Colorado Water Institute
Annual Technical Report
FY 2014

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 become 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, the University of Northern Colorado, and Colorado School of Mines.

Our charges this year included requests from the legislature as well as state and federal agencies. The Colorado Legislature continues to call upon CWI to provide science-based approaches to 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 Colorado'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 two faculty research project, seven student research projects, and five 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 Request for Proposal, (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. *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)
2. *ICIWaRM Advisory Board Meeting and Workshop*, Reagan Waskom, Colorado State University, $132,743 (104s)

Student Research (Faculty advisor in parenthese)

1. *Ecological Functions of Irrigation Dependent Wetlands*, Erick Carlson (Cooper), Colorado State University, $4,987 (104b)
2. *WOOD: Windows of Opportunity for Debris Retention in Response to 2013 Front Range Flooding*, Natalie Anderson (Wohl), Colorado State University, $5,000 (104b)
3. *The Effect of Normative Trends on Water Conservation*, Anastasia Bacca (Mortensen), Colorado State University, $4,983 (104b)
4. *Impact of Limited Irrigation on Health of Three Ornamental Grass Species*, Samuel Hagopian (Klett), Colorado State University, $5,000 (104b)
5. *Nutrient Retention and Productivity in Rocky Mountain Streams Under Alternative Stable States*, Adam Herdrich (Winkelman), Colorado State University, $5,000 (104b)
6. *Investigation of the Effects of Whitewater Kayak Parks on Aquatic Resources in Colorado*, Timothy Stephens (Bledsoe), Colorado State University, $5,000 (104b)
7. *Exploration of Morphometric Approaches for Estimating Snow Surface Roughness*, David Kamin (Fassnacht), Colorado State University, $5,000 (104b)

Internships

1. MOWS - Modeling of Watershed Systems, (Steve Regan), USGS, $78,509, Michael Sanders (University of Colorado), Andrew Reimanis (Colorado State University), Samuel Saxe (Colorado School of Mines), Ryan Logan (Colorado School of Mines)
2. WEBB – Water, Energy, and Biogeochemical Budgets, $40,219, Sydney Wilson (Colorado School of Mines)
3. CWCB Interns – None

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
USGS Grant Number:	G11AP20213
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.

Annual Report

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

<u>Conference Presentations</u>

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.

Ecological Functions of Irrigation Dependent Wetlands

Basic Information

Title:	Ecological Functions of Irrigation Dependent Wetlands
Project Number:	2014CO296B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Biological Sciences
Focus Category:	Ecology, Hydrogeochemistry, Irrigation
Descriptors:	None
Principal Investigators:	David Cooper

Publications

There are no publications.

Ecological Functions of Irrigation Dependent Wetlands: Nitrate Mitigation

Erick A. Carlson, PhD Student, Ecology, Colorado State University

Advisor: David Cooper, Forest and Rangeland Stewardship, Colorado State University

Background

Nitrate has been reported in Weld County, Colorado irrigation, drinking water, and monitoring wells in agricultural areas at levels exceeding the EPA drinking water standard. Improvements to irrigation and fertilizer application efficiency have not yet significantly reduced groundwater nitrate levels in the region. We propose investigating the functioning of wetlands created by irrigation runoff to trap and process nitrate.

The goal of this pilot project was to locate and instrument sites to explore the hydrology of these irrigation dependent wetlands and test methods of investigating the potential fate of nitrate $(NO_3)^-$ exiting the field as runoff and shallow groundwater. The primary objective was to test the acetylene block technique for inhibiting microbial denitrification. In anaerobic (waterlogged) conditions, some microorganisms use nitrate in the absence of oxygen (O_2) for respiration. The presence of acetylene gas (C_2H_2) blocks the chemical process that moves the intermediate nitrous oxide (N_2O) to elemental nitrogen gas (N_2). In a controlled experiment, nitrous oxide can be measured accurately and used to determine the denitrification activity in the soil, a potentially significant component to nitrogen cycling in wetlands. This method, however, is not commonly performed in the field, and experimental equipment and procedures needed to be tested for efficacy.

Methods

Site selection from aerial imagery of wetlands near irrigated crop fields was conducted and several dozen potential sites were initially considered. Networking with Colorado State University research scientist Troy Bauder narrowed the potential sites. Site visits with my advisor Dr. David Cooper and discussions with the landowners to explain the project and walk through the properties was conducted in May 2014. All three farmers contacted agreed to participate in the research in 2014 which led to the development of 4 field sites in Weld County (2 near Ault and 2 near Gilcrest) with diverse set of physical characteristics, irrigation type, crop type, and wetland vegetation.

Hydrology: The hydrologic setting was monitored through 2014 (June-Nov) using shallow groundwater wells (2" x 60" PVC and automated water level sensors (Rugged Troll 100-InSitu). Piezometers were also installed and water depths recorded to help determine groundwater flow paths. For comparison nearby publically available daily rain gage data were used to examine the effects of precipitation on the water table.

Denitrification (acetylene block technique): Microbial denitrification was tested in the field using soil incubation chambers and the acetylene block technique. PVC tubes (3” x 20”) were pounded into the ground 17”, leaving ~ 3” headspace. Caps with a gas port were installed and sealed onto the tubes. Acetylene gas (C_2H_2) was injected into the headspace to comprise about 10 percent of the volume. The equal amount of air was removed just prior to injection such that the end result was a neutral pressure. Pre-injection samples were taken and again every hour after incubation began for up to 5 hours. 30mL of gas was extracted and 30mL of N_2 was injected to maintain neutral pressure. Gas samples were analyzed on a Shimadzu GC14B gas chromatograph with FID, methanizer ECD, and autosampler. This measured the amount of methane (CH4), carbon dioxide (CO2), and nitrous oxide (N2O).

Results and Discussion

Hydrology: Observation of the hydrologic setting of the four sites was illuminating, even during an anomalously wet summer. Clear trends in water table rise with rain events and assumed irrigation events took place. Farm A and B for base level control as they were adjacent to open water ponds. The stability of water level in the ponds can be seen from the nearest well. Farm A showed a wide range of variability in pond level, over 1m during the reported period, while Farm B only varied 30cm. Farm C represents a sprinkler irrigated system in very sandy soil. The groundwater wells were located the same distance apart as in Farm A and B (10m), but the soil was very sandy with high hydraulic conductivity, while farms A and B were clay dominated soils.

All three sites showed a gradual rise in water tables during the growing season which would suggest irrigation water as major cause of the trend. Additionally correlation was weak between water table levels and precipitation at all sites (<0.25 with 1.0 being a perfect correlation). The summer was exceptionally wet, however, with frequent substantial rains limiting many farm operators to irrigating half as often (per. com., Bauder 2015). Water table analysis of an average year might show irrigation events more prominently.

Denitrification (acetylene block technique): The experimental component of the research was to test efficacy of the acetylene inhibition technique in the field. This method is commonly used a laboratory setting to determine *potential* denitrification. I was interested in the actual denitrification under field conditions. The size of the incubation chamber and incubation time were unknown variables. The goal was to determine the maximum N_2O levels that could be obtained from blocking the denitrification chemical reaction. My results showed that 5 hours (3 hour incubation presented) was not enough time for the acetylene to diffuse into the soil and block most denitrification. The slowing CO_2 accumulation suggests that the commonly observed reduction in microbial respiration was occurring which supports that some diffusion was occurring and denitrification was impeded. The ideal result would have been a line that would begin to level off as most denitrification had been blocked at the nitrous oxide intermediate. We estimate this could take as long as 24 hours in dense, saturated clay soils after further literature review.

Continued Work

Additional funding through the Colorado Corn Growers Association and the Colorado Water Institute will continue to support this investigation into the question of wetland nitrate dynamics near irrigated agricultural fields. An additional site has been developed and intensive sampling is planned for summer 2015. Analysis on other physical parameters likely to affect denitrification will be measured and analyzed for influence including soil nitrate, soil temperature, soil pH, soil bulk density, soil type, soil carbon, and microbial biomass. Plant uptake is another pathway that will be investigated with measurements of total plant N at the end of the growing season. The goal is an estimate of the amount of nitrogen endogenous to the wetland (cycling locally with plant tissues and soil reserves) and the amount entering the wetland through surface flow and shallow groundwater.

The work conducting with the Colorado Water Institute grant was essential to characterizing the systems, testing experimental equipment and adjusting and understanding the need for data collection on additional physical parameters of the system. I want to sincerely thank the Colorado Water Institute for its continued support.

The Effect of Normative Trends on Water Conservation

Basic Information

Title:	The Effect of Normative Trends on Water Conservation
Project Number:	2014CO298B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Social Sciences
Focus Category:	Water Use, Conservation, Education
Descriptors:	None
Principal Investigators:	Chad Mortensen

Publications

There are no publications.

The Effect of Normative Trends on Water Conservation

Anastasia M. Bacca, Undergraduate Student, Psychology, Metropolitan State University of Denver

Advisor: Chad R. Mortensen, Assistant Professor, Psychology, Metropolitan State University of Denver

Background

Colorado's proclivity for drought and the fact that it is the only state other than Hawaii in which water flows out, but not in, makes conservation of water resources in the state vitally important. Encouraging socially responsible behaviors—like conservation of water resources—among the population can be successfully carried out in many ways, such as fines for improper water use or financial incentives for conservation. However, communication campaigns are a relatively inexpensive way to further reduce water use through more psychological means. Recent campaigns have already sought to do so, but perhaps harnessing the powerful influence of group behavior can further increase the effectiveness of these types of communication campaigns.

The effect of social norms on individual behavior has been frequently documented. Studies have reported that messages reporting pro-environmental behaviors as normative (i.e., commonly done) increases the likelihood others will perform these behaviors more than messages containing only appeals to help the environment. For example, communicating a norm that the majority of guests participate in towel reuse at hotels increases reuse beyond just asking guests to help the environment. However, what has not been properly researched is the additional effect that can potentially be had by providing information regarding *changes* in these norms, which may even further engender increases in conservation behavior.

People from Western cultures tend to believe that change over time will continue in the same direction. Because most Colorado residents subscribe to Western thinking, we hypothesized that communicating a norm for engaging in water conservation behaviors is increasing in popularity would have a greater effect on water conservation behaviors than presenting a norm alone. To test this in previous research, we first exposed participants to conservation statistics then asked these participants to take part in what they believed to be a separate study on toothpaste preferences. As they sampled the toothpaste, a hidden water meter measured their water use. As expected, communicating that the number of people conserving water was increasing (i.e., 63 percent engage in the behavior, and this is up from 52 percent) led people to use significantly less water than presenting a norm alone (i.e., 63 percent engage in the behavior).

Two experiments were proposed in our grant application; however, we completed an additional third experiment as well. The project had two objectives. First, we sought to conceptually replicate our previous research using a different conservation behavior (i.e., washing hands). Second, previous research has found that people will not be likely to perform behaviors they believe most others are *not* performing. However, communicating that a numerical minority is *increasing* in size may be able to overcome this problem. We hoped to find that this could provide people wishing to promote a conservation behavior a way to leverage social norms even when most people do not engage in conservation behavior, as long as the minority engaging in it is sufficiently increasing. Our final experiment examined whether explicitly asking participants to think about the popularity of water conservation behaviors in the future after being exposed to trending norm information may render these messages even more effective.

Method

Three experiments were conducted. In each, participants were told they would be participating in two short studies conducted by separate researchers. In our first experiment, participants were told the first study examined the relationship between personality and editing skills, and they read a brief statement regarding fellow students' water conservation behaviors and edited the message. The statement included the experimental manipulation. While some the participants read that 63 percent of students at their university engaged in one or more of several listed water conservation behaviors, the remaining participants also read that participation in these water conservation behaviors had increased from 52 percent the year before. Participants then completed several personality surveys and were directed to what they believed was the second, separate study. A second experimenter informed the participant that they would be participating in a study examining the relationships between characteristics of hands and personality. Participants were asked to hold out one hand palm up and the experimenter applied washable ink after which the participants placed their palms on a piece of paper to make a handprint. The researcher then excused herself, supposedly to store the handprints, while the participants where told they could use the sink in the room to wash off the ink. Participants were then debriefed, after which the researcher recorded a water meter reading to measure how much water participants had used.

The second experiment was identical to the first, except the second study in the experiment was presented as a toothpaste taste-test study instead of a study related to characteristics of hands. Additionally, the percentages used in this second experiment were all numerical minorities (48 percent of students engage in water conservation behaviors, which those in the trending norm condition read had increase from 37 percent the year prior), and a control condition was added in which participants read about trends unrelated to water conservation.

The third experiment was identical to the second, but added conditions in which participants made explicit predictions about the popularity of water conservation in the future.

Results

In the first experiment, there was a tendency for participants to use less water after being exposed to a trending norm (63 percent of students engage in water conservation behaviors, up from 52 percent; Mean = 0.486 gal) compared to the norm alone (63 percent of students engage in water conservation behaviors; Mean = 0.496 gal). However, statistical analyses were not significant, indicating there was a high possibility that this could have been due to random chance alone.

The second and third experiments we more successful, however. In the second experiment, we examined whether communicating a trending norm can make a message urging water conservation effective even when only a minority of others engage in the behavior, and used tooth brushing as the behavior under investigation. We found that those who read the norm only (48 percent of students engage in water conservation behaviors) used the same amount of water (0.44 gal) as those who did not read about water conservation at all (0.44 gal). So, when a numerical minority of people engages in water conservation behaviors, communicating this information is ineffective in reducing water usage. However, when information regarding an increasing trend was added to this normative message (48 percent of students engage in water conservation behaviors, up from 37 percent), participants *did* reduce water usage (0.26 gal). Statistical analyses showed that this effect was large and statistically significant (unlikely due to chance). The results also showed that participants believed water conservation to be more popular if they read the trend information than if they didn't.

The third experiment was similar to the second except that it also explicitly asked some of the participants to answer how popular they thought water conservation behaviors would be in the future. Results from this experiment showed that after reading the trending norm message, water usage in the tooth brushing task was even lower if participants were asked to think about popularity of these behaviors in the future than if they weren't. Statistical analyses determined that this was a medium-sized effect and that it was significant (unlikely due to chance).

Discussion

Overall, this research examined the how to improve messages promoting water conservation that use social norms as leverage. We found that messages communicating social norms are even more effective when communicators include trend information stating that these social norms are becoming more popular. Doing so also makes messages stating most people are actually *not* engaging in water conservation behaviors effective in increasing water conservation in others as long as the number of those said to be engaging in water conservation behaviors is sufficiently increasing. Finally, we found that the effectiveness of these messages can be increased to an even greater degree by explicitly asking people to think about how popular water conservation will be in the future.

Though social norms are already known to be effective in communication campaigns, our research shows there may be ways to further increase the their effectiveness. Notably, these strategies for improving communication campaigns are not only effective, but also low cost or free, allowing for greater conservation of valuable water resources without having to increase funding for campaigns. Specifically, this research demonstrates strategies that can be used to encourage water conservation, but more generally, it can also be seen as helping to demonstrate the value of taking a psychological approach to promoting water conservation.

Impact of Limited Irrigation on Health of Three Ornamental Grass Species

Basic Information

Title:	Impact of Limited Irrigation on Health of Three Ornamental Grass Species
Project Number:	2014CO299B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Biological Sciences
Focus Category:	Water Use, Drought, Irrigation
Descriptors:	None
Principal Investigators:	James E Klett

Publications

There are no publications.

Impact of Limited Irrigation on Health of Three Ornamental Grass Species

Sam Hagopian, MS Candidate, Horticulture and Landscape Architecture, Colorado State University

Advisor: James Klett, Horticulture and Landscape Architecture, Colorado State University

This is a two-year study. All data reported in this paper serve as a preliminary report of data from year one. No conclusive results have been made from this first year of research.

Literature Review

Water availability in the United States has decreased in the past twenty years as populations steadily increase (Sun et al., 2008). Populations coupled with diminishing growing grounds and widely used unsustainable growing practices are reducing water availability across the country (Boyer, 1982). Colorado specifically is a considered dry state with annual precipitation averaging 15.47 inches per year (US Department of Interior, 2012). To combat this drought, attention to irrigation efficiency has the greatest potential for water conservation for most residents (Whiting, 2012: 261). Ornamental grasses tend to go hand-in-hand with the principles of water-wise growing. They are regarded as problem-free, and highly drought tolerant (Janik and Whipkey, 2002). For this reason it is essential to find species that require minimal irrigation for survival in the hot and dry environment of Colorado. This information will have a great impact on the horticultural industry as it affects large industry growers and individual landscapers and homeowners.

Introduction

The purpose of this study is to quantify a feasible irrigation standard at which ornamental grasses should be watered. More generally, it is important to know if deficit irrigation is feasible with ornamental grasses. More important to Colorado, is this deficit irrigation feasible once periods of drought are introduced? While studies have touched on growing these grasses, this study serves as a pioneer in linking ornamental quality with physiological stress and growth. Discovering critical water potentials and other aspects of plant stress will help give a baseline for the levels of stress these plants can endure while maintaining aesthetic quality. A final goal lies in quantifying the actual Evapotranspiration (ET) that these plants undergo. Industry personnel and researchers tend to base a majority of irrigation practices on ET, and this is why effective quantification of ET is a key aspect of precise irrigation management (Irmak, 2009).

Materials and Methods

Two studies are being performed, termed the **Water Use Study** and **Lysimeter Study**. The **water use study** examined three species of ornamental grasses: *Panicum virgatum* ‘Rotstrahlbusch’ (Rotstrahlbusch Switchgrass) (*Panicum*), *Schizachyrium scoparium* ‘Blaze’

(Blaze Little Bluestem) (*Schizachyrium*), and *Calamgrostis brachytricha* (Korean Feather Reed Grass) (*Calamgrostis*). The study consisted of four treatments; zero percent, 25 percent, 50 percent, and 100 percent Bluegrass ET (ET_o). ET_o was recorded using an atmometer. Irrigation treatments were calculated and applied once a week.

Two generalized categories of data were collected, plant stress, and ornamental quality. Plant stress parameters include predawn water potential (Ψ), infrared canopy temperature, and dry weight. Plant ornamental quality parameters included height, width, circumference, green-up date, flowering date, floral impact, landscape impact, overall habit/lodging, color, self-seeding, and representative photographs.

The **lysimeter study** examined one species of ornamental grass: *Schizachyrium scoparium* 'Blaze', chosen for its vigorous growth, lack of extreme deep rooting, and ornamental popularity. After establishment, plants were placed in the field in a pot-in-pot system. The three treatments applied were 25 percent, 50 percent, and 100 percent of actual plant ET (ET_s). The same plant stress and aesthetic measurements were chronicled in the lysimeter study as in the water use study. In addition, four dry down periods were conducted. This consisted of providing each treatment with its relative level of irrigation, and then allowing plants to dry out to critical stress levels. During dry down periods, entire pot and plant weight was measured on a daily basis, recording weight loss, and in turn ET_s. Photographs and water potential readings were also taken daily.

Results

Water Use - Stress Measurements: For water potential, five of the ten dates showed the trend of the zero percent treatment being significantly lower than the other three treatments (Fig. 1). Infrared canopy temperature showed the same trend, with the zero percent treatment being significantly higher than the other three treatments (Fig. 2). End of season dry weight was calculated, showing no differences between treatments for *Panicum* and *Calamgrostis*. *Schizachyrium* showed less dry mass between the zero percent treatment and all others.

Water Use - Ornamental Measurements: End of season height showed differences between treatments for each species. *Calamgrostis* values were lower for the zero percent and 50 percent treatments, and significantly higher for 25 percent and 100 percent treatments. *Panicum* values showed that zero percent was lower than 100 percent. *Schizachyrium* values were lower for zero percent than all three other treatments (Fig. 3). End of season width also showed differences between treatments for each species. *Calamgrostis* values were lower for zero percent than all three other treatments. *Panicum* values showed zero percent have lower values than 100 percent treatment, and 25 percent being smaller than the 50 percent treatment. *Schizachyrium* values showed that all three lower treatments are smaller than the 100 percent treatment. End of season circumference showed that *Calamgrostis* values in zero percent were lower than those in the 50 percent and 100 percent treatment. *Panicum* values showed that zero percent was lower than 50 percent and 100 percent, and 25 percent was lower than 50 percent. *Schizachyrium* values showed that zero percent was lower than all other three treatments.

Self-seeding showed no differences between treatments. Floral impact for *Calamgrostis, Panicum, and Schizachyrium* showed that zero percent was lower than all other treatments. Landscape impact and overall habit follow the same trend. Each ornamental category had slight differences between treatments on certain dates, however they are negligible with one year of data.

<u>Lysimeter - Stress Measurements:</u> The third dry down resulted in ET of 25 percent being the same as 50 percent, but less than 100 percent. The 50 percent treatment was also significantly less than the 100 percent. The fourth dry down showed that the 25 percent was lower than both 50 percent and 100 percent (Fig 4). When evaluating water potential, dry down 1 showed no differences between treatments until day 7, where 25 percent has lower values that both 50 percent and 100 percent. Dry down 2 showed no differences between treatments. Dry down 3 resulted in 25 percent being similar to 50 percent but lower than 100 percent, and 50 percent was lower than 100 percent. Dry down 4 showed no differences until the sixth day, in which 25 percent was lower than both 50 percent and 100 percent (Fig 5). There were no differences between treatments for end of season plant dry weight.

<u>Lysimeter - Ornamental Measurements:</u> There were no significant differences for height, width, circumference, floral impact, landscape impact, or overall habit between treatments.

Discussion

<u>Water Use Study:</u> Water potential and Infrared Thermometer values indicates that 25 percent plants are under the same levels of low stress as 100 percent plants. Dry weight of *Schizachyrium* indicates that this species will have less mass when given no water, and 25 percent plants will be the same size as 100 percent plants. These three parameters combined suggest that zero percent plants are significantly more stressed, while plants receiving 25 percent water are just as stress-free as those receiving 100 percent. This has massive impacts, suggesting that plants receiving 25 percent ET are as physiologically healthy as plants receiving 100 percent ET.

Height measurements indicate that zero percent treatments will result in smaller plants, no matter the species. Regardless of species, all plants grew the most in 25 percent and 100 percent treatments. Width measurements indicate that zero percent treatments result in narrower plants. Circumference, Floral Impact, and Landscape Impact holds true to the same trends as width. This suggests that zero percent plants will be smaller and less showy than their watered counterparts. Overall habit showed that zero percent results in more prostrate plants, while 100 percent results in very upright plants. These results are also very promising, as plants receiving 25 percent ET are as ornamentally pleasing as plants receiving 100 percent ET.

<u>Lysimeter Study:</u> Evapotranspiration during dry down 3 showed that 25 percent and 50 percent will use less water than 100 percent. Dry down 4 showed that 25 percent used less water than 50 percent and 100 percent. These results together indicate that 25 percent plants will use much less water than 50 percent or 100 percent. Water potential during dry downs 1, 3, and 4 indicate that 25 percent plants are more stressed than their well-watered counterparts.

All ornamental measurements showed that there is no difference between treatments. Coupling this information with the physiological data implies that plants are aesthetically pleasing regardless of irrigation amount, however 25 percent plants are much more stressed than 50 percent or 100 percent. This is perhaps very harmful if plants receiving lower amounts of water are ever subject to periods of drought.

When combining the results of both studies, plants grown in the 25 percent treatment are as aesthetically pleasing and ornamentally healthy as those in the 100 percent treatment. However, if these plants are ever subject to periods of drought they are much more likely to succumb to physiological stress than those in the 100 percent treatment. This implies that ornamental grasses put on a deficit irrigation schedule must be constantly watered to ensure health and aesthetics.

Future Work

This study will continue in the summer of 2015. Data will be combined with one year of previous work to formulate conclusions regarding a feasible level of irrigation under which ornamental grasses maintain long-term health and aesthetics.

Nutrient Retention and Productivity in Rocky Mountain Streams Under Alternative Stable States

Basic Information

Title:	Nutrient Retention and Productivity in Rocky Mountain Streams Under Alternative Stable States
Project Number:	2014CO300B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Biological Sciences
Focus Category:	Ecology, None, None
Descriptors:	None
Principal Investigators:	Dana Winkelman

Publications

There are no publications.

Nutrient Retention and Productivity in Rocky Mountain Streams Under Alternative Stable States

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Introduction/Statement of Regional Problem

Streams of the southern Rocky Mountains suffer legacy effects of beaver trapping, wood removal, timber harvest, log floating, and other activities that have greatly reduced the size and frequency of large wood (LW) and resulting log jams (Wohl 2001, Wohl & Cadol 2011). Historical studies of LW and effects on fish and habitat have focused on streams in the wet coastal forests of the Pacific Northwest (e.g., Murphy and Hall 1981; Bilby and Ward 1991; Fausch and Northcote 1992; Richmond and Fausch 1995; Harvey 1998). However, differences in precipitation rates, geology, flow regimes, forest composition, tree sizes, LW sizes, and LW decay rates (Wohl and Cadol 2011) exist between coastal forest ecosystems and the Southern Rocky Mountains of the Front Range in Colorado (Richmond and Fausch 1995; Fausch and Young 2004). For example, while abundance of LW pieces have been found to be similar in undisturbed sites in both Colorado, Alaska, and British Columbia (Robinson and Beschta 1990; Fausch and Northcote 1992; Richmond and Fausch 1995), overall volume of LW in the Rocky Mountains can be 2-10 times less than the Pacific Northwest (Bragg et al. 2000). Further, large-scale studies of jam effects on watersheds are lacking, with most previous studies limited to the 10-100m scale (see Wallace et al. 1995; Warren et al. 2007; Entrekin et al. 2009), or occurring in the Pacific Northwest (Fausch and Young 2004). Few other studies have attempted to link land management/disturbance to wood load and animal production in headwater streams (e.g., Bernhardt et al. 2003; Keeton et al. 2007).

Construction of in-stream structures to increase habitat heterogeneity has become one of the most common techniques in stream restoration (Kauffman et al. 1997; Roni et al. 2002). However, previous studies of stream restoration via LW replacement have shown variable results in increasing fish communities (Lepori et al. 2005; Whiteway et al. 2010), and LW additions are not beneficial for all species or all ontogenetic stages (Langford et al. 2012). Previous studies in Rocky Mountain streams have shown that the addition of LW increases fish populations through immigration of individuals from relatively long distances (Gowan et al. 1994; Gowan and Fausch 1996b) and not by increasing forage, habitat, or survival. Also, Mitsch and Jørgensen (2004) propose that a lack of *a priori* endpoints and post-project monitoring make it difficult to classify most restoration projects a success or failure (reviewed by Moerke et al. 2004).

Objectives

The objective of our study was to determine population and individual level effects of in-stream large wood on brook trout populations residing in streams located on the Eastern slope of the

Rocky Mountains. Specifically, the project goals were to address differences in trout (i) population size, (ii) population biomass, (iii) individual growth rates, (iv) individual fish condition, and (v) individual diet across a gradient of wood loading.

Summary of Progress: **Methods and Preliminary Results**

Sampling Design and Habitat Measurements

Twenty Four separate reaches were sampled on 13 distinct streams across a gradient of wood loading in Northern Colorado and Southern Wyoming during the summers of 2013 and 2014. Streams and reaches were selected based on size, elevation, amount of LW, and dominant fish species. We measured average stream width (using wetted width), average stream depth, pool volume and number, and volume and number of large wood pieces at each site (provided by Ellen Wohl [CSU] who is collaborating on the main project).

Population Sampling

Population sizes were estimated using multi-pass depletion sampling. Sampling was accomplished using backpack electrofishing equipment that were set at approximately 900V. At least 3 passes were made in each reach and stunned fish were captured with handheld dipnets. Fish were then identified to species, measured, weighed, and returned to the stream. Approximately 40 fish were sacrificed at each site for individual metrics (see below). Population estimates were then calculated using a Huggins' removal estimator in ProgramMARK. It appears that population density is not a simple function of wood load but is also controlled by other site specific factors. Analyses of other factors such as resource availability and temperature are ongoing. However, wood loading does seem to stabilize fish density at approximately 20 cubic meters per hectare of wood loading (Figure 1)

Individual Sampling

Approximately 40 individual fish were removed at each sampling reach for analysis of growth rates, lipid contents, and diets. Growth rates are being examined using otoliths from individual fish. Both right and left sagittal otoliths were removed, cast in epoxy, and cut on the transverse plane on either side of the otolith core to remove excess otolith and epoxy material. Sections were then polished and photographed using a camera attached to a microscope. Growth rings were counted and measured using ImageJ, by two separate readers, to ensure accuracy. To date, approximately 70% of otoliths have been analyzed and analyses will be completed by April 30th, 2015. Preliminary analyses indicate that growth rates are similar among sites (Figures 2 and 3).

Individual fish condition is being analyzed using length-weight regressions (in progress), and by extracting lipid contents from whole fish collected at a subset of sampling reaches. Lipid level is being analyzed using the Folch method (Folch et al. 1956). Lipid content was determined by homogenizing whole fish, extracting lipids, and comparing the weight of total lipids to the weight of the original sample. To date, we have analyzed 38 individual fish lipid samples from 7 different sites and further analyses are contingent upon evaluation of diet analyses. Length-weight regressions will be completed by April 30th, 2015. Preliminary results suggest a highly seasonal change in lipid contents at each site (Figure 4).

Individual diets are being analyzed from stomach contents taken from fish that were sacrificed for otolith aging. Stomachs were removed in field and stored in 95% ethanol. Stomach contents are being identified to lowest possible taxonomic level, and data analysis has begun with comparisons of biomass per gram of fish in the diet and multivariate approaches. To date, diet analyses have been completed for two sites, North St. Vrain Creek (representative high large wood loading site) and Glacier Creek (representative low large wood loading site). Preliminary results suggest that increased large wood loading significantly affects both the amount and type of macroinvertebrate prey consumed by brook trout (Figures 5 and 6). Further stomach content analyses are currently taking place (with emphasis placed on specific sites related to high and low wood loading) and are expected to be completed by Fall 2015. Additionally, the diet data will be compared with prey availability that is being analyzed by our collaborators.
All field sampling has been completed and only laboratory analyses are being performed.

Investigation of the Effects of Whitewater Kayak Parks on Aquatic Resources in Colorado

Basic Information

Title:	Investigation of the Effects of Whitewater Kayak Parks on Aquatic Resources in Colorado
Project Number:	2014CO301B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Engineering
Focus Category:	Ecology, Management and Planning, Recreation
Descriptors:	None
Principal Investigators:	Brian Bledsoe

Publications

There are no publications.

Effects of Whitewater Parks on Fish passage: A Spatially Explicit Hydraulic Analysis

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ABSTRACT
In order to evaluate and design hydraulic structures for successful fish passage, hydraulic conditions within the structure must be described at a scale meaningful to a fish. We describe novel approaches combining fish movement data and hydraulic descriptions from a three-dimensional computational fluid dynamics model to examine the physical processes that limit upstream movement of trout across 3 unique in-stream structures at a whitewater park (WWP) in Lyons, Colorado. These methods provide a continuous and spatially explicit description of velocity, depth, vorticity, and turbulent kinetic energy along potential fish swimming paths in the flow field. Logistic regression analyses indicate a significant influence of velocity and depth on limiting passage success and accurately predict greater than 87 percent of observed fish movements. However, vorticity, turbulent kinetic energy, and a cost function do not significantly affect passage success. Unique combinations of depth and velocity exist at each WWP structure that reflects variation in passage success. The methods described in this study provide a powerful approach to quantify hydraulic conditions at a scale meaningful to a fish and to mechanistically evaluate the effects of hydraulic structures on fish passage. The results of these analyses can be used for management and design guidance, and have implications for fishes with lesser swimming abilities.
Keywords: whitewater park; fish passage; barrier; hydraulic modeling; flow complexity; design.

1. Introduction

The reproductive success of migratory fishes and other organisms depends on the quantity, quality, and connectivity of available habitats that vary spatially and temporally across dimensions and scales. (Frissel et al., 1986; Frissell et al., 2001; Fausch et al., 2002). For example, many fishes migrate in search of optimal habitats for spawning, rearing, overwintering, and other life-cycle requirements (Schlosser and Angermeier, 1995). Human extraction of water resources has resulted in fragmentation of many rivers by dams, diversions, and other in-stream structures (Fagan, 2002; Nilsson et al., 2005; Perkin and Gido, 2012). When impassable, these structures cut-off necessary habitat linkages and migration routes of aquatic organisms, particularly fishes (Dudley and Platania, 2007;

Fullerton et al., 2010; Walters et al., 2014). Successful passage for fishes of all life stages across barriers to migration is imperative to restore and maintain ecosystem function (Wohl et al., 2005; Beechie et al., 2010; Bunt et al., 2012).

In-stream structures must operate within the physiological limits of a fish's swimming abilities, and understanding how fish respond to micro-hydrodynamic and macro-hydrodynamic conditions within a structure is necessary to effectively design for passage success (Williams et al., 2012). However, structures are often designed and constructed without direct knowledge of fish passage success in response to altered hydraulic conditions.

Fish exhibit multiple modes of swimming when encountering different flow velocities in order to maximize ground speed and minimize energy expenditure (Beamish, 1978; Katopodis, 2005). Velocity can act as a burst swimming barrier in which the velocity of the water is greater than the fish's maximum swim speed. Velocity can also act as an exhaustive swimming barrier where a fish is unable to maintain positive ground speed over the required distance. Adequate depth is required for a fish to reach its full swimming potential (Webb, 1975). Insufficient depth to submerge a fish impairs its ability to generate thrust through body and tail movements, exposes the gills limiting oxygen consumption, and exposes the fish to physical trauma through contact with the channel bed (Dane, 1978). Turbulence can increase or decrease a fish's swimming ability (Liao, 2007; Cotel and Webb, 2012; Lacey et al., 2012); however, high levels of turbulence pose a stability challenge to fish (Tritico and Cotel, 2010), and turbulence reduces fish swimming abilities at high current speeds (Pavlov et al., 2000; Lupandin, 2005). In particular, vorticity and turbulent kinetic energy (TKE) are recognized as meaningful measures of turbulence (Lacey et al., 2012).

Previous attempts to directly correlate fish passage with hydraulic variables yielded only poor predictors of passage success (Castro-Santos et al., 2009). Studies examining the effects of hydraulics on fish passage are constrained to laboratory settings or limited by scale, quantifying hydraulic conditions by point measurements or averaging over larger spatial scales (Crowder and Diplas, 2000, 2006; Cotel and Webb, 2012). Fish experience hydraulic conditions locally (Eulerian frame) and continuously along a movement path (Lagrangian frame) in a highly complex hydraulic environment (Goodwin et al., 2006).

A whitewater park (WWP) consists of one or more in-stream structures primarily constructed to create a hydraulic jump that is desirable to recreational kayakers and other boaters. The hydraulic jump is typically formed by grouting a laterally constricted chute over a steep drop into a downstream pool. WWPs provide a valuable recreational and economic resource (Hagenstad et al., 2000) that is rapidly growing in popularity. WWPs were originally thought to enhance aquatic habitat (McGrath, 2003); however, recent studies (Fox, 2013; Kolden, 2013) have shown that WWPs can act as a partial barrier to upstream migrating trout, and WWP pools may contain lower densities of fish compared to natural pools. Further, the magnitude of suppressed fish movement varies at different

WWP structures and among size classes of fish. Higher velocities with larger spatial extents were recorded in WWPs compared to natural reaches, and unique hydraulic conditions exist at individual WWP structures as a result of seemingly subtle differences in their design and configuration. Concerns have arisen that the hydraulic conditions required to meet recreational needs are contributing to the suppression of movement of upstream migrating fishes and disruption of longitudinal connectivity. Without a direct understanding of the factors contributing to the suppression of movement in WWPs, making informed management and policy decisions regarding WWPs will continue to be difficult and could have unintended consequences.

In order to determine the effect of hydraulic conditions on passage success, detailed fish movement data must be assessed in conjunction with hydraulic characteristics at a scale meaningful to a fish (Williams et al., 2012). Advancements in quantifying fish movement through passive integrated transponders (PIT) tags have increased our ability to monitor and evaluate passage success. Additionally, computational fluid dynamics (CFD) models provide a powerful means of estimating the fine-scale hydrodynamic conditions through which fish pass.

1.1. Objectives

We describe novel approaches combining fish movement data and hydraulic results from a 3-D computational fluid dynamics model to examine the physical processes that limit upstream movement of trout in an actual WWP in Lyons, Colorado. The objectives of this study were to:

1. Use the results from a 3-D CFD model to provide a continuous and spatially explicit description of velocity, depth, vorticity, and TKE along the flow field at WWP structures containing PIT antennas.
2. Compare the magnitudes and distribution of velocity, depth, vorticity, and TKE among three unique WWP structures on the St. Vrain River in Colorado.
3. Determine the relationship between velocity, depth, vorticity, and TKE on the suppression of movement of upstream migrating fishes through statistical analysis of movement data from PIT-tag studies at the St. Vrain WWP.
4. Provide design recommendations and physically-based relationships that help managers better accommodate fish passage through WWP structures.

2. Methods

2.1. Study site

The North Fork of the St. Vrain River originates on the east slope of the Rocky Mountains where it flows east to the foothills region in the town of Lyons and its confluence with the South Fork of the St. Vrain River at 1637 m. The study site consists of nine WWP structures along a 400 m reach in Meadow Park. The natural river morphology at the study site can be described as the transition zone between a step-pool channel and a meandering pool-riffle channel with a slope of 1%. The natural river channel is characterized by riffles, runs, and shallow pools with cobble and boulder substrates. The North Fork of the St. Vrain River experiences a typical snowmelt hydrologic regime with a drainage area of 322 km^2 and peak flows occurring in late May to early June. In September 2013, the river was the site of massive catastrophic flooding; field data collection was performed before this flooding occurred. A stage-discharge rating relationship was empirically developed at the site over the course of the study to provide a continuous record of discharges. Three of the nine WWP structures were selected for the study to represent the range of structure types and hydraulic conditions at the site. WWP1 is the downstream-most structure characterized by a short, steep drop constructed by large boulders. WWP2 is the middle structure producing a wave over a longer distance with the maximum constriction at the exit of the chute into the downstream pool. WWP3 is the upstream-most structure producing a wave similar to WWP2, but over a longer chute.

2.2. Fish movement data and hydraulic modeling results

2.2.1. Fish movement data

Fish passage was assessed at three WWP structures by obtaining 14 months of fish movement data from PIT-antenna arrays (Fox, 2013). Tagged rainbow trout (*Oncorhynchus mykiss Hofer x Harrison* strain) and brown trout (*Salmo trutta*) were included in the analysis totaling 536 tagged fish ranging in size from 115 to 435 mm as total length. Due to safety risks involving park users, PIT antennas were installed directly upstream of the WWP structures and in the tail-out of the pools directly downstream of the WWP structures (Fig. 1). The PIT-antenna configuration associated a time stamp and river discharge with a successful movement, but it did not provide information on individual fish that failed to cross the upstream antenna. Therefore, fish were classified as fish that did pass a structure versus fish that did not pass a structure.

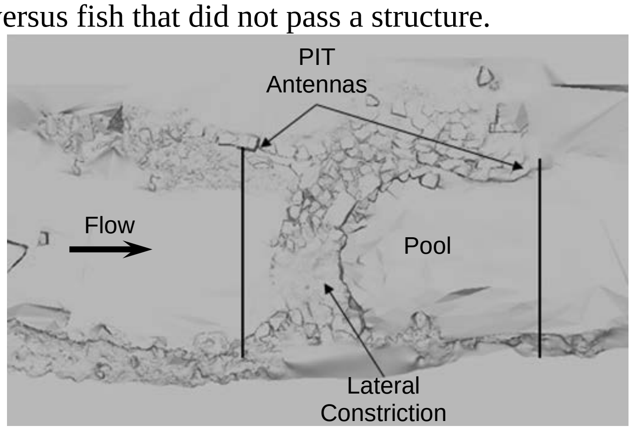


Fig. 1. Plan view of a WWP structure with PIT-antenna configuration**.**

Passage success was evaluated over four discrete time intervals: October 2011 – March 2012, March 2012 – October 2012, October 2012 – November 2012, and November 2012 – December 2012. The start of each time interval was defined by a stocking or electroshocking event in which fish were observed in the pool directly below a structure. Movements were evaluated over the duration of that respective time interval. A successful movement across a structure was only included in the analysis if a fish was observed in the pool directly below that structure at the start of the time interval. This prevented overestimating passage success at structures where fishes with greater swimming abilities were able to migrate upstream crossing multiple structures over the duration of a time interval. There were 429 successful movements over the duration of all the time intervals.

2.2.2. Hydraulic modeling results

Seven discharges were modeled at three WWP structures containing PIT antennas using the 3-D CFD software FLOW-3D® v10.0 (Kolden, 2013). The modeled discharges include: 0.42, 0.85, 1.70, 2.80, 4.20, 4.80, and 8.50 cms, representing a range of flows that produce various habitats throughout the year. The annual flow duration exceedance probabilities for the modeled discharges range from 90 percent to less than 10 percent (Fox, 2013). FLOW-3D® described the flow field by solving the Reynolds-Averaged Navier-Stokes (RANS) equations of fluid motion and a default renormalization group (RNG) turbulence closure with dynamically computed turbulent mixing length. The fluid domain was comprised of a series of discrete points making-up a mesh. The uniform grid sizes of the mesh ranged from 4 to 15 cm. The free surface was represented in the structured mesh by a process called volume of fluid (VOF; FLOW Science, 2009), and channel roughness elements were assumed to be adequately resolved through surveyed bathymetry obtained by ground a ground-based Light Detection and Ranging System (LiDAR), a Leica Total Station, and a Topcon® HiPer XT™ Global Positioning System (GPS) base and rover system (Kolden, 2013). A measured water surface elevation for each volumetric flow rate was used to specify a downstream pressure boundary. Field measurements of water surface elevations, velocity profiles, and wetted perimeter ensured the model was performing within an acceptable range of error (Kolden, 2013). Additional model validation was infeasible due to severe floods in September 2013 that significantly altered the channel geometry. Post-processing of the hydraulic results from the CFD model was performed using EnSight® Standard v10.1 (Computational Engineering International, Inc., https://www.ceisoftware.com).

2.3. Defining the flow field

In order to equally compare the hydraulics among WWP structures and across a range of discharges within WWP structures, a physically-based criterion was needed to define the upstream and downstream boundaries of the analysis domain. The Froude number provided a physically meaningful criterion for establishing boundary conditions that captured the full extent of potential hydraulic barriers to fish passage. The upstream and downstream boundaries were defined by a Froude number of 1 and 0.8, respectively. The upstream boundary condition includes supercritical flow and the most challenging velocities that must be traversed by a fish at all discharges. The downstream boundary encompasses the hydraulic jump from supercritical flow to subcritical flow and the highest levels of turbulence.

EnSight® was used to create a flow volume consisting of the total modeled domain. Additional reduced flow volumes were created that consisted of the total modeled domain below a specified Froude number. The cross-sectional area of the reduced and total flow volumes were sampled at 8-cm longitudinal increments throughout the entire reach. A deviation in the cross-sectional area, between the total flow volume and the reduced flow volume, indicated areas with a Froude number greater than the thresholds used to define the boundaries of the analysis domain. This process was repeated for all modeled discharges at each structure. The upstream-most point for all discharges at which the cross-sectional areas diverged was used as the upstream boundary, and the downstream-most point at which the cross-sectional areas diverged was used as the downstream boundary. The Froude criteria were thoroughly analyzed to ensure the boundaries captured all features of the flow field relevant to fish passage.

2.4. Particle trace and potential movement path development

Releasing particle traces through the flow field and quantifying hydraulic variables along each trace provides a meaningful description of the hydraulic conditions a fish might encounter while migrating upstream. EnSight® was used to emit particle traces from nodes within the gridded mesh. A particle trace consists of a series of points that track a massless particle through both time and space in the fluid domain. The trajectory of the particle trace is parallel to the velocity vector field at that point and time. Particle traces were emitted forward and backward in time from volumes at the upstream and downstream boundaries encompassing important hydraulic features and the entirety of the flow field including eddies and zones of reverse flow.

A portion of the particle traces released from volumes at the upstream and downstream boundaries both forward and backward in time nevertheless stopped prematurely and did not reach the opposite boundary. A particle trace stopped prematurely if the trace moved outside the space in which the vector field was defined or the particle trace entered a location where the velocity was zero (EnSight®; Computational Engineering International, Inc., 2013). Additional particle traces existed that recirculated in an eddy before stopping prematurely or continuing through the flow field. Particle traces that stopped prematurely or recirculated within the flow volume introduce bias when quantifying hydraulic variables along each particle trace and assessing the conditions a fish might experience as it swims upstream.

To resolve this bias, particle traces that recirculated to the upstream or downstream boundary were divided at the point where they began to recirculate relative to the upstream/downstream directions. Two particle traces that do not make it through the entire flow volume result from each circulation. Each trace that did not make it through the entire volume (incomplete trace) was connected to a trace that did travel through the entire flow volume (complete trace) providing a path that represents the hydraulic conditions a fish might experience when migrating upstream. This task was accomplished by searching for the point within all the complete traces with the shortest Euclidean distance (maximum connection distance of 15 cm) to the terminus of an incomplete trace. The new trace consisted of the incomplete trace, the point of connection, and the needed portion of the complete trace to continue through the entire flow volume and account for recirculating particle traces. Approximately 6,500 to 20,000 particle traces were used to describe the flow field at each structure depending on the flow volume being analyzed.

2.5. Hydraulic conditions along potential movement paths

Each particle trace was evaluated as a potential fish movement path (flow path). Velocity, depth, vorticity, and TKE were defined in 3-D at every point along a flow path and used to define hydraulic variables that relate to fish swimming abilities. The maximum velocity relative to fish swimming ability, a cumulative cost in terms of energy and the drag force on a fish, the minimum depth, and the sum and maximum vorticity and TKE were quantified along the entire length of each flow path providing a distribution of hydraulic variables for each modeled discharge. The magnitude and distribution of these hydraulic variables were compared among WWP structures.

2.5.1. Velocity

The magnitude of a velocity vector was calculated as the root-mean-square (*rms*) of velocity in the *x*, *y*, and *z* planes with a directional component relative to the *x*-direction (Eq. 1):

$$v_{rms} = \sqrt{v_x^2 + v_y^2 + v_z^2} \cdot \left(\frac{|v_x|}{v_x} \right) \qquad \textbf{Eq. 1}$$

By definition, the *rms* of velocity is always positive and does not take into account the direction of flow. This is important because a velocity vector with a resultant in the positive upstream direction might be advantageous to a fish migrating upstream. Therefore, positive and negative signs were assigned to the v_{rms} based on the velocity in the downstream (v_x) and upstream directions, respectively. A positive value indicates a resultant in the downstream direction, while a negative value indicates a resultant in the upstream direction. Velocity vectors that were limited to the *y* (v_y) and *z* (v_z) planes were assigned a positive value.

Velocity was used to define a variable that assesses the hydraulic environment relative to burst swimming ability. The velocity ratio is defined as the ratio of the local water velocity (v_{rms}) to the burst swimming ability (v_{burst}) of a particular fish (Eq. 2):

$$\text{velocity ratio} = \frac{v_{rms}}{v_{burst}} \qquad \textbf{Eq. 2}$$

This variable is evaluated at every point along a flow path. If the ratio is ≥ 1, theoretically the fish cannot traverse that point. The maximum velocity ratio (MVR) was determined along each flow path and the fraction of traces with a MVR ≥ 1 was determined. If this fraction equals 1, every trace contains a point greater than a fish's burst swimming ability. If this fraction is zero, theoretically, none of the flow paths are greater than a fish's burst swimming ability. The MVR was determined for 100- to 400-mm fish with burst swimming abilities of 10 and 25 BL/s (MVR_{10} and MVR_{25}, respectively) (Peake et al., 1997; Castro-Santos et al., 2013).

Velocity was also used to define a cost variable (Eq. 3) in order to compare relative measures of cumulative energy expenditure through the length of a structure:

$$\text{cost} = \int v_{rms}^2 \cdot d \cdot \left(\frac{v_{rms}}{|v_{rms}|} \right) \qquad \textbf{Eq. 3}$$

where v_{rms} is the average *rms* velocity between two nodes; and d is the distance between two nodes. The square of velocity is proportional to energy and the drag force on a fish (Chow, 1959; McElroy et al., 2012). The distance term accounts for the length over which a fish might experience those velocities. By squaring the v_{rms}, it is always positive; thus, the fraction term containing the v_{rms} adds a directional component to the cost based on the upstream/downstream directions. If the flow is traveling downstream, the cost between nodes will be positive as a fish will have to expend more energy to swim against the flow and vice versa. Cost is calculated over the distance in between nodes and summed along the length of the flow path. Therefore, the length of the hydraulic jump at a structure has a direct effect on cost.

2.5.2. Depth

A minimum of 0.18 m was used to evaluate depth as a barrier to upstream passage for this study. Without direct knowledge of fish body depths, 0.18 m provides an average minimum depth criterion (MDC) across the range of suggested values and fish size (Hotchkiss and Frei, 2007). Any location along a flow path where the fluid was less than 0.18 m was defined as a passage barrier. The minimum fluid depth along each flow path was evaluated, and the fraction of flow paths that did not maintain at least 0.18 m along the entire length of the path was determined (MDC). The MVR and MDC were also assessed in combination (MVR & MDC). If the minimum depth along a flow path was less than 0.18 m or the maximum velocity along the path was greater than a fish's swimming ability, the flow path was considered a passage barrier. Each flow path was evaluated, and the fraction of flow paths that exceeded a fish's burst swimming ability or did not provide adequate depth was determined.

2.5.3. Turbulence

Vorticity and TKE were selected as measures of turbulence meaningful to a fish. Vorticity is a vector representing the rotation rate of a small fluid element about its axis (Crowder and Diplas, 2002). EnSight® was used to calculate 3-D vorticity ($\bar{\xi}$) at each element within the gridded mesh (Eq. 4):

$$\bar{\xi} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\hat{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\hat{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\hat{k} \qquad \textbf{Eq. 4}$$

where u, v, and w are the x-, y-, and z-components of velocity, respectively, and i, j, and k are unit vectors in the x, y, and z directions, respectively. TKE is a measure of the increase in kinetic energy due to turbulent velocity fluctuations in the flow (Eq. 5) (FLOW Science, 2009; Lacey et al., 2012):

$$\text{TKE} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right) \qquad \textbf{Eq. 5}$$

where σ_u, σ_v, and σ_w are the standard deviations of velocity in the x, y, and z directions, respectively.

The magnitudes of vorticity and TKE at each point along a flow path were summed over the length of the path quantifying the cumulative effect of vorticity and TKE a fish might experience. Additionally, the maximum vorticity and TKE along the length of a path was determined to examine the largest magnitudes of vorticity and TKE a fish might experience. Specific thresholds of turbulence relative to fish swimming abilities are unknown; therefore, we are limited to a relative comparison of turbulence among WWP structures and passage success. Examining the cumulative effect and maximum magnitudes of vorticity and TKE along each flow path highlights potential barriers due to turbulence cumulatively through the flow volume and in locations characterized by the highest levels of turbulence.

2.6. Data analysis

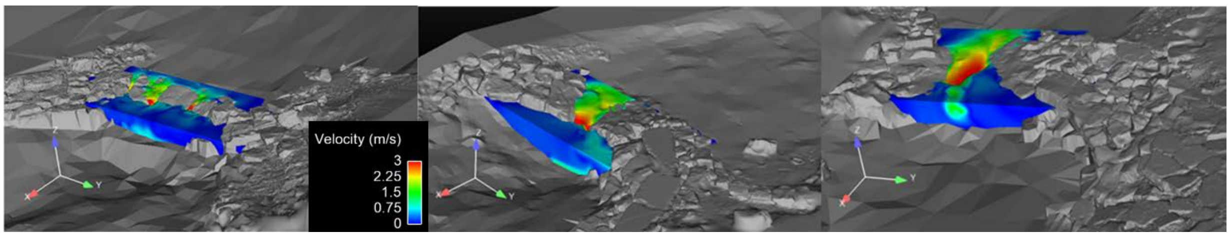
Individual fish were designated as making a successful movement or an unsuccessful movement for each time interval. The hydraulic variables associated with a successful movement were determined based on the discharge at which the movement occurred. However, the hydraulic variables associated with an unsuccessful movement were determined based on the most frequent discharge that occurred during the respective time interval. Logistic regression was used to test for a significant influence of the hydraulic variables on passage success. Significance was evaluated using the chi-square (χ^2) statistic. Stepwise forward regression with a minimum Akaike Information Criterion (AIC) stopping rule was used to determine the hydraulic variables to include in logistic regression. Collinearity was assessed by examining the bivariate fits among the hydraulic variables. To avoid issues of collinearity, combinations of variables were manually selected to be tested for significance by stepwise forward regression. All statistical procedures were completed using JMP® Pro 11 (SAS Institute Inc., 2013).

3. Results

Quantifying the hydraulic conditions along potential fish swimming paths highlights the magnitude and distribution of potential barriers to upstream migrating trout at each WWP structure. The magnitude and distribution of the hydraulic variables vary among WWP structures, relative to each size class of fish, and across discharges, similar to passage success. Further, logistic regression shows a statistically significant influence of specific hydraulic variables on passage success.

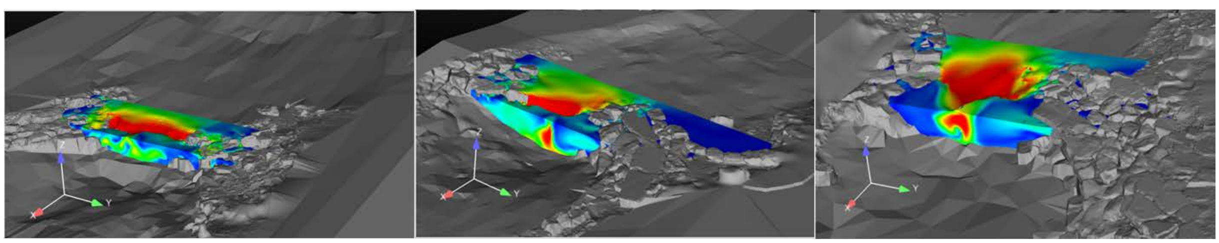
3.1. Hydraulic variables

WWP1 WWP2 WWP3



(a) 0.42 cms

WWP1 WWP2 WWP3



(b) 4.20 cms

Fig. 2. Analysis flow volume at each WWP structure for (a) 0.42 cms and (b) 4.20 cms.

3.1.1. Velocity and Depth

At lower discharges, continuous passage routes across WWP1 are only accessible through narrow chutes (less than 0.3 m) flowing in between boulders that may not provide adequate depth or flow area for larger fish, but do provide lower velocities accessible to smaller fish (Figure 2). As discharge increases more flow paths might become available for larger fish, while smaller fish are inhibited by velocity. This is confirmed through the MVR, MDC, and observed passage success by size class. For example, the MVR_{25} at WWP1 indicates that there are more flow paths available (flow paths that are not barriers to migration) at 0.42 cms compared to 8.5 cms for a 125-mm fish (Table 1). In contrast, there are more flow paths available at 8.5 cms compared to 0.42 cms for a 150-mm fish. Depth presents the greatest challenge across all discharges at WWP1 (Figure 3), and examining the MVR_{25} & MDC and MVR_{10} & MDC indicates that WWP1 provides the most available flow paths for smaller fish (Tables 4 and 5).

WWP2 constricts the flow to the center of the chute at lower discharges and forces fish to traverse shallow flow depths characterized by the highest velocities. This is reflected in the lack of flow paths meeting the MDC at 0.42 cms and the fraction of flow paths that exceed burst swimming ability for 25 BL/s at 0.85 cms. At 0.85 cms, the fraction of accessible flow paths is limited and similar among size classes for a 175- to 300-mm fish, indicating concentrated flow. When observing higher discharges and the fraction of available flow paths for 10 BL/s, there is a positive linear increase in the amount of available flow paths with fish size that is reflective of a linear increase in passage success (Table 2). As discharge increases, flow spills over the wing walls and a small zone adjacent to the left bank provides lower velocities (Fig. 2 and Tables 1-2).

In general, there are more available flow paths across discharges and size classes of fish at WWP3, with a majority of the flow paths becoming available for fish exceeding 150 mm in length (Table 1). At WWP3, recirculation zones exist adjacent to the main velocity jet. At lower flows these low-velocity zones may not provide adequate flow depth, forcing fish to pass through the main velocity jet (Fig. 2 and 3). As discharge increases, water spills over the wing walls, flow depths increase adjacent to the main velocity jet, and more flow paths become available to larger fish. These flow patterns are confirmed by examining the MVR_{10} & MDC. Depth appears to prevent passage at 0.42 cms, while passage is accessible to larger fish as discharge increases to 0.85 cms, indicating velocity as the limiting factor. A threshold appears in the MVR_{10} with a large fraction of flow paths becoming available at 0.42 to 1.70 cms.

There is a general trend at all WWP structures for fish less than 175 mm in length that neither the lowest nor highest discharge presents the greatest challenge; rather, an intermediate discharge appears to be most limiting (Tables 1 and 2). Simultaneously examining the MVR_{25} and MDC shows that greater than 80 percent of the flow paths are inaccessible to fish of all size classes at flows less than 0.85 cms (Table 3). Additionally, combining the MVR_{10} and MDC as barriers to migration indicates that greater than 90 percent of the flow paths are unavailable for fish less than 300 mm in length (Table 4).

Table 1
Fraction of flow paths that exceed burst swimming abilities (25 BL/s) for each size class, discharge, and WWP structure (red = no flow paths are available, green = all flow paths are available).

		Fish body length												
	Discharge (cms)	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	0.89	0.2	0.12	0.07	0.02	0.02	0	0	0	0	0	0	0
	0.85	1	0.44	0.12	0.08	0.01	0	0	0	0	0	0	0	0
	1.70	1	0.28	0.13	0.06	0.05	0	0	0	0	0	0	0	0
	2.80	1	0.95	0.21	0.07	0	0	0	0	0	0	0	0	0
	4.20	0.99	0.9	0.1	0.03	0.03	0	0	0	0	0	0	0	0
	4.80	0.98	0.86	0.35	0.09	0	0	0	0	0	0	0	0	0
	8.50	0.96	0.54	0.05	0.01	0	0	0	0	0	0	0	0	0
WWP2	0.42	1	0.85	0.11	0	0	0	0	0	0	0	0	0	0
	0.85	1	1	0.39	0.25	0.23	0.23	0.23	0.23	0.23	0.03	0.03	0.03	0
	1.70	1	1	1	0.19	0.01	0	0	0	0	0	0	0	0
	2.80	1	0.97	0.62	0.28	0.17	0	0	0	0	0	0	0	0
	4.20	1	0.76	0.62	0.15	0	0	0	0	0	0	0	0	0
	4.80	1	0.99	0.45	0.2	0.07	0	0	0	0	0	0	0	0
	8.50	1	0.98	0.23	0.03	0	0	0	0	0	0	0	0	0
WWP3	0.42	1	0.07	0	0	0	0	0	0	0	0	0	0	0
	0.85	1	0.07	0	0	0	0	0	0	0	0	0	0	0
	1.70	1	0.27	0	0	0	0	0	0	0	0	0	0	0
	2.80	1	0.83	0.36	0.01	0	0	0	0	0	0	0	0	0
	4.20	1	0.9	0.5	0	0	0	0	0	0	0	0	0	0
	4.80	0.57	0.55	0.27	0.07	0	0	0	0	0	0	0	0	0
	8.50	1	0.76	0.34	0.01	0	0	0	0	0	0	0	0	0

Table 2
Fraction of flow paths that exceed burst swimming abilities (10 BL/s) for each size class, discharge, and WWP structure (red = no flow paths are available, green = all flow paths are available).

	Discharge (cms)	Fish body length 100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	1	1	1	1	1	0.93	0.89	0.75	0.53	0.16	0.12	0.12	0.11
	0.85	1	1	1	1	1	1	1	0.75	0.58	0.39	0.2	0.12	0.09
	1.70	1	1	1	1	1	1	1	0.99	0.96	0.26	0.17	0.13	0.12
	2.80	1	1	1	1	1	1	1	1	0.96	0.93	0.62	0.21	0.12
	4.20	1	1	1	1	1	1	0.99	0.94	0.92	0.86	0.48	0.1	0.07
	4.80	1	1	1	1	1	1	0.98	0.92	0.88	0.81	0.7	0.35	0.23
	8.50	1	1	1	1	1	0.99	0.96	0.84	0.62	0.44	0.18	0.05	0.01
WWP2	0.42	1	1	1	1	1	1	1	1	0.88	0.25	0.15	0.11	0.06
	0.85	1	1	1	1	1	1	1	1	1	1	0.45	0.39	0.28
	1.70	1	1	1	1	1	1	1	1	1	1	1	1	0.88
	2.80	1	1	1	1	1	1	1	0.99	0.98	0.71	0.69	0.62	0.47
	4.20	1	1	1	1	1	1	1	1	0.76	0.72	0.67	0.62	0.36
	4.80	1	1	1	1	1	1	1	1	1	0.6	0.58	0.45	0.32
	8.50	1	1	1	1	1	1	1	1	0.99	0.95	0.35	0.23	0.08
WWP3	0.42	1	1	1	1	1	1	1	0.51	0.14	0.01	0	0	0
	0.85	1	1	1	1	1	1	1	0.96	0.61	0	0	0	0
	1.70	1	1	1	1	1	1	1	0.68	0.65	0.04	0.01	0	0
	2.80	1	1	1	1	1	1	1	0.87	0.84	0.76	0.57	0.36	0.26
	4.20	1	1	1	1	1	1	1	0.98	0.96	0.74	0.64	0.5	0.1
	4.80	1	1	1	1	1	0.82	0.57	0.57	0.56	0.5	0.35	0.27	0.17
	8.50	1	1	1	1	1	1	1	1	0.81	0.74	0.67	0.34	0.24

3.1.2. Minimum depth criterion (MDC)

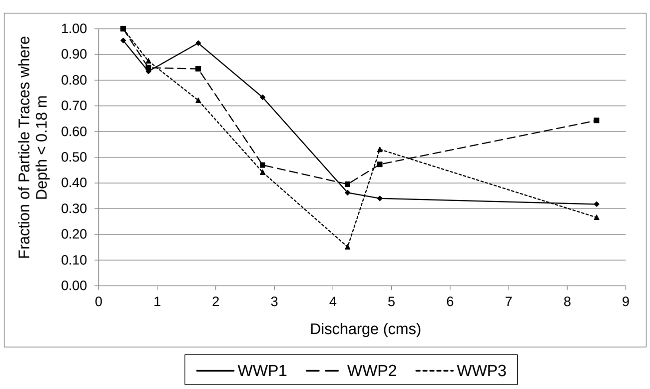


Fig. 3. The fraction of flow paths where the minimum depth is less than 0.18 m for each discharge and WWP structure.

Table 3
Fraction of flow paths that either exceed burst swimming abilities (25 BL/s) or do not provide adequate depth for each size class, discharge, and WWP structure (red = no flow paths are available, green = all flow paths are available).

		Fish body length												
	Discharge (cms)	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	1	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	0.85	1	0.98	0.88	0.87	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	1.70	1	1	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.94	0.94	0.94	0.94
	2.80	1	0.99	0.78	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	4.20	1	0.99	0.39	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	4.80	1	0.96	0.55	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
	8.50	1	0.73	0.36	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
WWP2	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	1	0.91	0.86	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	1.70	1	1	1	0.89	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	2.80	1	1	1	0.72	0.64	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	4.20	1	1	0.96	0.54	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	4.80	1	1	0.9	0.66	0.55	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
	8.50	1	1	0.81	0.67	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
WWP3	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	0.88	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
	1.70	1	0.92	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	2.80	1	1	0.78	0.45	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
	4.20	1	1	0.65	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	4.80	1	1	0.79	0.6	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
	8.50	1	1	0.61	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

Table 4
Fraction of flow paths that exceed burst swimming abilities based on the MVR & MDC (10 BL/s) for each size class, discharge, and WWP structure (red = no flow paths are available, green = all flow paths are available).

		Fish body length												
	Discharge (cms)	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm	275 mm	300 mm	325 mm	350 mm	375 mm	400 mm
WWP1	0.42	1	1	1	1	1	1	1	1	0.96	0.95	0.95	0.95	0.95
	0.85	1	1	1	1	1	1	1	1	1	0.97	0.88	0.88	0.87
	1.70	1	1	1	1	1	1	1	1	1	0.99	0.95	0.95	0.95
	2.80	1	1	1	1	1	1	1	1	0.99	0.98	0.87	0.78	0.74
	4.20	1	1	1	1	1	1	1	0.99	0.99	0.96	0.67	0.39	0.37
	4.80	1	1	1	1	1	1	1	1	0.98	0.93	0.86	0.55	0.45
	8.50	1	1	1	1	1	1	1	0.97	0.8	0.65	0.43	0.36	0.33
WWP2	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	1	1	1	1	1	1	1	1	1	0.96	0.91	0.89
	1.70	1	1	1	1	1	1	1	1	1	1	1	1	0.96
	2.80	1	1	1	1	1	1	1	1	1	1	1	1	0.89
	4.20	1	1	1	1	1	1	1	1	1	1	1	0.96	0.7
	4.80	1	1	1	1	1	1	1	1	1	1	0.98	0.9	0.77
	8.50	1	1	1	1	1	1	1	1	1	0.99	0.92	0.81	0.7
WWP3	0.42	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.85	1	1	1	1	1	1	1	1	0.96	0.88	0.87	0.87	0.87
	1.70	1	1	1	1	1	1	1	1	1	0.75	0.72	0.72	0.72
	2.80	1	1	1	1	1	1	1	1	1	0.99	0.97	0.78	0.68
	4.20	1	1	1	1	1	1	1	1	1	0.86	0.76	0.65	0.25
	4.80	1	1	1	1	1	1	1	1	1	0.97	0.87	0.79	0.7
	8.50	1	1	1	1	1	1	1	1	1	1	0.94	0.61	0.5

3.1.3. Cost

The magnitude and distribution of cost vary among WWP structures and discharges (Fig. 4a). The total length of the flow volume from the upstream boundary to downstream boundary was 3.4 m at WWP1, 5.0 m at WWP2, and 6.0 m at WWP3 (Fig. 2). The difference in the lengths of the flow volumes is a direct result of differences in the length of the hydraulic jump. The length of the hydraulic jump is greatest at WWP3, resulting in greater distances of supercritical flow and higher velocities. Consequently, WWP3 is characterized by the highest 50th percentile of cost. However, similar costs exist at WWP2 and WWP3 at lower flows. As discharge increases, lower velocities along the channel margins result in broader distributions of cost indicating greater hydraulic heterogeneity within the flow field. WWP1 consistently has a lower cost at all discharges.

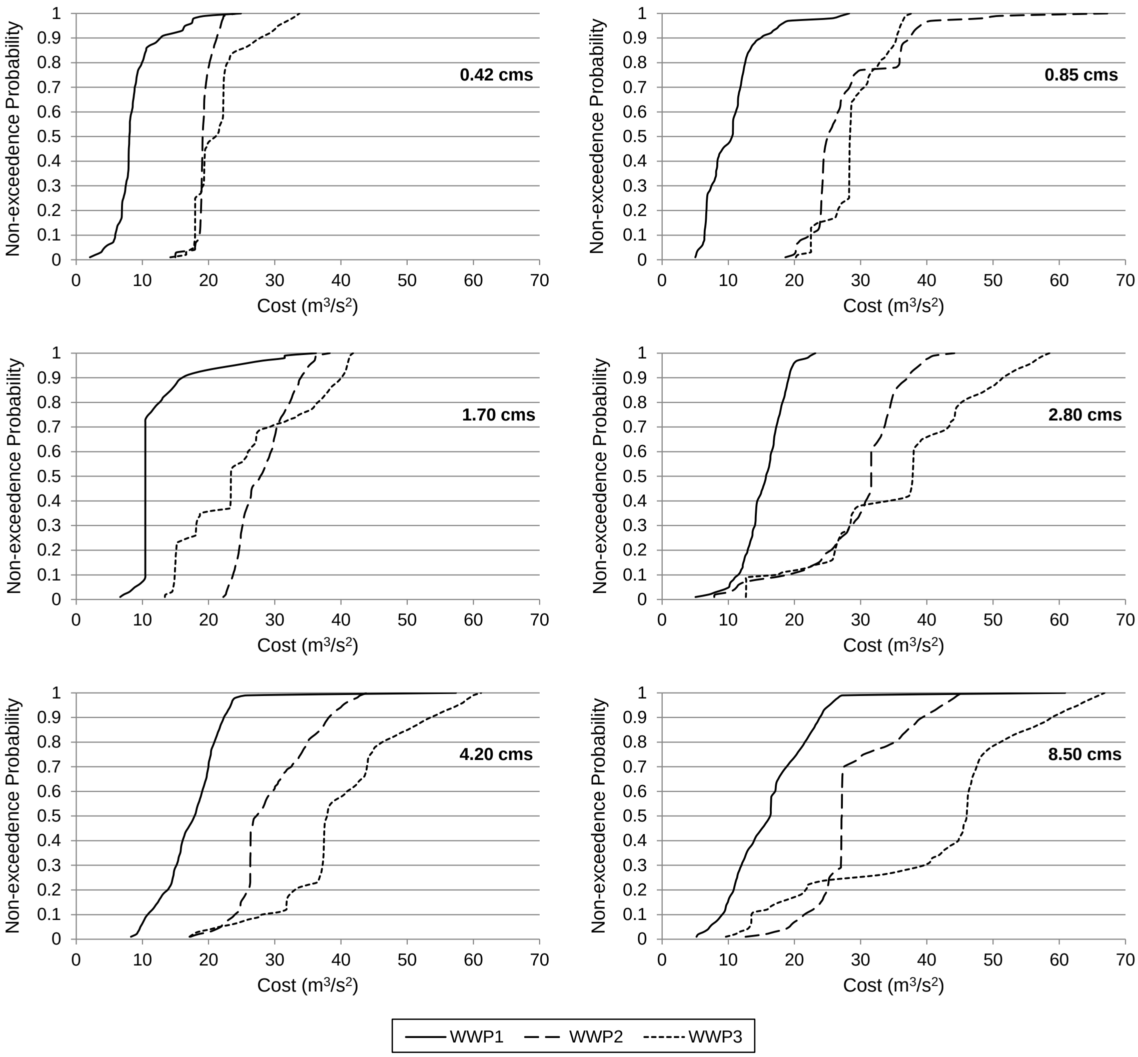


Fig. 4a. Non-exceedence probabilities for the cost along flow paths at each WWP structure and modeled discharge.

3.1.4. Turbulence

The highest magnitudes and broader distributions of the maximum vorticity generally occur at the lowest discharges (0.42 cms). WWP3 has the greatest 50^{th} percentile of maximum vorticity at 0.42 cms (Fig. 4b). The magnitude and distribution of the maximum vorticity is similar among WWP structures at discharges $\geq$ 4 cms. The maximum of the sum of vorticity along a flow path varies between WWP2 and WWP3 depending on the discharge and percentile being analyzed (Fig. 4b). However, there is a general trend that WWP1 contains the lowest sum of vorticity along a flow path. Additionally, narrow distributions of the sum of vorticity for each WWP structure exist at 0.42 and 8.50 cms.

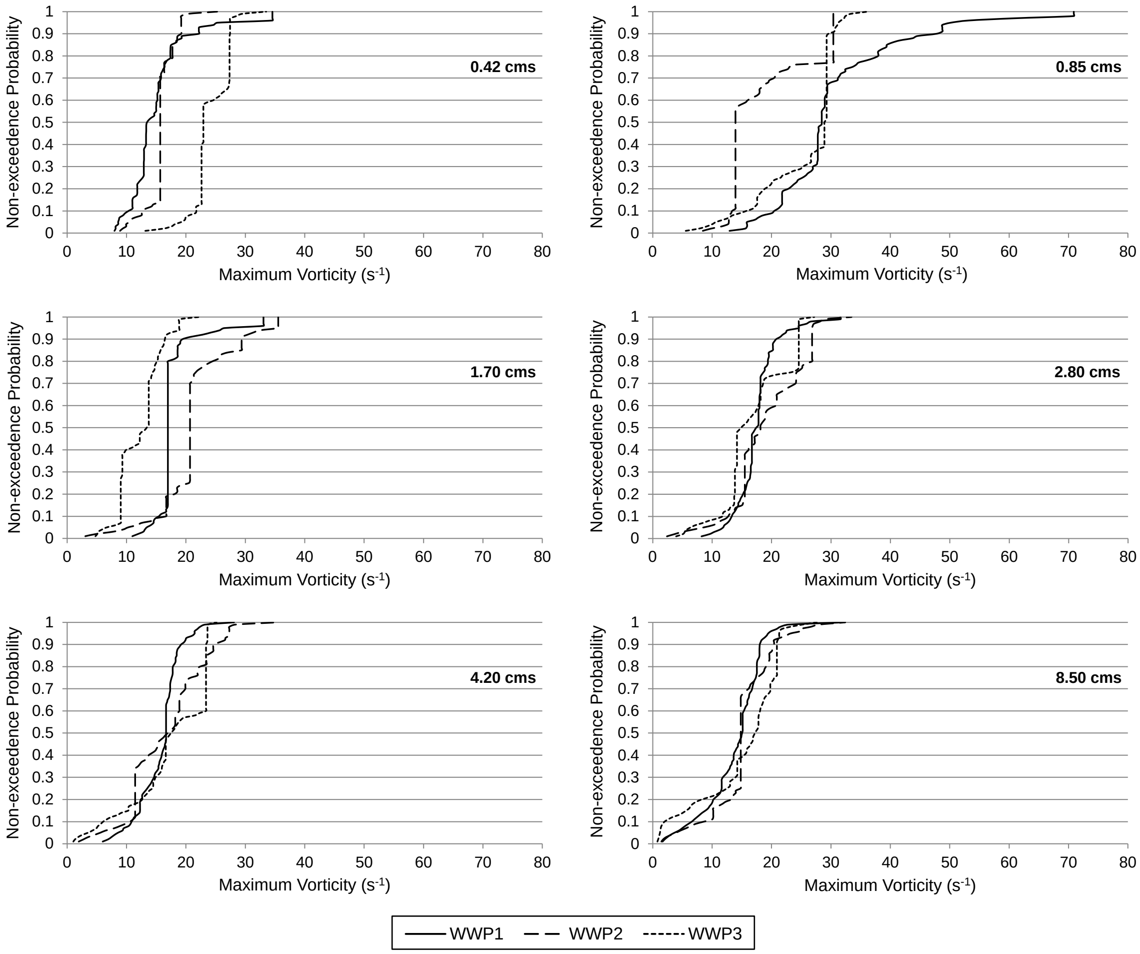


Fig. 4b. Non-exceedence probabilities for maximum vorticity along flow paths at each WWP structure and modeled discharge.

The magnitude and distribution of the maximum TKE and the sum of TKE along a flow path also vary substantially among WWP structures and discharges (Fig. 4c). At a specific discharge, the maximum TKE among WWP structures depends on the percentile of the distribution. WWP2 has the greatest 50^{th} percentile of the maximum TKE at all discharges except 0.42 cms (Fig. 4c). WWP3 appears to have a more narrow distribution of the maximum TKE at all discharges compared to WWP1 and WWP2. Similar trends in the relative magnitude of the 50^{th} percentile of the sum of vorticity and TKE exist at each individual WWP structure (Fig. 4c). The 50^{th} percentile of the sum of TKE is lowest at WWP1 for all discharges. However, WWP1 has the overall maximum of the sum of TKE along a flow path at 8.50 cms. Each structure is characterized by a narrower distribution of the sum of TKE at 0.42 cms.

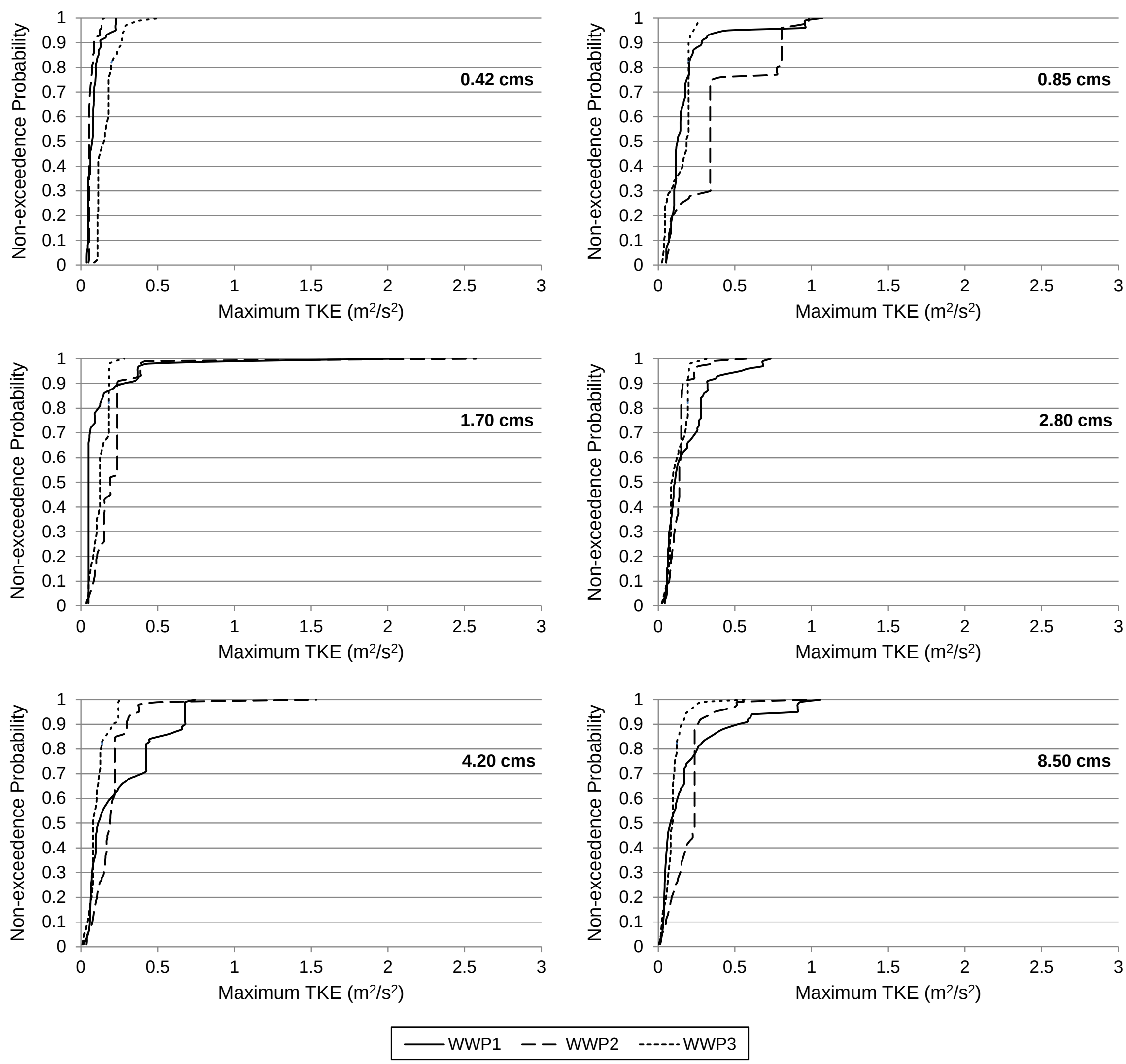


Fig. 4c. Non-exceedence probabilities for the maximum TKE along flow paths at each WWP structure and modeled discharge.

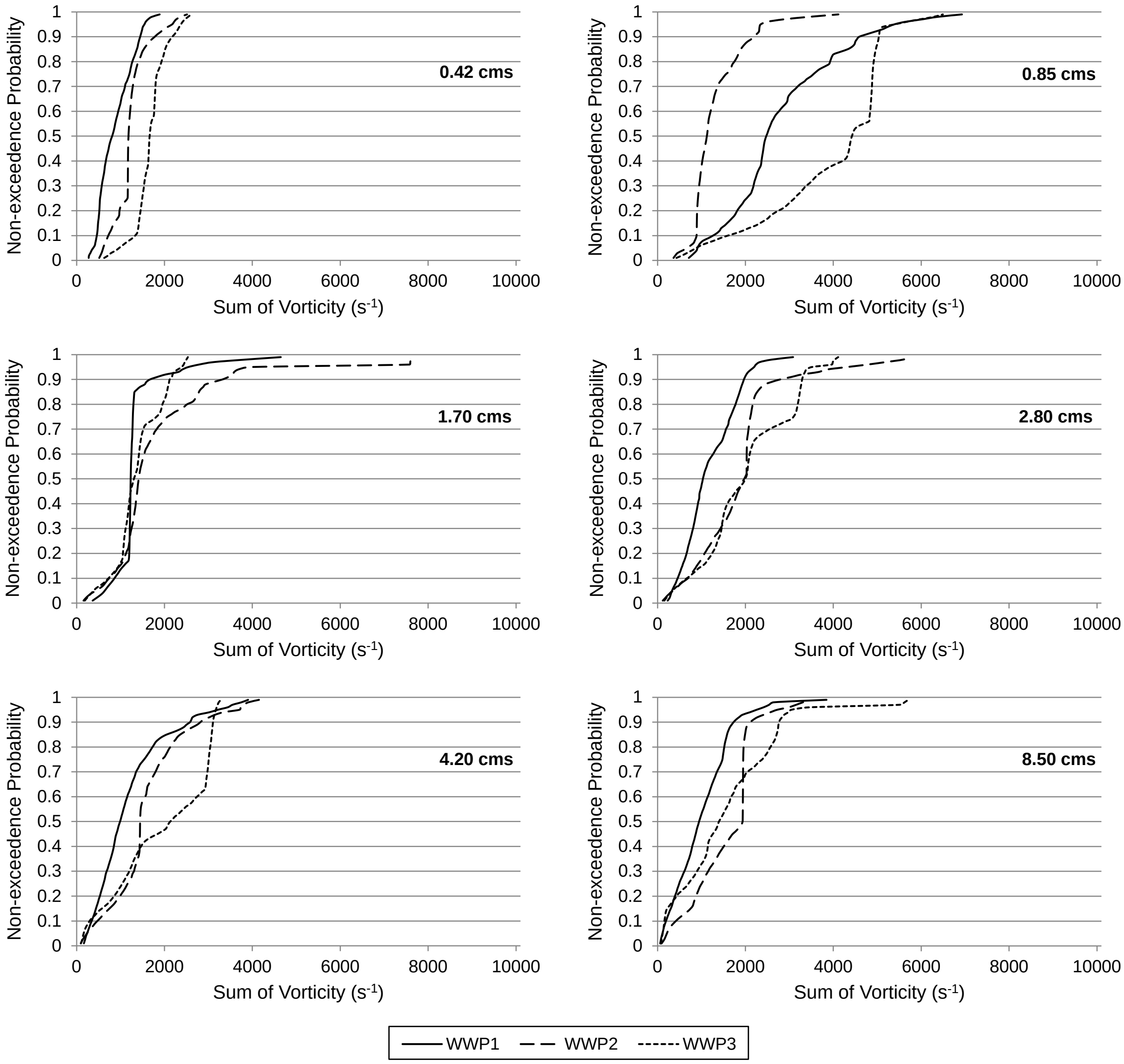


Fig. 4d. Non-exceedence probabilities for sum of vorticity along flow paths at each WWP structure and modeled discharge.

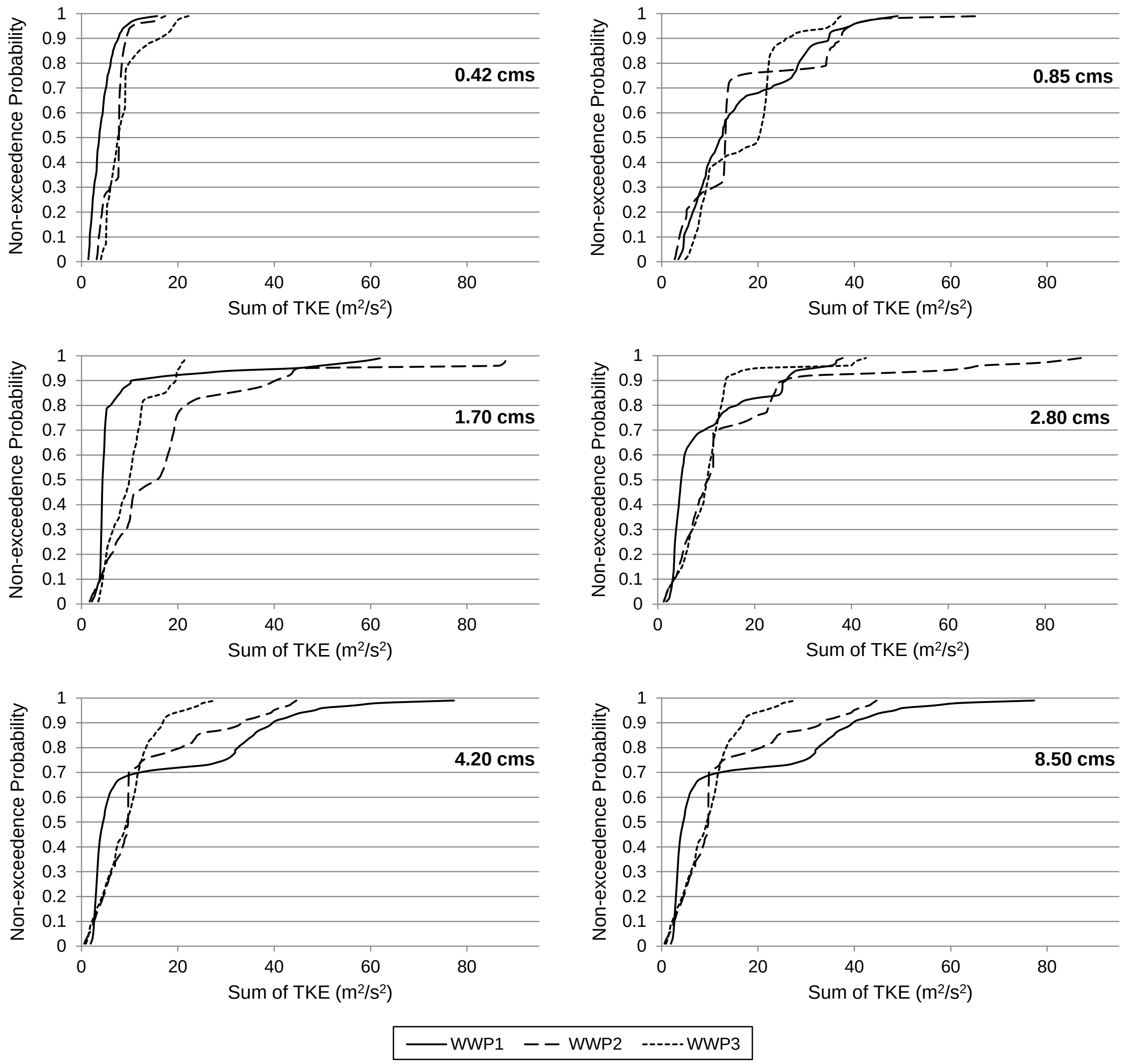


Fig. 4e. Non-exceedence probabilities for the sum of TKE along flow paths at each WWP structure and modeled discharge.

3.2. Fish passage

Direct observations of fish movement obtained from the PIT-tag movement study (Fox, 2013) indicate that fish passage success varies among WWP structures and size classes of fish (Fig. 5). Passage success is greatest at WWP1 for fish 200 mm in length and smaller; however, passage success decreases as fish size increases at WWP1. WWP2 has the highest proportion passing for larger fish. Additionally, there appears to be a positive linear relationship with passage success and fish size. At WWP3, passage success increases from 28 to 80 percent when fish length exceeds 300 mm. Different fractions of successful movements at each WWP structure occurred over different discharges (Fig. 6). At 0 – 0.42 cms, the largest fraction of successful movements occurred at WWP2. There is a mode of successful movements for all WWP structures at 0.42 – 0.85 cms. Indeed, more than 80 percent of fish passage at WWP1 occurred at 0.42 – 0.85 cms, which has a much longer exposure time than the higher discharges we examined (Fig. 7). At 0.85 – 1.70 cms, a larger fraction of successful movements occurred at WWP3 compared to WWP1 and WWP2. As discharge increases from 2.80 to 8.50 cms, the fraction of successful movements at each WWP structure greatly decreases as would be expected based on the frequency each discharge occurred.

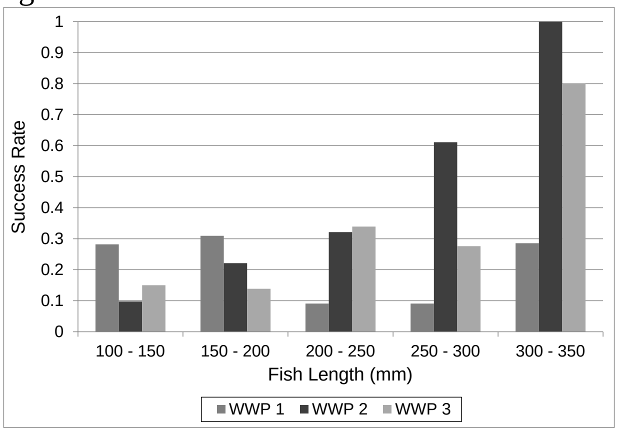


Fig. 5. The fraction of observed fish by size class at each WWP structure that successfully passed that structure.

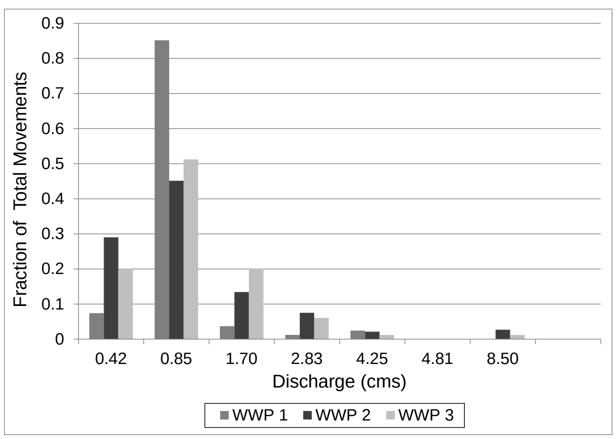


Fig. 6. The fraction of successful movements occurring over the range of modeled discharges at each WWP structure.

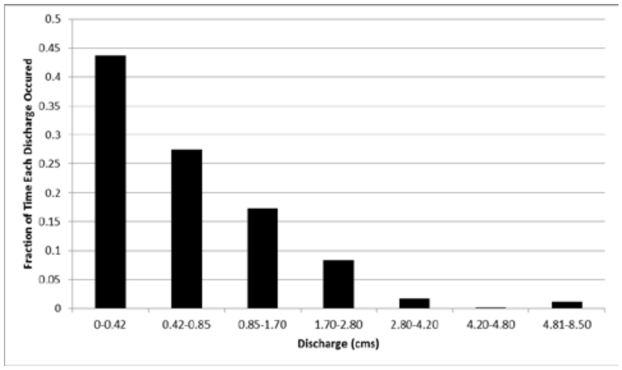


Fig. 7. The fraction of time each discharge occurred at the site over the course of the study.

3.3. Logistic regression analysis

Logistic regression analysis of hydraulic variables, i.e., the percentile of cost tested individually with the MVR_{10} and MVR_{25}, MDC, 50^{th} percentile of the maximum vorticity, and 50^{th} percentile of the maximum TKE consistently indicated that the MVR_{10}, MVR_{25}, and MDC were the best predictors of passage success across all WWP structures (Table 5). In contrast, the cost variable had an odds ratio close to 1 and was a poor predictor of passage success. Removing the cost variable from the logistic regression model does not have a significant effect on the model fit.

Model parameter estimates indicate that passage success decreases with increases in the fractions of flow paths that exceed burst swimming ability and do not meet the MDC (Table 5). A unit change in the MDC results in the greatest response in passage success compared to the MVR (odds ratio = 6.73×10^{-13}). The final model was highly significant ($p < 0.05$) with classification accuracies of 71.7 and 92.5 for successful and unsuccessful movements, respectively (Table 5).

Table 5
Logistic regression analysis for passage success.

Logistic regression model		Predicted logit of (passage success) =	Likelihood ratio test (p-value)	Goodness-of-fit test (p-value)	Odds ratio (e^{β})		Observations accurately predicted (%)
All WWP Structures		27.69 + (–2.422)*MVR_{10} + (–5.516)*MVR_{25} + (–28.03)*MDC	<0.0001	0.1222	MVR_{10} MVR_{25} MDC	0.0888 0.0808 6.73E-13	87.5
All WWP Structures		24.67 + (–27.27)*MVR_{25} & MDC	<0.0001	<0.0001	MVR_{25} & MDC	1.44E-12	87.5
Individual Structures	WWP 1	31.98 + (–36.32)*MDC	<0.0001	0.0068	MDC	1.69E-16	76.1
	WWP 2	29.72 + (–4.874)*MVR_{25} + (–31.74)*MDC	<0.0001	0.9674	MVR_{25} MDC	7.64E-03 1.64E-14	88.5
	WWP 3	26.81 + (–3.248)*MVR_{10} + (–26.22)*MDC	<0.0001	0.1389	MVR_{10} MDC	3.89E-02 4.09E-12	86.0
Individual Structures	WWP 1	45.01 + (–49.73)*MVR_{25} & MDC	<0.0001	<0.0001	MVR_{25} & MDC	2.51E-22	90.7
	WWP 2	24.89 + (–27.00)*MVR_{25} & MDC	<0.0001	0.6235	MVR_{25} & MDC	1.88E-12	87.5
	WWP 3	20.42 + (–22.61)*MVR_{10} & MDC	<0.0001	0.9513	MVR_{10} & MDC	1.51E-10	85.7

Logistic regression analysis of each individual WWP structure shows a significant influence of different hydraulic variables at each structure. Depth is statistically significant at WWP1, depth and the MVR for 25 BL/s are significant at WWP2, and depth and the MVR for 10 BL/s are significant at WWP3. The parameter estimates and odds ratio for the hydraulic variables at each individual WWP structure show a decrease in the probability of success as the fraction of flow paths that exceed burst swimming ability increase (Table 5). The goodness-of-fit test at WWP1 indicates that more complex variables could be added to the model ($p < 0.05$). Despite the results from the goodness-of-fit test at WWP1, the likelihood ratio test indicates that the models predict passage success with high accuracy ($p < 0.05$) (Table 5). Additionally, the model correctly predicted 91.2 percent of the observations. The logistic regression models accurately predicted 88.5 and 86 percent of the observations at WWP2 and WWP3, respectively (Table 5).

Logistic regression analysis of the MVR & MDC across all structures indicates a significant influence of the MVR_{25} & MDC; however, the MVR_{10} & MDC was not significant. The MVR_{25} & MDC has a negative parameter estimate and odds ratio less than 1, indicating that passage success decreases as the fraction of flow paths that exceed burst swimming ability (25 BL/s) or do not meet the MDC increases (Table 5). The likelihood ratio test indicates that the model predicted passage success with high accuracy ($p < 0.05$); however, the goodness-of-fit test indicates that additional variables could be added to improve the model fit. The model accurately predicted 87.5 percent of the observations (Table 5).

Logistic regression analyses of each individual structure indicated a significant influence of the MVR_{25} & MDC at WWP1 and WWP2, while MVR_{10} & MDC was significant at WWP3. According to the odds ratios and parameter estimates, passage success decreases with an increase in the fraction of traces that exceed burst swimming ability (10 and 25 BL/s) or do not meet the MDC (Table 5). The likelihood ratio test indicates that each model predicts passage success with high accuracy ($p < 0.05$) (Table 5). Additionally, the goodness-of-fit tests at WWP2 and WWP3 indicate that the inclusion of additional variables would not improve the model fit ($p > 0.05$); however, the addition of more complex variables at WWP1 might improve the model fit ($p < 0.05$). The model accurately predicted passage success for 90.7, 87.5, and 85.7 percent of the observations at WWP1, WWP2, and WWP3, respectively (Table 5).

4. Discussion

The methods used in this study provide a novel and powerful approach to mechanistically evaluate fish passage over a wide range of hydraulic structure types. Describing the hydraulic conditions along potential fish movement paths continuously quantifies important flow features at a scale meaningful to a fish. Simply averaging the hydraulic conditions over large spatial scales or evaluating point measurements do not take into account the continuous complexity of the flow field along a fish's movement path. This is supported by evidence from a previous study that did not find maximum threshold velocities or burst swimming abilities as satisfactory predictors of passage success when quantified as cross-sectional velocity quantiles within the chute of WWP structures (Fox, 2013).

The logistic regression analyses indicate that the MVR_{10}, MVR_{25}, and MDC accurately predict passage success for over 87 percent of observed trout. The fraction of available flow paths that exceed a fish's burst swimming ability or do not provide adequate depth had a negative influence on passage success. This strongly suggests that both depth and velocity are contributing to the suppression of movement of upstream migrating salmonids. Logistic regression analysis indicates a significant influence of the MVR & MDC across all WWP structures and at each individual WWP structure. A potential movement path might meet the minimum depth criteria but serve as a velocity barrier and vice versa. This underscores the importance of concurrently considering depth and velocity as barriers to upstream migration. Additionally, evaluating velocity and depth concurrently and combining them into a single predictor variable allows for a simplified, but highly accurate, statistical analysis.

Although the MVR & MDC accurately captures the effects of velocity and depth, additional analyses of the variation in statistically significant hydraulic variables among WWP structures and across discharges highlights unique hydraulic characteristics at each WWP structure that affect passage success differently. For instance, depth presents a greater challenge at WWP1 as it is characterized by a shorter, steeper drop compared to WWP2 and WWP3. Velocity is more limiting at WWP2 and WWP3 compared to WWP1 due to longer chutes with minimal roughness and constricted flow. Variation among the chute configuration at similar structure types, such as WWP2 and WWP3, dictates variation in the magnitude of velocity vectors and heterogeneity within the flow field among structures. The evaluation of the MVR, MDC, and their combined influence on passage success by size class and discharge emphasizes the importance of site-specific characterization of subtle differences in structure design. However, depth has lowest odds ratio in all logistic regression analyses, suggesting it has the strongest effect on passage success.

It is interesting that the MVR for burst swimming abilities of 10 and 25 BL/s are both statistically significant. Fish naturally vary in their physical capabilities much like humans (Williams et al., 2012). Thus, a variation in swim capacity among fish is likely illustrated through the inclusion of the MVR for burst swimming abilities of 10 and 25 BL/s at different structures. This is consistent with a previous study examining passage success through fishways, where not all fish were able to pass a structure equally well (Caudill et al., 2007). Further, a mixed population of hatchery fish and naturally producing fish supports the inclusion of different burst swimming abilities. It has been shown that hatchery rearing can alter the behavior and swimming ability of fish (Duthie, 1987; Peake et al., 1997). The inclusion of the MVR for different burst swimming abilities at individual structures could also indicate the influence of additional hydraulic variables, such as depth or turbulence, to reduce a fish's swim capacity.

The goodness-of-fit test at WWP1 shows that more complex variables could improve the model fit. This suggests that additional variables to depth could be contributing to the suppression of movement at WWP1. A study examining the effects of turbulence on passage success in three different experimental pool-type fishways found that the fishway with the highest turbulence had the worst passage success, but passed smaller fish better than the other configurations (Silva et al., 2012). Similarly, WWP1 has the worst overall passage success; however, smaller fish experience higher success rates at WWP1 compared to larger fish. WWP1 is also characterized by the highest magnitudes and larger distribution of the maximum vorticity along flow paths at discharges when the majority of the movements occurred. This suggests that turbulence could be an additional factor affecting passage success at WWP1. Flow and interstitial space width may be limiting passage of larger fish (WWP1), as narrower widths have been shown to limit upstream passage success for brook trout (Brandt et al., 2005)

The fact that our models did not identify turbulence as a significant influence could be an issue of scale. It has been suggested that the intensity, periodicity, orientation, and scale (IPOS) of turbulence should be considered in conjunction when relating turbulence to fish swimming abilities (Lacey et al., 2012). The magnitude or intensity of vorticity and TKE do not account for the spatial scale at which fish experience turbulent eddies relative to body length. Turbulent eddies that are small compared with the fish scale lack momentum required to negatively affect a fish, and in some cases assist in forward movement (Hinch and Rand, 2000; Haro et al., 2004; Lacey et al., 2012). Turbulent eddies with a diameter close to the length of a fish can pose stability challenges and reduce a fish's swimming ability (Pavlov et al., 2000; Lupandin, 2005; Tritico and Cotel, 2010). However, examining these relationships remains difficult without direct observations of flow/fish interactions and established thresholds of the effects of turbulence on fish swimming abilities.

The cumulative effects of velocity a fish experiences while crossing a structure have the potential to influence passage success. Studies have shown that as the swim speed of a fish increases the time to fatigue decreases (Bainbridge, 1960; Peake et al., 1997). Considering a fish chooses the least cost path (McElroy et al., 2012) through a structure, it is unlikely that an exhaustive swimming barrier will exist. Logistic regression analysis does not indicate a negative effect of cost on passage success; however, visual observations of failed attempts will reveal direct relationships on passage success and velocity as an exhaustive swimming barrier.

This study examines hydraulic conditions as physiological barriers to migration and does not take into account fish behavior. Accessible movement paths might exist at a structure. However, a fish might feel the cumulative effects of fatigue or lack motivation after several failed attempts to locate accessible movement paths (Castro-Santos et al., 2013). It is important to consider the timing of fish migrations and other life-cycle processes. Brown trout spawning migrations primarily occur in the fall when discharges are the lowest. However, rainbow trout spawning migrations primarily occur in the spring as discharge increases. The target species and local hydrologic regime could have implications for designing hydraulic structures to accommodate fish passage during critical seasons. Although higher discharges provide a higher fraction of accessible flow paths for fish at the Lyons WWP structures, discharges at 0.42 to 1.70 cms occur much more frequently throughout the year at the study site.

Despite the remaining uncertainties in additional factors that might be contributing to the suppression of movement, management guidance and design recommendations can be provided based on the strong relationship of passage success with velocity and depth. Care should be taken to ensure that velocity and depth requirements are met continuously along likely fish movement paths. Multiple field studies indicate that fish exploit boundary layers created by objects in the flow field (Fausch, 1993; Nestler et al., 2008). Interstitial spaces within the center of the chute may provide zones of lower velocity for smaller fish. Increasing the size of interstitial spaces to at least the body depth of the largest fish likely encountered at a WWP structure may provide adequate flow depth and lower velocities to accommodate a broader range of fish sizes. Increasing the width of interstitial spaces and passage routes could also prove beneficial for larger fish (Brandt et al., 2005). Continuous low-velocity zones along the margins of the chute with adequate flow depth should be provided, allowing fish to avoid the main velocity jet. Low-velocity zones along the channel margins can be achieved by allowing water to spill over the wing walls at all discharges. If the wing walls are not grouted they act as roughness elements providing flow refugia for fish. Large eddies that recirculate back into the chute at all discharges can provide additional low-velocity zones as seen at higher discharges at WWP3. These low-velocity recirculation zones should come up the sides of the main velocity jet as far as possible.

Similar hydraulic analyses can provide information on the effects that velocity and depth might have on passage success at additional hydraulic structures. Evaluating additional hydraulic structures is highly recommended to determine the range of hydraulic conditions that fish are required to pass. Further, assessing passage success of non-salmonid fishes with different swimming abilities or behaviors could highlight the need for lower velocity zones or higher topographic diversity within hydraulic structures. A more in-depth analysis of turbulence incorporating flow/fish interactions could reveal new thresholds and additional factors that affect passage success. Additionally visual observations of successful and failed attempts of individual fish will allow for a more-detailed comparison of the hydraulic conditions that affect passage success and shed light on behavioral limitations.

5. Conclusions

This study used the results from a 3-D CFD model to provide a continuous and spatially explicit description of the hydraulic conditions along potential fish movement paths and examine their influence on fish passage at a WWP on the St. Vrain River in Lyons, Colorado. Quantifying the hydraulic conditions in this manner captured important and unique hydraulic characteristics at each WWP, and described velocity and depth throughout the flow field at a scale meaningful to a fish. Logistic regression indicated a significant influence of velocity and depth on passage success, and accurately predicted 87 percent of individual fish movement observations. However, cost, vorticity, and TKE did not have a significant effect on passage success. Specific combinations of depth and velocity were statistically significant at individual WWP structures highlighting the effects of unique hydraulic conditions at each WWP on passage success. Further, a comparison of velocity and depth relative to a fish's swimming ability was reflective of the variation in passage success among WWP structures, across discharges, and among size classes of fish. The results indicate that additional variables such as turbulence might also be contributing to the suppression of movement. Further research is needed to examine the range of hydraulic conditions at existing hydraulic structures and their effectson native fishes with lesser swimming abilities. Additionally, studies involving flow/fish interactions are needed to evaluate fish behavior in response to hydraulic conditions and define turbulence at a scale relative to fish size. Similar hydraulic analyses coupled with fish movement data can be utilized to evaluate the effects of hydraulic conditions on passage success at other types and sizes of hydraulic structures. This study lays the groundwork for a novel and powerful approach to mechanistically evaluate the effects of hydraulic structures on fish passage. Further, the results of this study can serve as a reference for managers and policy makers, provide design guidance for future hydraulic structures, and be used to evaluate existing structures of similar size, design type, and hydrologic regime.

Acknowledgments

We thank the Colorado Water Conservation Board, Colorado Parks & Wildlife, and the Colorado Water Institute for funding support. Chris Myrick and Peter Nelson provided helpful reviews of an earlier version of this paper.

Please contact CWI for references.

Exploration of Morphometric Approaches for Estimating Snow Surface Roughness

Basic Information

Title:	Exploration of Morphometric Approaches for Estimating Snow Surface Roughness
Project Number:	2014CO302B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Climate and Hydrologic Processes
Focus Category:	Climatological Processes, Hydrology, Methods
Descriptors:	None
Principal Investigators:	Steven Fassnacht

Publications

There are no publications.

Exploration of a Geometric Approach for Estimating Snow Surface Roughness

David Kamin, MS Student, Watershed Science, Colorado State University

Advisor: Steven Fassnacht, Ecosystem Science and Sustainability, Colorado State University

Background

In cold climates, the snow surface is often the interface between the atmosphere and the earth. Changes in this surface can have important effects on the hydrologic process, but it is difficult to characterize and model these changes. One measure used to understand the flow of air, temperature, and moisture over a surface is called surface roughness length (Z_0). This is a measure of the vertical turbulence that occurs when a horizontal wind flows over a rough surface. The greater Z_0, the greater the magnitude of turbulence that arises when wind passes over a roughness element. Due mainly to the difficulty and cost of obtaining estimates of Z_0, most land surface models and climate models do not address the variability of this value due to changing snow surfaces. This research, funded by a grant from the Colorado Water Institute, compares methods for estimating Z_0 and tests the viability of an approach that does not rely on expensive wind tower instrumentation.

Methods

The traditional method for estimating Z_0 is an **anemometric** approach. This method relies on field observations of wind turbulence movement to generate a logarithmic wind profile and solve for aerodynamic parameters such as Z_0. The anemometric method can be used for any surface or roughness elements, but its disadvantage is the expense and difficulty involved in installing and operating a wind tower to obtain measurements. In contrast, the **geometric** method uses algorithms relating aerodynamic parameters to measures of surface roughness elements. Geometric methods have the advantage that values of Z_0 can be determined without tower instrumentation. However, most geometric methods are based on empirical wind tunnel tests which do not account for changing wind directions and irregular roughness elements like boulders and trees. This project obtained Z_0 values from both procedures and used the more standard anemometric approach to test and validate the geometric method.

Data collection took place during the winters of 2013-2014 and 2014-2015 at an experimental site east of Fort Collins, CO at the Colorado State University Horticultural Farm. A meteorological tower was constructed and instrumented on the east end of a 100 m by 35 m field in an area with prevailing winds from the west. The upwind fetch was left undisturbed for part of the winter then plowed with regular furrows orthogonal to the prevailing wind direction in order to induce surface roughness.

The meteorological tower was instrumented at ten levels over a 5m height with anemometers, temperature and humidity sensors. Data was quality controlled so that the only wind profiles used were those which best met the theoretical conditions for aerodynamically rough flow. In practice, this means profiles where wind speed was above $4ms^{-1}$, winds were coming from the upwind fetch, and the profile showed strong correlation (r>0.95). A least squares linear regression fitted to these profiles yielded slopes and intercepts which were in turn used to compute the aerodynamic roughness length Z_0. For the geometric evaluation, ground-based light detection and ranging (LiDAR) technology was used to generate a point cloud of the upwind fetch being measured by the meteorological tower. Multiple scans were conducted during the winters to capture changing snow conditions. The geometric approach is limited by the accuracy of the description of roughness elements, so this LiDAR scanning is a good solution because it can describe the surface at sub-centimeter resolution. These surface scans were evaluated using the Lettau and Counihan methods to empirically compute Z_0 based on the height and area covered by the roughness elements.

Results

Work is still ongoing to process and analyze the LiDAR scans, but preliminary results are promising. The table below shows examples of the Z_0 values and comparisons between the different approaches:

Surface Condition and Snow Covered Area (SCA)	Anemometric Zo (m)	Geometric Zo Lettau Method (m)	Geometric Zo Counihan Method (m)
Unplowed Field, 100% SCA	0.0005 ± 0.001	0.00006	0.003
Unplowed Field, ~30% SCA	0.0006 ± 0.001	0.0003	0.009
Plowed Field, 100% SCA	0.0024 ± 0.002	0.0014	0.036

At any specific location, the physical roughness of the snow surface changes over the season and can be affected by snow redistribution and changes in wind direction. These results are encouraging because they show the responsiveness of the geometric methods to changing surface conditions. The Lettau and Counihan methods use different formulations to take into account the roughness of the surface, so it is expected that they yield different results. The geometric results do not match precisely with the anemometric Z_0 values, but they do follow the correct trends with changing surfaces and further analysis is expected to strengthen the correlation between the two approaches.

Conclusions

Gaining a better understanding of snow surface roughness is a key component to improving models of the snow surface interaction with the atmosphere. Snow surface roughness is a complicated metric and improvements to methods for estimating Z_0 will aid researchers and modelers working on this subject. Climate models like the flagship Community Land Model (CLM4) rely on metrics like Z_0 to estimate snow sublimation and melt. The results of this work indicate the effectiveness of evaluating Z_0 on diverse surfaces using geometric techniques and

LiDAR technology. Other work in this field is starting to show the potential for mobile LiDAR and passive microwave remote sensing as methods to evaluate surface roughness on a larger scale. The present work informs these future efforts by demonstrating a tested geometric method for analyzing surface roughness lengths. A question for further research is how to scale this method into study of larger areas. The geometric method in this research relies on the accuracy of the ground-based scanner, but sub-centimeter resolutions are impossible over larger scales. Future work must address these questions of scale in order to deliver accurate Z_0 values over larger areas to feed into climate models.

ICIWaRM Advisory Board Meeting and Workshop

Basic Information

Title:	ICIWaRM Advisory Board Meeting and Workshop
Project Number:	2014CO304S
USGS Grant Number:	G14AP00025
Sponsoring Agency:	COE_COState
Start Date:	2/1/2014
End Date:	6/30/2015
Funding Source:	104S
Congressional District:	
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	

Publications

There are no publications.

United Nations Educational, Scientific and Cultural Organization
International Center for Integrated Water Resources Management under the auspices of UNESCO

International Center for Integrated Water Resources Management (ICIWaRM)
Advisory Board Meeting

FY2014 Progress Report

ICIWaRM Advisory Board Meeting will be held April 10-11, 2015 in Seoul, Korea at the JW Marriott Hotel, Dongdaemun Square Seoul 279, Cheonggyecheon-ro, Jongno-gu Seoul 110-1206.

Meeting objectives: a) Review the most recent 2.5 years of ICIWaRM's activities—its organization, strategy, accomplishments, and integration with IHP-VII and IHP-VIII and b) Present/discuss/receive advice on new strategies and initiatives to integrate with IHP-VIII, and funding sources to support them.

Water-Energy-Food Nexus Workshop

Purpose: Prepare a synthesis of discussions about the water-food-energy nexus and key messages that the U.S. can deliver to the Nexus Dialogue on Water Infrastructure Solutions at a meeting in Beijing in late 2014.

Organization: Colorado State University is working with the U.S. Army Corps of Engineers and the U.S. Department of State to organize the event and to target contributions to the ongoing discussion (see www.waternexussolutions.org/).

Date and Venue: 1.5 day meeting in Golden Colorado (Denver area);
June 23-24, 2014

Activities: Participants responded to key questions to aid in preparation of advance papers to prepare the workshop dialogue. A strawman paper will be prepared for the workshop to facilitate discussion and development of positions on key points. A final paper was prepared for the State Department.

Participants: About 30 participants from government, industry, utilities, NGOs, and academic institutitons.

Coordinators:
Reagan Waskom (Director, Colorado Water Institute) Reagan.Waskom@colostate.edu
Neil Grigg (Professor of Civil and Environmental Engineering) neilg@engr.colostate.edu

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 included:

- 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

Technology Transfer and Information Dissemination

Basic Information

Title:	Technology Transfer and Information Dissemination
Project Number:	2014CO295B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Reagan M. Waskom

Publications

1. Colorado Water Newsletter, Volume 31 - Issue 2 (March/April 2014), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 37 pages.
2. Colorado Water Newsletter, Volume 31 - Issue 3 (May/June 2014), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 37 pages.
3. Colorado Water Newsletter, Volume 31 - Issue 4 (July/August 2014), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 41 pages.
4. Colorado Water Newsletter, Volume 31 - Issue 5 (November/December 2014), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 37 pages.
5. Colorado Water Newsletter, Volume 32 - Issue 1 (January/February 2015), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 33 pages.
6. Waskom, Reagan, Akhbari, Masih, Grigg, Neil. September 2014. United States Perspective on the Water-Energy-Food Nexus. Colorado Water Institute, Colorado State University, Fort Collins, CO. 186 pages. http://cwi.colostate.edu/publications/IS/116.pdf
7. Herzog, Margaret, Labadie, John, Grigg, Neil. December 2014. Social Network Analysis Workshop for Water and Resource Management. Colorado Water Institute, Colorado State University, Fort Collins, CO. 3 pages.
8. McCray, John. December 2014. Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts. Colorado Water Institute, Colorado State University, Fort Collins, CO. 21 pages.
9. Venable, Niah B. H., Fassnacht, Steven. February 2015. Reconstructing a Water Balance for North Crestone Creek: Streamflow Variability and Extremes in a Snowmelt Dominated Internal Drainage Basin. Colorado Water Institute, Colorado State University, Fort Collins, CO. 29 pages.
10. Gates, Timothy. December 2014. Arkansas River Basin. Colorado Water Institute, Colorado State University, Fort Collins, CO. 170 pages.
11. Boone, Karie. December 2014. Where Are We Now? Socio-Ecological Risks and Community Responses to Oil and Gas Development in Colorado. Colorado Water Institute, Colorado State University, Fort Collins, CO. 52 pages.

Colorado Water Institute Activities

- Water Tables 2015, January 29, 2015
- Humans, Resilience and Water, Interdisciplinary Water Resources Seminar, Spring 2014
- Water, Climate and Extreme Events, GRAD592, Fall 2014
- *Colorado Water*, Colorado Water Institute, March 2014-February 2015
- South Platte River Forum, October 2014
- Poudre River Forum, January 2015
- Special Presentation, Kevin Fedarko's *The Emerald Mile*, CSU Hydrology Days, March 24, 2014
- International Colloquium on Future Earth Features Water Issues in Panel, October 6-8, 2014

WATER RESOURCES ARCHIVE

Colorado State University
MORGAN LIBRARY

SAVE THE DATE

Thursday, January 29, 2015

Water Tables 2015

lib.colostate.edu/archives/water/water-tables/2015

Reception, dinner and presentation to benefit
the Morgan Library Water Resources Archive

In conjunction with the Colorado Water Congress
Hyatt Regency Denver Tech Center
Denver, CO

Spring 2014
CSU Interdisciplinary Water Resources Seminar

Theme: *Humans, Resilience and Water*

Mondays From 4:00 to 5:00 PM

January 27 LSC Room 222	Stephanie Kampf – Colorado State University *The Role of Flooding in River Systems: A Panel Discussion on Biophysical Impacts and Research Needs in the Aftermath of the 2013 Front Range Floods*
February 3 LSC Room 222	Jorge Ramirez, Neil Grigg, N. LeRoy Poff, and A. Scott Denning – Colorado State University *Integrated Water, Atmosphere, Ecosystems, Education and Research*
February 10 LSC Room 222	Pinar Omur-Ozbek – Colorado State University, Department of Civil Engineering *Disasters Bring Disastrous Water Quality*
February 17 LSC Room 222	Mike Gooseff – Colorado State University, Department of Civil Engineering *Hydrologic Response to Climate Variability in the Dry Valleys, Antarctica*
February 24 LSC Room 222	Tom Trout – USDA-ARS *Can Deficit Irrigation Help Sustain Colorado Irrigated Agriculture?*
March 3 LSC Room 222	Steve Malers – Open Water Foundation *Using the Colorado Decision Support System in Teaching and Research*
March 10 LSC Room 222	Pete Taylor – Colorado State University, Sociology *'Everybody has their Own Idea of Paradise': Emerging Experiences with Environmental Flow Governance on the Upper Colorado River*
March 17	No Seminar Spring Break
March 24	No Seminar Hydrology Days
March 31 LSC Room 222	Pat Byrne and Mary Stromberger – Colorado State University, Soil and Crop Sciences *Breeding for Drought Tolerance in Winter Wheat through Above-Belowground Interactions*
April 7 LSC Room 222	Tony Cheng – Colorado State University – Forest and Rangeland Stewardship *Collaboration as an Essential Component of Restoring Resilient Forests and Watersheds in Colorado's Front Range*
April 14 LSC Room 222	Paul Brooks – University of Arizona *What Happens to the Rain (Snow)? Quantifying the Effects of Climate and Land Cover Change on Western Water Resources*
April 21 LSC Room 222	Edgar Andreas – NorthWest Science Associates *Aerodynamic and Scalar Roughness over Snow and Sea Ice*
April 28 LSC Room 230	Mark Fiege – Colorado State University, History *Of Time and the River: History as an Analytical Tool in Colorado Water Management*
May 5 LSC Room 224	Peter Nelson – Colorado State University, Department of Civil Engineering *Flooding, Erosion, and Sedimentation Following the 2012 High Park Fire*

Sponsored by: CSU Water Center, USDA-ARS, Civil and Environmental Engineering, and Forest and Rangeland Stewardship.

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

For more information, contact Reagan Waskom at reagan.waskom@colostate.edu or visit watercenter.colostate.edu

Interdisciplinary Water Resources Seminar GRAD592

Fall 2014 Theme:
Water, Climate & Extreme Events
Monday 4:00 – 5:00 PM,
Engineering Room E104

The purpose of the 2014 Interdisciplinary Water Resources Seminar (GRAD592) is to examine how climate change and/or extreme hydrologic events will impact the major water sectors in Colorado - municipal water supply, agriculture, stormwater, wastewater, ecosystems and recreation. What are the vulnerabilities each sector faces and how can we enhance resiliency to flood, fire, drought, and hydrologic uncertainty. The course will consist of a series of guest lectures provided by Colorado water professionals. Specific course objectives include:

1. Examine the physical mechanisms whereby the water sector is vulnerable to climate change and variability steps;
2. Understand how climate vulnerability assessment and planning is occurring in Colorado;
3. Discuss the intra and interstate issues related to climate and extreme events that increase the complexity of water supply planning in the 21st Century;
4. Examine the various water use sectors including public water supply, stormwater, agricultural water, wastewater, ecosystems and recreation.

Students interested in taking the one-credit seminar should sign up for GRAD592, Water Resources Seminar, Section ID Number: 74006. The seminar will be held 4:00pm Monday afternoons in **Engineering Room E104.** (Students who have enrolled in GRAD592 in the past, may also enroll for this offering)

Aug 25	Organizational Meeting	Seminar Organizers
Sept 1	No Class	Labor Day
Sept 8	Scott Denning, CSU	Understanding Climate Change and Extreme Events
Sept 15	Dennis Ojima, CSU NREL	Assessing Colorado's Vulnerability to Climate Change
Sept 22	Graeme Aggett, AMEC	Planning for Extremes in Water Resources
Sept 29	Laurna Kaatz, Denver Water	Municipal Water Planning for Climate Change
Oct 6	Taryn Finnessey, CWCB	Drought Planning and Implementation
Oct 13	Iain Hyde, COEM	Colorado's Approach to Emergency Management
Oct 20	Ken Mackenzie, Urban Drainage	Stormwater Management during Extreme Events
Oct 27	Sean Cronin, SVLHWCD	Flood Impacts on Infrastructure
Nov 3	Bill McCormick, DWR	Dam Safety and the 2013 Flood
Nov 10	Eric Reckentine, City of Greeley Kevin Gertig, City of Fort Collins	Poudre Watershed Fire Impacts
Nov 17	Justin Derner, USDA-ARS	Agriculture, Climate Change and Extreme Events
Nov 24	No Class	Fall Break
Dec 1	Presentations	Student Groups
Dec 8	Presentations	Student Groups

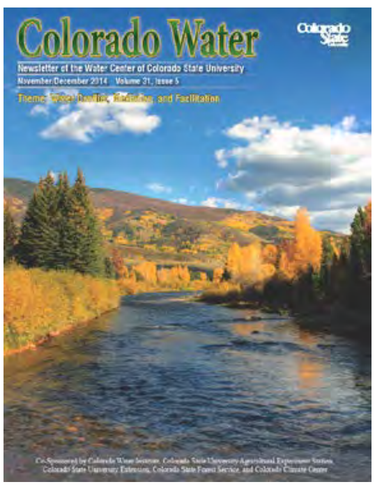
Seminar Organizers: Ryan Bailey, Troy Bauder, John Stednick, Pete Taylor, and Reagan Waskom

All interested faculty, students, and off-campus guests are encouraged to attend.
For more information, contact Reagan Waskom at reagan.waskom@colostate.edu or visit watercenter.colostate.edu.

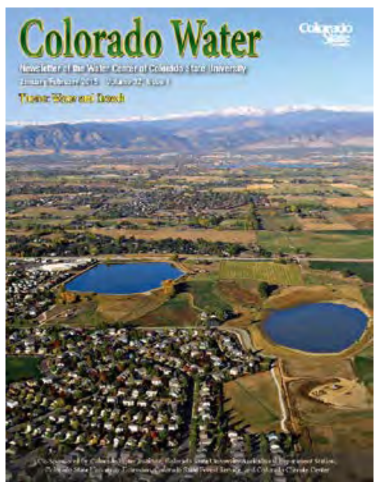
Colorado Water
Volume 31, Issue 2
Stormwater

Colorado Water
Volume 31, Issue 3
Student Research

Colorado Water
Volume 31, Issue 4
Fish and Wildlife



Colorado Water
Volume 31, Issue 5
Water Conflict, Mediation,
And Facilitation



Colorado Water
Volume 32, Issue 1
Water Storage and
Development

Colorado State University

Department of Public Relations
301 Administration (0150)
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Twenty-five years of exploration: South Platte Forum

For Immediate Release
Tuesday, October 14, 2014

Contact for Reporters:
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The 25th annual South Platte River Forum will be held Wednesday, Oct. 22, and Thursday, Oct. 23, at the Plaza Event Center, 1850 Industrial Circle, Longmont. The forum, "Water and Wisdom," will examine issues such as flood impacts on stream restoration, fisheries and hydrology, oil and gas exploration, hydraulic fracturing as well as hydropower, and overviews of South Platte River basin projects. The forum strives to provide an avenue for a timely, multidisciplinary exchange of information and ideas important to resource management in the basin.

The first day of the forum includes several presentations on flood recovery efforts, updates and concerns, as well as a history of floods on the South Platte. The Friends of the South Platte Award will be presented to Patricia J. Rettig, Head Archivist, Water Resources Archive, at Colorado State University Libraries. The keynote luncheon on Oct. 22 will be "Proposed Rule: Definitions of Waters of the U.S." by Karen Hamilton, Chief of the Aquatic Resource and Accountability Unit, U.S. EPA Region 8. Afternoon sessions will discuss oil and gas exploration and hydraulic fracturing, and water education efforts. The day will conclude with a reception and information on water storage projects in the basin.

The final day of the forum will include a presentation on the Colorado Water Plan by John Stulp, special policy advisor to Colorado Gov. John Hickenlooper on water, followed by presentations on South Platte basin water plans, and a panel focused on water quality concerns. The day will conclude with a luncheon presentation on "At the Confluence: The Poetry of Colorado Water" by Colorado Supreme Court Justice Gregory J. Hobbs, Jr.

Winners of this year's photo contest will be recognized during the forum and their photographs will be on display.

The South Platte River begins high in the Colorado mountains near Fairplay. It flows through Denver and continues eastward into Nebraska, joining the North Platte River near the town of North Platte, Neb.

The South Platte Forum is sponsored by Deere & Ault Consultants, Inc.,; SP WRAP,; XRI Geophysics; Applegate Group, Inc.; the Consortium for Research and Education on Emerging Contaminants (CREEC); Platte River Recovery Implementation Plan (PRRIP); Riverside Technology; Tetra Tech,and Integral Consulting, Inc. The Forum is organized by Colorado State University Extension, Colorado Water Institute, Aurora Water, Denver Water, Northern Water, Metro Wastewater Reclamation District, Colorado Division of Parks and Wildlife, St. Vrain and Left Hand Water Conservancy District, U.S. Fish and Wildlife Service, U.S. EPA, U.S. Geological Survey.

Registration is available at the door for $115 per person. For a schedule of events, visit www.southplatteforum.org/schedule. For additional information, contact Jennifer Brown at (402) 960-3670 or Jennifer@southplatteforum.org.

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CSU News Service

Poudre Runs Through It Launches the First Annual Poudre River Forum

MaryLou Smith, Policy and Collaboration Specialist, Colorado Water Institute
Zoe Whyman, Community Relations Manager, City of Fort Collins Natural Areas Department

What motivates 275 people to spend a Saturday talking about water? The Poudre River Forum; which posed the challenge: "Let's make the Cache la Poudre River the world's best example of a hard working river that's also healthy. Agricultural and urban water rights owners joined in with environmentalists and recreation promoters to learn about and celebrate their common ground. The event was held February 8 in Larimer County.

Mayors from Greeley, Windsor, Timnath, and Fort Collins—the four communities through which the Poudre River flows—greeted water enthusiasts from one end of the river to the other, reading from historical passages tying their particular community to the river.

The fast moving day also featured "spring run-offs"—ten-minute brief but critical insights into the Poudre River. The "working river" run-offs covered uses of the river for agriculture, cities and towns, industry, and tourism/recreation, as well as an overview of where water in the Poudre comes from, how it's diverted for various uses, and who administers it, by water commissioner Mark Simpson. "Healthy river" run-offs shared insights about fish, riparian habitat, flows, water quality, and how it all ties together. Floods and Fires: Extraordinary Challenges for the Poudre and an inspiring keynote speech by Supreme Court Justice Greg Hobbs rounded out the presentations, the latter being the highlight of the day for many. Hobbs' colorful stories about the history of humans in the region intrigued the audience. He told the story of how prior appropriation got its start with conflict on the Poudre and pointed out that we are in an era of cooperation—that we have to be, because the resource we all depend on is severely limited.

A lively audience dialogue showed interest in a variety of topics, including the potential for creative

City of Greeley showed off a giant water faucet at their display promoting urban water conservation.
Photo by Stephen Smith

Healthy River presenters Sara Rathburn, Dave Merritt, Boyd Wright, Joe Konovik, and Jen Shanahan relax before their ten minute "Spring Runoff" presentations. *Photo by Stephen Smith* "nutrient trading" between agricultural non-point sources of nitrogen and phosphorous and cities, like Greeley, who must reduce point source nutrient loads through expensive waste water treatment upgrades.

Why stage a Poudre River Forum? The Poudre Runs Through It Study/Action Work Group has spent 18 months learning about the Poudre from a variety of viewpoints and then deciding on a trio of collaborative actions—actions that appeal to farmers just as much as environmentalists: Forum, Flows, and Funding. The Flows Initiative seeks to increase water flows in the Poudre in order to improve the health of the river while maintaining private property rights. The third initiative is generating funding for the improvements.

John Stulp, Governor Hickenlooper's special advisor on Water, tells the crowd about the Colorado Water Plan. Photo by Stephen Smith

Paul Ackerman, Barb Perusek, and Dale Trowbridge gave away ice cream bars at the New Cache la Poudre Irrigating Company display. *Photo by Stephen Smith*

The Work Group has 30 members and a steering committee that includes a water lawyer, a city natural resources manager, a ditch company manager and agriculture producer, a conservation group administrator, and a retired ecologist—very much representative of the diverse group.

The Colorado Water Institute at Colorado State University is the facilitator of the Poudre Runs Through It Study/Action Work Group. Director Reagan Waskom says that the group was formed as a means to bring together those who in the past have often talked past one another. This forum exemplified the same spirit of learning from one another and contemplating actions that the group itself has fostered. One participant said the best part of the forum was "the coming together of issues and cross community collaboration." Though the first Poudre River Forum laid a foundation of understanding many aspects about the Poudre, future forums will likely dig into issues more deeply. Whatever topics and issues are addressed, the Poudre Runs Through It Study/Action Work Group are devoted to making sure that those who are concerned about the ecology of the river and those who are intent on protecting water rights for agricultural and urban diversions have a forum for finding common ground. As Justice Hobbs said, "We must manage our waters through smart cross-connections of all our values." For more information about the Poudre Runs Through It Study/Action Work Group, visit www.cwi.colostate.edu/thepoudrerunsthroughit.

Kevin Fedarko and CSU's Confucius Institute Join CSU Hydrology Days

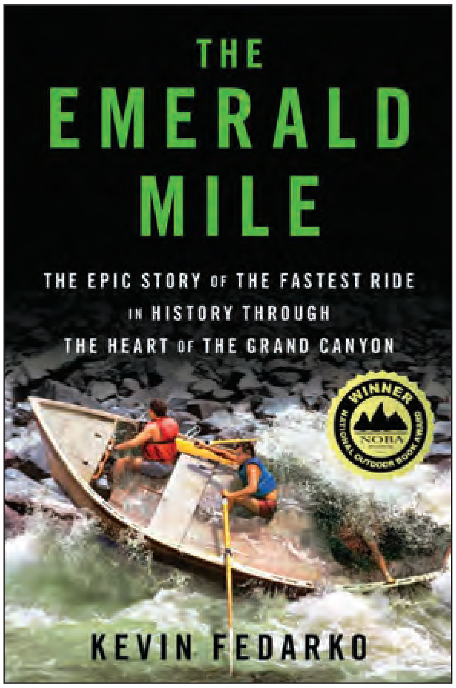
Julie Kallenberger, *Research and Outreach Coordinator, CSU Water Center*
Jorge Ramirez, *Professor, Department of Civil and Environmental Engineering*
Emilie Abbott and Ajay More, *Student Intern, CSU Water Center*

In conjunction with Colorado State University's (CSU) 34th Annual Hydrology Days, the CSU Water Center hosted Kevin Fedarko, author of *The Emerald Mile: The Epic Story of the Fastest Ride in History Through the Heart of the Grand Canyon* on Monday, March 24 at the Lory Student Center Theater. Over 130 campus and local community members gathered to hear Fedarko share this riveting story.

Fedarko first described his personal and professional backgrounds and how he was inspired to write about *The Emerald Mile*, a dory rafting boat, which in June 1983, accomplished the fastest journey down the Colorado River. Fedarko spoke about how he became a river guide so that he could experience firsthand the countless intricacies of the Colorado River and channel his experiences into his writing. During his journeys down the river, he, along with his fellow boatmen and rafting passengers, shared stories around the evening campfire about the river and its canyon, their majestic past, and their uncertain future. A particular campfire story that resonated with Fedarko described the historical flooding that occurred in June 1983 and the events that unfolded simultaneously over a few short days. He then decided to write and narrate his book based on the story of *The Emerald Mile*.

During the winter of 1983, the Upper Colorado River Basin experienced an unprecedented amount of snowfall, and with the onset of spring, a sudden surge in temperature and heavy spring rain caused all of the snow to melt in a very short period of time. Fedarko spoke in detail about the Glen Canyon Dam, situated at the upper end of the Grand Canyon. Its outlet works consisted of four 14-foot diameter pipes and two emergency tunnel spillways, each 41 feet in diameter. He described how the runoff had destroyed its emergency tunnel spillways, and consequently created the potential for uncontrolled releases which could exceed the dam's crest. This disaster was avoided by increasing the capacity of the reservoir by constructing plywood flashboards around the tops of the spillway gates, buying engineers precious time to evaluate the integrity of the dam. Still, enough water had passed through the emergency spillways to create the largest flood the Grand Canyon had experienced in the past 25 years. On Saturday, June 25, 1983, downstream rafters would soon experience the wrath of the water as it rushed down the canyon. One life was lost, and many more were forever changed that day. That same evening, three experienced rafters launched *The Emerald Mile* to experience the fastest journey down the Colorado River—a trip usually measured in days or weeks, not in hours. This reckless and defiant trip has been described by Fedarko as "one of the purest and most perfect journeys the Grand Canyon has ever seen, a voyage that embodied the essence of the river by moving through its corridor under conditions that were not only beset by immense

The Colorado River near Marble Canyon in Arizona.
Photo by Denny Armstrong



The Emerald Mile book cover.

Troy Bauder (CSU, Department of Soil and Crop Sciences) demonstrates farm equipment used for experimental tilling to Chinese visitors. Photo courtesy of Glenn Patterson

Kevin Fedarko greeting community members and signing copies of The Emerald Mile before his presentation. Photo by Kim Hudson physical challenges, but more important, were freighted with the extraordinary power of metaphor."

Fedarko shared many different perspectives that he encountered while writing his book, especially the damming of the Colorado River at Lake Powell. Even though many had a deep desire for the Colorado River to remain free flowing, Fedarko personally learned to appreciate the creative and brave efforts of the U.S. Bureau of Reclamation officials who were responsible for avoiding a catastrophic failure of the Glen Canyon Dam. He also described the fleet of boats whose names were fashioned after natural landmarks that were negatively impacted by humans. These names serve as a stark reminder that we must minimize our footprint on our natural environment, especially this beloved river.

Fedarko was formerly a staff writer for *Time* magazine. His work has been featured in *Esquire* and *Outside* magazines and has been included in *The Best American Travel Writing*. He lives in Santa Fe, New Mexico, and works as a part-time river guide in the Grand Canyon National Park.

Visit books.simonandschuster.com/Emerald-Mile/Kevin-Fedarko/9781439159859 to view more information about *The Emerald Mile*.

Hydrology Days

The 34th Annual American Geophysical Union Hydrology Days conference was held March 24-26 at Colorado State University. More than 110 papers and posters were presented in sessions on topics addressing hydrologic and climatic variability and change, eco-hydrology, watershed science, emerging contaminants, water quality, fluvial geomorphology, erosion and sedimentation, snow hydrology, urban hydrology, and hydro-epidemiology. In addition, there was a special session on the hydrologic, meteorological, eco-hydrologic, and socio-economic aspects of the September 2013 Colorado floods.

Fedarko speaking the Colorado River during his presentation.
Photo by Kim Hudson

The Hydrology Days Award Lecturer was Professor William W-G. Yeh of the University of California at Los Angeles who gave the lecture, "Optimization of hydro-system management and operation." Other special presentations included the Borland Lecture in Hydrology, "Role of the environment in shaping malaria transmission in Africa," by Professor Elfatih A.B. Eltahir of the Massachusetts Institute of Technology, and the Borland Lecture in Hydraulics, "Eulerian and Lagrangian approaches in sediment transport, biogeochemistry and environmental law," by Professor Martin Doyle of Duke University.

In addition, the NSF-funded I-WATER program (I-WATER.ColoState.edu/) held its annual research symposium as an integral part of Hydrology Days where I-WATER fellows and faculty mentors presented their research projects. Topics included: flood, drought, energy development, watershed health, air and water quality, and ecosystem services.

Among the Hydrology Days participants was a delegation of faculty and water experts from China associated with the Confucius Institute at CSU. During the afternoon of March 26, The Confucius Institute and the CSU Water Center hosted a symposium on water and environmental sustainability which featured presentations from CSU and China researchers, as well as a discussion about potential joint research projects between CSU and China institutions. More information about the Confucius Institute can be found online at international.colostate.edu/cicsu/.

Proceedings and abstracts of Hydrology Days are available online at HydrologyDays.ColoState.edu/. Next year's Hydrology Days will be held the week of March 23.

Learn more about the CSU Water Center and upcoming events by visiting our website at www.watercenter.colostate.edu.

International Colloquium on Future Earth Features Water Issues in Panel, Lunch Sessions

Emilie Abbott, Student Intern, CSU Water Center

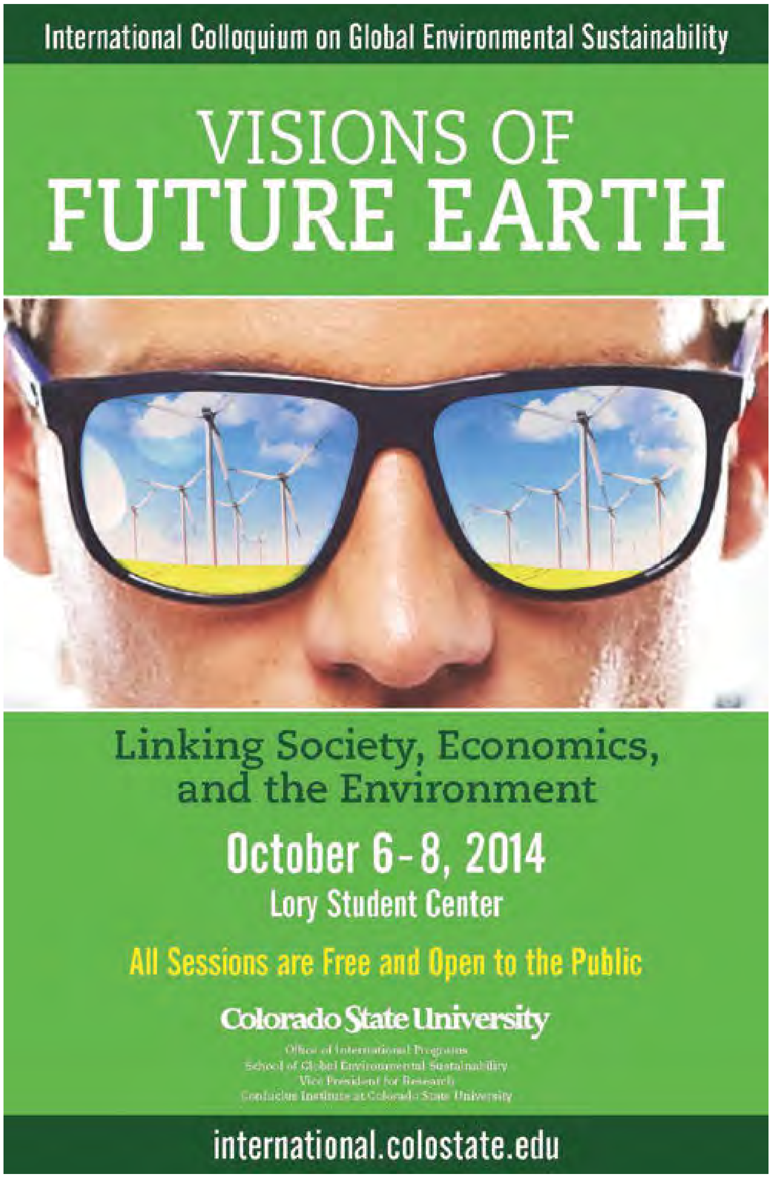
Colorado State University hosted its fifth International Colloquium on October 6-8, 2014. The theme was *Visions of Future Earth: Linking Society, Economics, and the Environment*. The university was recently selected to be a hub for Future Earth in the U.S., along with the University of Colorado at Boulder. Future Earth is a worldwide initiative to research environmental change and sustainability. This colloquium "provided students, faculty, staff, and the public with opportunities to learn about the concept of Future Earth and our shared role in global environmental sustainability," according to Jim Cooney, Vice Provost for International Affairs.

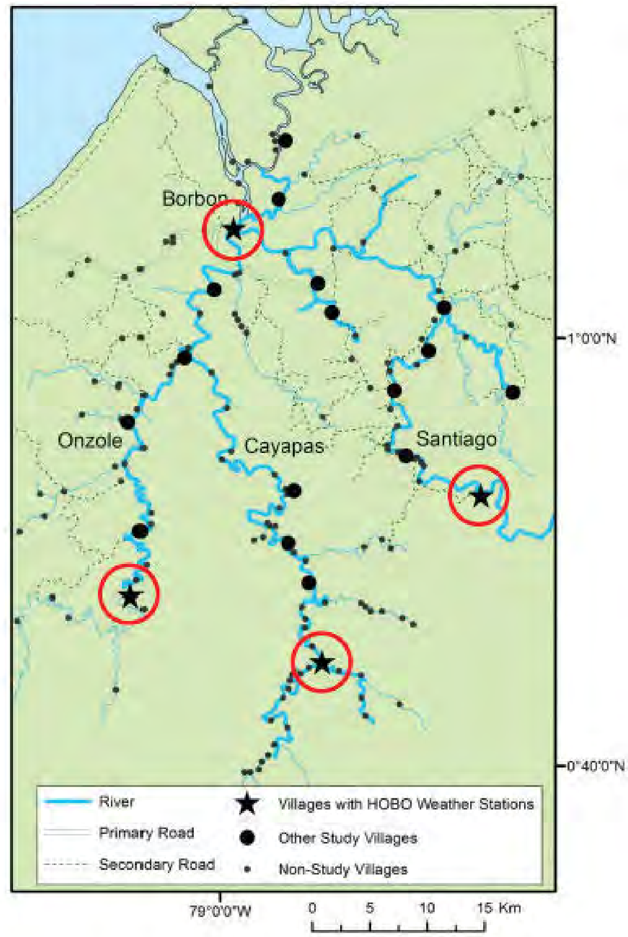
When thinking of major themes that will play a role in sustainability in the future, water undoubtedly comes to mind. To kick off the colloquium, the first panel session examined the topic of "Forging a Vision for a Sustainable Water Future." This panel featured Ben Grumbles, President of U.S. Water Alliance and former Assistant Administrator for Water, U.S. EPA; Jianjun Zhou, Professor at State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China; and Stephanie Kampf, Associate Professor, CSU Department of Ecosystem Science and Sustainability. This session was moderated by Reagan Waskom, Director of the Colorado Water Institute. Session organizers were Glenn Patterson, Ph.D. candidate in the department of Ecosystem Science and Sustainability; John Moore, Professor and Department Head of Ecosystem Science and Sustainability; and Wei Gao, Professor of Ecosystem Science and Sustainability.

Forging a Vision for a Sustainable Water Future panel speakers. From left to right, Stephanie Kampf, Jianjun Zhou, and Ben Grumbles. Photo by Emilie Abbott

The session began with a presentation from Ben Grumbles, who addressed a need for innovation and collaboration to tackle current and future water challenges. Grumbles outlined three main threats to water sustainability. The first was the fact that water is forgotten and taken for granted. Water infrastructure is hidden and is in disrepair in many places. Also, water's low cost does not reflect its full value. The second threat is fractured and fragmented policies. He argued that sustainability comes from thinking about energy, water, and land together, which necessitates collaboration between agricultural and municipal entities, among others. The third threat is fearful and frozen innovators—Grumbles advocated for a system that would encourage innovation in the water industry. Grumbles went on to outline some possible scenarios for the future that would improve the current system in innovative ways. One example of this is the idea of a Watershed Protection Utility. Another idea which is already being implemented at a relatively small scale in many places around the globe is green infrastructure. Grumbles suggested that this needs to extend far beyond simple rain gardens and green roofs into cities where natural features are fully integrated into the urban environment.

Jianjun Zhou focused on changes in the Yangtze River in recent decades, specifically changes due to the construction of many dams, including the famous Three Gorges





Left Photo: *Visions of Future Earth: Linking Society, Economics, and the Environment Colloquium poster*
Above Photo: *Map of data collection sites in Ecuador.*
Courtesy of Elizabeth Carlton

Dam. One of the changes caused by these dams is the endangerment or extinction of species. In addition, the amount of discharge in the river is decreasing, causing once-rare droughts to become common. This is especially true in the fall season, which then results in the reservoirs not having sufficient water in the spring. Sediment loads are also affected, especially during the dry season at sites such as the Yichang station (immediately downstream from the Three Gorges Dam) where instead of a pattern of sedimentation and erosion, there is only erosion. This pattern continues down the Yangtze. Lake Dongting, to which water from the Yangtze is diverted, has seen a steady decrease in volume and sediment load due to decreased flows overall and retention of water in the Three Gorges Reservoir. Zhou also addressed nutrient loads, temperature fluctuations, and chlorophyll a concentration. In summary, Zhou stated that although the full effects of these megadams are not yet known, adding more dams will only intensify these negative effects. Zhou stressed that water sustainability can only be achieved when humans prioritize rivers over the GDP—when we care for, preserve, and restore the rivers instead of dumping and exploiting as we have done and continue to do.

While Ben Grumbles discussed water on a national scale and Jianjun Zhou brought an international perspective, Stephanie Kampf focused her presentation on the Poudre River, specifically related to distributed impacts of snow, fire, and floods. Snowpack is extremely important in the Poudre River watershed as over half the water supply comes from snowy areas covering less than 20 percent of the basin. To monitor this snowpack, there are currently snow telemetry (SNOTEL) water supply forecasting stations around the watershed. A problem highlighted by Kampf is that in Colorado, there are no SNOTEL stations in areas of intermittent snow, which are most sensitive to losses in the persistent winter snow. These gaps in crucial data must be filled in order to be able to understand and protect these vulnerable areas.

Aside from snow, Kampf addressed the recent High Park fire and some concerns it raised about water, such as water quality degradation, flood hazard, debris flow hazard, and road washout. High-intensity localized rains following the fire caused channel scouring and erosion and washed sediment into the Poudre River. There is now a need for mulching and other restoration projects to mitigate these water quality impacts in the future, focusing on the areas with the greatest downstream impacts. Kampf then spoke about the September 2013 flood. Again, this flood was an example of distributed impacts of extreme events. While roads were destroyed and previous peak flow records were shattered in some areas, this event was not out of the normal rainfall range in other areas. For future flood events, there is a need for rapid warnings, responses targeted to the most affected areas, and long-term land use planning to reduce vulnerability. As far as water sustainability, Kampf identified different needs for dry times and wet times. In dry times, we must diversify our water supply by employing techniques such as rain collection and reduce demand by xeriscaping and installing efficient irrigation systems. In wet times, we must take into account that developed areas have higher peak flows and create solutions to lessen these flows, such as allowing for stormwater infiltration along roads and planning recreation areas that double as stormwater management. Lastly, Kampf noted the importance of community education to encourage awareness of and participation in the local watershed.

On October 7, Elizabeth Carlton of the Department of Environmental and Occupational Health at the University of Colorado at Denver presented a lunchtime talk on "Estimating the effects of climate change on waterborne diseases: Challenges and opportunities." Carlton is an environmental epidemiologist who works with neglected tropical diseases. Her goals are to study climate-disease relationships and to account for demographics and social and environmental stressors occurring along with climate change. In this lecture, Carlton detailed three projects she has worked on which dealt with disease and climate change. The first project examined the correlation between heavy rainfall events and diarrhea incidence in villages of northern coastal Ecuador. The study also looked at whether the incidence of diarrhea was related to the vulnerability of the community: level of sanitation, drinking water treatment, hygiene, and social cohesion. Carlton also described a graduate student's project on the impact of climate change on the water-borne disease burden in China. This study looked at potential future changes in access to safe water and sanitation via an exponential increase in access, a linear increase, or maintenance of the current trend. The study then modeled each of these scenarios paired with different projected levels of greenhouse gas emissions to examine effects of climate change on reducing the disease burden. Carlton's third project studied the potential impact of climate change on O*pisthorchis viverrini*, a parasite that is usually transmitted to humans through raw fish and which causes bile duct cancer. This parasite is common among the poor in Thailand and other areas of Southeast Asia. The research looked at a combination of three lakes that flood in the wet season, increasing the amount of feces in the water. In the dry season, the lakes are isolated, providing an opportunity to examine the role fish dispersion may play in the spread of disease. This study also has a cultural element—raw fish is especially common among the Laotian population in Thailand, so any efforts to change the local diet for safety reasons have cultural implications. Carlton also participated in a panel session later the same evening which addressed how changing environmental conditions impact emerging disease.

> *A problem highlighted by [presenter Stephanie] Kampf is that in Colorado, there are no SNOTEL stations in areas of intermittent snow, which are most sensitive to losses in the persistent winter snow. These gaps in crucial data must be filled in order to be able to understand and protect these vulnerable areas.*

The colloquium was hosted by the Office of International Programs with support from the School of Global Environmental Sustainability, the Confucius Institute, and the Vice President for Research. Other sessions addressed topics such as the Arctic, biodiversity, education abroad, and climate-smart agriculture.

Other Colorado Water Institute Research and Activity Reports

- Determination of Consumptive Water Use of Corn in the Arkansas Valley of Colorado, A. A. Andales, CWCB
- Modeling the Influence of Conjunctive Water Use on Flow Regimes in the South Platte River Basin Using the South Platte Decision Support System Groundwater Flow Model, Ryan Bailey, CWCB
- Continuation of Project Funded in 2013: Assessing the Agronomic Feasibility of Single-season Irrigation Deficits on Hay as Part of a Western Slope Water Bank, Joe Brummer, CWCB
- Developing an Unmanned Aerial Remote Sensing of ET System, Jose L. Chavez, CWCB
- Improving Data Quality for an Enhanced Climate Data Delivery System for CoAgMet (Colorado Agricultural Meteorological) Network, Nolan J. Doesken, CWCB
- Data Collection and Analysis in Support of Improved Water Management in the Arkansas River Basin, Timothy K. Gates
- Development of Visualization Tools for the South Platte, Steve Malers, CWCB
- Investigation of the Effects of Whitewater Parks on Aquatic Resources in Colorado, Brian Bledsoe, CWCB

Determination of Consumptive Water Use of Corn in the Arkansas Valley (Year 2)

Dr. Allan A. Andales, Associate Professor of Irrigation and Water Science; Department of Soil and Crop Sciences, Colorado State University
Dr. Michael E. Bartolo, Research Scientist; CSU-Arkansas Valley Research Center, Rocky Ford, CO;
Mr. Lane Simmons, Research Associate; CSU-Arkansas Valley Research Center; Rocky Ford, CO;

LOCATION WHERE THE WORK IS TO BE CONDUCTED: This project will be conducted at the Colorado State University (CSU) – Arkansas Valley Research Center (AVRC), Rocky Ford, CO.

PURPOSE OF THE RESEARCH

One of the recommendations that came out of the Kansas v. Colorado Arkansas River Compact litigation is for Colorado to use the American Society of Civil Engineers (ASCE) Standardized Penman-Monteith equation (PME) to estimate crop ET in the Arkansas River Basin. This equation requires accurate measurements of hourly weather data (solar radiation, air temperature, humidity, and wind speed) to calculate a reference crop ET (ET_r), which is a measure of local atmospheric demand for water. Crop ET (ET_c) is then calculated by multiplying ET_r by a crop coefficient (K_c) that varies with crop growth and development. This project will continue the long-term research to date, to more accurately calculate the ET_c of major irrigated crops in the basin, by defining the crop coefficients (K_c) used to convert ET_r to ET_c values and by validating (ground-truthing) the ET_r values calculated by the ASCE-PME for local conditions in the Arkansas River Basin. Corn is a dominant irrigated crop in the basin and has been the focus of this project in 2013. At least 2 growing seasons of data are required to develop a seasonal crop coefficient curve that is representative for the area. Therefore, a second growing season (2014) of corn data will be collected using the large (crop) lysimeter. The more accurate calculations of ET_c will ultimately improve the estimates of river flow that are used to determine compliance with the Arkansas River Compact. Related to this, accurate hourly weather data from 12 automatic weather stations in the basin are continuously needed to calculate ET_r and ET_c for the entire basin. These weather stations are part of the Colorado Agricultural Meteorological Network (CoAgMet). This work will also capitalize on the progress to date in validating calculated ET_r from ASCE-PME with measured alfalfa ET_r from the reference (small) lysimeter.

OBJECTIVES and METHODS

1. Develop a seasonal crop coefficient curve for corn that accounts for local environmental conditions in the Arkansas basin.
2. Assess the agreement between calculated alfalfa reference ET values from the ASCE-PME and measured alfalfa ET values from the reference lysimeter.

The objectives will be achieved in close collaboration with engineers in the Colorado Division of Water Resources (CDWR). Corn ET_c from the large lysimeter and alfalfa ET_c from the reference lysimeter will be calculated by mass balance (from automated weighing scale readings) and aggregated to 5-minute, 15-minute, and hourly totals. A full time research associate will manage the daily operations, crop management, maintenance, and data quality control of the 2 lysimeters. The following will be the major deliverables of the project: (1) Seasonal crop coefficient curve that characterizes corn ET_c (2014 growing season combined with 2013) at different developmental phases; and is appropriate for local conditions in the Arkansas Basin; (2) Observed seasonal consumptive water use (ET_c) of corn (2014); (3) Accurate hourly weather data from 12 CoAgMet stations in the basin, made available through the CoAgMet online database; (4) Comparison of calculated alfalfa ET_r from ASCE-PME and measured alfalfa ET from the reference lysimeter. A comprehensive analysis will be done of the behavior of the ASCE-PME under varying weather conditions in the Arkansas Valley. The analysis will reveal differences between ASCE-PME ET_r and lysimeter-measured alfalfa ET in standard conditions. The specific weather conditions that cause significant differences will be characterized; (5) One technical report published by the Colorado Water Institute detailing the methods and findings of the CSU research team. A draft of the report shall be provided to CDWR and CWCB by June 30, 2015.

This project will be conducted from July 1, 2014 to June 30, 2015.

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

Dr. Domenico Baú, Assistant Professor, Department of Civil and Environmental Engineering, Colorado State University

Location of the Work: South Platte River Basin, Colorado

Background: The surface watershed of the South Platte River Basin (SPRB) lies on alluvial deposits that form an unconfined aquifer system connected with the surface water, with a thickness that reaches 200 ft in the lower SPRB. The aquifer, which sustains the base flow in the river, is recharged by infiltrations from precipitation and irrigation canals, as well as seepage from surface water bodies and streams. The SPRB constitutes a major source of water for eastern Colorado and has allowed agricultural growth to approach 1 million acres of irrigated cropland. Conjunctive use of surface and groundwater resources in the SPRB is regulated accordingly with the 1969 Groundwater Administration Act [Senate Bill 81], which requires all non-exempt groundwater rights to come into priority. Prior to 2003, about 9,000 groundwater irrigation wells were active in the SPRB [Nettles, 2011] with augmentation requirements of 5-10% of their water consumptive use in order to protect surface water rights. Following legislative changes that occurred in 2003-2004, water resources have been administered following strict priority rules since 2006, with all non-exempt wells required to have a decreed augmentation plan that replaces 100% of their stream depletion. As a consequence of the increased cost for acquiring augmentation water, in the last six years, about 4,000 wells have been totally or partially curtailed from pumping [Nettles, 2011], potentially resulting in reduced aquifer drainage and rising water table levels in several areas of the SPRB.

Purpose: In 2012, CSU started a research project funded by the Colorado Water Conservation Board (CWCB) to study the critical linkages between groundwater pumping for irrigation and the coupled groundwater/surface water regimes in the SPRB. This study has relied on the use of the alluvial groundwater flow model developed as a fundamental component of the South Platte Decision Support System (SPDSS). The SPDSS was developed starting in 2001 by the Colorado Department of Natural Resources (DNR), the CWCB and the Division of Water Resources (DWR) in order to support State officials and water users in the optimal planning and management of water resources [Colorado Water Conservation Board, 2001]. The SPDSS groundwater flow model has been developed by CDM-Smith [2008, 2011] using the USGS finite-difference groundwater flow code MODFLOW [Harbaugh, 2005]. The model simulates, on a monthly step, flow regimes over the entire area of the SPRB in Colorado (~2,500 mi^2) during the period 1950-2006 and constitutes a crucial tool to support and improve the planning and management of water resources in the SPRB.

The overarching goal of this project is to provide the Colorado Water Conservation Board (CWCB) with an independent evaluation of the SPDSS groundwater flow model, highlighting model capabilities, strengths and weaknesses. The proposed project is carried out over a three-year period. In the first two years, CSU has focused on the following tasks:

a) Analysis of model grid and time discretization to provide general considerations and directions regarding the spatial and temporal scales for which the SPDSS model seems most adequate as water management simulation tool;

b) Analysis of hydrogeological parameter distributions used in the model (hydraulic conductivity; storage properties, streambed conductance) to gain a general understanding of the extent to which the parameter distributions are representative of the SPRB hydrogeological setting;

c) Analysis of representativeness of hydrological stress data used in the model (time series of surface boundary and lateral flow conditions, groundwater pumping, and aquifer recharge) with respect to the SPRB hydrogeology;

d) Preliminary runs performed to test the numerical robustness and stability of the model with respect to hypothetical, yet realistic, changes in hydrologic stress conditions, thus assessing its ability to provide reasonable water level distributions under hydrologic stress conditions different than those utilized during model development and calibration.
e) Sensitivity study on:

- Effects of hypothetical increased stream augmentation by aquifer recharge that reproduces quantitatively the changes in water administration practices enacted in 2006.
- Changes in aquifer pumping based upon realistic estimates of the reduction in groundwater withdrawal and its spatial distribution across the SPRB that have occurred since 2006.
- Effects on groundwater and surface water flow regimes of hypothetical drought conditions producing reduced snowmelt upstream inflows and increased evapo-transpiration in relation to modified atmospheric conditions and rising water table levels, respectively.

Completion Date: The proposed project is conceived to be three-year long. Since funding is available only on a yearly basis, a proposal for renewal of funding is submitted to the CWCB at the end of each year. This proposal concerns works envisioned for the third year of the project.

Proposed Tasks for Year 3: It is anticipated, in the fiscal year 2013, the SPDSS groundwater flow model will be applied to verify the adequacy of analytical, semi-analytical and numerical models currently used to assess:
(a) The impact of well pumping from alluvial formations on the flow in hydraulically connected to streams and irrigation canals.
(b) The plans for stream augmentation that permitted wells are currently required to meet for consumptive use of groundwater.

In both tasks, the SPDSS groundwater model will be applied to simulate the effects on stream flows of hydrological stresses (well pumping and artificial recharge) applied to the alluvial aquifer system. The results of the model will be compared to corresponding stream-aquifer interaction laws used for water administration. Since the SPDSS groundwater model simulates realistic conditions of unconfined subsurface flow and, given its considerable spatial extent, uses an upscaled griblock size (1000×1000 ft^2) this study will also focus on the influence that effects that local heterogeneity and unconfined-flow related non linearity may have on the calculation and the adopted constitutive laws for stream depletion and recharge. It is worth mentioning that this proposed application of the SPDSS groundwater flow model is one of the goals originally specified by the CWCB in their original SPDSS feasibility study (CWCB, 2001).

Deliverables: At the end of the third year, a final technical report describing project activities and findings will be submitted to CWCB. In particular, this report will include all results of the analysis conducted in the Tasks listed above. In addition, the PI will meet with CWCB representatives at least twice a year, either at the CSU campus, at CWCB offices or via teleconference, to best coordinate the project activities, discuss project progress and future direction.

Continuation of Project Funded in 2013: Assessing the Agronomic Feasibility of Single-season Irrigation Deficits on Hay as Part of a Western Slope Water Bank

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Calvin Pearson, Professor/Research Agronomist, Colorado State University, Western Colorado Research Center – Fruita
Abdel Berrada, Research Scientist, Colorado State University, Southwestern Colorado Research Center

Location: Seven irrigated, established hay fields (4 grass and 3 alfalfa) located in six Western Colorado counties: Delta, Montezuma, Gunnison, Mesa, Grand, and Routt.

Purpose and Need: To determine potential water savings, crop responses, and environmental impacts from strategic deficit irrigation of hay fields in Western Colorado.

Under the 1922 Colorado River Compact, the four Upper Division States may not allow the flow at Lee's Ferry to drop below a 10-year running average of 75 million acre-feet (MAF) or else be subject to curtailment. The current 10-year average is about 90 MAF, and while the threat of curtailment is not imminent, there is growing concern in Colorado that a combination of factors may conspire to hasten the onset of curtailment. These factors include the possibility of a new trans-mountain project, full use of existing systems, new demands from energy development including oil shale, and growth in demands and water use stemming from climate change.

Western Slope water users account for about 1.3 million acre feet of Colorado River Basin (CRB) water of which about 1 million are pre-1922 and exempt from compact administration. The populated Front Range diverts about a half-million acre feet of CRB water of which the majority is junior to 1922. A possible curtailment scenario is Colorado's post-1922 water rights forgoing use (or a negotiated fraction) until all of the 75 million acre feet 10-year average delivery requirements to the Lower Basin States are restored. A water bank arrangement might consist of short-term leases allowing pre-1922 agricultural rights to be used temporarily by post-1922 municipal and industrial – mostly Front Range - water right holders.

Western Colorado includes the headwaters of the Colorado and numerous tributaries, such as the Yampa, White, and Gunnison. Together, these four basins include about 350,000 acres of irrigated grass and alfalfa hay. Many water bank discussions focus on the legal framework, administration logistics, and return flow implications of a possible water bank. Still to be determined is the agronomic feasibility for individual irrigators.

Objectives: "Deficit irrigation" refers to withholding water during non-critical crop growth stages. In mid to lower elevation environments, deficit irrigation is typically carried out by seasonally irrigating alfalfa and/or grass hay to the first cutting only. For higher elevation mountain meadows where only one cutting of hay is taken per season, a "deficit" treatment means no water is applied to the field for the entire growing season.

Using side-by-side, i.e. “deficit” versus “business as usual” irrigation treatments, this project will answer three basic questions about these approaches: 1) What is the likely impact on hay stand life, productivity (measured as tons per acre), and quality due to a single-season deficit? 2) What is the potential range of marketable, saved (otherwise consumed) water per acre of single-season deficit irrigated hay in Western Colorado? and 3) Are there any obvious environmental benefits or concerns to deficit irrigating hay?

Timeline and completion date: This proposal is a request to fund the second year of a two-year project that was initiated in the spring of 2013. Completion of data collection and reporting of final results will occur in the fall of 2014. A graduate student was recruited in the spring of 2013 and she has completed the first year of data collection and is now in the process of analyzing and summarizing the data. We plan to collect data at the seven sites established in 2013 and hope to add several additional sites if possible to make the data set more robust.

Developing an Unmanned Aerial Remote Sensing of ET System

José L. Chávez, Assistant Professor, Civil and Environmental Engineering Department, Colorado State University,

Location: Greeley, La Salle, Fort Collins, and Rocky Ford, CO

Purpose: The proposed research will integrate proven remote sensing (RS) sensors into a small unmanned aerial system (sUAS). Data derived from the aerial RS platform will be used to develop a suitable RS of crop evapotranspiration (ET) method for Colorado.

The grant will make possible the development of a sUAS and in addition it will allow collaborative and will make future proposals more competitive (state, federal).

The type of information to be gained include: a) suitable (accurate) RS of crop ET algorithm for CO; b) ability to map (monitor) ET at high spatial resolution on demand; and c) documentation of spatial crop water stress and ET not used, for water rights, court, transfer purposes.

Considering an increase competition for water, the development of a sUAS for RS of ET purposes will be highly beneficial for irrigation ditch companies, water conservation districts, crop growers assoc., cities (landscape ET), and state and federal agencies.

Objectives, methods, timeline, completion date:

Remote sensing ET models are being used in agricultural irrigation water management. These models either rely on distributed information on surface vegetation indices (visible and near infra-red bands) or on surface temperature images. RS of ET models perform better on certain regions, environments and surface conditions. Therefore, there is a need to develop a reliable RS of ET model for Colorado. Furthermore, a main challenge regarding RS imagery, is that the temporal resolution of multispectral satellite images is not adequate (e.g., every 16 days in the case of Landsat 8) to estimate daily crop ET. If there is cloud cover during a satellite overpasses then estimates of ET for a month will not be possible. Using airborne RS platforms may be cost-prohibited (~$5,000 per campaign/farm) and may not be available on demand (due to the nature of their commercial applications and commitments). Therefore, it is believed that with the integration of multispectral sensors in a small unmanned aircraft system (sUAS), a robust and dependable high spatial resolution ET model can be developed.

The sensors (multispectral scanner and infra-red thermometer) that will be mounted on the new sUAS have been used at ground level. The collected data have proved to be useful in promoting a more efficient and sustainable management of agricultural water. However, a major critique is the time difference between data points collection. Mounting sensors on a sUAS will enable the collection of needed high resolution (~30 m) crop water use data on a spatial fashion on demand. Hence, with the development of the sUAS larger areas will be able to be covered and the evaluation and development of a suitable RS of ET method will be more efficient since a wider range of surfaces/conditions will be covered on demand (i.e., not depending on the limitation of ground-based sensors, satellite overpass, or costly aircraft imagery).

Objectives

The objectives of the proposed research include: a) integrating multispectral remote sensing sensors in a sUAS, b) development of a suitable remote sensing of crop evapotranspiration (ET) method for Colorado, and c) evaluation of items (a) and (b).

Methods

A small Unmanned Aerial Vehicle (sUAV) will be acquired from UASUSA and multispectral RS sensors will be mounted on the aerial platform. The PI has secured funds from a Borland Grant (CEE Dept.); thus requesting $15,000 from CWI to complete funds to purchase the aerial system.

A graduate research assistant (GRA) will help operate the system to acquire high spatial resolution data (~30 m footprint diameter by flying ~50 m from the ground) over research fields. The GRA will be trained in remote sensing of ET methods. The different research locations include: a) corn and alfalfa fields, managed under center pivot (CP) full and deficit irrigation, near La Salle, CO (Collaborator: Randy Ray, CCWCD); Randy has funded an in-field soil moisture sensor network to estimate crop ET; b) corn and alfalfa fields, fully furrow irrigated, near Rocky Ford, CO (Collaborators: Mike Bartolo/Lane Simmons/Allan Andales, CSU AES AVRC); where two weighing lysimeters are located; c) limited drip irrigated corn fields near Greeley, CO (Collaborators: Jon Altenhofen, Northern Water; and Tom Trout, USDA ARS); and potentially d) limited CP irrigated corn near Fort Collins, CO (R. Khosla, A. Andales).

RS data will be used in three ET algorithms: a) a two-source energy balance (EB) model, b) a surface aerodynamic temperature EB model, and c) a crop water stress index (CWSI) model. Resulting ET values will be evaluated with ET derived from soil TDR, neutron probe, and lysimetric ET data. The model that better performs will be enhanced for the conditions found in CO. For instance, the CWSI approach could be enhanced by modeling the canopy temperature based on the sUAS data. Similarly, the aerodynamic temperature could be modeled based on the accurate characterization of percent vegetation cover, etc.

Timeline and Completion Date

It is proposed to start the project on March 1st of 2014 and end it by February 28th of 2015. March/April: acquisition of sUAV and recruitment of GRA; May/June/July/August: sUAS development, field tests and data acquisition and analysis; September, October, November: ET model development, evaluation; December, January, February: research article production; and March/April 2015: Report due to CWI.

Improving data quality for an enhanced climate data delivery system for CoAgMet (Colorado Agricultural Meteorological) network

Nolan J. Doesken, State Climatologist, Colorado State University
Wendy A. Ryan, Assistant State Climatologist, Colorado State University

Location: Work will be conducted throughout Colorado.

Purpose: CoAgMet is a statewide weather network that was mainly designed to support Colorado's agricultural industry. With this funding request, the Colorado Climate Center will continue to develop, improve and maintain a climate data system for Colorado. Use of CoAgMet data to schedule irrigation is the most prominent use of this network, but without quality data as inputs to evapotranspiration (ET) equations, questions arise about the validity of ET estimates. The new eRAMS irrigation scheduling tool and the Arkansas Valley lysimeter projects rely heavily on ET estimates from CoAgMet stations and improved quality control is essential for these efforts. These funds will be used to build more robust data quality control into the CoAgMet database so that users are aware of potential problems with data inputs. This is a large undertaking but a worthy effort to increase reliability of the data being distributed.

Objectives, Methods, Timeline and Completion Date: The objectives of this work are to create a more reliable climate data delivery system for CoAgMet by improving upon both quality control of data and updating equipment to be used throughout the network. Researchers at the Colorado Climate Center will build automated quality control standards following the standards set by the FAO in Irrigation and Drainage Paper 56 for both weather data integrity and statistical analysis for filling in missing/suspect data. This will result in complete time series with flags for the data that is deemed questionable. The data flags will alert users to raw data that has been changed and for what purpose.

New sensors will be purchased and installed where it is deemed necessary during routine maintenance. Equipment will mainly include wind sensors, rain gages, pyranometers, and temperature/humidity probes.

Timeline:

July, 2014: Procure equipment and begin database investigations for programming quality control and data completeness algorithms once funds become available.

July - September 2014: Annual maintenance is performed on all stations; equipment will be installed at locations where sensors are found to be failing. Begin testing and implementation of data QC/completeness algorithms.

October 2014 - June 2015: Once testing of the data QC is completed internally, users will be solicited to test the algorithms. After the work is completed, the new database will be rolled out on the website and through web services. Final report writing begins.

June 30, 2015: Project completed and final report submitted to Colorado Water Institute.

Data Collection and Analysis in Support of Improved Water Management in the Arkansas River Basin

PI: Timothy K. Gates, Professor, *Department of Civil and Environmental Engineering, Colorado State University*
Co-PI: Jeffrey D. Niemann, Associate Professor, *Department of Civil and Environmental Engineering, Colorado State University*

Location: Arkansas River Basin, Colorado

Purpose: Colorado's Arkansas River Basin, the largest in the state, comprises a varied and complex water system. Emerging as a snowmelt-fed alpine stream, it extends about 165 miles and drops more than 4900 ft before gathering into Pueblo Reservoir to be released again onto the southeastern plains. Along the remaining 195 miles of its course before it flows into Kansas, the river winds through a broad and varied alluvial valley that supports extensive irrigated agriculture. In the Upper Arkansas River Basin (UARB), above Pueblo Reservoir, the water resources of the stream-aquifer system supply the demands of mountain communities and Front Range cities, recreation and fisheries, and some irrigated agriculture. In the Lower Arkansas River Basin (LARB), irrigated agriculture is the predominant water consumer with a growing municipal and industrial demand. In addition to natural snowmelt and rainfall, the Colorado River Basin provides inflow to the Arkansas River Basin via the Fryingpan-Arkansas and Twin Lakes trans-mountain diversions.

Water managers and users in the Arkansas River Basin need information to help them enhance overall beneficial water use, redress serious problems of water quality degradation (e.g., salinity, selenium, and uranium), conserve water, and find innovative ways (e.g., the Super Ditch) to address mounting pressures for increased diversions out of the Basin. Sound water management requires a good database to characterize the stream-aquifer system and to undergird existing and future modeling tools. For over fourteen years in the LARB and three years in the UARB, Colorado State University (CSU) has conducted extensive field monitoring to build such a database. *The purpose of the project proposed herein is to collect and analyze key field data in representative regions of the Arkansas River Basin needed to maintain and enhance the Arkansas River Basin database in support of improved water management. Thereby, the project will provide funds needed to prevent interruption of long-term data collection efforts.*

Objectives: The data-focused objectives of this one-year project are:

(1) Gather data on water table levels and water quality in existing groundwater monitoring wells distributed over representative study regions in the UARB and LARB, for characterization of the aquifer system and to support flow and transport models developed by CSU, the Lease-Fallowing Accounting Tool currently under development, and the proposed Arkansas Basin Decision Support System to be developed over the coming years by the Colorado Water Conservation Board;

(2) Gather data on water quality and flows at selected sites along canals, tributaries, and the main stem of the Arkansas River in the UARB and LARB to characterize the stream system and to support current and future models;

(3) Conduct quality-control tests of the gathered data and enter them into the SQL database for the Arkansas River Basin developed and maintained by CSU; and

(4) Conduct a preliminary analysis of the data gathered under this project and summarize in a final report for use in system characterization and model support.

Methods: About 150 landowners have cooperated with CSU to provide access to sampling sites for water and related characteristics in the UARB and LARB. *Availability of these sites provides valuable in-kind matching support for this proposed project.* Field data on water table depth and in-situ water quality parameters (electrical conductivity, temperature, pH, dissolved oxygen, and oxidation reduction potential) will be gathered at about 22 existing groundwater monitoring wells in a study region in Chaffee County in the UARB and about 140 groundwater monitoring wells in two study regions within Otero, Bent, and Prowers Counties in the LARB. Four to five sampling events will be conducted in each of the three study regions. Water samples will be extracted from the wells in the UARB during one of the sampling events for analysis of major dissolved ions, nutrients, and selected metals. During two of the sampling events in both regions of the LARB, water samples will be extracted from a subset of about 50 wells and analyzed for major dissolved ions, nutrients, selenium, and uranium. In-situ water quality parameters will be measured during the sampling events at about 24 surface-water sites in the UARB and at about 145 sites in the LARB. Flow rates will be measured at about 18 of the surface-water sampling sites in the UARB. Water quality samples will be analyzed by EPA-approved laboratories.

Standard procedures and protocol will be followed in maintaining, cleaning, and calibrating probes and pumping equipment for field measurements and sample collection. Field data will be checked to insure that values are physically reasonable and will be subjected to statistical outlier tests in comparison with data previously collected at the same locations.

Data will be added to CSU's SQL database (compatible with Colorado Division of Water Resources HYDROBASE). Preliminary data analysis will describe spatiotemporal variability of measured values and basic statistical characteristics in relation to previous data gathered in the study regions. Field measurement methods, along with procedures and results of preliminary analysis, will be documented in a final project report.

Timeline & Completion Date: Data collection will commence shortly after the proposed start date of 1 Mar 2014. Three irrigation season sampling trips and one to two off-season trips are planned for each of the study regions in the UARB and LARB. Data will be checked and entered into the database over the course of the one-year project. Final data analysis will commence on about 1 Oct 2014 and final report preparation will begin on about 15 Jan 2015. The project is scheduled for completion on 28 Feb 2015..

Development of Visualization Tools for the South Platte

Principal Investigator: Steve Malers, Open Water Foundation

Location of the work and project team: The work will be performed in Fort Collins utilizing CSU faculty, students, and in collaboration with the Open Water Foundation (OWF), a nonprofit that focuses on open source software for water resources and specifically Colorado's Decision Support System (CDSS) software.

Purpose: The South Platte River Basin system is complex, involving aspects of natural and engineered physical systems, water law and administration, operations, and many other factors. A water manager in the South Platte Basin recently stated "People need to understand systems and the space/time/water quality continuum." It is challenging to present complex water resource data in a way that can be understood by a variety of interests. This project will build on South Platte Decision Support System (SPDSS) data and tools to create reusable and operational data visualization tools that can be used to educate the public, public servants, and professionals about water resource issues in the basin.

Objectives:

1. Leverage SPDSS data and software to develop enhanced data visualization tools applicable to SPDSS and other State data
2. Demonstrate use of visualization software tools that are accessible to the public, for example Google Earth, Tableau Public (Tableau was used in Colorado River Study), Mapstory, Gapminder, and open source web visualization tools
3. Apply tools to system-wide data visualizations in ways that increase understanding of interactions in the system, for example:
    a. Online integrated map of current South Platte River conditions, such as calls, free river conditions, reservoir levels, suitable for State website
    b. System-wide summary of historical trends focusing on identifying sustainable systems
    c. Visualization of water rights transfers and diversion coding "water color" over time
    d. Interactive line diagrams and "snake diagram" that can be efficiently updated
4. Demonstrate collaboration that leverages the technical capabilities and funding potential of multiple organizations, for example students and staff from:
    a. Integrated Decision Support Group – The IDS Group combines advanced techniques with software engineering to create Decision Support Systems for water and natural resources management.
    b. Geospatial Centroid - The Centroid is a resource and research center at Colorado State University established to provide students, faculty, and the Colorado community with information about GIS at CSU and how these activities link to broader statewide, regional and global initiatives
    c. CitSci - CitSci.org is a website that allows citizen science organizations and their volunteers to streamline data collection, management, mapping, and analysis

Method (Approach): If awarded, one or more students will be identified to work with CSU and OWF technical leadership to develop visualization tools and techniques:

1. Meet with key CWCB staff to identify needs for data analysis and visualization. For example, requirements from the Colorado Water River Availability Study (CRWAS), SPDSS modeling, and Colorado Water Plan may provide guidance.
2. Evaluate the needs identified in the previous task and determine tools that can be leveraged, such as Google Earth, Tableau, CDSS software, and open source visualization tools.
3. Identify CSU student(s) that have technical skills and interest to develop tools.
4. Develop/configure visualization tools and apply to the identified visualization needs.
5. Make tools available to the State and public for SPDSS data.

The result of this approach will be working data visualization tools appropriate for the South Platte and other basins. The results will be suitable for use by a variety of organizations that need to visualize and understand complex water resource data.

Timeline and Completion Date:

- Within 1 month of award, meet with CWCB to determine visualization needs
- Within 2 months of award, determine technologies and identify student(s)
- Within 10 months of award, develop visualization tools and demonstrate implementation to meet needs that have been identified
- Within 12 months of award, integrate tools with SPDSS software and make available to State and public for general use, provide project overview to State

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

Prepared for the

Colorado Water Conservation Board

Prepared by

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September 2014

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EXECUTIVE SUMMARY

Whitewater parks (WWPs) have become a popular recreational amenity in cities across the U. S. with Colorado being the epicenter of WWP design and construction. WWPs 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 opinions without having any concrete studies to inform those opinions. 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 three major sections of this report provide condensed versions of three complementary Colorado State University theses focused on the effects of WWPs on aquatic resources in Colorado.

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 summarized studies (Fox, 2013; Kolden, 2013; Stephens 2014). 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 River, and they have performed fish biomass surveys in the same reaches and pools described in this study. 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. 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.

Kolden (2013) modeled two sections of the North St. Vrain River in Lyons, Colorado: 1) one natural section, and 2) one section containing a WWP with three engineered drop structures. A two-dimensional (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. 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.

The three-dimensional (3-D) computation fluid dynamics (CFD) software FLOW-3D® v10.0 was used to model each of the reaches. 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 CR 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.

A continuous and spatially-explicit hydraulic model was created by Stephens (2014) to further analyze the data from the North St. Vrain WWP. The model describes hydraulic conditions along potential fish movement paths and examines their influence on fish passage. Quantifying the hydraulic conditions in this manner captured important and unique hydraulic characteristics at each WWP, and described velocity and depth throughout the flow field at a scale meaningful to fish. Logistic regression indicated that both depth and velocity were major predictors of passage success, and underlined the importance of jointly considering hydraulic variables when assessing the probability of passage success. This model accurately predicted over 87% of non-movements and over 92% of upstream movements in the WWP based on individual fish PIT observations.

Seven different discharges, ranging from 15 to 300 cfs, were used in the model, and it was found that neither the highest nor lowest discharges presented the greatest challenge for passage. While the higher discharges provide a larger fraction of accessible flow paths for fish, discharges at 15 to 60 cfs occur much more frequently throughout the year at the study site. Both interstitial spaces and recirculation eddies were found to create important zones of lower velocity and improve fish passage throughout the range of discharges.

DESIGN RECOMMENDATIONS

Knowledge gained from these studies of the WWP structures on the North St. Vrain River 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 amount of acceptable suppressed movement is a question that should be answered by natural resource managers on a case-by-case basis. Criteria to consider when assessing passage requirements include the previous fragmentation of the system (existing diversions, barriers, etc.), site-specific constraints, target species, and potential benefits due to increased community awareness and personal connection to the environment.

The hydraulic analysis and statistical model developed by Stephens (2014) shows that flow depth is critical in determining the probability of fish passage success. This study strongly suggests that flow depths greater than 0.6 ft should be maintained for all expected discharges. The hydraulic modeling and subsequent statistical analysis also show that velocity is a key factor affecting fish passage. However, hydraulic nuances exist for each type of WWP structure and, therefore, velocity thresholds vary with each design type. The passable velocity also varies with the size class of fish attempting to move upstream. Without site-specific analysis, it is recommended that velocities remain under 10 to 25 BL/s. Care should be taken to ensure that *both depth and velocity requirements are met continuously along likely fish movement paths*.

Evidence from the North St. Vrain WWP studies also underscores the importance of providing continuous zones of lower velocity, away from the main velocity jet, as alternate passage routes. The use of non-grouted wingwalls provides interstitial spaces where smaller bodied fishes (with inherently lesser swimming abilities) can pass the structures through lower velocity paths. These interstitial spaces should have a range of sizes comparable to the expected body sizes of the fish population. A design with non-grouted wingwalls also creates additional roughness elements along the channel margins, providing refugia for fishes attempting to move upstream. Large eddies that reach as far as possible up the sides of the main velocity jet also provide low-velocity zones, especially during high discharges. The recommended non-grouted wingwall design should allow water to spill over the wingwalls at some location, with adequate flow depth, even at base flow discharges.

It is worth noting that the resulting recommendations are best applied to a system of geomorphic class, hydrologic regime, and scale similar to the study reach. 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. 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 either case, 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 adequate zones of lower velocity would exist to allow potential upstream passage routes. It is likely that a site-specific analysis would also be required to determine if an existing WWP needed to be modified to provide additional zones of lower velocity. However, without greater understanding of the specific mechanism(s) causing the suppression of movement, developing detailed design guidelines will remain challenging.

Although suppression of fish movement exists at the WWP evaluated in this study, the observations of successful movements indicate that WWPs producing hydraulic conditions within the range of those described in this study have the potential to meet both recreational and fish passage goals for salmonids. 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.

The research described in this report provides a foundation for understanding how and why WWPs affect fish movement, yet new questions and uncertainties have emerged. Important areas for future study include: the minimum resolution of hydraulic models needed to characterize fish passage potential and habitat suitability in WWP pools; further analysis of the mechanisms causing upstream movement suppression through WWPs; cumulative effects of inline structures; transferability of results from the North St. Vrain WWP studies; and the impact of WWPs on native non-salmonid species. As the popularity of WWPs continues to grow in Colorado and elsewhere, it is imperative to also continue increasing our knowledge base concerning the design and potential impacts of these recreational structures.

WOOD: Windows Of Opportunity for Debris Retention in Response to 2013 Front Range Flooding

Basic Information

Title:	WOOD: Windows Of Opportunity for Debris Retention in Response to 2013 Front Range Flooding
Project Number:	2014CO297B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	CO-004
Research Category:	Biological Sciences
Focus Category:	Geomorphological Processes, Management and Planning, Surface Water
Descriptors:	None
Principal Investigators:	Ellen Wohl

Publications

There are no publications.

Management of Large Wood in Streams of Colorado's Front Range

Natalie Kramer Anderson, PhD Candidate, Geosciences, Colorado State University

Advisor: Ellen Wohl, Fluvial Geomorphology, Colorado State University

Large wood in rivers provides numerous physical and biological benefits to river corridors, but may also pose risks to inhabitants, infrastructure, property, and public safety. This project provided managers with a framework and tools to be able to assess the benefits and risks of leaving wood in river corridors via a technical report titled: "Management of Large Wood in Streams of Colorado's Front Range: A Risk Analysis Based on Physical, Biological, and Social Factors." The authors of the report included water faculty: Ellen Wohl (fluvial geomorphology), Kurt Fausch (Fisheries), Kevin Bestgen (Fisheries), Mike Gooseff (Ecohydrology), and Brian Bledsoe (Civil Engineering) as well as a graduate student, Natalie Kramer (Dept of Geosciences). The team met and advised water resources professionals at the city and county levels in Boulder and Larimer Counties during Fall 2013 and Spring 2014. These meetings provided valuable feedback to the academic team on how to design guidelines for assessment and monitoring that would be practical and regularly implemented by staff in stormwater utilities, floodplain management, and natural resources programs. Based on this feedback, the team wrote and distributed the technical guide in the Fall of 2014. Informal feedback in the form of emails and verbal communications indicate that the pdf of the report has been widely circulated among interested parties and is now being used by private consulting firms and non-profit watershed groups, as well as by local governmental agencies.

The project was initiated after the September 2013 Front Range floods, which deposited large amounts of wood within the river corridors and onto the floodplains of the Colorado Front Range. The goal of the project was to be able to assist managers in deciding whether individual wood pieces or jams must be removed, can be stabilized and left in place, or can simply be left alone, as opposed to the current default of always removing wood. It was the hope of the team that the report would lead to the decision to leave in place wood that poses little to no risk to human infrastructure and safety, to the benefit of river ecosystems. This project was featured in the July/August 2014 issue of this newsletter wherein the project justification and background was fully discussed. Thus, the focus here will be on some of the tools developed and the results of the project.

Within the report, a decision process for managing large wood is outlined, particularly for assessing the relative benefits and risks associated with individual pieces and with accumulation of wood. The process is designed so that varying levels of effort can be applied, from a cursory visual assessment to detailed numerical modeling, and is usable by individuals with diverse technical backgrounds working in a range of rivers, from urban to natural.

The report begins with background information on the physical and biological benefits of wood followed by a summary of the hazards that wood may create for inhabitants, infrastructure, and recreational users. The decision of whether to retain, remove, or modify wood is highly dependent on context. Thus, several technical tools are introduced, including a large wood structure stability analysis spreadsheet, flow and habitat models, and a framework of easy-to-use decision bands that facilitate assessment of risk for three categories: ecological, recreation, and public safety. Eight decision bands were designed, and an overall decision band score sheet was developed to easily compare relative risks for any piece or accumulation of wood within any context. The report also outlines seven reasonable management responses based on the risk analysis: no action, monitor, stabilize, signage/outreach, remedial pruning, close reach, and move wood.

The risk assessment designed in the report has been enthusiastically taken up by the management community, especially by Boulder County Parks and Open Space. Local government agencies and consulting firms across the Front Range are currently using the document to help design and implement new waterways master plans. The success of this project is partially due to swift response of the team from concept to publication following the 2013 flooding. To reach a broader national and global audience, a version of this report has been submitted to the peer-reviewed Journal of American Water Resources Association. It is currently in review, with expected publication date in the Fall of 2015.

USGS Summer Intern Program

Basic Information

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

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	Good
Learning Experience	Very Good
Travel	About Right
Field Experience Provided	About Right
Overall Rating	A

Additional Remarks

The folks at USGS MOWS all care about the work I do and always have valuable insights… great people to work with.

Basic Information

Start Date:	3/1/2014
End Date:	2/28/2015
Sponsor:	DOI-USGS-Geological Survey
Mentors:	Robert S Regan
Students:	Samuel Saxe

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

Basic Information

Start Date:	3/1/2014
End Date:	2/28/2015
Sponsor:	DOI-USGS-Geological Survey
Mentors:	Edward Stets
Students:	Sydney Wilson

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

It was great!

Basic Information

Start Date:	3/1/2014
End Date:	2/28/2015
Sponsor:	DOI-USGS-Geological Survey
Mentors:	Robert S Regan
Students:	Michael Sanders

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

I definitely enjoyed working with the USGS and WRRI. I was trusted to be capable and learned a lot through working as a team member.

Basic Information

Start Date:	3/1/2014
End Date:	2/28/2015
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

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	12	0	0	3	15
Masters	5	0	0	9	14
Ph.D.	1	1	0	3	5
Post-Doc.	0	0	0	0	0
Total	18	1	0	15	34

Notable Awards and Achievements

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 recipient, Taylor M. Baird.

Taylor is currently a senior studying Environmental Engineering with a minor in Humanitarian Engineering at the Colorado School of Mines. She intends to pursue a master's degree in hydrological engineering from the Colorado School of Mines, and then would like to become a Peace Corp volunteer. She hopes to lead a career in providing clean water to developing nations. She enjoys running and being outdoors when she has free time.

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

- Lindsay Bearup earned Graduate Student of the Year award for the interdisciplinary Hydrologic Science and Engineering graduate program at Colorado School of Mines (2013-2014 academic year)
- John McCray published five peer-reviewed journal papers in environmental and water resources journals
- John McCray published a paper in the prestigious journal *Nature Climate Change*.

Shear Resistance of the Nuisance Diatom Didymosphenia Geminata

Diane McKnight received the 2014 Hydrologic Sciences Award at the 2014 American Geophysical Union Fall Meeting, held 15–19 December in San Francisco, Calif. The award is for outstanding contributions to the science of hydrology.

Publications from Prior Years

1. 2009CO195G ("Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping") - Conference Proceedings - Neupauer, R.M., Efficient modeling methods for estimating stream depletion, 2015 World Environmental and Water Resources Congress, American Society of Civil Engineers, 2015.
2. 2009CO195G ("Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping") - Articles in Refereed Scientific Journals - Lackey, G.D., R.M. Neupauer, and J. Pitlick, Effects of streambed conductance on stream depletion, Water, 7, 271-287, doi:10.3390/2/7010271, 2015.
3. 2011CO245G ("Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts ") - Other Publications - Bearup, L., Mikkelson, K., Wiley J., Navarre-Sitchler, A.K., Maxwell, R.M., Sharp, J.O., McCray, J.E., 2014. Metal fate and partitioning in soils under bark beetle-killed trees, Science of the Total Environment, 496: 348-357
4. 2011CO245G ("Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West: Heavy Metals and Disinfection Byproducts ") - Other Publications - Bearup, L., Maxwell, R.M., McCray, J.E., 2015. Mixing analysis of hillslope response to land cover change: an integrated model of chemical hydrograph separation, submitted to Water Resour. Res.
5. 2010CO219B ("Shear Resistance of the Nuisance Diatom Didymosphenia Geminata") - Articles in Refereed Scientific Journals - Cullis, James D.S.; Diane M. McKnight; and Sarah A. Spaulding, 2015, Hydrodynamic control of benthic mats of Didymosphenia geminata at the reach scale. Canadian Journal of Fisheries and Aquatic Sciences, 10.1139/cjfas-2014-0314