habitat modeling results and examine whether 3-D modeling is justified for assessing habitat quality in WWPs.

Two sections of the North St. Vrain River in Lyons, Colorado, were modeled: one natural section, and one section containing a WWP with three engineered drop structures. The 3-D computation fluid dynamics (CFD) software FLOW-3D® v10.0 (hereafter referred to as FLOW-3D) was used to model each of the reaches.

A 2-D habitat suitability analysis for juvenile and adult brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), longnose dace (*Rhinichthys cataractae*), and longnose sucker (*Catostomus catostomus*) predicted substantially higher habitat quality in the WWPs than in the natural reaches for adult brown and rainbow trout at some flow rates, while in-stream surveys showed higher fish biomass per volume in the natural pools. All hydraulic metrics (depth, depth-averaged velocity, turbulent kinetic energy (TKE), 2-D vorticity, and 3-D vorticity) had higher magnitudes in the WWP pools than in the natural pools. In the WWP pools, 2-D model results did not resolve the spatial distribution of flow characteristics or the magnitude of variables as well as 3-D results. This study supports the use of 3-D modeling for complex flow

found in WWPs, but other projects should be evaluated case-by-case to determine if the simplified 2-D rendering of flow characteristics is acceptable. For 3-D modeling to be widely useful, improved understanding of linkages between 3-D aquatic habitat quality and hydraulic descriptors such as TKE, vorticity, and velocity is needed.

Fox (2013) completed a field evaluation of the effects of WWPs on upstream fish passage by concurrently monitoring fish movement and hydraulic conditions at three WWP structures and three adjacent natural control (CR) pools. Fish movement was evaluated using a network of Passive Integrated Transponder (PIT) antennas installed at the study sites for a period of 14 months. 1,639 individual fishes including brown trout, rainbow trout, longnose sucker, and longnose dace were tagged and released within the WWP and CR study sites. Detailed hydraulic conditions occurring during the study period were evaluated by developing a fully 3-D hydraulic model using FLOW-3D.

Results indicate that WWP structures can incorporate a broad range of design types that affect small-scale hydraulics and potentially create unique hydraulic conditions that affect fish passage differently. Successful upstream movement of salmonids from 115 to 416 mm total length was observed at all of the WWP locations over the range of flows occurring during the study period, thus demonstrating that the WWPs in this study are not complete barriers to movement of salmonids in these size ranges. However, results indicate that WWPs can suppress movement by size class, and the magnitude of this suppression appears to vary among different WWP structures and CR sites. The differences in passage efficiency from release location range from 29 to 44% in WWP sites and 37 to 63% for control sites. Further, this difference in movement may be related to the variation of hydraulic conditions among the WWP structures, but does not appear to have a strong relationship with burst swimming abilities of salmonids. It is probable that the reduced movement may be attributed to other hydraulic and biologic variables such as turbulence, fish behavior, and motivation. Because of the small numbers of native species monitored in this study, no direct conclusions can be drawn on how this WWP affected their upstream movement ability. This study provided a starting point for understanding how WWPs affect fish movement. Future studies should focus on broadening structure type and species evaluated for passage, and perform more-detailed assessment of how hydraulic conditions other than velocity are affecting upstream movement behavior and motivation.

DESIGN CASE STUDY

The construction of a planned WWP on the Cache La Poudre River in Fort Collins, Colorado, would be an ideal site for a design case study. This project would allow for pre- and post-construction monitoring and data collection; however, there have been significant delays and uncertainty in the initialization of this project. Therefore, the WWP located on the North St. Vrain River in Lyons, Colorado, was utilized for a design case study due to the wealth of data obtained in the aforementioned studies (Fox, 2013; Kolden, 2013). Results from this case study can be used to support management decisions for both existing and future WWPs.

Colorado Parks & Wildlife (CPW) has an ongoing study to quantify biomass of introduced and native fishes in the North St. Vrain. They are surveying fish biomass in the same reaches and pools described in this study. Beginning in Fall 2010, electroshocking surveys occurred each fall (in October or November) and spring (in April). Fall surveys were conducted during low flow and timed to coincide with brown trout spawning, while spring surveys corresponded with rainbow trout spawning. Spring and fall surveys occurred well before and after the summer period of heavy recreational use in the river.

When normalized by pool surface area, adult brown trout biomass was not significantly different in natural pools and WWP pools for either year. However, when biomass was normalized by pool volume, biomass averages were significantly higher in the natural pools than the WWP pools for both years. The per volume analysis accounts for the fact that the WWP pools are much deeper than the natural pools and, therefore, provide much more physical space for fish to inhabit. Continuation and further analysis of the biomass surveys, including detailed methods, will be completed by CPW researchers and will be presented in a forthcoming publication.

Additionally, while the suppression of fish movement may exist, the observations of successful movements indicate that WWPs producing hydraulic conditions within the range of those in this study have the potential to meet both recreational and fish passage goals for salmonids. However, the amount of suppressed movement that is acceptable for a given site is a question that must first be answered through criteria defined by natural resource managers, site-specific constraints and requirements of the target species. In addition, assessing the level of habitat impairment and fragmentation already existing from the presence of diversions, culverts, or other potential passage barriers may help assess the risk of adding a WWP with unknown passage effects. Selection of a site that already has degraded habitat conditions such as existing dams and urban environments where ecological improvement potential is limited may be ideal locations for WWPs. However, without a clear understanding of what is an unacceptable level of impaired passage, it is difficult to objectively weigh the magnitude of any negative effect against the positive benefits of WWPs, and difficulties in decision-making will persist.

DESIGN RECOMMENDATIONS

Knowledge gained from these studies can be applied to future designs to maximize the probability of successful upstream movement of trout. The results suggest that WWPs with laterally-constricted grouted chutes that are installed in streams of similar size and hydrologic characteristics do not serve as complete velocity barriers to upstream migrating salmonids. Structures that maintain short high-velocity zones should be passable for species with similar swimming abilities, behavior, and motivation. In addition, lower velocity routes around high-velocity zones and roughness elements on the lateral margins of the channel would improve passage success by reducing the length and magnitude of a potential velocity challenge.

The unique hydraulic conditions observed at each WWP structure affect passage success differently. Large eddies with lower velocities adjacent to the main velocity jet in the pool were observed in the WWP structure with the highest passage success. Large eddies with low velocities can provide zones for fish to rest and may reduce the length of the high-velocity zone that fish are required to traverse. A lateral expansion near the chute outlet into the pool produced the large eddies adjacent to the main velocity jet. Decreased passage success was observed at a structure where the maximum constriction of the chute was near the outlet into the pool preventing the formation of the large, low-velocity eddies. Roughness elements along the channel margins reduce the local velocity providing high-velocity refugia and passage routes with reduced velocities. Additionally, providing interstitial spaces within the chute may provide zones of lower velocity and potential passage routes for smaller fishes with reduced swimming abilities. The passage success of smaller fishes was more pronounced in the WWP structure that contained interstitial wetted spaces within the center of the chute.

Considering that the formation of a hydraulic jump requires supercritical specific energy ($Fr > 1$) within WWP features, zones of high velocity must occur at some point within a structure. In order to achieve supercritical specific energy on rivers larger than the one examined in these studies, it is possible that higher velocities that exceed salmonid burst swimming abilities within the chute might be required to generate a wave that achieves recreational objectives. As such, any attempt to transfer results of this research to larger rivers must account for scale-dependent differences in the velocities required to generate the type of hydraulic waves preferred by boaters relative to the trout swimming abilities documented in this and other studies. Further, streams with smaller mean discharges will require greater levels of lateral width constriction and vertical drop for the hydraulic wave to meet recreational goals. In such cases, a bypass channel or alternative route around the chute may be required to provide lower velocity passage routes, while meeting recreational needs.

To fully evaluate the variations in design elements and discharge for future WWPs, a site-specific analysis would likely be required to determine if additional zones of lower velocity would exist to allow potential upstream passage routes. It is likely that a site-specific analysis would also be required in order to determine if an existing WWP needed to be modified to provide zones of lower velocity. However, without greater understanding of the specific mechanism causing the suppression of movement, developing detailed design guidelines will remain difficult.

Prepared for the Colorado Water Conservation Board

Agricultural Economics and Water Resources: Methods, Metrics and Models – A Specialty Workshop

February 18, 2014

[Insert Graphical Overlay]

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Section 1

Introduction

The purpose of this project was to convene a Specialty Workshop, gathering experts on the subject of Agricultural Economics and Water Resources. Particular attention was paid to the presentation of methods, metrics, and models for economic valuation of agriculture and its relationship to water supplies, both consumptive and non-consumptive.

The Specialty Workshop was formal in nature. The Colorado Water Institute identified prominent experts in the field of Agricultural and Resource Economics and invited them to participate. These experts represented the top of their professions and eagerly accepted our invitations to join the event. These notable experts were invited on the basis of their interest and potential contribution to an "informed dialogue" on the manner by which agriculture can be assessed in terms of its value within a basin-wide, regional, or state economy.

The two basic groups of questions considered at the workshop were:

1. How do we talk about the economics of agriculture? Is there a conventional dialogue that can be used to maintain an informed discussion on this subject? What are the available metrics and methods that exist in the body of research on this topic?
2. How do we translate metrics and methods into a model that relates agriculture's value to larger statewide economy? How do these metrics and methods help us understand the economic relationship between agriculture and water resources?

The Specialty Workshop was moderated by faculty at the Colorado State University Department of Agricultural and Resource Economics, Prof. James Pritchett and Prof. Chris Goemans, along with Dick Brown, President of Sand Dollar Research. A moderated "long-panel" format was for the workshop, designed to maximize interaction with the panelists on this highly nuanced topic.

1.1 Event Support and Funding

The conference received support from the Water Supply Reserve Account (WSRA) via the CWCB and the Arkansas Basin Roundtable ($9,746) and additional support from sponsors and stakeholders ($5,000). A registration fee of $50 was charged for early registrants, $75 for late registrants and $100 for those registering on the day of the event. Registration fees ($6,900) garnered additional support from 156 total attendees (including speakers). Public Education, Participation and Outreach (PEPO) funding ($2,000) yielded support from the Arkansas and South Platte Basins. Significant in-kind support was provided by the Colorado Water Institute, CSU Extension, Colorado Department of Agriculture and Sand Dollar Research, along with the time and contribution of CAWA members.

USGS Summer Intern Program

Basic Information

Start Date:	3/1/2013
End Date:	2/28/2014
Sponsor:	DOI-USGS-Geological Survey
Mentors:	Robert S Regan
Students:	Andrew Reimanis

Internship Evaluation

Question	Score
Utilization of your knowledge and experience	Good
Technical interaction with USGS scientists	Very Good
Treatment by USGS as member of a team	Very Good
Exposure and access to scientific equipment	Good
Learning Experience	Very Good
Travel	About Right
Field Experience Provided	About Right
Overall Rating	A

Additional Remarks

All the employees that I work with are very friendly and hlepful; it is a very good environment to work under.

Basic Information

Start Date:	3/1/2013
End Date:	2/28/2014
Sponsor:	DOI-USGS-Geological Survey
Mentors:	Edward Stets
Students:	Sydney Wilson

Internship Evaluation

Question	Score
Utilization of your knowledge and experience	Very Good
Technical interaction with USGS scientists	Very Good
Treatment by USGS as member of a team	Very Good
Exposure and access to scientific equipment	Very Good
Learning Experience	Very Good
Travel	About Right
Field Experience Provided	About Right
Overall Rating	A+

Additional Remarks

Basic Information

Start Date:	3/1/2013
End Date:	2/28/2014
Sponsor:	DOI-USGS-Geological Survey
Mentors:	Robert S Regan
Students:	Michael Sanders

Internship Evaluation

Question	Score
Utilization of your knowledge and experience	Very Good
Technical interaction with USGS scientists	Good
Treatment by USGS as member of a team	Good
Exposure and access to scientific equipment	Good
Learning Experience	Very Good
Travel	About Right
Field Experience Provided	About Right
Overall Rating	A

Additional Remarks

The USGS MOWS department treated me as a capable and valuable member of their team. They were also responsive as a resource when needed. Overall I had a successful experience working with the USGS.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	9	0	1	2	12
Masters	1	0	2	7	10
Ph.D.	0	1	0	2	3
Post-Doc.	0	0	0	0	0
Total	10	1	3	11	25

Notable Awards and Achievements

- Upper Yampa Scholarships Announced
- Dr. John E. McCray Awarded Fulbright Technical Specialist Award

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Upper Yampa Water Conservancy District Scholarships Announced

The Upper Yampa Water Conservancy District John Fetcher Scholarship provides financial assistance to a committed and talented student who is pursuing a water-related career in any major at a public university within the state of Colorado. Congratulations to this year's recipients, Marina Meneakis, Jonathon Roberts, Zach Dufault, and Amanda Snyder.

Marina Meneakis is an undergraduate student at Wester State College who majors in Environmental Studies with a Water Emphasis. She is interested in stormwater, water sampling, and efficient use. "Currently, I am a student Intern at Los Alamos National Laboratories (LANL) through their student program and have been since 2009. My plans are to stay with LANL's student program until I graduate, because the program I am in applies greatly to my major and I enjoy the variety of tasks that our unit performs. Then, I hope to obtain a permanent position at LANL in the Environmental Program or apply with other similar organizations and businesses such as the Forest Service."

Jonathon Roberts is an undergraduate at Mesa State College who majors in Environmental Science and minors in Watershed Science. "My goals are very basic but not easy. I wish to make where I live a better place and am not afraid to work hard to do it. I volunteer with my local fire department as a firefighter and EMT and also with our community center. After starting my environmental education everything about water has interested me, from the science to the politics. Living in an area with a growing population and dwindling water supply, thinking outside the box is essential. I feel that there is a need to use the resource but at the same time preserve resources for things like biological reasons. I wish to live on the western slope of Colorado. I enjoy the atmosphere, the people and the land. With water being the foundation of the lives of everybody and everything in my valley and all the land of the state we need more scientists to be able to provide good data so water managers can make informed decisions. Resource extraction, tamarisk infestation, selenium contamination, endangered species needs, and many others are issues that have a need to be addressed and resolved. I want to start my career in the field to be able to get the experience needed to be a great leader. These issues were not created in a day and will not be resolved quickly. They may not be fixed during my time, but I do want to move it in the right direction."

Zach Dufault is an undergraduate who recently transferred to Colorado State University, interested in environmental science and watershed science. "After graduation, I would like to stay in western Colorado and work for an environmental agency/firm or work for a government agency such as Colorado Department of Parks and Wildlife, Bureau of Land Management, or U.S. Forest Service. Being an avid hunter and fisherman, I would love to work in either of those areas of the environment. If graduate school becomes more of a focus, attending school after working a few years in the work force would be preferred. Changing the way people look at and treat the environment in their daily lives is of interest to me. With the environment (water especially) becoming more threatened and resources becoming more scarce, the general public needs to be educated on how their daily lives harm certain aspects of the environment. Being as involved as possible in the environment and helping to protect and conserve what we have is my ultimate goal."

Amanda Snyder is an undergraduate at Colorado State University studying watershed science and interested in water quality and restoration work. "I truly enjoy being in the Watershed Science

program. Within my degree, I am especially interested in water quality. I would like to start out in the Glenwood and/or Rifle, Colorado area. A company that appeals to me as a possible place to start a career would be the Sonoran Institute. They work to make sure the environment is protected in the west. Specifically, I would like to work in the area of clean water. Other jobs along the western slope that would be of interest to me are city and government jobs that allow me to work in the department of water. I could be doing anything from switching out sprinkler heads to make them more efficient to being a watershed planner to assist in maintaining the health and appearance of the watershed. As I grow in my career, I would eventually like to get into restoration. I would also like to expand my career outside of Colorado and even out of the United States eventually. Moving to Alaska is one of my main goals after I get my feet wet in the real world. I would mostly consider a government job there as well working in water quality or restoration. I think it would be extremely rewarding to work in third world countries, as well, and possibly come up with a system to better their water."

Dr. John E. McCray Awarded Fulbright Technical Specialist Award

Dr. John E. McCray was able to give talks using material from his project to the Fulbright Commission of Chile and the U.S. State Department; in Santiago, Chile in March 2013. He was awarded with the Fulbright Technical Specialist Award to visit Universidad de Concepcion in Chile for his expertise in mountain hydrology and water quality. For more information visit: http://www.cies.org/grantee/john-mccray

Publications from Prior Years

1. 2009CO195G ("Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping") - Other Publications - Griebling, S.A. and R.M. Neupauer, 2012, "Adjoint Methodology to Simulate Stream Depletion due to Pumping in a Non-linear Coupled Groundwater and Surface Water System", Computational Methods in Water Resources.
2. 2009CO195G ("Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping") - Other Publications - Lackey, G., R.M. Neupauer, and J. Pitlick, 2013, "Effects of varying stream channel conductance on siting new pumping wells in an aquifer", 2013 World Environmental and Water Resources Congress, American Society of Civil Engineers.
3. 2009CO195G ("Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping") - Other Publications - Lackey, G., R.M. Neupauer, and J. Pitlick, 2013, "Effects of spatial and temporal variations of streambed hydraulic conductivity on stream depletion calculations", MODFLOW and More Conference.
4. 2009CO195G ("Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping") - Other Publications - Neupauer, R.M. and S.A. Griebling, 2013, "Comparison of forward and adjoint approaches to calculate stream depletion with application to the Upper San Pedro Basin", MODFLOW and More Conference.
5. 2010CO226B ("Paleohydrology of the Lower Colorado River") - Other Publications - Author (Wade, L.C.; all others;B. Rajagopalan; J.J. Lukas; D. Kanzer), 2011, Beyond Lees Ferry: Assessing the Long-term Hydrologic Variablility of the Lower Colorado River Basin, American Geophysical Union, Fall Meeting 2011, Abstract #H43A-1184.
6. 2010CO226B ("Paleohydrology of the Lower Colorado River") - Articles in Refereed Scientific Journals - Author (Nowak, Kenneth; Martin Hoerling; Balaji Rajagopalan; Edith Zagona), 2012, Colorado River Basin Hydroclimatic Variability, Journal of Climate, Vol. 25 Issue 12, p4389-4403, 15p. 20 Graphs, 1 Map.
7. 2010CO226B ("Paleohydrology of the Lower Colorado River") - Other Publications - Mendoza, Pablo; Martyn Clark; Balaji Rajagopalan; Naoki Mizukami, 2013, Comparing Hydrologic Sensitivities to Climate Change in the Headwaters of the Colorado River Basin, EGU General Assembly 2013, held 7-12 April, 2013 in Vienna, Austria, id. EGU2013-6377
8. 2011CO245G ("Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts ") - Articles in Refereed Scientific Journals - Bearup, Lindsay A., Reed M. Maxwell, David W. Clow, John E. McCray, 2014, Hydrological Effects of Forest Transpiration Loss in Bark Beetle-Impacted Watersheds, Nature Climate Change (2014). doi:10.1038/nclimate2198
9. 2011CO245G ("Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts ") - Articles in Refereed Scientific Journals - Kristin M. Mikkelson;Lindsay A. Bearup, Alexis K. Navarre-Sitchler, John E. McCray, Jonathan O. Sharp, 2014, Changes in Metal Mobility Associated with Bark Beetle-Induced Tree Mortality, Environ. Sci.: Processes Impacts, 2014, Advance Article DOI: 10.1039/C3EM00632H
10. 2011CO245G ("Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts ") - Other Publications - Mikkelson, Kristin M.; Eric R.V. Dickenson; Reed M. Maxwell; John E. McCray, Jonathan O. Sharp, 2012, Water-Quality Impacts from Climate-Induced Forest Die-Off, Nature Climate Change 3, 218–222.
11. 2010CO219B ("Shear Resistance of the Nuisance Diatom Didymosphenia Geminata") - Articles in Refereed Scientific Journals - Cullis, James D.S.; John P Crimaldi, Diane M. McKnight; 2013, Hydrodynamic Shear Removal of the Nuisance Stalk-Forming Diatom Didymosphenia Geminata, Limnology and Oceanography: Fluids and Environments, Volume 3 (2013): 256–268.