Colorado Water Institute Annual Technical Report FY 2010

Introduction

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

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 closely with all institutions of higher education in Colorado. CWI coordinates research efforts with local, state, and national agencies and organizations. Recent state funding allowed CWI to fund research projects at CSU, the University of Colorado, and Colorado School of Mines.

Our charges this year included requests from the legislature and state and federal agencies. Water allocations and agreements and the potential treatment and reuse of industrial water are two examples. Colorado State Legislature requested a briefing on water education activities of the Institute. 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.

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

Research Program Introduction

Colorado Water Institute funded 2 faculty research projects, 3 student research projects, and 1 internship this fiscal year; one of these projects was designated to receive federal funding due to its relation to water supply issues. 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, the preliminary exploration of new ideas that address water problems or expand understanding of water and water-related phenomena, 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. We received 1 new proposals for consideration this year from the University of Colorado. The general criteria used for proposal evaluation included: (1) scientific merit; (2) responsiveness to RFP; (3) qualifications of investigators; (4) originality of approach; (5) budget; and (6) extent to which Colorado water managers and users are collaborating. A peer review process and ranking by the CWI Advisory Committee resulted in funding four new projects for FY10.

Active NIWR projects and investigators are listed below:

Faculty Research

1. Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping, Roseanna Neupauer, University of Colorado, $117,847
2. Paleohydrology of the Lower Colorado River Basin, Balaji Rajagopalan, University of Colorado, $29,235

Student Research

1. Shear Resistance of the Nuisance Diatom Didymosphenia Geminata, James Cullis (McKnight), University of Colorado, $5,000
2. Impact of Limited Irrigation on Health of Four Common Shrub Species, Jason Smith (Klett), Colorado State University, $5,000
3. Evaluation of Herbicide Combinations for Control of Sago Pondweed (Stukenia pectinata) in Irrigation Canals, Joseph Vassios (Nissen), Colorado State University, $5,000

Internships

1. GEOLEM Internship, Roland Viger, USDA, $30,000

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.

Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping

Basic Information

Title:	Adjoint Modeling to Quantify Stream Flow Changes Due to Aquifer Pumping
Project Number:	2009CO195G
Start Date:	9/1/2009
End Date:	8/31/2012
Funding Source:	104G
Congressional District:	Colorado - 2
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Surface Water, None
Descriptors:	Stream Depletion, Adjoint Model, Modeling
Principal Investigators:	Roseanna M Neupauer

Publication

1. Neupauer, Roseanna M, 2011, "Adjoint Modeling to Quantify Stream Flow Changes Due to Pumping," pg. 16-17 of Colorado Water, Volume 28 issue 2.

Adjoint Modeling to Quantify Stream Flow Changes Due to Pumping

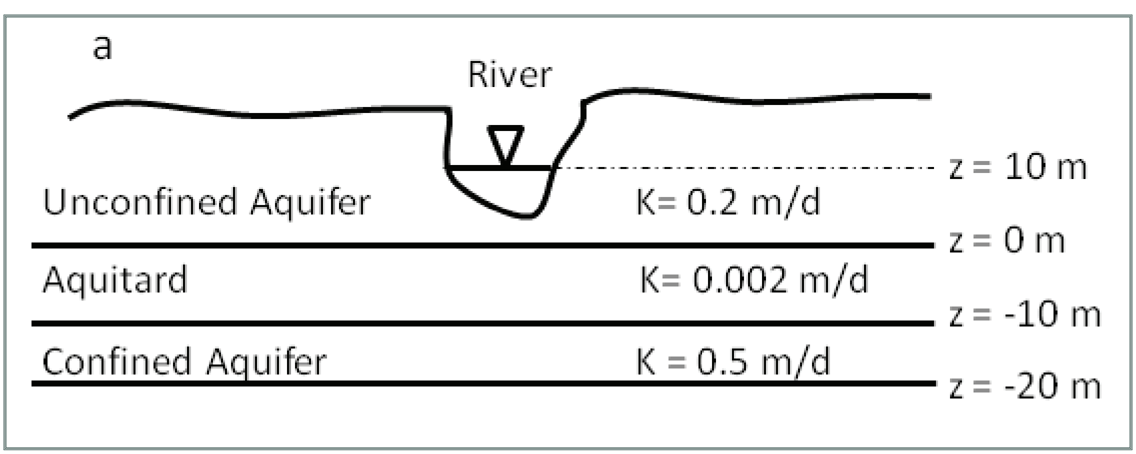
Roseanna M. Neupauer, Associate Professor, University of Colorado

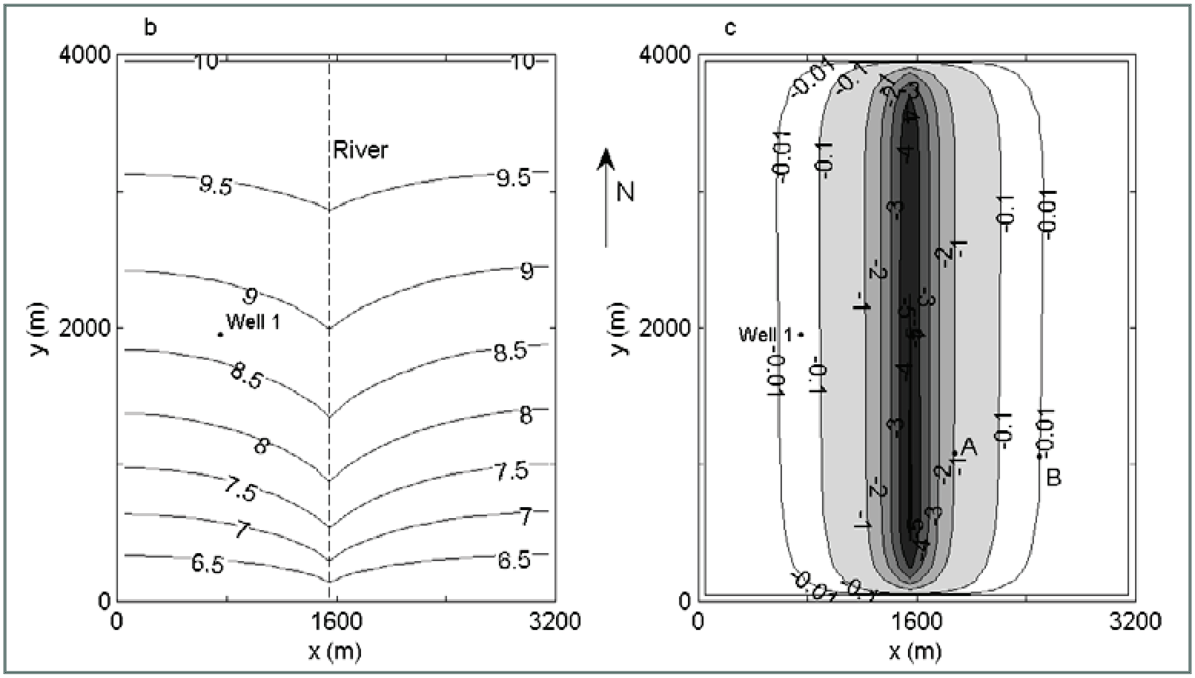
In Colorado, groundwater that is extracted from pumping wells is subject to water rights unless demonstrated to be non-tributary groundwater, which is defined as groundwater that, if extracted, will not deplete a stream by more than 1/10 of one percent of the annual withdrawal rate in any one year period within one hundred years. Groundwater modeling is typically used to determine whether or not groundwater can be considered as non-tributary. The approach is to first simulate conditions in the stream-aquifer system in the absence of pumping to quantify the stream flow rate under natural conditions, and then to simulate conditions with pumping for a 100-year period to quantify the stream flow rate when the well is pumped. If the depletion in the stream flow rate never exceeds 1/10 of one percent of the pumping rate, the groundwater that is withdrawn from the well is demonstrated to be non-tributary groundwater.

The approach described above is applicable if the pumping well under consideration is already in place or if the well location is already chosen. If the well location has not yet been chosen, it may be desirable to install the well where it will have little impact on stream flow, i.e., where it will pump non-tributary groundwater. For this situation, the modeling approach described above is inefficient, because one simulation must be run for each potential well location. We are developing a new modeling approach that solves directly for the change in stream flow or stream volume due to pumping from a well at any location in an aquifer. With this approach, the model results will identify locations where a well can be installed to ensure that pumping has minimal impact on stream flow.

The model development is being conducted by Scott Griebling, a graduate student in the Civil, Environmental, and Architectural Engineering Department at the University of Colorado, under the supervision of Roseanna Neupauer. Using adjoint theory on the governing equation for groundwater flow, we have developed the adjoint equations that describe changes in stream volume or stream flow rate as a function of time due to pumping at a well at any location in the aquifer. We have identified several scenarios for which these adjoint equations have the same form as the groundwater flow equations, and therefore can be solved with standard groundwater flow models, such as MODFLOW. We have also identified several scenarios for which these adjoint equations are similar but different from the groundwater flow equations, so we are developing approaches to use standard groundwater flow models to solve these adjoint equations.

Figure 1. Aquifer system used in the example. (a) Cross-sectional view. (b) Plan view. The northern and southern boundaries are constant head boundaries, and the east and west boundaries are no flow boundaries. The river stage and bottom elevation are 10 m and 5 m, respectively, along the entire river length. The contour lines represent head (in m) in the unconfined aquifer in the absence of pumping. (c) Stream depletion as a percentage of the pumping rate for a well installed at any location in the aquifer. Units are dimensionless.





Here we provide an example of the former scenario. We use the hypothetical aquifer system shown in Figure 1. The system is comprised of an unconfined aquifer, an aquitard (a bed of low permeability adjacent to an aquifer), and a confined aquifer, with a river running from north to south in the unconfined aquifer. The aquifers and aquitard are assumed to be homogeneous (hydraulic conductivity values shown in Figure 1a). Flow in this system was simulated using MODFLOW with the RIV package to simulate interaction between the river and the aquifer. The results show that in the absence of pumping, the flow rate of water from the river into the unconfined aquifer is approximately 4200 m^3/yr. Using standard simulation methods, we also simulated flow in the system when Well 1 is pumped at a rate of 3650 m^3/yr in the confined aquifer. When a well is pumped, head is lowered in the aquifers, and additional water is drawn out of the river. For example, results of the standard simulation show that after five years of pumping at Well 1, stream flow in the river is depleted by 1.24 m^3/yr, or about 0.034% of the withdrawal rate.

We have found that we can use MODFLOW with the RIV package to solve directly for the stream depletion caused by pumping at any location in the aquifer. The only new assumption that must be made is that the change in head in the unconfined aquifer is small relative to the saturated thickness. Figure 1c shows a plot of stream depletion as a percentage of pumping rate for any location in the confined aquifer. The results are shown after five years of pumping. For example, if a well is installed at Point A in Figure 1c, approximately 1% of the water that is pumped in Year 5 will come from depletion of the river. This exceeds the criterion for non-tributary groundwater, so if a well were installed at Point A, it would pump tributary groundwater that would be subject to water rights. Similarly, if a well were installed at Point B in Figure 1c, approximately 0.01% of the water that is pumped in Year 5 would come from depletion of the river; making this a candidate well location. As a verification of these results, note that the stream depletion due to pumping at Well 1 is approximately 0.034% of the pumping rate, which is equal to the value obtained from the standard simulation method.

A well installed near the river will cause more stream depletion than a well is installed farther away. For example, at (x,y)=(1600m, 2000m) in Figure 1c, which is near the river, stream depletion is approximately 5% of the pumping rate; however, at Well 1, which is farther away from the river, stream depletion is much lower.

The model results show essentially no stream depletion for a well near the northern or southern boundary. In the model, these boundaries are simulated as constant head boundaries, so they can provide an unlimited supply of water to the aquifer; therefore, a well near these boundaries will draw most of its water from outside of the model domain and relatively little from the river. If the constant head boundary is not physically realistic, the model results may not meaningful near the boundary.

This example demonstrates that with a single simulation of MODFLOW, we can determine stream depletion for pumping at any location in the aquifer. The model results can be used to choose a well location that will minimize the impact of the well on surface water flows. The method has been developed and demonstrated for a single well in a confined aquifer. Additional work is being conducted to address other scenarios.

Shear Resistance of the Nuisance Diatom Didymosphenia Geminata

Basic Information

Title:	Shear Resistance of the Nuisance Diatom Didymosphenia Geminata
Project Number:	2010CO219B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	4th
Research Category:	Biological Sciences
Focus Category:	Ecology, None, None
Descriptors:	None
Principal Investigators:	Diane Marie McKnight

Publications

1. McKnight, Diane Marie, 2011, Shear Resistance Diatom Didymosphenia Geminata, Colorado Water Institute Proposal, 6 pages.
2. Cullis, James, 2010, "Hydrologic Control of the Nuisance Diatom, Didymosphenia Geminata," pg. 4-6 of Colorado Water, Volume 27 issue 3.
3. Cullis, James, 2011, "Shear Resistance of Nuisance Diatom Didymosphenia geminate," pg. 5-8 Colorado Water, Volume 28 issue 2.

Shear Resistance of the Nuisance Diatom *Didymosphenia geminata*.

Didymosphenia geminata is a nuisance diatom species that can form large amounts of stalk material that covers the streambed (Larnard et al. 2006). These blooms impact the aesthetic value and biodiversity of mountain streams across many parts of North America particularly the Rocky Mountain states. In recent years there has been an increase in nuisance blooms, as well as spreading to new watersheds (Spaulding and Elwell 2007). *D. geminata* tends to prefer regulated flow conditions downstream of reservoirs (Kirkwood et al. 2009). Studies in Boulder Creek, CO (Cullis 2009; Miller et al. 2009) and elsewhere (Kilroy et al. 2005; Kirkwood et al. 2007) have shown that elevated shear stress and bed disturbance are important in controlling growth.

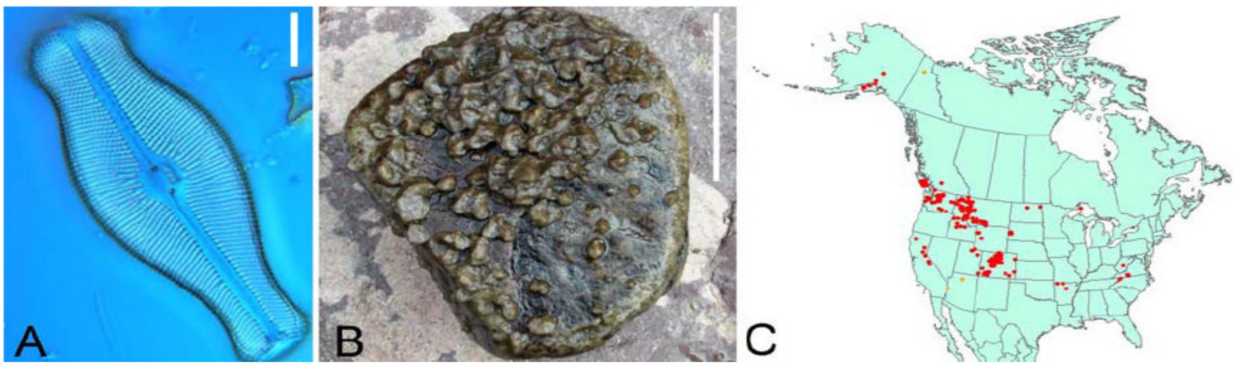


Figure 1: A. Image of *D. geminata* cell under the light microscope. Scale bar is equal to 10 microns. B. Cobble from stream showing typical growth habitat. Scale bar is approximately 10 cm. C. Map showing the confirmed distribution records of *D .geminata* (Spaulding and Elwell, 2007).

Figure 2: Large-scale blooms of *D. geminata* in streams in New Zealand (Source: www.biosecurity.govt.nz)

Flood releases from reservoirs are being considered as a potential mitigation measure (Spaulding and Elwell 2007). In February 2009, a flood release from the Benmore Dam in New Zealand resulting in the removal of *D. geminata* from the Waitaki River (Bruce 2009). Consideration of managed flood releases in the western US is limited by existing water demands. It is therefore important to determine the shear resistance of *D. geminata* in order to quantify the magnitude, duration and timing of the floods required for maximum efficiency of control. Studies of other benthic algae ((Biggs and Thomsen 1995) have shown that shear resistance varies significantly both in terms of the intrinsic nature of the algae type and conditional factors associated with the stage of growth and average growing conditions.

The objective of this study is to determine the shear resistance of *D. geminata*. The studies will either be conducted in the hydraulics laboratory at the University of Colorado or in conjunction with the USGS research laboratory in Golden. Specially designed rough substrate elements will be placed in a stream and allowed to accumulate *D. geminata* for a number of months prior to the flume experiments. These will be removed at different times during the growing season (May to October) and placed in the flume. The flow rate will be increased in steps and velocity profiles measured using either an acoustic Doppler velocimeter (ADV) and/or a laser Doppler velocimeter (LDV) to determine the bed shear stress. Removed algae will be captured in a net and the contents analyzed in terms of total biomass and cell densities after each flow rate.

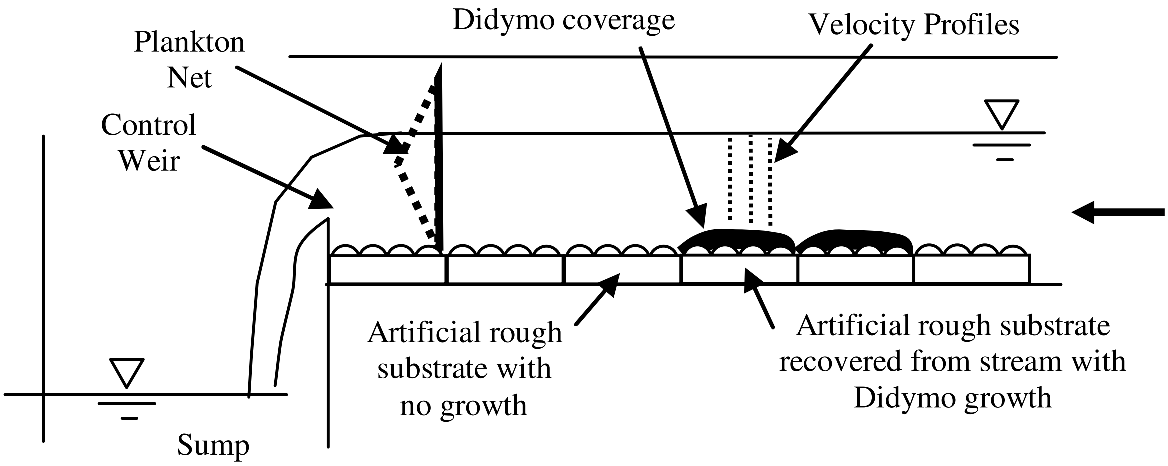


Figure 3: Proposed experimental set up.

The intended result is a shear removal relationship for *D. geminata* at different growth stages, similar to those shown in Figure 1. This relationship can then be used to quantify the magnitude and timing of floods required to control the growth of this nuisance diatom. An additional result will be to compare the measured velocity profiles with and without algal growth to determine the impact of *D. geminata* on the flow conditions and in particular the effective roughness of the stream.

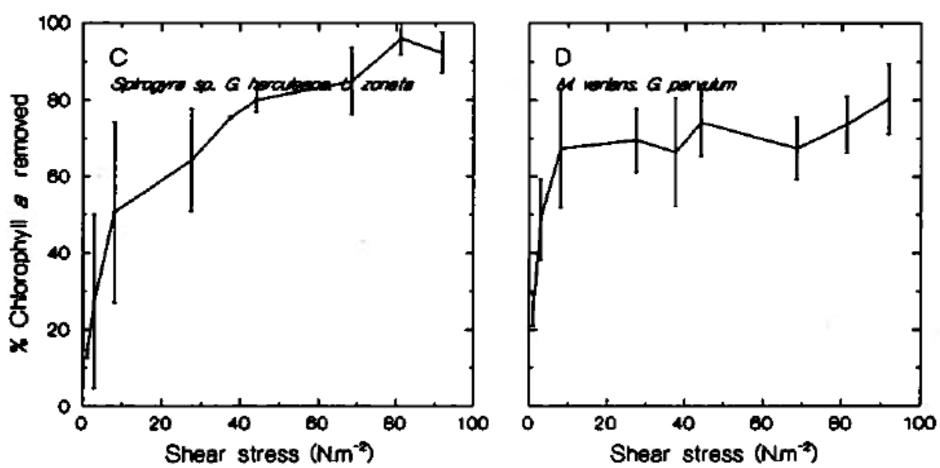


Figure 4: Chlorophyll a removal kinetics as a function of experimental shear stress in two different periphyton communities (Biggs and Thomsen, 1995)

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Hydrologic Control of the Nuisance Diatom, *Didymosphenia Geminata*

by James Cullis, PhD Candidate, Civil, Environmental and Architectural Engineering, University of Colorado at Boulder
Faculty Sponsor: Diane McKnight

In recent years, particularly since the 2002 drought, have you noticed your favorite mountain stream in Colorado becoming less pristine? Have you noticed a thick brown algal mat coating the streambed that looks horrible and snags your fly when you are fishing? In some places it is particularly troublesome, with mats 1-2 centimeters thick and long white streamers resembling wet toilet paper. Does it feel gritty like wet cotton wool? Chances are that your stream is another victim to an emerging nuisance algal species called *Didymosphenia geminata, o*therwise known as "didymo" or "rock snot."

James Cullis holds a rock covered with didymo in South Boulder Creek. (Courtesy of James Cullis)

An Emerging Nuisance Species

Traditionally, algal blooms in rivers and lakes can be associated with increased nutrient loading. This is often due to human impacts downstream of wastewater treatment plants or agricultural runoff. Not so with didymo. This type of diatom is uniquely adapted to grow in low-nutrient conditions typical of many otherwise unimpacted mountain streams. Didymo is not new to Colorado; this diatom has always been a part of the natural environment of mountain rivers in North America and northern Europe, and periodic blooms have been part of the natural cycle. In recent years, however, the tendency of this nuisance species to bloom and spread to new watersheds has increased. Most significantly, in 2004 it was first detected in streams in the South Island of New Zealand. The conditions in these streams were ideally suited to its growth, and it quickly spread to other watersheds and resulted in algal mats many centimeters thick. It now represents a significant threat to local economies and stream ecosystems in these areas.

Controlling Factors and Ecological Impacts

The invasion of streams in New Zealand sparked an interest in determining the factors contributing to the growth of this nuisance species. Studies have been conducted in New Zealand, the United Kingdom, Canada, and the United States. These studies have confirmed the tendency to bloom under low-nutrient conditions, specifically in streams with a relatively

These two photos of the stream bed in Boulder Creek show the impact of high-flow events in the spring of 2009, which resulted in significant removal of didymo coverage.

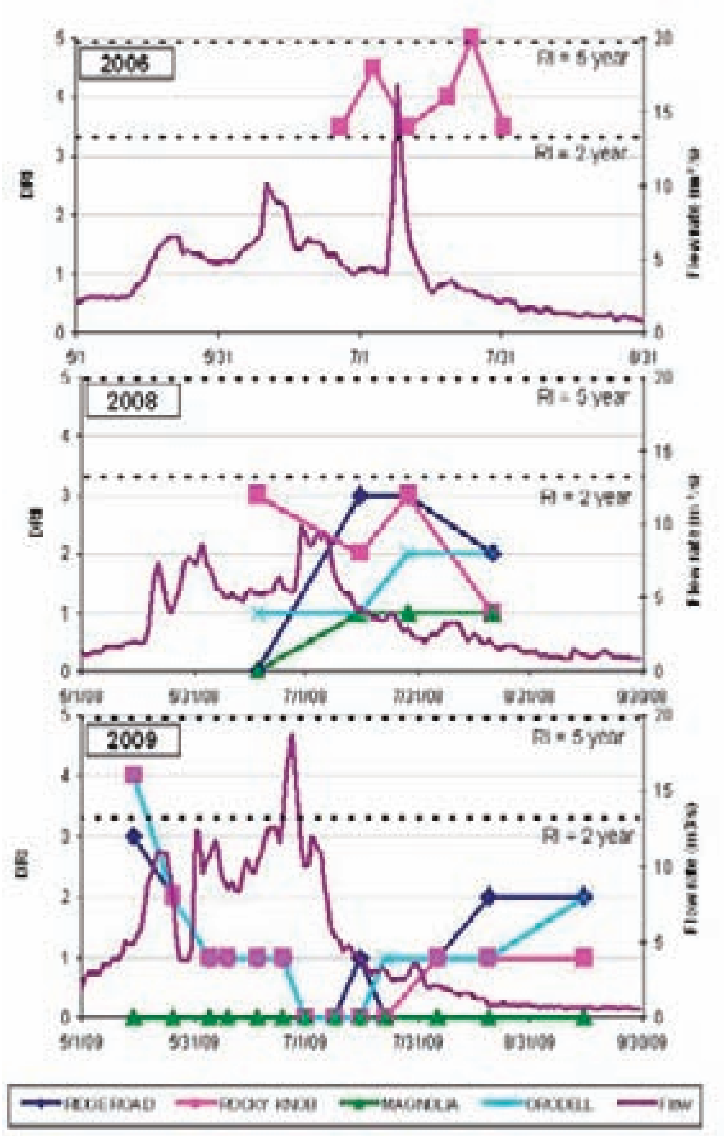


Figure 1: This graph shows observed didymo coverage, as measured by the Didymo Rating Index (DRI) at four study sites in Boulder Creek in relation to stream flow. Note that flows above 10m3/s result in a reduction in the coverage, but that the reduction depends on the time that the high flow occurs. The rate of recovery depends on the subsequent flows and can be rapid when high flows are not maintained.

high proportion of organic phosphorus in the total dissolved phosphate (TDP) concentration. Flow rate is also an important factor. High flows, and particularly the physical scouring and disturbance of the stream bed, are considered to be a primary control on didymo growth. The regulated flow regime downstream of dams and reservoirs provides a hot spot for growth. The thick algal mats have a significant impact on benthic macroinvertebrates, increasing the abundance of small worms and reducing the overall species diversity. It is unclear, however, what the resulting impact is on larger species such as fish.

Recreational users, such as fishermen, are one of the main contributors to the spread of this nuisance species. Individual cells can remain viable on the felt soles of wading boots for many days, facilitating the transport from one stream to another. This has resulted in a massive public awareness campaign in New Zealand, where felt-soled waders are now banned and wader wash stations have been established at popular fishing spots. There is mounting pressure in Canada, Alaska, and other parts of the United States to implement similar cleaning and disinfection control and to phase out the use of felt-soled waders.

Studies in Boulder Creek, Colorado

For the past several years, students at the University of Colorado at Boulder have been studying *D. geminata*. This species represents an excellent subject, as it is relatively easy to identify both in the field and under the microscope, is abundant in nearby streams, and can be used as the basis for discussions of stream ecosystems, human impacts, and watershed management. A particular area of ongoing research is to investigate the role of flood events, with the objective of determining the critical flow requirements necessary to remove the didymo mats from the streambed.

Preliminary data were collected during the summer of 2006, and further monitoring was conducted in Boulder Creek in 2008 and 2009. The primary metric for monitoring the growth of didymo was a qualitative Didymo Rating Index (DRI). The DRI takes into account the extent of the coverage and the thickness of the algal mat. It ranges from zero, representing no obvious signs of didymo growth, to a maximum of ten, representing 100% coverage and mats greater than 5 cm thick, as have been observed in New Zealand. The maximum for Boulder Creek was 100% coverage with a mat thickness of 1 to 2 cm, representing a 6 or 7 on the DRI scale. In addition to the DRI, physical samples from individual rocks were taken and analyzed in terms of the ash-free-dry-mass (AFDM), chlorophyll concentration, and didymo cell densities.

Determining the Critical Flow Requirements

The results of monitoring the growth of didymo at four study sites in Boulder Creek are shown in Figure 1. The coverage is measured in terms of the DRI on the left axis and is compared to the average daily flow rate on the right axis. The dashed lines represent the estimated 1 in 2-year and 1 in 5-year annual maximum flow, based on 100 years of flow records. The results show the importance of high flows in controlling the growth of didymo. In 2006 the spring melt was relatively low, but a heavy rainstorm produced a late-season flood, resulting in a significant reduction in the didymo coverage. 2008 was an average flow year with limited impact on the didymo coverage. In contrast, 2009 was

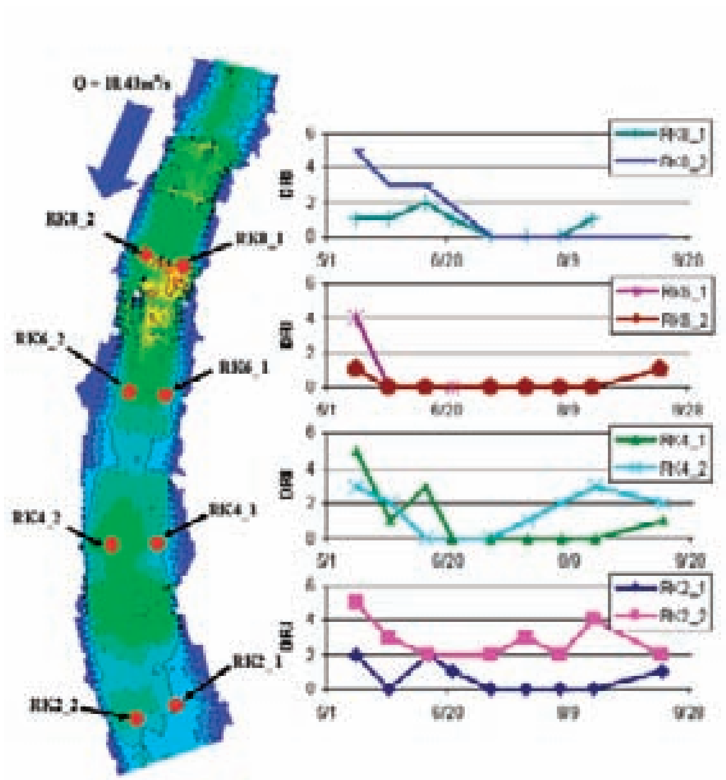


Figure 2: The graphic on the left shows the spatial variation in bed shear stress at the maximum flow rate of 10.43m3/s for the Rocky Knob site. The yellow and orange areas indicate higher shear stress, and the red dots indicate the sampling locations. The graphs on the right show the change in the Didymo Rating Index for each sample location. Note that for 2009, the maximum flow resulted in very high shear stress values and potential for bed disturbance over most of the study site. There is still, however, some difference in the impact at the different sampling locations

a very high flow year. The result was almost complete removal of didymo from the streambed at all study sites and limited recovery due to the sustained high flows.

The results indicate that a flow of $10m^3/s$ is a critical level for the removal of didymo in Boulder Creek, which is about the average annual maximum flow. Analysis of the average shear stress associated with this flow suggests that it is similar to the flow required to initiate significant bed disturbance. This supports the hypothesis that flows need to be high enough to result in the physical scouring of didymo due to bed disturbance rather than just elevated bed shear stress. It is unclear at this stage if these findings can be applied to other streams where didymo is a problem, and this should be a focus of future research using data from other locations and countries. Further studies to be conducted during the summer of 2010 will also determine the shear resistance of the didymo mats directly using flume experiments.

The Importance of Spatial Variation

One goal of the research being conducted in Boulder Creek is to quantify spatial variation within a stream habitat. During a flood event, shear stress is not evenly distributed across the stream bed. This results in spatial variations in the potential for bed disturbance and the removal of algae such as didymo. The resulting patchiness is considered important in maintaining the diversity of stream ecosystems. Spatial variation in the removal of didymo is being studied at the four study sites in Boulder Creek by developing a two-dimensional hydraulic model of each site. Preliminary results from the Rocky Knob site are shown in Figure 2, which illustrates the spatial variation in shear stress resulting from the maximum flow rate observed in 2009 of $10.43m^3/s$. The result of this spatial variation in shear stress is apparent in the difference in the observed DRI at eight specific locations within the study site. By studying this spatial variation in shear stress and the impact on the removal of didymo, we hope to better determine the critical shear stress needed for removal.

Using Managed Flood Releases for Future Control

The overall objective of this study is to determine the critical flow requirements necessary to remove didymo in streams. This information will be useful in considering the potential to use managed flood releases from reservoirs to control future growth. This approach is already being used in New Zealand, where a number of flood releases have flushed the didymo out of impacted streams. In New Zealand, this approach is supported by an awareness of the negative impact of didymo on local economies and stream ecosystems, as well as the availability of spare water. In other parts of the world, such as Colorado, there is neither the level of awareness of the threat nor the availability of spare water. It is therefore important to not only better understand what the impact of didymo is in these areas, but also to improve our quantitative understanding of the magnitude, duration, and timing of flood events that would be most efficient in controlling future growth. The aim of this study is to provide this quantitative understanding that will enable water resources managers to consider the trade-offs between making flood releases with the objective of controlling didymo growth and considering the many other current and future demands on this precious resource.

Acknowledgements

Funding for this research is provided by the Colorado Water Institute, the Boulder Creek Critical Zone Observatory, the University of Colorado, the American Society of Civil Engineers, and the Aurecon Group.

For more information on the ecology and impact of *Didymosphenia geminata* and on what can be done to control the spread and future growth of this nuisance species, visit the Environmental Protection Agency web site at: http://www.epa.gov/region8/water/didymosphenia.

Shear Resistance of the Nuisance Diatom *Didymosphenia geminate*

James Cullis, *PhD Candidate, Civil, Environmental and Architectural Engineering, University of Colorado at Boulder*
Faculty Sponsor: Diane McKnight

Shear Removal of Benthic Algae

The removal of benthic algae is important in maintaining the diversity and patch dynamics of stream ecosystems, since it opens up spaces for the growth of different species. Benthic algae is removed primarily during periods of increased bed shear stress (stress or force exerted by flowing water) resulting from flood events, but it can also be removed by abrasion from suspended particles or physically scoured when the bed material is disturbed under very high flow conditions. Diversity in the benthic algae community results not only from spatial and temporal variations in the disturbance metric (i.e., shear stress and potential for bed disturbance), but also in terms of variations in the resistance and resilience of different species or the same species under different conditions. These differences are due both to "inherent" properties, i.e., physical properties such as shape, size, texture, tensile strength, and attachment strength, and "conditional" properties, i.e., factors relating to the community and its environment such as age, occurrence of secondary structure, and acclimation to a given shear stress and/or resource conditions. Determining the response of specific types of benthic algae to increasing shear stress is therefore important in assessing the resilience of stream ecosystems to natural and anthropogenic alterations of the flow regime.

A Threat to the Sustainability of Stream Ecosystems

Didymosphenia geminata (didymo) is a mat-forming benthic diatom species that is increasing in significance as a nuisance algal species in freshwater streams throughout the United States, Europe, Asia and New Zealand. Globally, it is acknowledged as the most harmful invasive species in lotic systems (flowing bodies of fresh water). Didymo can form thick mats that cover the stream bed. These mats significantly impact the aesthetic appeal of the stream, but also potentially impact the sustainability of stream ecosystems by blanketing the substrate, reducing diversity and altering the food web structure. These impacts then propagate through the community structure to impact economically valuable species, such as trout. The potential impacts on aesthetics and recreational fishing are concerning for tourism and local economies in the impacted areas. Despite these concerns, we still know very little about the factors controlling its growth and tendency to bloom. This hampers our potential to mitigate and manage this nuisance species.

The author (James Cullis, left) and his advisor (Prof. Diane McKnight, right) collecting algal samples for a related project on the significance of spatial and temporal variations of shear stress on the removal of benthic algae in the streams of the McMurdo Dry Valleys in Antarctica.

Shear Removal Experiments

Didymo mats have been found in a wide range of hydraulic habitats, but appear most abundantly in areas of stable substrate or regulated flows downstream of lakes and reservoirs. These observations have led to the hypothesis that didymo mats are highly resistant to increasing shear stresses and that physical removal due to disturbance of the substrate under very high flow conditions is the primary mechanism for removal. Testing this hypothesis, and quantifying the shear removal rate, is therefore important in terms of improving our understanding of growth dynamics of this nuisance species and in considering potential mitigation measures.

To test this hypothesis we conducted a series of shear removal experiments in the research flume at the University of Colorado at Boulder. Rocks with significant didymo coverage were obtained from two study sites on Boulder Creek, Colorado and on two different sampling dates. The first site was the Rocky Knob site on Middle Boulder Creek and the second was on South Boulder Creek in Eldorado Canyon State Park. Both sites offer ideal habitat for didymo growth; cold, clear mountain streams with high light availability and very low nutrient concentrations. For each test, between six and eight rocks with didymo growth on them were removed from the stream and placed on a plastic tray for transport back to the laboratory (Figure 1).

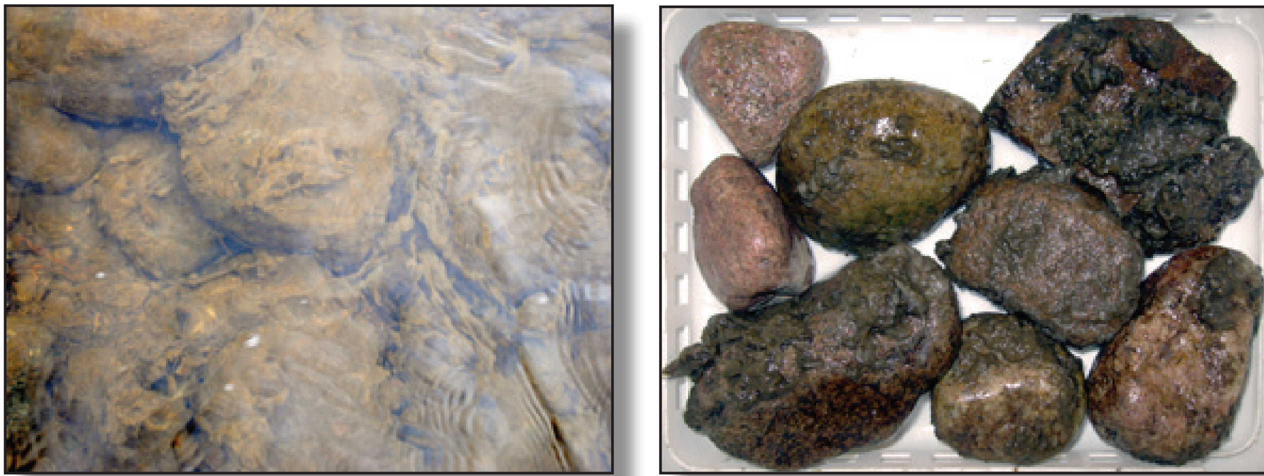


Figure 1. Pictures of didymo coverage in the stream at the Rocky Knob site in May 2010 (left) and rocks taken from the Eldorado Canyon site in south Boulder Creek in November 2010 on the plastic tray ready for transport back to the lab (right). Note the much higher didymo coverage for the May 2010 samples.

In the laboratory the sample trays were placed in the flume and subjected to increasing flow rates (Figure 2). A plankton net was placed at the end of the flume to collect any material removed (Figure 3). The samples were subjected to increasing flow rates for 30 minutes at each flow rate, and the net was removed after each flow rate. The content of the net was analyzed for ash-free-dry-mass (AFDM), chlorophyll-a (chl-a), and didymo cells density. The shear stress over the samples at each flow rate was estimated based on the extrapolation of the vertical velocity profile upstream of the sample using the "law of the wall" and averaged over the sample based on a horizontal Reynold's stress profile at a level just above the tops of the rocks used in the sample.

Discussion of Results

The results of the tests are shown in Figure 4 in terms of the cumulative amount of material removed with increasing shear stress expressed per unit area of the sampling tray. The results suggest a linear cumulative removal function for all four tests and for all three biomass metrics. This is despite the differences in the total amount of biomass and the seasonal differences. Figure 5 suggests that the removal rates are a function of the total amount of biomass in the case of AFDM and didymo cell density, but not for chl-a. While the shear removal rate for AFDM appears to increase linearly with increasing biomass, the relationship for cell density appears to be limited at higher biomass. This may be a function of the fact that the growth of the mats themselves impacts the near bed hydraulics, reducing the potential to remove the well-attached and healthy cells

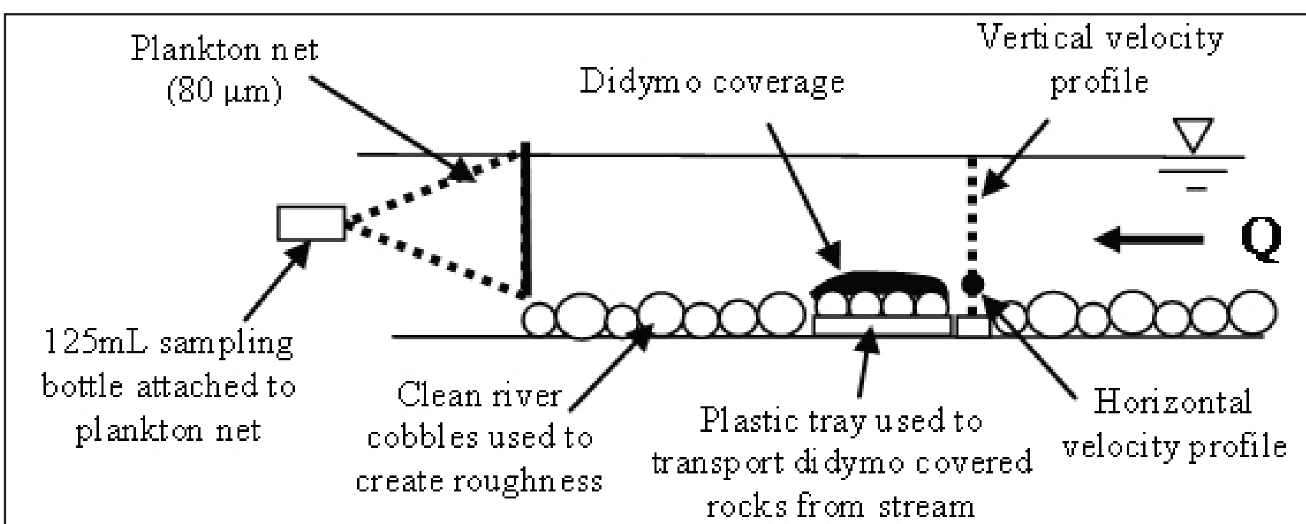
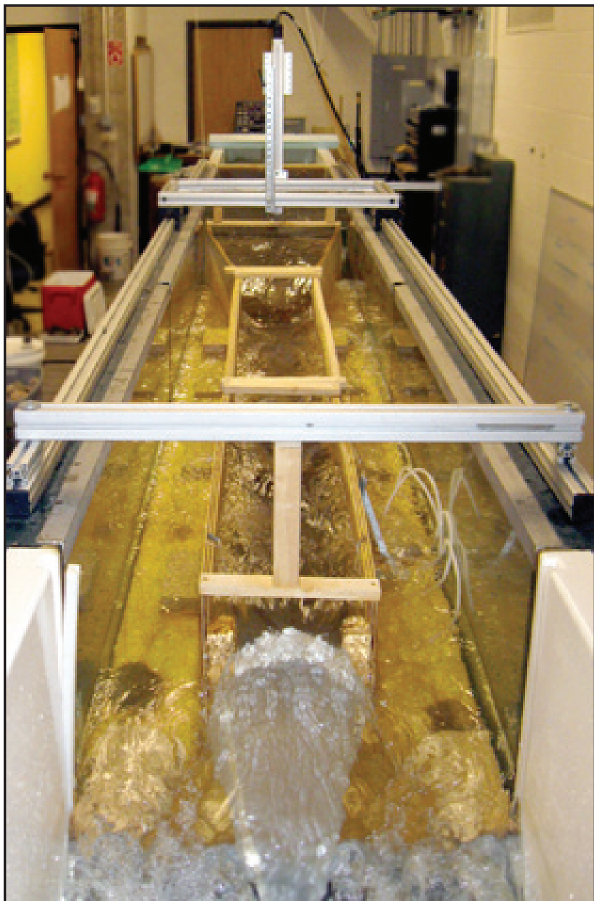


Figure 2. Experimental setup (not to scale).

Figure 3. Photograph of the setup for the shear removal experiments showing the flume running at its highest flow rate. The photograph shows the temporary contraction used to increase the shear stress over the samples, the ADV probed used to measure the velocity and turbulence profiles, and the plankton net used to collect the removed material at the end of the flume. The samples themselves cannot be see under the flow of water, but are located in the middle of the straight portion of the temporary contraction.



with increasing shear stress, but can still remove biological material trapped within the mats. Alternatively, this may be a function of the better condition of the cells and the mats during the May samples, which represents the sample with the highest biomass.

The total percentage of the biomass removed during each of the tests is given in Table 1. There appears to be a marked difference in the response to increasing shear for the May sample compared to the November samples. The May sample was taken prior to spring runoff, which research has found is the peak period for didymo growth in Boulder Creek. The spring floods that followed in 2010 were very high and resulted in the almost complete removal of didymo from Boulder Creek. There was no significant recovery of Middle Boulder Creek during the summer, which is why the November samples had to be taken from a different site where there was persistent didymo growth. It is therefore likely that the condition of the mats was very different, with the May sample being much healthier and better conditioned, having been taken from the main flow areas. The November samples were taken at the end of a hard season for didymo growth and from areas that had not been exposed to elevated shears, which was why growth still occurred in these areas. Hence the November samples were less conditioned to the normally high shear environment of these rivers. This is reflected in the findings: almost 90% of the didymo cells were removed from the mats in the November samples while only 30% of the cells were removed from the May sample. The amount of AFDM and chl-a removed for the November samples is also higher, but not so significantly. This suggests that the didymo cells are more resilient to removal in May than in November, where the majority of didymo cells are either weakened or dead and/or located on the surface of the mat, and therefore preferentially removed with increasing shear stress.

Table 1. Total percentage of biomass removed during each test

(Maximum Average Shear stress ≈ 87 N/m^2)

Test	Date	AFDM	Chl-a	Didymo Cells
RK1	5/19/2010	18%	9%	33%
SBC1	11/9/2010	48%	48%	91%
SBC2	11/9/2010	27%	16%	93%
SBC3	11/9/2010	28%	21%	85%

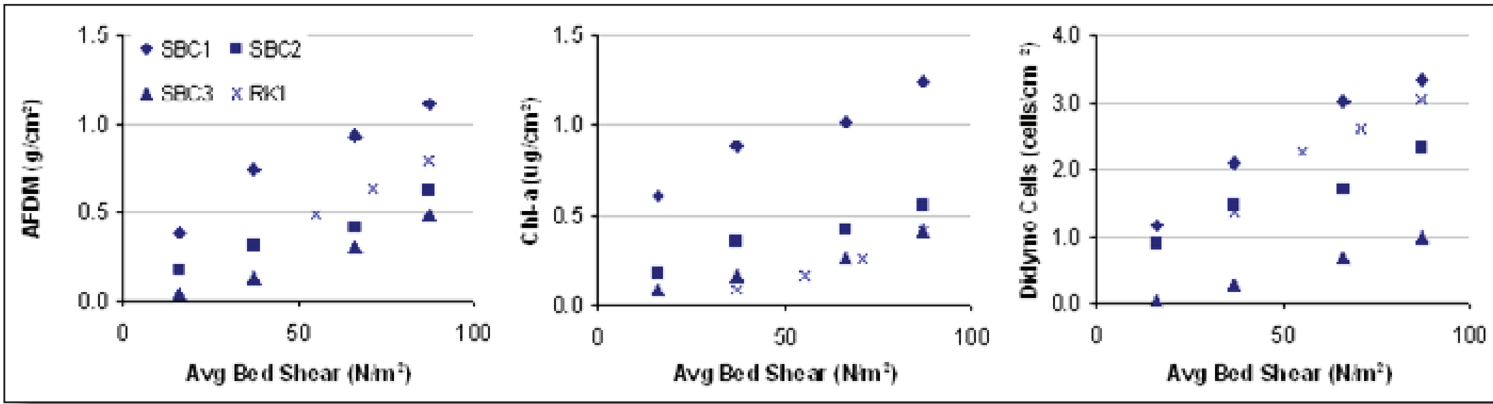


Figure 4. Cumulative amount of material removed from substrate with increasing average bed shear stress.

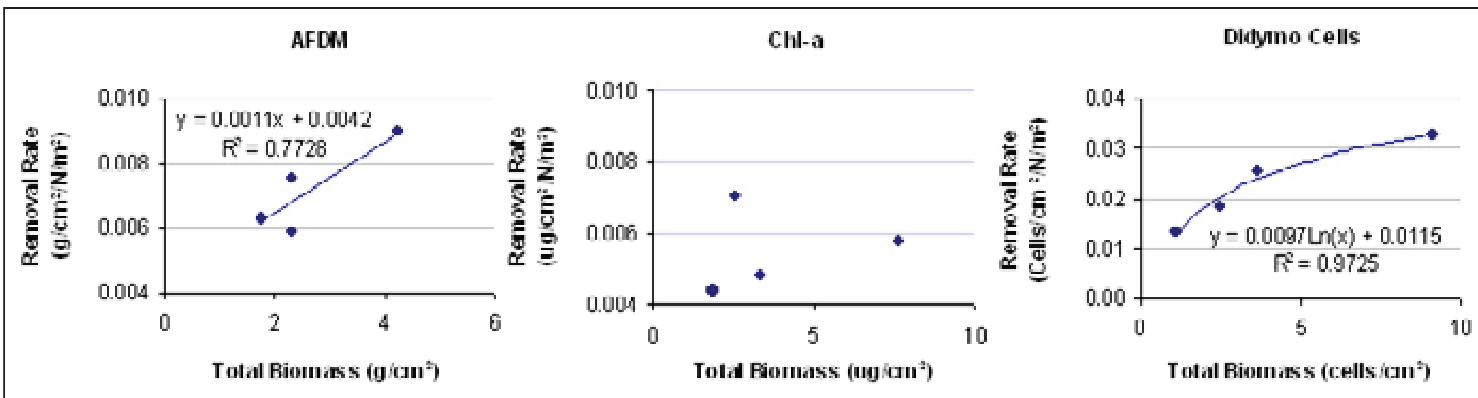


Figure 5. Relationship between removal rate due to increasing shear stress and the total amount of organic and inorganic material present on the substrate at the start of each test.

Conclusion

The above results are useful in improving our understanding of factors affecting the removal of didymo from impacted stream beds. Further tests, however, are required to augment the above data. These tests will be conducted in March 2011, when we anticipate that the didymo growth in Boulder Creek will have recovered from the high flows that resulted in very low coverage during the summer and fall of 2010. The laboratory studies described here complement the ongoing analysis of the hydrologic factors controlling the growth of didymo in Boulder Creek (See Cullis, J, 2010, "Hydrologic Control of the Nuisance Diatom, *Didymosphenia Geminata*" *Colorado Water* 27(3) pp 4-6). The ultimate objective is to combine the information from these and other studies into a conceptual model describing the growth dynamics of this nuisance species. Such a growth model could then be used to investigate the potential for future blooms, as well as to assess the threat of future altered flow regimes and the potential for mitigation measures, including the use of flushing flows.

Acknowledgements

Funding for this research is provided by the Colorado Water Institute (CWI) and the Boulder Creek Critical Zone Observatory (CZO). Laboratory facilities were provided by the Department of Civil, Environmental and Architectural Engineering (CEAE) at the University of Colorado and valuable support in using the flume was provided by Professor John Crimaldi.

For more information on the ecology and the potential impact of *Didymosphenia geminata* on stream ecosystems, go to the EPA website: www.epa.gov/region8/water/didymosphenia/ or contact the author (james.cullis@colorado.edu).

Impact of Limited Irrigation on Health of Four Common Shrub Species

Basic Information

Title:	Impact of Limited Irrigation on Health of Four Common Shrub Species
Project Number:	2010CO220B
Start Date:	3/1/2010
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Focus Category:	Conservation, None, None
Descriptors:	None
Principal Investigators:	James E Klett

Publications

1. Klett, James E, 2011, Impact of Limited Irrigation on Health of Four Common Shrub Species, Colorado Water Institute Proposal, 1 page.
2. Smith, Jason, 2011 "Impact of Limited Irrigation on Health of Four Common Shrub Species," pg. 2-4 of Colorado Water, Volume 28 issue 2.

Colorado Water Institute FY10 Student Water Research Grant Program
Proposal Title: Impact of limited irrigation on health of four common shrub species

Proposal Narrative

Throughout much of Colorado the demand for water has increased and the available water supply has decreased. It is increasingly more important to conserve water wherever possible. One possible way to conserve water in planted landscapes is to plant low water use plants. Unfortunately little research has been conducted on determining the water use of common plant species that are used in urban landscapes and that are distributed throughout nurseries and garden centers in the Rocky Mountain region. As a result, a shrub water study was initiated in 2005 at Colorado State University to monitor the responses of some common landscape shrubs when subjected to four different irrigation regimes (0%, 25%, 50%, and 100%) based on the evapotranspiration rates of *Poa pratensis* (Kentucky bluegrass). The shrub species studied thus far include *Acer ginnala* (Amur maple), *Amelanchier alnifolia* (serviceberry), *Caryopteris incana* (blue mist spirea), *Chamaebatiaria millefolium* (fernbush), *Cornus sericea* (redosier dogwood), *Hydrangea arborescens* 'Annabelle' (Annabelle hydrangea), *Perovskia atriplicifolia* (Russian sage), *Physocarpus opulifolius 'Monlo'* (Diablo® ninebark), *Rhus trilobata* (three leaf sumac), *Salix pupurea* (arctic blue willow), *Syringa meyeri* (Meyer lilac), and *Syringa vulgaris* (common lilac). Data collection occurred each growing season and the types of data that were collected included soil moisture, plant heights and widths, predawn leaf water potentials, daily water use (using plants grown in lysimeters), visual ratings, end of season leaf areas, and end of season leaf fresh and dry weights.

In 2009 data collection primarily focused on the redosier dogwood, Annabelle hydrangea, Diablo® ninebark, and arctic blue willow. Data collection was limited during June and most of July as a result of heavy hail damage incurred on June 7th. Data collection effectively ceased until the plant foliage returned. After the shrubs had re-leafed, data collection occurred from the end of July until mid-September.

The 2009 data are currently undergoing statistical analyses and interpretations, and will be complete sometime after the submission of this grant proposal. Preliminary results suggest that in-ground planted redosier dogwood, Annabelle hydrangea, Diablo® ninebark, and arctic blue willow will all ***survive*** without supplemental irrigation when receiving ten inches of precipitation (less than an inch a week) during the growing season, since none of the plants in the in-field repetitions died due to insufficient soil moisture during 2009. However, growth and aesthetics varied depending upon the species and the treatment. Annabelle hydrangea and redosier dogwood appear to prefer at least some supplemental water to reduce physiological stress (leaf wilting and low leaf water potential). Additionally, Diablo® ninebark appears to increase in size as irrigation amounts increase. Responses of irrigation treatments on arctic blue willow have yet to be determined.

In 2010 data collection will continue on the same four species studied during the 2009 season in order to supplement the data already collected and to further quantify shrub species responses to progressively decreased amounts of irrigation.

Impact of Limited Irrigation on Four Common Shrub Species

Jason Smith, MS Candidate, Horticulture and Landscape Architecture, Colorado State University
Faculty Advisor: James Klett

Throughout much of Colorado, the demand for water increases while the available water supply decreases. As a result, it is increasingly more important to conserve water wherever possible. One way to conserve water is to plant low-water-use shrubs in the urban landscape. Unfortunately, little scientific research has been conducted on determining the water use of common plant species that are used in urban landscapes and distributed throughout nurseries and garden centers in the Rocky Mountain region. Most plant species' responses to limited irrigation are based solely upon opinion or visual observation, and as a result, a shrub water use study was conducted during the 2010 growing season at the W.D. Holly Plant Environmental Research Center at the Fort Collins Colorado State University campus (Figure 1).

The purpose of the study was to determine the growth response of four shrub species that are commonly marketed throughout Colorado nurseries and garden centers for planting in Colorado landscapes. The shrubs were subjected to progressively decreased amounts of irrigation based on the evapotranspiration (ET) of a short reference crop, and the resulting responses were assessed. The species that were tested were: *Cornus sericea* (redosier dogwood), *Hydrangea arborescens,* 'Annabelle' (Annabelle hydrangea), *Physocarpus opulifolius 'Monlo'* (Diablo® ninebark), and *Salix pupurea* (arctic blue willow); one cool-season grass was used as a control: *Poa pratensis* (Kentucky bluegrass).

The experiment consisted of two separate components. The first was an in-field component in which the shrubs and turf were planted in the ground. This in-field component tested all four species of shrubs and the turf using four separate treatments (0%, 25%, 50%, and 100% of ET of a short reference crop). The second part of the experiment was a lysimeter component, in which two of the species were grown in a pot-in-pot system and received 25%, 50%, or 100% of ET. Only the redosier dogwood and Annabelle hydrangea were tested in the lysimeter component due to space limitations. All plants (in both components) were planted during the 2008 growing season and were provided with 100% ET so that the shrubs could establish. In 2009 and 2010, irrigation treatments were implemented weekly, and the average amounts provided during 2010 are depicted in Table 1. Data collection included plant heights and widths, predawn leaf water potentials, daily water use (using the plants grown in the lysimeter component only), visual ratings, infrared temperatures (turf only), end of season sample leaf area, end of season sample leaf fresh and dry weights, and end of season whole above ground plant fresh and dry weights.

The Kentucky bluegrass in the in-field component responded as expected when irrigation amounts decreased; however, the shrubs did not follow such a predictable pattern. As irrigation amounts decreased for the Kentucky bluegrass, surface temperatures of the turf increased and overall visual appeal decreased. Interestingly, the tested

Figure 1. Shrub Water Study at Colorado State University

Courtesy of Jason Smith

Table 1. Mean Gallons of Water Applied per Week per Shrub				
	0%	**25%**	**50%**	**100%**
In Field Trials (5/17/10 — 10/5/10)*	0	0.63	1.23	2.48
Lysimeter Trials (5/17/10 — 5/24/10)*	N/A	0.27	0.54	1.09
Lysimeter Trials (5/25/10 — 7/8/10)**	N/A	1.01	2.01	4.03
Lysimeter Trials (7/9/10 — 10/5/10)**	N/A	2.58	5.16	10.33

**Watering amounts calculated using estimated rooting area*
***Watering amounts calculated using estimated leaf area*

shrubs responded much differently than the control. The tested shrubs results showed that all species had good survival rates regardless of irrigation amounts received, and some species looked just as healthy visually in the lower watered treatments as they did in the higher watered treatments. The redosier dogwood shrubs that received 100% ET were wider, had less negative seasonal mean water potential readings (less stressed), had larger end of season sample leaf area, and had larger end of season whole plant biomass than the shrubs in the 0%, 25% and 50% treatments. Additionally the 100% treatment was slightly more visually appealing than the other treatments. However, the dogwoods in all treatments looked visually acceptable for landscape use. Treatments appear to have had no impact on the growth rate for the ninebark or the willow. However, more water did result in lower seasonal mean water potential readings (less stressed) for both species in the 100% category. The hydrangea was most affected by the varying watering amounts. The hydrangea's overall size, sample leaf area and sample leaf fresh/dry weights were greater in the 100% category than in any other treatment. However, the Annabelle hydrangea in the 100% treatment had higher pressure chamber readings (more stressed) than the other treatments. This counterintuitive result can be explained by the size differences. Since the hydrangea plants were larger and had more overall biomass in the 100% treatment, more transpiration occurred. More transpiration resulted in more water required to maintain the larger plants. Since the larger hydrangeas were more stressed, it is possible that hydrangeas require more than 100% ET of a short reference crop to perform the best.

All in-field plants had a good survival rate, since all tested plants survived with the exception of one hydrangea replication in the 0% treatment. The ninebark, willow, and dogwood all looked acceptable for landscape use when receiving 0% ET. The hydrangeas appeared to look better with more water but they also grew in size, which further increased their water demand. However, the hydrangeas in the 0% treatment had an 80% survivability rate. If water becomes limited, all species should be able to survive and look quite acceptable for landscape use with the exception of the hydrangea. However, the hydrangea can probably survive a short period with little to no water and rebound when water becomes more readily available.

In the lysimeter component of the study, both the redosier dogwood and Annabelle hydrangea demonstrated that the more water provided, the better they grow. Treatments began on these two species in 2009 and Figure 2 is a representative photo of both species in each of the three treatments coming out of dormancy. As the plants were breaking dormancy in 2010, the plants receiving 100% ET came out of dormancy more quickly than any of their counterparts in the other treatments. In fact, all of the redosier dogwood replications in the 25% died back to the ground and broke dormancy by starting all of its new growth from the base of the plant. Thus, if these two shrub species go into dormancy in a stressed state, the plants will come out of dormancy more slowly the following season.

The watering amounts for the lysimeter plants not only affected the speed at which both plants broke dormancy, but also affected their growth habits. More water given to both potted redosier dogwoods and Annabelle hydrangeas resulted in larger plants. As irrigation amounts increased the height, width, and end of season entire above ground plant biomass also increased. Interestingly, end of season sample leaf area and sample leaf fresh/dry weights showed no significant differences among treatments for either species. However, as a result of the plants having a similar relationship with overall size and water use, data collected during dry down periods (periods where the plants were not watered and purposefully stressed to monitor the result) showed that the plants in the 100% treatment used water at a faster rate than the 50%, and the 50% used water at a faster rate than the 25%. Additionally, by the end of each dry down period, in general, the 100% redosier dogwoods had greater pressure chamber readings (more stressed) than their counterparts in the 25% treatment, and the 100% hydrangeas were equally stressed as the hydrangeas in the 25% treatment. Since the plants increased in size as watering amounts increased, more water was needed to maintain the larger plant sizes. Both species in each of the three treatments grew at a rate at which they could support themselves with the water supply provided to them.

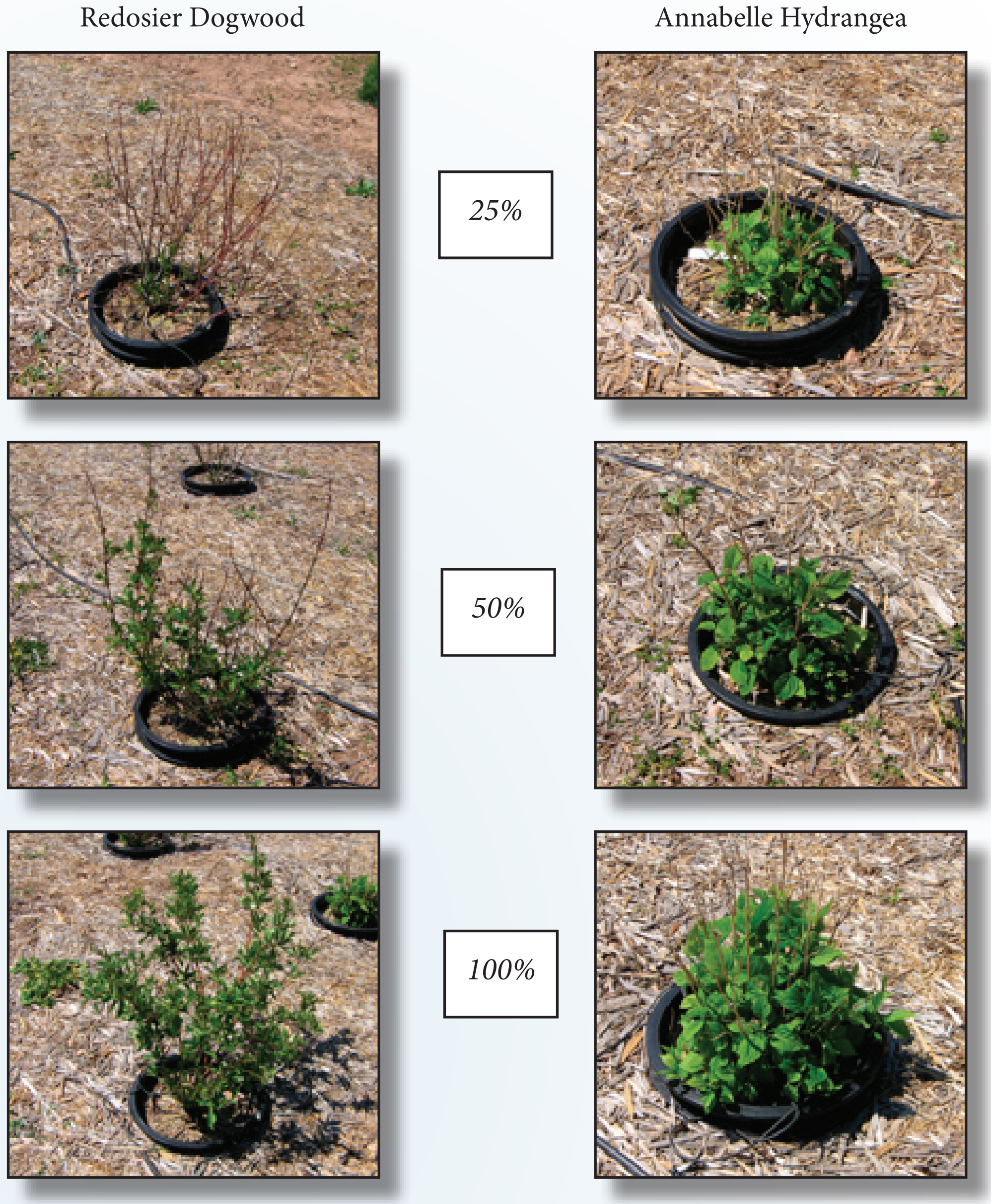

Figure 2. Redosier dogwood and Annabelle hydrangea coming out of dormancy (5/25/10)

The infield study results showed that more water given to dogwoods, ninebarks, and willows may affect some plant characteristics, but after two years of establishment, these three species appeared acceptable for landscape use with little to no additional water during normal precipitation years. Hydrangeas planted in the ground get larger with more water, and as they get larger, their demand for water also increases. However, hydrangeas may be able to survive a short period with no water and rebound when water becomes more available. In the lysimeter study, the potted dogwoods and hydrangeas displayed that they adjusted their growing habits to account for the water amounts provided to them. If more water is available, the plants will come out of dormancy at a faster rate and more seasonal growth will result.

James Klett, Dept. of Horticulture and Landscape Architecture, Jason Smith's faculty advisor, (left) and Jason Smith (right).

Evaluation of Herbicide Combinations for Control of Sago Pondweed (Stukenia pectinata) in Irrigation Canals

Basic Information

Title:	Evaluation of Herbicide Combinations for Control of Sago Pondweed (Stukenia pectinata) in Irrigation Canals
Project Number:	2010CO221B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	4th
Research Category:	Water Quality
Focus Category:	Ecology, None, None
Descriptors:	None
Principal Investigators:	Scott Nissen

Publications

1. Nissen, Scott, 2011, Evaluation of Herbicide Combinations for Control of Sago Pondweed (Stukenia pectinata) in Irrigation Canals, Colorado Water Institute Proposal, 2 pages.
2. Vassios, Joseph, 2011, "Alternatives for Sago Pondweed Control in Irrigation Canals," pg. 12-13 of Colorado Water, Volume 28 issue 2.

Sago pondweed (*Stuckenia pectinata*) is a submerged, perennial aquatic species that is native to Colorado. When present in standing water, sago pondweed is not usually problematic; however, irrigation canals across Colorado provide optimal growing conditions for sago pondweed. When sago pondweed is present the efficiency of water delivery can be severely impacted. Sago pondweed reaches maximum growth in July and August when water demand is highest.

Common control methods in Colorado include acrolein (Magnacide) applications and canal dredging. These methods are expensive and in the case of acrolein, very dangerous for applicators. Since current methods are limited, alternative control strategies are needed to provide water districts with additional tools for sago pondweed management in irrigation canals.

Previous studies have indicated that several aquatic herbicides have synergistic effects when applied to submerged aquatic plants. When copper sulfate pentahydrate (CSP) was combined with endothall or diquat there appeared to be a synergist interaction with respect to hydrilla (*Hydrilla verticillata*) control. Diquat and several copper formulations are currently registered for the sago pondweed control in irrigation canals, and endothall will be registered by spring 2010. While these compounds are registered for sago pondweed control, they provide only marginal control much of the time. The objective of this study will be to determine if combinations of diquat and endothall with copper formulations will provide better control compared to the herbicides applied individually.

Greenhouse studies will be conducted to evaluate control using combinations of endothall, diquat, copper sulfate pentahydrate, and four chelated copper formulations. Sago pondweed tubers will be planted in topsoil and allowed to produce approximately six inches of top growth. Plants will then be transferred to simulated irrigation canals (Shown in Figure 1) to simulate the forces of flowing water, and treated with these herbicides applied alone and combination. Plants will exposed to the herbicides for 2, 4, 6, and 8 hours. Following herbicide treatment plants will be rinsed in clean water and then place in clean water in the simulated canals. This will be followed by a 30 day grow-out period. After the grow-out period, plants will be harvested, dried, and biomass will be recorded. Data will then be analyzed and the effectiveness of herbicide combinations compared.

If any of the herbicide treatments appear synergistic they may provide a new alternative for the sago pondweed control in irrigation canals. In addition to providing better control, the combinations may reduce the required exposure time and may also provide lower cost alternatives compared to the current control methods.

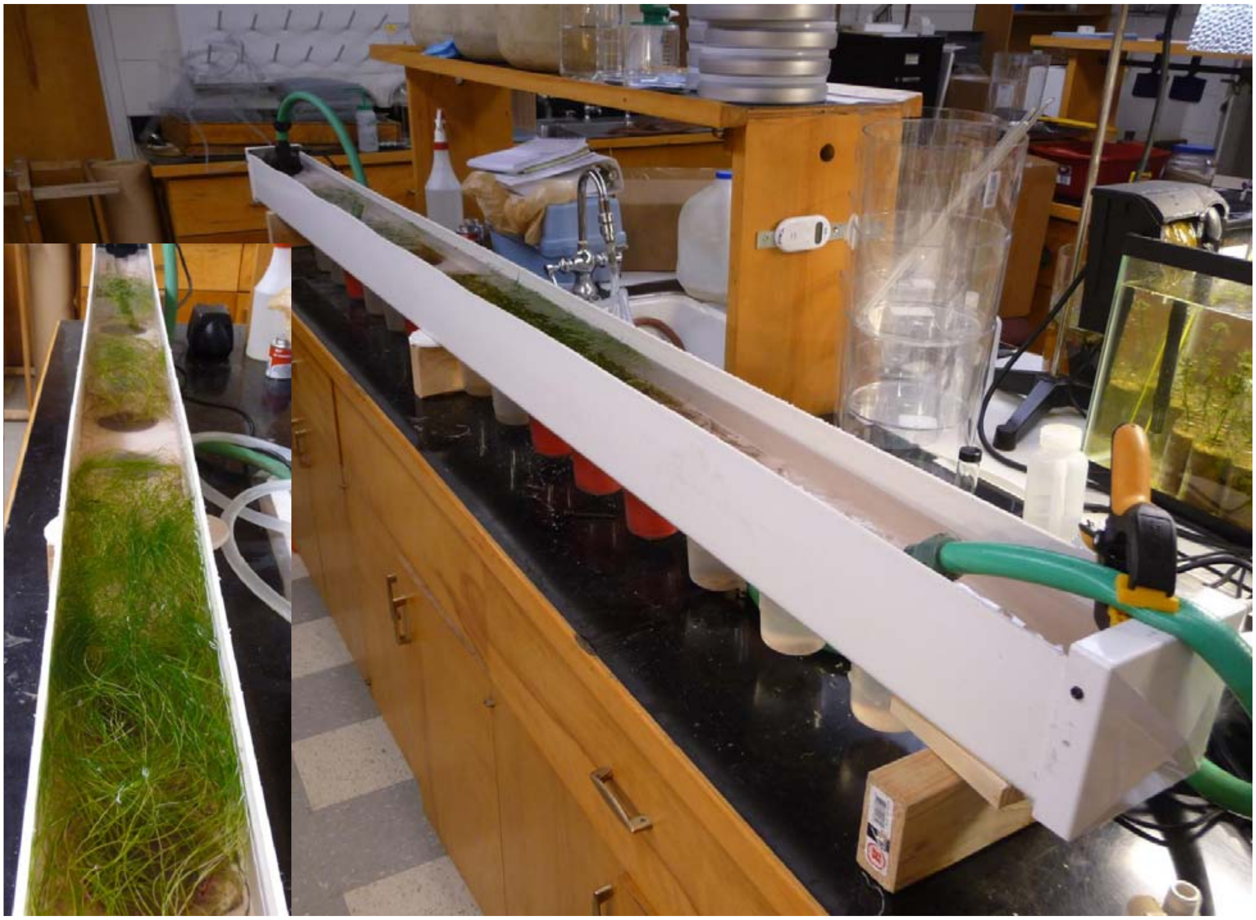

Figure 1: Simulated irrigation canal setup.

Alternatives for Sago Pondweed Control in Irrigation Canals

Joseph D. Vassios, PhD Candidate, Bioagricultural Sciences and Pest Management, Colorado State University
Faculty Advisor: Scott J. Nissen

Unlike other well-known nuisance plant species that are non-native, sago pondweed is a submersed perennial species that is native across much of the U.S., including Colorado. While it does not usually cause problems when present in lakes and ponds, sago pondweed is well-adapted to growing in canals. Adaptations include the ability to form belowground tubers, allowing sago pondweed to survive seasonal drawdowns. This ability to survive dry conditions, paired with a high growth rate corresponding with peak water demand, makes sago pondweed troublesome for irrigation districts in much of the Western U.S.

Joeseph Vassios and his advisor for the project, Scott Nissen

Traditionally, few options have been available for sago pondweed control in flowing water. The methods most commonly used in Colorado include in-season dredging to remove plant material and treatment with Magnacide® (acrolein, Alligare LLC). Magnacide® can provide aquatic weed control but is also toxic to aquatic invertebrates and vertebrates. In addition to aquatic toxicity, it can be hazardous to applicators. Due to safety concerns, Magnacide® applications in Colorado are usually made by a few highly-qualified applicators. Many chelated copper herbicides, including Clearigate® (Applied Biochemists), are available for in-season treatments and have been used with varying degrees of success depending on infestation density and water quality. In 2010 Cascade® (endothall, United Phosphorus Inc.) was labeled for use in flowing water, and it was widely used during summer 2010. Endothall was first labeled for aquatic use in 1960 and has been widely used for submersed aquatic plant control in lakes and ponds. While the use of this herbicide in irrigation systems is still new, it appears to provide good sago pondweed control.

As previously mentioned, Magnacide® can be hazardous to applicators and is listed as a restricted use pesticide. Those handling this material must complete a training course and use personal protective equipment (PPE), including a full-face respirator. Other herbicides, such as Clearigate® and Cascade®, are significantly less hazardous. These herbicides are not restricted use, and they require minimal PPE. The fact that these herbicides are not restricted use allows them to be suitable for application by irrigation district personnel without additional training.

Cascade® applications are relatively straightforward. The herbicide is metered into the canal for a duration determined by a concentration/exposure time relationship. Herbicide applications are made using a small pump, and exposure times usually range from 8-24 hours. Herbicide concentration is determined using a "factor of 24" concept. For example, if the herbicide is applied at two parts per million (ppm), an exposure time of 12 hours would be required (two ppm x 12 hours = 24 ppm-hours). Following applications, injury symptoms will be seen within one-two weeks, with plants turning brown and dropping to the bottom of the canal. Plants will continue to die back and in many cases, a single application will provide season-long control in Colorado canals. Photos in Figure 1 show sago pondweed control at zero days after treatment (DAT) and 28 DAT. While control with Cascade® is good, this herbicide does have its limitations.The formulation of endothall in Cascade® provides control of aquatic plants but will not control filamentous algae. Algae growth can be extensive on dense sago pondweed beds, and it often contributes to impeded canal flow as much as sago pondweed alone. In situations where algae are common, chelated coppers, such as Clearigate®, may provide both aquatic plant and algae control.

Figure 1. Sago pondweed control at 0 (top) and 28 days after treatment (bottom) following treatment with Cascade® herbicide.

From as early as 1971, evidence has suggested that the combination of endothall and copper could act synergistically to improve aquatic weed control. Our recent work has focused on evaluating the effectiveness of combination treatments containing endothall and chelated copper formulations for sago pondweed control in flowing water. This combination could be a solution for canals where both sago pondweed and algae are present. These combination treatments could reduce herbicide concentrations and exposure times, resulting in significant cost savings. In these studies we have evaluated treatments of Cascade® in combination with Clearigate®. These studies were carried out in the Weed Research Lab at Colorado State University using a flowing water system to simulated canal treatments.

Treatments included Cascade® alone (one and two ppm), Clearigate® alone (0.5 and one ppm) and Cascade® plus Clearigate®. Plants were exposed to these treatments for four, eight, and 12 hours. After the appropriate exposure times, canals were drained and refilled with clean water, and treated plants were allowed to grow under flowing water conditions for an additional 30 DAT. Plants were then harvested and dry biomass was determined.

The results of our greenhouse study provided good evidence for an interaction between Cascade® and the chelated copper formulation, Clearigate® (Figure 2). This interaction was highly significant when comparing the reduction in sago pondweed biomass resulting from the four-hour exposure to one ppm Cascade® and one ppm Cascade® plus 0.5 ppm Clearigate®. The combination of one ppm Cascade® plus 0.5 ppm Clearigate® for four hours reduced sago pondweed biomass to a level equivalent to two ppm Cascade® for 12 hours.

The cost saving could be substantial for canal companies. To treat a 50 cubic feet per second canal with two ppm Cascade® for 12 hours would require 64 gallons of product; however, the combination treatment would require only 11 gallons of Cascade® and about 70 gallons of Clearigate® to achieve the same level of sago pondweed control. In addition, the combination treatment would control filamentous algae. While these results are encouraging, a significant amount of field validation will be required to determine if these combination treatments are commercially viable. One potential issue with this herbicide combination is that the two products may dissipate at different rates as they move down the canal.

Sago pondweed will continue to be a significant problem for many canal companies in Colorado for several reasons. Once established, sago pondweed produces tubers that allow an infestation to increase in density and survive when canals are de-watered during the winter. It can also reproduce from seed and from floating fragments that can root to start new infestations downstream. The recent registration of Cascade® provides canal operators with new opportunities to manage sago pondweed without a significant investment in equipment or applicator training. Funds provided by the Colorado Water Institute have provided the opportunity for us to explore new management options for canal operators. This summer we plan to validate our greenhouse results with full-scale field tests.

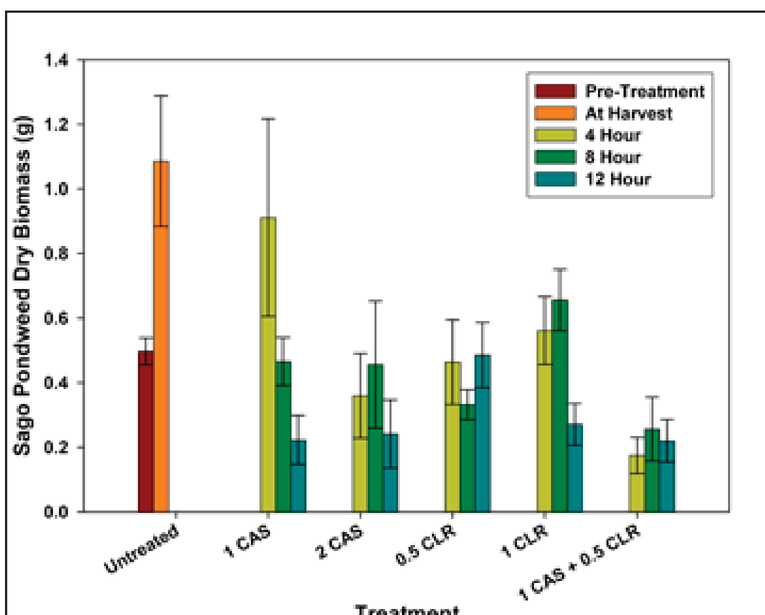

Figure 2. Average (± Standard Error) sago pondweed biomass 30 days after treatment following four, eight, and 12 hour exposure to listed treatments.

Paleohydrology of the Lower Colorado River

Basic Information

Title:	Paleohydrology of the Lower Colorado River
Project Number:	2010CO226B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	4th
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Focus Category:	Surface Water, Hydrology, Climatological Processes
Descriptors:	None
Principal Investigators:	Rajagopalan Balaji

Publication

1. Lukas, Jeffrey, 2011, "Paleohydrology of the Lower Colorado River Basin," pg. 9-11 of Colorado Water, Volume 28 issue 2.

Paleohydrology of the Lower Colorado River Basin

Jeffrey Lukas, Associate Scientist, Western Water Assessment

Background and Goals of the Project

The State of Colorado draws a substantial portion of its water supply from the Colorado River. The reliability of this supply is a function of natural hydrologic variability, upon which anticipated changes in future climate will be superimposed. Thus, the range of this natural variability in the basin streamflows must be understood in order to obtain a robust estimate of the water supply risk and, consequently, devise effective management and planning strategies. Observed flow data that are limited in time (~100 years) cannot provide the full range of variability, even with stochastic models built on them. Paleohydrologic reconstructions of annual flow using tree rings, however, provide much longer (500-1000+ years) records of past natural variability, and thus a much richer sampling of potential flow sequences, including the severe and sustained droughts of greatest concern to water resource managers (see Figure 1 for an example). Such reconstructions are available for the Upper Colorado River basin flows at Lees Ferry, Ariz., but there is no equivalent dataset for the Lower Basin (Figure 2). The Colorado River District—which is responsible for the conservation, use, protection, and development of Colorado's apportionment of the Colorado River—has acknowledged the need to include all of the Lower Basin in paleohydrologic reconstructions so as to develop a more robust assessment of the natural variability of the entire Colorado River Basin.

With funding from the Colorado Water Institute (CWI), the National Institute for Water Resources (NIWR), and the University of Colorado-National Oceanic and Atmospheric Administration (CU-NOAA) Western Water Assessment, as well as graduate student support from the CU Department of Civil and Environmental Engineering, in 2010 we began a project to fill in this need for the Lower Basin. The overall project objectives are to:

- Develop robust paleohydrologic reconstructions of the total Lower Colorado River Basin streamflow, commensurate with existing reconstructions of Upper Basin streamflow (e.g., Meko et al., 2007);
- Compare multiple reconstruction approaches to assess the robustness of each approach, and the sensitivity of the results to the chosen approach;
- Use the reconstructions in basin-wide water-balance modeling to assess the risks of the paleo-derived variability to Colorado River Basin water supplies.

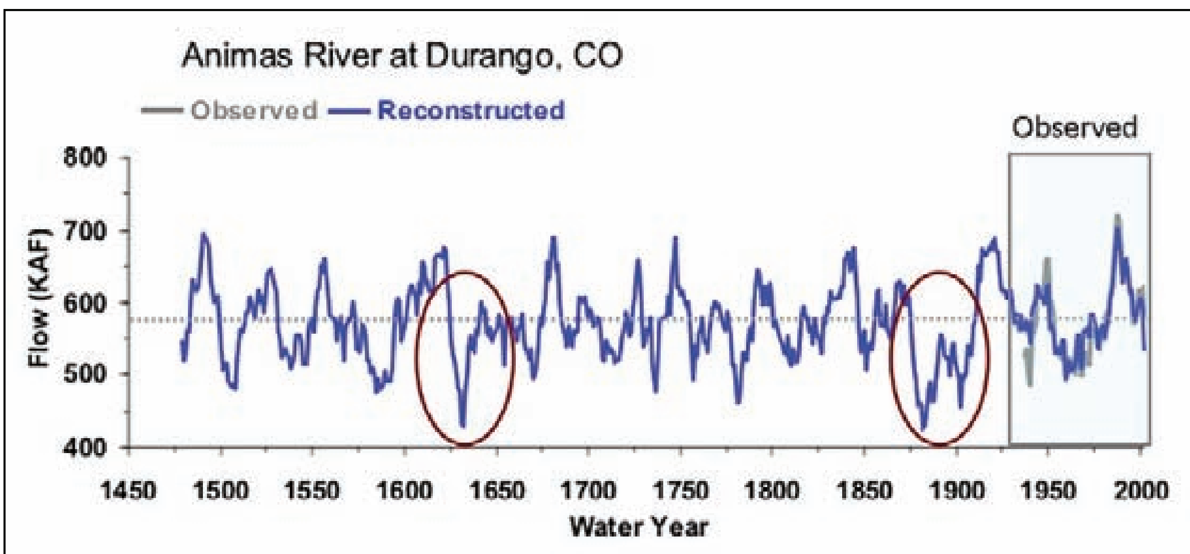

Figure 1. Paleohydrologic reconstruction, from tree rings, of the Animas River at Durango, CO, from 1470—2002. The 10-year running means of the observed and reconstructed flows are shown. The red ovals highlight sustained droughts which have no analog during the observed period, demonstrating the utility of reconstructions in capturing past hydrologic variability.

Figure 2. The Lower Colorado River Basin (shaded), showing the mainstem Colorado River, major tributaries, and important gauge locations (white squares).

Methods

The tasks and specific methods for the first year of the project are as follows:

1. *Generate naturalized annual flow records for the Lower Basin for the historic period (~1906 onwards) to use as targets for the paleo reconstructions, for these two locations:*

- *The intervening flow on the mainstem Colorado River between Lees Ferry and Imperial Dam ("Imperial")*
- *The flow for the Gila River ("Gila") at the most downstream feasible point*

Naturalized flow records—corrected for depletions, inter-basin transfers, and reservoir evaporation—must be used to calibrate with the tree-ring data. The U.S. Bureau of Reclamation (USBR) has a natural flow dataset for the mainstem Colorado and major tributaries (see Figure 3), but not all depletions have been corrected for. For the Gila River, relatively natural upstream gauge records (see Figure 3) will need to be corrected for the tributary inputs and significant diversions occurring downstream. The corrections will be made using a combination of historical records of depletions and simple hydrologic modeling.

2. *Compile all the available tree-ring chronologies within and adjacent to the Lower Basin.* Long-lived, moisture-sensitive conifers are widespread in the Lower Basin and adjacent areas of Arizona, New Mexico, Utah, and Colorado. While dozens of site chronologies developed from such trees have been publicly archived, most end prior to 1990 and can't be calibrated with the most recent streamflow data. Fortunately, two recent and ongoing projects at the University of Arizona have resulted in the collection of about 60 new chronologies, which will be recompiled by collaborators from the Laboratory of Tree-Ring Research at the university.

3. *Generate and evaluate tree-ring reconstructions for Imperial and Gila using multiple methods:*

- *Non-parametric K-nearest-neighbor (KNN; sensu Gangopadhyay et al., 2009)*
- *Generalized Linear Model (GLM)*
- *Standard Multiple Linear Regression (MLR)*
- *Variant on MLR: Robust Loess smoothing*

Paleohydrologic reconstructions have been generated using many different statistical approaches, all of which have particular strengths and weaknesses. Using several approaches will allow assessment of the uncertainty in the reconstructions that can be attributed to the methodology alone.

4. *Use stochastic simulation on the observed and reconstructed flows to compute statistics on run length, deficits and surpluses, and run other diagnostics.* These diagnostics will allow us to better understand the characteristics of hydrologic variability captured by the different reconstruction approaches relative to that contained in the observed record.

5. *Preliminary system response analysis using reconstructions as input to the Rajagopalan et al. (2009) water-balance model of the Colorado River Basin.* The water balance model is simple yet representative of the entire water resources system in the basin. We will work closely with the Colorado River District to perform exploratory analyses in using the long reconstructed streamflows to generate a rich variety of streamflow scenarios, which we will use to estimate the water supply risk in the basin under different climate and management scenarios.

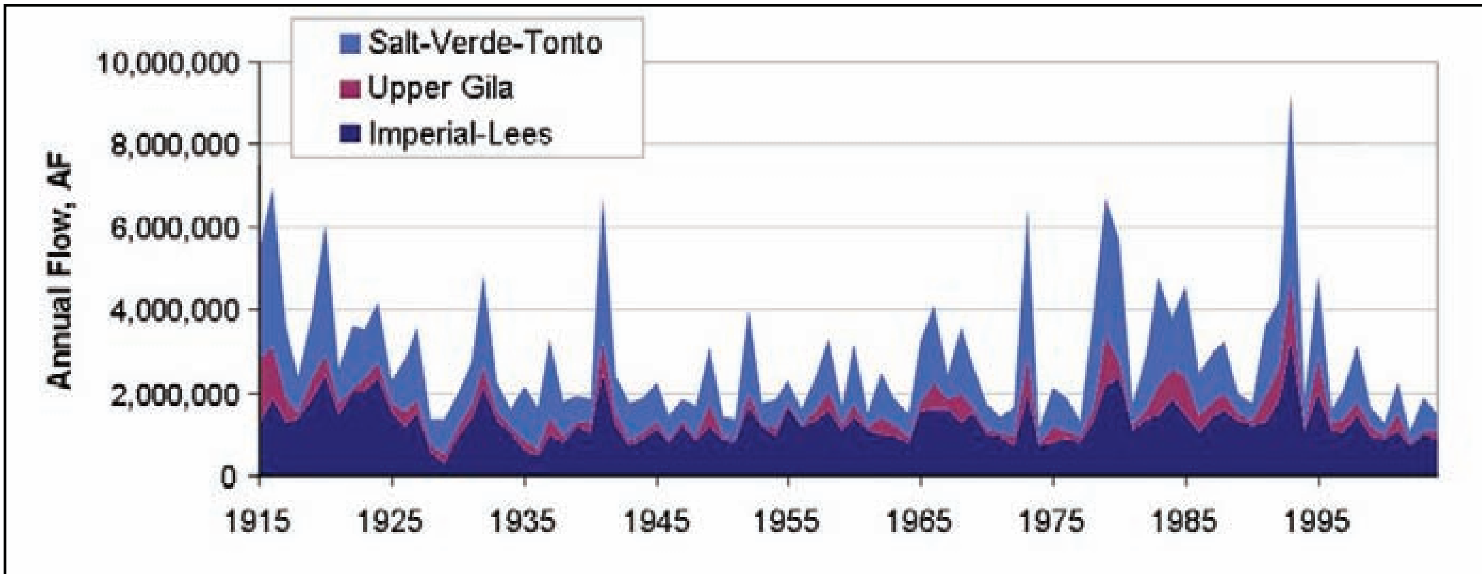

Figure 3. A rough approximation of total historical streamflows (1915-2004) for the Lower Colorado Basin can be made by summing the intervening flows between Lees Ferry and Imperial Dam (Imperial-Lees) on the mainstem and the gauged flows for upstream gauges in the Gila River Basin (Salt-Verde-Tonto and Upper Gila). See Figure 2 for gauge locations. These flow records are now being corrected for downstream depletions and inflows before being modeled with the tree-ring data.

Progress to Date

The project formally commenced with a project meeting in Boulder, Colo., in September 2010. The participants included all of the project personnel listed above as well as representatives from the USBR and the Colorado Water Conservation Board (CWCB). Presentations by the investigators covered both the proposed work plan and methods and past research projects on which this work will be based. The discussions during the meeting served to refine the work plan and methods.

Since the meeting, the bulk of the work has been carried out by Wade and Rajagopalan on task 1 above: *Generate naturalized annual flow records for the Lower Basin for the historic period.* Wade has conducted a literature review and data search to compile documentation of historic gauged flows and depletions, setting the stage for modeling the natural flows for Imperial and Gila. Rajagopalan has also been refining the software codes to implement portions of tasks 3 and 4, particularly those needed to use the KNN reconstruction approach.

At the September meeting, March 1, 2011 was set as the target date for the completion of tasks 1 and 2, and that date appears to be on track. The compilation of the naturalized flow records (the *predictands*) and the tree-ring data (*predictors*) will allow task 3 (generating the reconstructions) to proceed immediately, to be closely followed by tasks 4 and 5. Completion of all tasks is expected in July 2011.

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Project Personnel

PI: Balaji Rajagopalan, University of Colorado

CO-PIs: Jeffrey Lukas, Western Water Assessment; Jose Salas, Colorado State University. Other Investigators: Connie Woodhouse and David Meko, University of Arizona; Lisa Wade, University of Colorado (Rajagopalan MS student)

Collaborators: Dave Kanzer, Eric Kuhn, and John Currier, Colorado River District; Kiyomi Morino, University of Arizona; Joe Barsugli, University of Colorado

Information Transfer Program Introduction

Requests from the Colorado legislature to facilitate and inform basin-level discussions of water resources and help develop an interbasin compact for water management purposes emphasized the role Colorado Water Institute plays in providing a nexus of information.

CWI publications include research reports and *Colorado Water*, a bimonthly newsletter containing information on research, faculty, conferences and other events with a water focus. Outreach activities are conducted in conjunction with CSU Extension, the U.S. Department of Agriculture, the Colorado Department of Agriculture, the Environmental Protection Agency, and The Colorado Department of Public Health and Environment.

Some major technology transfer efforts this year include:

- Provide training for Extension staff in various water basins to help facilitate discussions of water resources
- Encourage interaction and discussion of issues between water managers, policy makers, legislators, and researchers at Colorado Water Future one-day conference
- Publication of the bi-monthly newsletter which emphasizes water research, current water issues
- Posting of 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
- Work 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:	2010CO211B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	4th
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Reagan M. Waskom

Publications

1. Colorado Water Newsletter, Volume 27 - Issue 2 (March/April 2010), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 32 pages.
2. Colorado Water Newsletter, Volume 27 - Issue 3 (May/June 2010), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 40 pages.
3. Colorado Water Newsletter, Volume 27 - Issue 4 (July/August 2010), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 44 pages.
4. Colorado Water Newsletter, Volume 27 - Issue 5 (September/October 2010), Colorado Water Institute, Colorado State University, Fort Collins Colorado, 44 pages.
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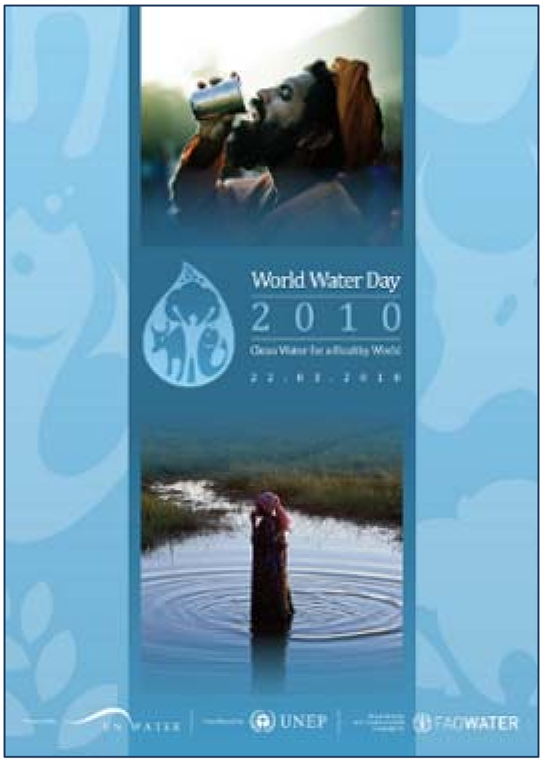
Colorado Water Institute Activities

COLORADO STATE UNIVERSITY PRESENTS WORLD WATER DAY
in conjunction with Hydrology Days



WHAT: **World Water Day**
WHEN: **Monday, March 22, 2010**
WHERE: **Lory Student Center, Fort Collins, CO**

KEYNOTE: **Dr. John Matthews**
Senior Program Officer of Freshwater Program,
World Wildlife Fund

CSU is hosting its first World Water Day event at the Lory Student Center on March 22, 2010. Activities include a World Water Day Fair, dignitary and keynote speakers, workshops, demonstrations, and community service projects. World Water Day at CSU will highlight local, regional, and global educational and outreach programs.

For more information about CSU World Water Day and Hydrology Days please visit the CSU World Water Day web site at www.globalwater.colostate.edu. To participate, please contact faith.sternlieb@colostate.edu.

30th Annual American Geophysical Union

Hydrology Days

March 22 - March 24, 2010

Hydrology Days Award Lecturer:

Professor Andrea Rinaldo

Ecole Polytechnique Federale de Lausanne, Switzerland
and
Universita degli Studi di Padova, Italy

For more information and/or to submit abstracts, go to:

http://hydrologydays.colostate.edu

2010 Arkansas River Basin Water Forum

The 2010 Arkansas River Basin Water Forum will be held on April 6-7, 2010, in Cañon City, Colorado, at the Historic Abbey.

Purpose: The Forum has been a focal point for highlighting current water issues in the Arkansas River Basin and in Colorado since its inception in 1995. Planners, presenters, and attendees represent a wide variety of organizations, agencies, and public citizenry working on water resources issues in the Basin.

Description: As the Basin contends with an array of resource management goals, the Forum theme this year is "The Arkansas River: Our Multifaceted Gem." Topics will include economic benefits of water use and water quality issues in the Upper Arkansas, planning for future water supply variability, water supply planning for rural and small municipalities, stormwater runoff management, and an overview of major projects in the Lower Arkansas Valley. Our keynote speaker this year will be Doug Kemper, executive director at the Colorado Water Conservation Board.

Scholarships: The Forum sponsors are pleased to offer $2000 in scholarships to outstanding graduate students. More information is available on our web site.

Registration prior to March 26 is $45 for both days and $25 for one day. Please visit the Forum website at http://www.arbwf.org/ or contact Dr. Perry E. Cabot at (719) 549-2045 for more information.

Colorado Water Science Day 2010

New Challenges, New Science For Managing Colorado Water

Wednesday, June 23, 2010
9:00 am – 3:30 pm
University Memorial Center, Room 235
University of Colorado
Boulder, Colorado 80302

Keynote Speakers

Matt Larsen, Associate Director for Water, USGS — *USGS Water Science Program Priorities & Directions*

Mike Sullivan, Deputy State Engineer, Colorado — *Using Science to Manage Colorado's Water*

Speakers

Ken Leib, USGS
Impacts of Land Use Change on Water-Quality

Thomas Borch, Colorado State University
Emerging Contaminants

John Elliott, USGS
River Restoration in Colorado

Noah Molotch, University of Colorado
Remote Sensing of Snowpack

Sarah Spaulding, USGS
Nuisance Alga

John McCray, Colorado School of Mines
Carbon Sequestration

Brad Udall, University of Colorado
Climate Change & Water Supply

Poster Session

Volunteered poster/papers will be accepted on a space availability (first-come, first-serve) basis.

To register, go to http://www.cwi.colostate.edu.
Space is limited and early registration is encouraged.
Registration fee is $30 to cover meal and break costs.

USGS science for a changing world · Colorado State University · COLORADO SCHOOL OF MINES EARTH • ENERGY • ENVIRONMENT

Rolling Up the Sleeves: Agricultural/Urban/Environmental Leaders Tackle Water Sharing Obstacles in the Colorado River Basin

MaryLou Smith
Policy & Collaboration Specialist, Colorado Water Institute

What can a group of 35 highly motivated water leaders accomplish by retreating for two days to a secluded castle on a 3,100-acre ranch overlooking the Front Range of Colorado? Can a group selected to represent western agricultural, urban, and environmental interests agree on recommendations for overcoming obstacles to sharing water for all their needs?

Reagan Waskom, director of the Colorado Water Institute, facilitates a small group session.
Photo by John Foster

To answer the first question, a great deal can be accomplished. And yes, diverse interests can agree, and given a tightly focused agenda and pre-meeting assignments, two days of concentrated work can produce a bold set of recommendations.

Water presently diverted for agriculture is under intense pressure as urban and environmental needs increase. A grant to the Colorado Water Institute from the Walton Family Foundation funded the convening of stakeholders in a workshop to determine how the status quo approach of permanently transferring water from agriculture could be supplanted by overcoming obstacles to creative water-sharing strategies, which provide multiple benefits for agriculture, cities, and the environment.

An extensive interview process resulted in a rich toolbox of water sharing strategies. Participants selected from those interviews agreed to provide in advance of the workshop a one-page paper describing the strategies with which they had experience and the obstacles they faced. Sharing this information ahead of time enabled participants to hit the deck running—to immediately zero in on recommendations to address common obstacles.

A strategy and obstacle example provided by a pair of participants is that of the Elephant Butte Irrigation District and the New Mexico Audubon Society. Together they developed an environmental water transaction program so that Audubon could acquire water rights from a farmer to support habitat in the same way one farmer could acquire water rights from another farmer to grow a crop. Of concern is whether allowing agriculture to environmental transfers such as this will cause problems down the road if application of the acquired water is used to provide habitat for species listed as threatened or endangered. The unanswered question is whether an endangered species will get precedence over agriculture when the region experiences a low water year.

What was the motivation for all this? In a 2008 report, western governors asked the Western States Water Council (WSWC) to work with states and stakeholders to address the issue of how agriculture to urban water transfers could be accomplished without harming rural communities or the environment. WSWC reached out to the Family Farm Alliance, Western Urban Water Coalition, The Nature Conservancy, and others to cooperate in addressing the issue.

Choosing the right mix of participants was critical to the success of the workshop. Participants were chosen to reflect a diversity of states, primarily from the Colorado River Basin, but also from other western states. A representative mix of practitioners and academics added to the strength of the group, as did a mix of those falling in the categories of attorney, engineer, farmer, economist, professor, policy analyst, irrigation district manager, and municipal water provider.

The goal of the group of 35 who met in the summer of 2010 was to showcase real opportunities for policy improvement.

Their recommendations, along with the toolbox of water sharing strategies uncovered through the pre-workshop interviews, are included in the report *Agricultural/Urban/Environmental Innovative Water Sharing Strategies for the Colorado River Basin and the West* at cwi.colostate.edu.

Expedited Review Process Pilots

Participants find that even when they have broad support from urban, environmental, and agricultural stakeholders, projects and programs for effectively sharing water often get bogged down in regulatory review. They recommend that each state pilot an expedited review process to facilitate a one-stop-shopping means to reduce costs and gain more timely approval. Needed:

- A multi-use water sharing project or program that has broad support
- A governor-appointed liaison to guide the project through state and federal approvals
- A governor-requested lead federal party designated to be involved in all review process aspects
- Cooperation of the liaison and federal lead to minimize repetitive agency information exchanges and lead to reduced costs and timely approval

Flexible Basin Wide Approach

Participants believe that coordinating decisions about water infrastructure, storage, release, and other programs at the watershed level would lead to solutions for agricultural, urban, and environmental water sharing that might not otherwise be obvious when working only at smaller scales.

They recommend:

- Simulation of management strategies that benefit multiple uses and sectors
- Watershed scenario modeling and studies to look for opportunities for various sectors to cooperate
- Improved institutional frameworks for better operation and management, flexibility, and resiliency

View from Cherokee Park Ranch and Castle, where the event was held. Photo from Cherokee Park Ranch and Castle Files

- Planning tools that accurately depict the complexity of a basin's available flow and multiple demands across its geography, not just its mainstem rivers and large storage projects
- Promotion and restoration of Conservation Title funding to programs such as EQIP (Environmental Quality Improvement Program) in the next U.S. Farm Bill

Clearing Obstacles to Creative Water Sharing and Transfers

Because they experience significant obstacles to sharing water for multiple needs without permanent fallowing of agricultural lands, participants recommend ways to reduce those obstacles. Their recommendations include:

- The appointment of a cabinet level advocate in each state who would work to empower the success of collaborative water sharing solutions
- Incentives and pilot programs that encourage temporary transfers but do not infringe on vested property rights
- Development of multiple interest criteria and thresholds that define best management practices for transfers/water sharing strategies to be applied in lieu of expensive regulatory approval
- Encouragement of mutually beneficial infrastructure sharing and development, including cooperation in the optimal use of already existing infrastructure
- Voluntary water resource sharing zones based on grassroots water partnerships between municipal/industrial, agricultural, and environmental users, within which water and financial resources might be traded more freely to the mutual benefit of sectors, using such elements as tax incentives

Stakeholder Process to Facilitate Multi-Benefit Water Sharing Solutions

Participants believed that successful water sharing strategies require effective collaboration between multiple parties with a variety of interests. They believe that decision makers must pay serious attention to the process in which stakeholders are engaged in order to increase the likelihood of success. Their recommendations include:

- Early and broad stakeholder involvement in creating solutions that satisfy diverse needs
- Empowering relationship building and the development of partnerships between stakeholder groups via means such as basin wide water roundtables
- Interest-based process which addresses stakeholder needs and encourages the development of outcomes that address multiple needs and values
- Process tools and incentives including effective resources, information, and facilitation, including modeling tools and funding for studies and pilot projects
- Research-based public outreach

What's next? The Agriculture/Urban/Environmental Water Sharing Work Group that developed this initiative will lead in working with participants to carry these recommendations to the Western States Water Council, the Western Governors Association, the Bureau of Reclamation, all of their constituent groups and others. Their intent is to affect change in policy and procedure that currently creates obstacles to creative sharing of water to meet demands that are increasingly in conflict.

Perhaps a retreat to a castle on a ranch looking down on Front Range cities will result in down to earth, practical change to promote agricultural, environmental, and urban water sharing.

Group of participants at workshop representing seven western states and Washington, D.C. Photo by Ron Bend

Colorado State University - GRAD592
Interdisciplinary Water Resources Seminar

Fall 2010 Theme

Moving from Conflict to Collaboration in Water Resource Issues

Mondays at 4:00 PM, Natural Resources Building - Room 109, CSU Campus

8/23 **Moving from Destructive to Constructive Water Conflicts**
David Freeman, Professor Emeritus, Department of Sociology, CSU
Reagan Waskom, Director, Colorado Water Institute

8/30 **An Overview of Water Law and How We Have Historically Handled Water Conflicts in Colorado and the West**
Greg Hobbs, Colorado Supreme Court Justice

9/6 Labor Day — No class

9/13 **Communicating and Managing Conflict about Complex Environmental Issues**
Jessica Thompson, Assistant Professor, Warner College of Natural Resources, CSU

9/20 **Conflict Stages and Approaches to Resolution--from Litigation to Arbitration, Mediation and Collaboration**
Joseph P. McMahon, P.E., J.D.

9/27 **Colorado's Interbasin Compact Committee and the Basin Roundtables Process—Does it Promote Stakeholder Collaboration on Colorado Water Issues?**
Alexandra Davis, Colorado Department of Natural Resources, IBCC Chair
Melinda Kassen, Trout Unlimited, IBCC Member

10/4 **Resolving Water Conflicts Between States through Interstate Compacts**
Tanya Heikkila, Associate Professor, University of Colorado Denver, School of Public Affairs

10/11 **Case Study: The Republican River Dispute**
Dick Wolfe, State Engineer, Colorado Department of Natural Resources

10/18 **Case Study: The Arkansas River Dispute**
David Robbins, Water Attorney, Hill and Robbins Law Firm

10/25 **Shared Vision Process—How the Army Corps of Engineers is Using Computer-Aided Dispute Resolution in Northern Colorado's Halligan-Seaman Deliberations**
Bill Werick, Werick Solutions and Mark Lorie, U.S. Army Corps of Engineers

11/1 **Interest Based Negotiation vs. Positional Bargaining—How Things Could Have Played out Differently on the South Platte**
P. Andrew Jones, Water Attorney, Lind, Lawrence and Ottenhoff

11/8 **Demonstration of Interest Based Facilitated Dialogue on Poudre River Flow Issues**
MaryLou Smith, Facilitator, Colorado Water Institute

11/15 **Public Deliberation as a Conflict Resolution Tool**
Dr. Martin Carcasson, Director, CSU Center of Public Deliberation

11/22 Thanksgiving Break — No class

11/29 **Class Participation/Facilitated Deliberation on Poudre Flow Issues**
Martin Carcasson and Leah Sprain, CSU Center of Public Deliberation

12/6 **Continued Class Participation/Facilitated Deliberation on Poudre Flow Issues**
Martin Carcasson and Leah Sprain, CSU Center of Public Deliberation

12/13 Final Exams — No class

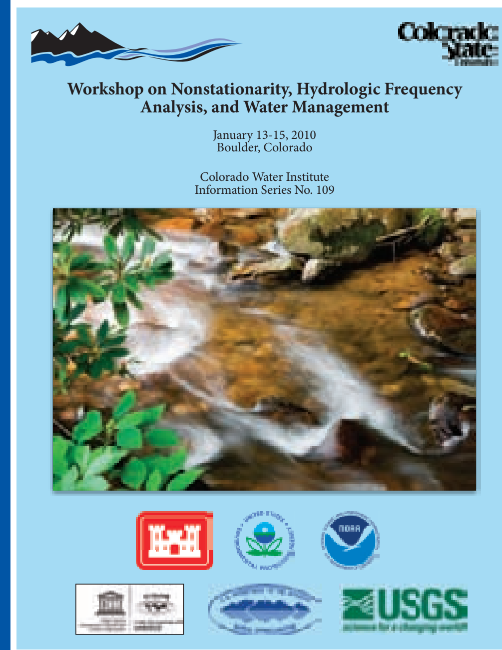
All interested faculty, students, and off-campus water professionals are encouraged to attend.
For more information, contact Reagan Waskom at reagan.waskom@colostate.edu or visit the CWI web site.
CWI Website: http://www.cwi.colostate.edu

Workshop on Nonstationarity Proceedings now available:

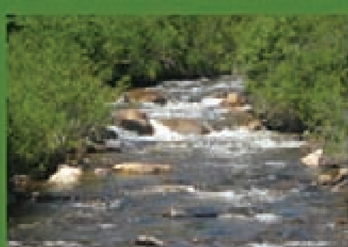
The workshop was held in Boulder, Colorado from January 13-15, 2010, and brought together researchers and practitioners from the U.S. and international institutions. The workshop program included five Nobel Peace Prize laureates, who were lead authors for Intergovernmental Panel on Climate Change reports. International participants came from Canada, the United Kingdom, Japan, Poland, Greece, and Italy.

The workshop objectives were to discuss in detail how water management agencies should plan and manage water resources in the face of climate change, and to form a coordinated action plan to help the agencies move forward. The workshop was organized into several main themes:

- Introduction to the problem nonstationarity poses for water management
- Understanding nonstationarity through data analysis and statistical methods
- Forecasting future hydrologic frequency through the use of climate model information
- Decision making with a highly uncertain future
- International perspectives on nonstationarity
- Summary and conclusions



Copies available online at http://www.cwi.colostate.edu/NonstationarityWorkshop



Nutrients and Water Quality: A Region 8 Collaborative Workshop

Salt Lake City, Utah February 15-17, 2011

Agencies and universities in the six states of EPA Region 8 (CO, MT, ND, SD, UT, WY) will host a three-day workshop in February 2011 exploring the science and institutional context regarding nutrients and water quality.

Why this Workshop?

Nutrients are a concern due to degradation of important water resources and the associated health and environmental risks. The science and policy surrounding nutrients is complex, affecting the management of wastewater, stormwater, drinking water and agriculture. This workshop will provide an opportunity for stakeholders and agencies to work together to develop a shared understanding of the science and to better understand the challenges associated with developing and implementing nutrient controls while preserving other important stakeholder values. We seek participation of those engaged in nutrient research, policy and management, and those affected by nutrient control issues - reflecting a diversity of states and roles.

Call for Participation/Presentations

We seek presentations to address key questions that are pertinent to this issue - presentations from the full spectrum of stakeholders, not only scientists. Please refer to the list of questions and topics we plan to address and information about participation and/or submitting a presentation proposal at www.cwi.colostate.edu/nutrients

Northern Plains & Mountains Regional Water Program · Colorado Water Institute · UWRL · United States Environmental Protection Agency

Join us for dinner and conversation to benefit the Water Resources Archive

WATER TABLES 2011

WESTERN WATER LAW: ADAPTING TO OUR CHANGING NEEDS?

Save the date:
Saturday, February 19, 2011
Location:
Morgan Library
Colorado State University,
Fort Collins

Tickets will be available in early January.
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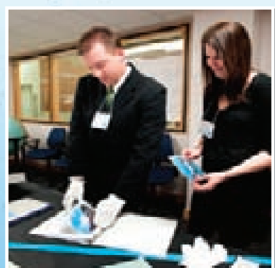
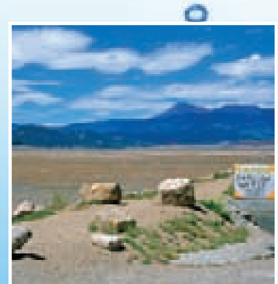
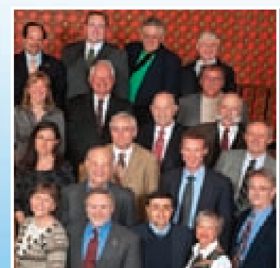
e-mail jane.barber@colostate.edu, or call (970) 491-5712.

Spring 2011
Interdisciplinary Water Resources Seminar

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

Thursdays from 12:00 to 1:00 PM

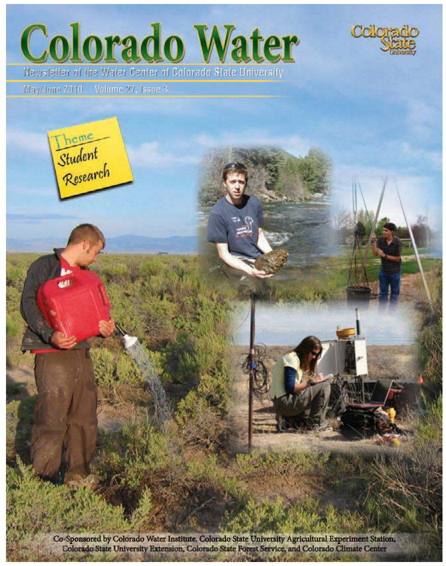
January 27 **LSC Room 208**	**Mazdak Arabi & Jorge Ramirez** **Joint Lecture: Building a Better Water Future in Education, Research, and Economic Development**
February 2 **LSC Room 224-226**	**Steve Silliman** **Darcy Lecture- Characterization of a Complex, Sole-Source Aquifer System in Benin, West Africa**
February 10 **LSC Room 208**	**Robert Ward & Mark Fiege** **Joint Lecture: History of the Poudre River**
February 17 **LSC Room 208**	**Steven Fassnacht & Mike Gillespie** **Operational Measurements of Snowpack Properties across the Cache la Poudre Watershed: Monitoring and Research to Increase Our Understanding of the Basin**
February 24 **LSC Room 228**	**Dennis Ojima & Brad Udall** **Climate, Water, and Ecosystems: The Changing Socio-Ecological Systems of the West**
March 3 **LSC Room 208**	**Deborah Entwistle, Carl Chambers & John Stednick** **Watershed Analysis on National Forest Lands**
March 10 **LSC Room 208**	**Stephanie Kampf & Jeffrey Niemann** **Basin and Catchment-Scale Hydrologic Regimes in the Cache la Poudre**
March 17	**No Seminar** **Spring Break**
March 24	**No Seminar** **Hydrology Days Mar. 21-23; www.hydrologydays.colostate.edu**
March 31 **LSC Room 208**	**John Bartholow & Brian Bledsoe** **Crafting a Flow Recommendation for the Cache la Poudre River through Fort Collins**
April 7 **LSC Room 208**	**George Varra** **Water Management on the Poudre River**
April 14 **LSC Room 208**	**Ken Carlson & Keith Elmund** **The Built Environment of the Cache la Poudre River**
April 21 **LSC Room 208**	**Ellen Wohl** **Geomorphology of the Poudre River**
April 28 **LSC Room 220-222**	**Boris Kondratieff & Ashley Ficke** **Biomonitoring of the Poudre River**
May 5 **LSC Room 228**	**Panel: Reagan Waskom, Mazdak Arabi, Jorge Ramirez, & Colorado Water Innovation Cluster** **Discussion of Poudre Watershed Monitoring Plan**

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

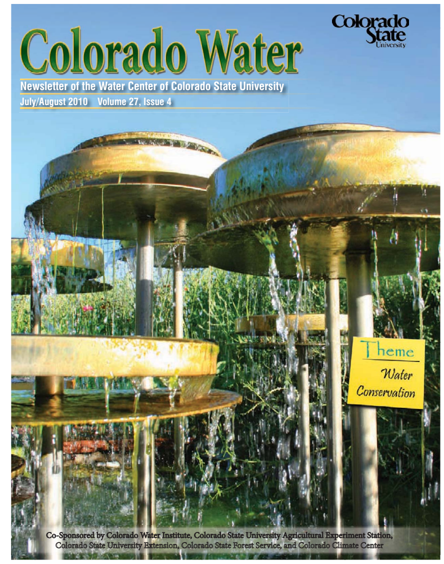
All interested faculty, students, and off-campus water professionals are encouraged to attend.

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

Colorado Water
Vol. 27, Issue 2
Nonstationarity



Colorado Water
Vol. 27, Issue 3
Student Research



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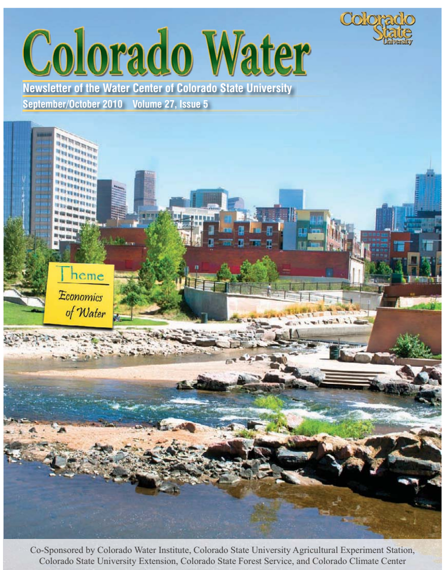
Water Conservation



Colorado Water
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Economics of Water

Colorado Water
Vol. 28, Issue 1
Decision Support Systems

Colorado Water Institute Reports

Bear Creek Watershed Partnership Project

by Kimberly Gortz-Reaves, MS Candidate, College of Architecture and Planning, University of Colorado Denver Faculty Sponsor: Charlie Chase

The headwaters of Bear Creek in the Mount Evans Wilderness. (Courtesy of Kim Reaves)

The purpose of the Bear Creek Watershed Partnership (BCWP) research was to identify stakeholders and potential partners operating in the Bear Creek watershed and suggest ways to create a system that aids the coordination of watershed-wide projects. The upper reaches of the Bear Creek watershed stretch from the Mount Evans Wilderness to the Bear Creek Reservoir between Morrison and Lakewood, Colorado. The final eight miles of Bear Creek flows through the dense urban environments of Lakewood, Sheridan, and Denver before joining the South Platte River. This diverse watershed has high altitude streams to heavily impacted reaches. The land and water is being managed by a multitude of land use agencies. This research aimed to identify all stakeholders in the upper watershed and the 8-mile reach below the Bear Creek Reservoir.

Initially, the research was facilitated by the BCWP, a volunteer collaboration between the City of Denver Parks and Recreation, University of Colorado at Denver, National Park Service Rivers, Trails, and Conservation Assistance (RTCA) Program, AmeriCorps, FrontRange Earth Force, and Groundwork Denver. The research was initiated by the facilitating partners for several reasons. First, it was believed there were various organizations and plenty of opportunities to create conservation experiences within existing programs. Yet, no one knew the extent of programs being implemented to meet regulatory requirements or of outreach events by community groups. Also, is it has been shown that partnerships create favorable circumstances to develop and support a watershed-based stewardship effort and improve management strategies. Furthermore, the Bear Creek watershed is unique in its stewardship learning opportunities for youth and communities because it physically encompasses a variety of environments and uses.

To forward the efforts, graduate students in Landscape Architecture and Planning at the University of Colorado at Denver were recruited to help answer the question of whom and to what extent stakeholders are operating in the watershed. With the help of a faculty advisor, a questionnaire was drafted to guide interviews for data collection. Organization representatives and program leaders were contacted to inform them of the burgeoning partnership and to collect the following information: contact information, organization mission, and the extent of their involvement in the watershed and interest in the partnership. The initial call list was compiled from names and contact information collected at a Young Conservation Stewards meeting held on December 12, 2007, and hosted by the National Park Service RTCA. Additional contacts were gathered as phone interviews were conducted. The long-term intent of the BCWP was to use the collected data to create a vehicle in

This aerial photo shows the influence of urban development on the lower reaches of the Bear Creek watershed. (Edited from Microsoft LiveMaps by Kim Reaves)

which partners would be able to share or coordinate their objectives and improve management strategies.

The 57 respondents represented various nonprofit community groups, volunteer organizations, and jurisdictional land management agencies. Of the 57 respondents, 41 were in favor of being involved in a partnership, 6 said no, 6 said maybe, and 4 did not indicate a preference. Several regulatory activities occurring in the watershed offer opportunities for collaboration, including promoting environmental health, safety, and water quality education. Sources for creating "on-the-ground" stewardship activities include stormwater awareness, mitigating pollution and erosion, and reducing environmental impacts from human activities.

Many of the public agencies already work with volunteer groups and individuals, but they usually do not coordinate with efforts outside of their jurisdiction. However, there is a marked consensus that the lack of cross-jurisdictional coordination related to management strategies or volunteer service opportunities needs attention. It was also recognized that creating cross-jurisdictional opportunities may economize and make management efforts more efficient. As a result, a few key agencies believe that a partnership could help organize conservation efforts and educate the public on watershed issues. Interest in a partnership is high, and many respondents wanted to come together to have a "roundtable" discussion.

After the initial identification of stakeholders, the facilitating partners discussed options for creating a system that aids the coordination of watershed-wide projects. Several possibilities were explored, including a web-based forum/map for posting projects. Data were used to create a model of a web-based map, which employed flash script to make roll-over buttons for highlighting contact information. Using this technique would also locate project sites. Other options explored included the formation of a funded entity similar to Cherry Creek Stewardship Partners, which would act as a guiding board of volunteer members.

Logistics or substantial commitment to the formation of a partnership has not currently manifested. The research concluded with the open-ended possibility for various stakeholders to have a "roundtable" meeting to establish the collective interest in a partnership and to set objectives. Currently, further research is being conducted to determine and document the extent and type of public/private "on-the-ground" youth and community projects. Further data on regulatory mandates will also be collected to find area agencies that can coordinate efforts to make programs more efficient and economical. It is the goal of those continuing to work on the partnership to have the roundtable gathering in June and facilitate a meeting between land managers and community groups to discuss the findings and move the partnership to the next level. The next level will involve creating a partnership model that has a mission befitting to the Bear Creek Watershed. It is hopeful that through the research efforts, watershed stakeholders will further efforts in solidifying a partnership that will coordinate "on-the-ground" youth and community projects and create a system for watershed-wide stewardship.

Developing Barriers to Prevent the Upstream Migration of the New Zealand Mudsnail

by Scott Hoyer, MS Candidate, Fish, Wildlife, and Conservation Biology, Colorado State University
Faculty Sponsor: Christopher Myrick

Waterways and aquaculture facilities throughout the western United States are at risk of invasion by the New Zealand mudsnail (*Potamopyrgus antipodarum*). Originally endemic to New Zealand, mudsnails were first discovered in the United States in 1987 near Hagerman, Idaho, and have since spread to all the western states, excluding New Mexico. The mudsnail's high reproductive capacity allows them to reach extremely high densities in some situations (> 500,000 snails per square meter), leading to concerns that native aquatic communities and valuable sport fisheries could be negatively impacted. Several recreational fisheries have already suffered in California and Colorado by the closure of popular stretches of streams following mudsnail invasion. Additionally, several western aquaculture facilities have been invaded by mudsnails, resulting in revenue losses associated with the costs of facility disinfection to eradicate this organism and declines in fish produced for fisheries enhancement and restoration. The mudsnails' wide range of physiological tolerances and lack of effective native predators or competitors raises the possibility that it could spread to the majority of western waterways unless positive steps are taken to limit further invasion.

This image shows a 21.5-cm diameter PVC arena that was used to evaluate the New Zealand mudsnails' response to various copper-based materials. (Courtesy of Scott Hoyer)

The New Zealand mudsnails' rapid and wide-ranging invasion across four continents over the last 150 years can partly be attributed to the ease in which it can be inadvertently spread by humans. Mudsnails are quite small (< 6 mm at maturity) and can survive long periods of desiccation, thus allowing them to "hitchhike" between waterways on gear such as boots, waders, and rafts. Management agencies are now working to eliminate this pathway by educating fisherman, biologists, and other recreational water users on the proper ways to disinfect gear. However, infested gear is not the only way in which mudsnails find their way into novel habitats; fish hatcheries are now being carefully monitored to ensure that their activities do not lead to further spread. Because an infested aquaculture facility could easily spread mudsnails through normal stocking, it is no surprise that facilities that are found to harbor mudsnails face harsh restrictions by management agencies. In some situations, a facility may be quarantined until all of the mudsnails have been eradicated, which can be very costly in terms of both time and money and may lead to bankruptcy for some small private operations.

The New Zealand mudsnail is a small (< 6 mm at maturity) freshwater snail endemic to New Zealand that has rapidly spread across western North America. The snail's high reproductive potential, lack of natural predators, and broad environmental tolerance range have raised concerns about its potential impact on native aquatic communities and valuable sport fisheries. (Courtesy of Scott Hoyer)

To protect these operations, it is important to find ways of preventing invasion in the first place. Mudsnails find their way into hatcheries in several ways, including crawling upstream through effluent pipes that connect a facility to an infested waterway. To eliminate this pathway, we need to develop a barrier system for these pipes. One potential class of barriers is copper-based substrates

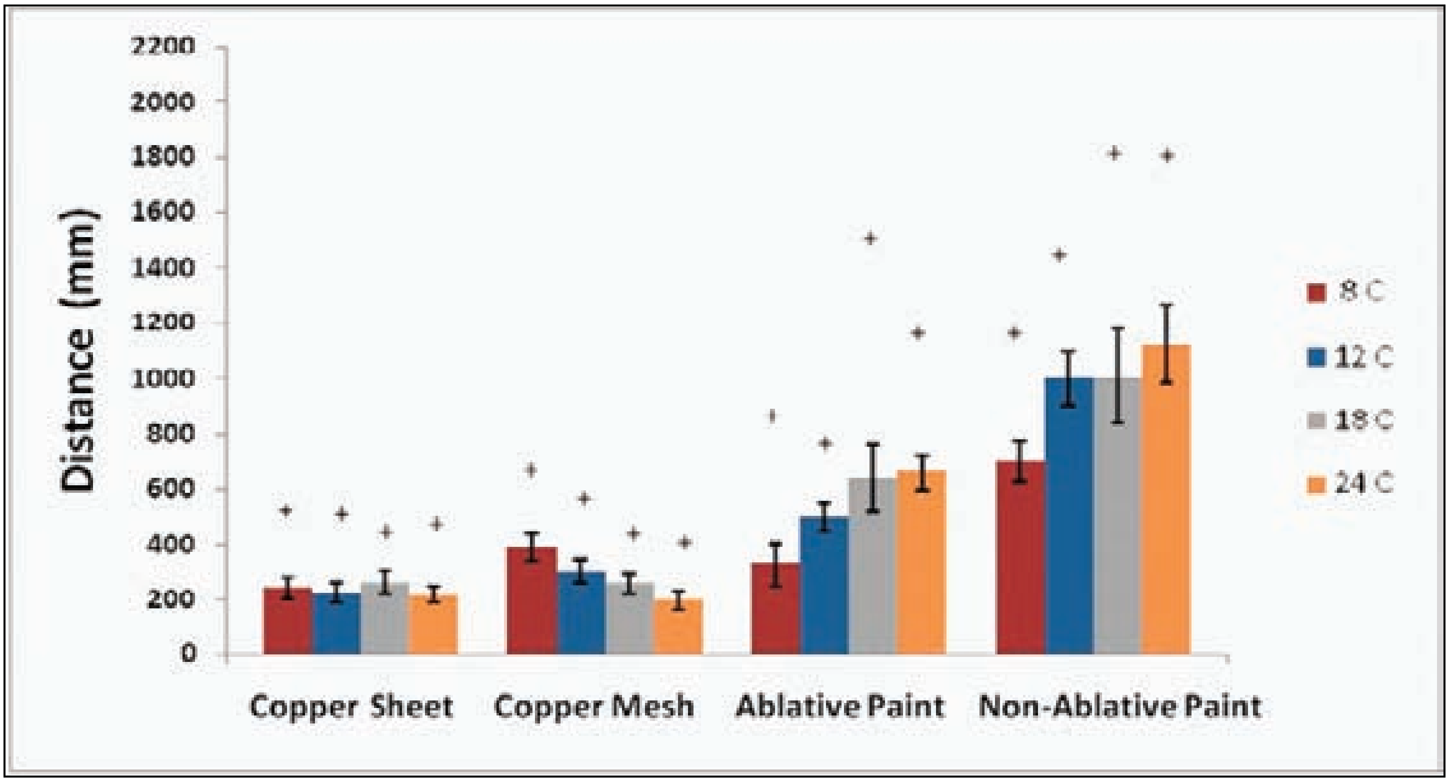

Figure 1: Average and maximum crawling distance of the New Zealand mudsnail on four copper-based substrates at various water temperatures. Averages are shown with standard error bars; + indicates the maximum distance traveled by any single snail within a treatment group.

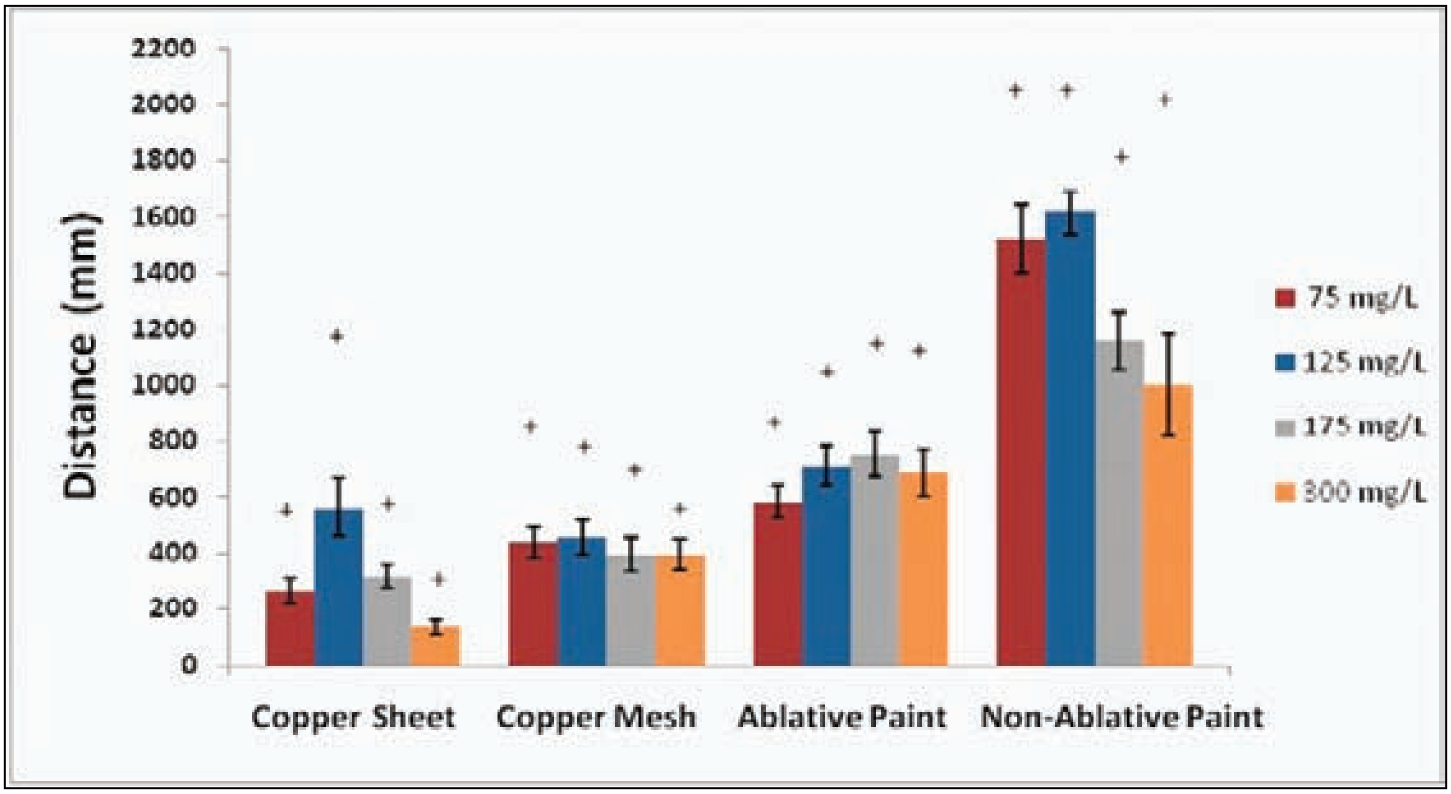

Figure 2: Average and maximum crawling distance of the New Zealand mudsnail on four copper-based substrates at various water hardness levels. Experiments were conducted at 18° C. Averages are shown with standard error bars; + indicates the maximum distance traveled by a single snail within each treatment group.

such as copper sheeting or marine anti-fouling paints. Copper-based materials are commonly used to control mollusk colonization on boat hulls and other submerged structures, so there is some possibility that they could also be used in this application. To test this hypothesis, Dr. Christopher Myrick and Sarah Conlin conducted a pilot study in 2007-2008, in which they exposed mudsnails to several types of copper-based materials. When compared to movements on bare PVC control surfaces, Myrick and Conlin found that the mudsnails' crawling distance was up to 7 times less on the copper surfaces, suggesting that these materials could indeed function as a barrier to mudsnails.

Over the last several years, some at-risk hatcheries have installed these copper materials in their effluent pipes, and while in some situations they were successful, in others they were not. There could be several reasons for this difference in effectiveness, perhaps most notably—differences in the physical and chemical characteristics of each hatchery's water supply.

It is well known that copper toxicity (and perhaps barrier efficiency) is affected by several variables including water temperature, water hardness, pH, and organic carbon concentration. The purpose of my current research is to determine the conditions under which copper-based materials function best as barriers to New Zealand mudsnails. Below I describe the findings of the first two phases of this project, in which we attempt to determine how water temperature and water hardness affected the mudsnails' response to potential copper barrier materials.

To address these questions, we conducted two separate experiments to test the barrier efficiency of the following four copper-based compounds: copper sheeting (99.9% pure), copper mesh (99.0% pure), ablative anti-fouling paint (25% cuprous thiocyanate as the active ingredient), and non-ablative anti-fouling paint (39% cuprous oxide as the active ingredient). All experiments were conducted at the Colorado State University Foothills Fisheries Laboratory.

For the water temperature experiment, mudsnails collected from Boulder Creek (Boulder, CO) were acclimated to 8, 12, 18, or 24°C for a period of two weeks before the initiation of the experiment. This temperature range was chosen to cover most of the mudsnail's temperature tolerance range and the range of temperatures likely to be discharged from a hatchery. For the water hardness experiments, we acclimated the mudsnails to one of four hardness levels (75, 125, 175, or 300 mg/L as $CaCO_3$) for a period of two weeks at 18° C. Following the acclimation period, we conducted experiments in circular PVC arenas, in which we covered one-half of the surface with a copper substrate and left the other half bare to serve as a control. At the beginning of a trial, a single mudsnail was placed in the center of the arena, and its movements were recorded for a two hour period. We later analyzed and compared movements on each the copper surface types.

After analyzing the data from these two experiments, we found that crawling distances were reduced on the copper sheet and mesh in both experiments (Figures 1 and 2). The non-ablative paint did not seem to limit the snails' movements in either experiment, which strongly suggests that substance would not be an effective barrier. We also determined that water temperature did not have a strong effect on the barrier ability of the four copper-based materials, although we did notice an increase in movement with increased temperatures (Figure 1). This observation was expected considering that the metabolic and activity rates of most cold-blooded organisms increase with temperature. Finally, water hardness did affect mudsnail movements across the copper surfaces, with crawling distance being the greatest in the 125 mg/L water hardness group (Figure 2).

Conclusions and Future Work

In both experiments, copper sheet and copper mesh consistently reduced the crawling distance and velocity of the mudsnails, suggesting that these materials have the ability to function as effective mudsnail barriers across a broad range of temperatures and water hardness levels. In contrast, the non-ablative anti-fouling paint did not appear to limit the mudsnails' movement under any of the experimental conditions. Upon considering the amount of copper in each of these materials, it appears that in order for a copper-based substrate to function as an effective barrier, it must contain a high percentage of copper. Furthermore, the maximum crawling distances that we observed in these experiments suggest that barriers must be at least 1.5 meters in length to stop 100% of the mudsnails. This last point is very important, because it is crucial to ensure that not a single mudsnail gets into a hatchery since the mudsnails reproduce asexually (i.e., it only takes one snail to start an entirely new population).

In 2010 we will continue to evaluate the performance of these copper-based compounds by testing each of them in a variety of conditions. We are currently evaluating barrier efficiency across a range of pH values. We will also determine how water velocity and the buildup of organic biofouling affect the mudsnails' response to these materials. Finally, to reduce the negative effects of copper on non-target species, we will evaluate the amount of copper that is leached from the materials. By doing so, we can determine the optimal barrier length that will block mudsnails, while also preventing unnecessary harmful effects to nearby aquatic communities.

High-Resolution Soil Moisture Retrieval in the Platte River Watersheds

by Chengmin Hsu, Ph.D. Candidate, Civil Engineering, University of Colorado Denver
Faculty Sponsor: Lynn E. Johnson

Research Question and Objective

Hydrological and other applications require soil moisture data at high spatial and temporal scales. Of the various methods to obtain soil moisture data, satellites hold promise of providing data at the appropriate scales. Currently, there are only two sources of operational global soil moisture data from satellites: (1) Advanced Microwave Scanning Radiometer (AMSR-E) aboard NASA's Aqua satellite, and (2) the Soil Moisture and Ocean Salinity (SMOS) satellite operated by the European Space Agency.

However, neither is a high-resolution product. The AMSR-E surface soil moisture product has a 25-km resolution, whereas SMOS can create only 50-km resolution products. Motivated by the urgent need for high-resolution soil moisture data, the purpose of this research is to develop an algorithm for disaggregating the 25-km AMSR-E daily soil moisture to a 250-m resolution product.

Study Site

The study site encompasses areas within the South and North Platte River watersheds and the Republican River watershed (Figure 1). The total study area is approximately 45,000 square kilometers. Most of the area is composed of open grassland and agriculture areas.

Data

Data used include: (1) X band (centered at 10.7 GHz) derived soil moisture from the AMSR-E sensor, (2) Moderate Resolution Imaging Spectroradiometer (MODIS) data, (3) data from the Soil Survey Geographic (SSURGO) database, (4) station data from the NRCS Soil Climate Analysis Network (SCAN), (5) wind speed measurements, (6) in-situ soil moisture data collected from the Automated Weather Data Network (AWDN) of the High Plains Regional Climate Center (HPRCC), and (7) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery collected over parts of Weld and Larimer Counties in Colorado.

The MODIS data used are version 5 MODIS/Terra and MODIS/Aqua 1-km resolution daily surface temperatures and MODIS/Terra 250-m resolution 16-day Enhanced Vegetation Index (EVI). The observations from the 16-day EVI product were cloud free and were used to generate fractional vegetation cover (Figure 3). Seven MODIS Version 5 surface temperature images with the least amount of cloud cover were acquired (July 13, 19, 20, 30, 31 and August 1 and 20, 2008). The ASTER image was captured on August 19, 2008. Land surface temperature was estimated from 90-m resolution L1B thermal radiances using the emissivity normalization method implemented in ENVI (ENvironment for Visualizing Images image processing software.

Disaggregation Algorithm

The soil moisture downscaling algorithm is composed of three sequential stages:

Stage 1: Downscaling of a 25-km resolution AMSR-E soil moisture to a 5-km resolution product. In this stage the basic concept is that the evaporation rate of the sub-pixel at 5-km resolution should be higher than the average evaporation of the pixel at 25-km resolution if the soil temperature of the sub-pixel is greater than that of theAMSR-E pixel. Thus, soil moisture of that sub-pixel will be drier than that in the 25-km resolution pixel.

Stage 2: Downscaling of 5-km resolution soil moisture to 1-km resolution soil moisture. In the second stage, the Percent Clay from SSURGO data and the

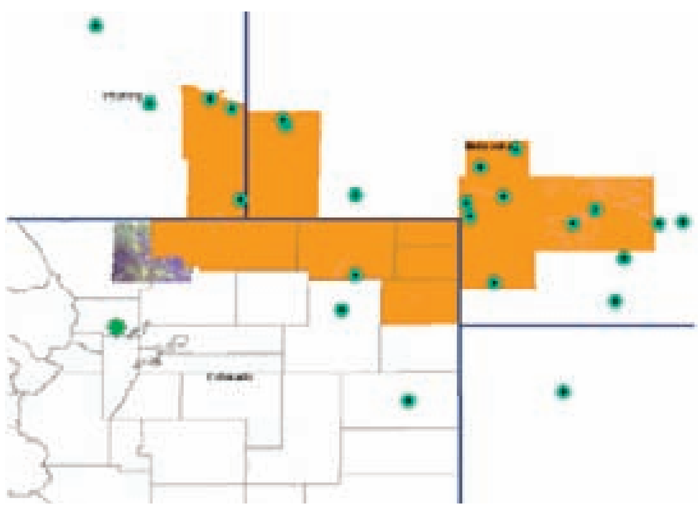

Figure 1: The study site (in orange) is located across Colorado, Nebraska and Wyoming, comprising the areas within the North and South Platte River Basin and the Republican River Basin. The malachite green points are Automated Weather Data Network (AWDN) stations from the High Plains Regional Climate Center (HPRCC).

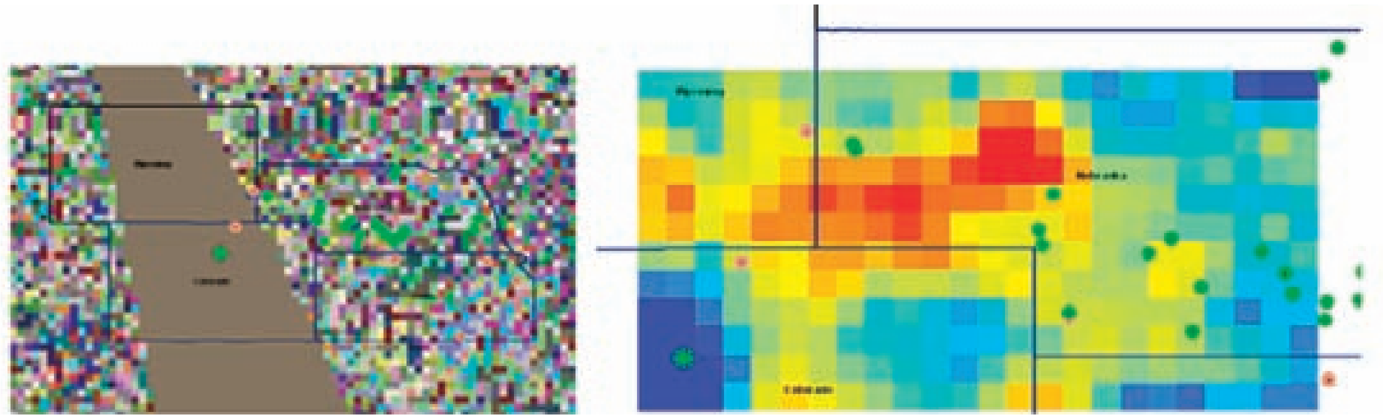

Figure 2: The graph on the left is the AMSR-E soil moisture imagery on July 20, 2008. It shows that a large area without data occupies the left edge of the study site. The graph on the right is the magnified interpolated soil moisture data, seen after using Krigirg interpolation method.

fractional vegetation cover derived from EVI are used for downscaling. This operation's purpose is to account for the lower soil moisture sensitivity of the MODIS surface temperature and the poor capability of AMSR-E to differentiate soil and vegetation signals.

Stage 3: Downscaling of 1-km resolution soil moisture to a 250-m product. The method applied in this stage is similar to that in Stage 1 but uses ASTER derived surface temperature and Normalized Difference Vegetation Index (NDVI).

The equations below represent the philosophy used for the first stage of downscaling AMSR-E soil moisture using MODIS data. Notice that all equations are also appropriate for disaggregation using ASTER data in Stage 3. This brings together soil properties and the philosophy mentioned above. The downscaling relationship for the first stage can be represented by:

with SMD as the MODIS-derived soil evaporative efficiency estimated based on the difference of soil

$$SM_{MODIS,\ 5km} = SM_{AMSR\text{-}E,\ 25km} \boxtimes \theta c \boxtimes SMD_{MODIS,5km}$$

temperatures between the 5-km resolution and its average within the AMSR-E pixel. The equation also integrates the lab findings of Komatsu (2003) by adding a downscaling coefficient, θc. θc is a semi-empirical parameter that depends on soil properties and boundary conditions of soil layers. In this research, the data extracted from the SSURGO database was used. SMD is assumed to be linear and can be defined as:

$$SMD_{MODIS,\ 5km} = \frac{T_{MODIS,\ 25km} - T_{MODIS,\ 5km}}{T_{MODIS,\ 25km} - T_{min,\ 1km}}$$

Here, $T_{MODIS,\ 5km}$ is the soil temperature at the 5-km resolution. It is derived by using MODIS derived EVI and surface temperature aggregated at the 5-km resolution. $T_{MODIS,\ 25km}$ is its average within the AMSR-E pixel, and $T_{min,\ 1km}$ is the minimum MODIS derived soil temperature at the 1-km resolution. The assumption for the minimum soil temperature is that it is equal to the minimum MODIS surface temperature. The soil temperature can be estimated by using a simple equation developed by Merlin et al. (2008). The equation can be defined as:

$$TMODIS,\ 5km = \frac{T_{surf,\ MODIS,\ 5km} - f_{v,\ MODIS,\ 5km} * T_{v,\ 5km}}{1 - f_{v,\ MODIS,\ 5km}}$$

Table 1: 5-km Resolution Soil Moisture Downscaling Validation

	Nunn Station		Johnson Farm Station	
Date	Observed Soil Moisture (%) at 5-cm depth	Estimated Soil Moisture (%) at 5-cm Depth	Observed Soil Moisture (%) at 5-cm depth	Estimated Soil Moisture (%) at 5-cm Depth
7/13/2008	0.113	0.119	0.072	0.091
7/19/2008	0.101	0.109	0.197	0.094
7/20/2008	0.100	0.110	0.105	0.095
7/30/2008	0.108	0.096	0.252	0.101
7/31/2008	0.105	0.101	0.153	0.106
8/01/2008	0.101	0.101	0.107	0.093
8/20/2008	0.320	0.112	0.235	0.089

with $T_{surf,MODIS,5km}$ as the MODIS-derived surface temperature, $T_{v,5km}$ as the vegetation temperature, and $f_{v,MODIS,\,5km}$ as the fractional vegetation cover at the 5-km resolution. In this research, $T_{v,5km}$ was estimated to $T_{min,\,1km}$. fv can be estimated using EVI directly. The coefficient θc, is calculated using von Karman wind turbulence models and SSURGO soil database. Detailed steps are described in a paper published by Komatsu (2003).

In Stage 2, a variable produced by multiplying the percent clay of SSURGO and f_v was used for downscaling. The equation is represented by:

$$SM_{1km} = SM_{5km} + 0.025 * \frac{f_v * P_{clay,\,1km} - f_v * P_{clay,\,5km}}{f_v * P_{clay,\,5km}}$$

where "P_{clay}" is the percentage of clay extracted from SSURGO. The concept is that clayish soil can retain a large percentage of water, but it is not good for vegetation growth. The pixels that have high fractional vegetation cover and also a high percentage of clay must be wetter than the pixels that do not have them.

Results

The results of downscaling at the 5-km and 1-km resolutions are quite good in the dry phase, based on the comparison of observed and downscaled soil moisture (Table 1). One day's result of the downscaled 5-km resolution soil moisture is shown in Figure 4.

However, in wet phases, downscaling results do not reflect the true soil moisture. For example, the in-situ soil moisture data on August 20, 2008, for the Nunn station is 0.32, while the downscaled soil moisture data for that specific pixel shows it as only 0.112. Further examination of the original AMSR-E soil moisture data finds that soil moisture in that specific pixel is only 0.104. This indicates that the AMSR-E sensor cannot capture the true soil moisture variability in wet phases.

The 5-km soil moisture data of July 13, 2008, was further downscaled to the 1-km resolution using the method depicted in the second stage (Figure 5). The derived soil moisture for the pixel where the Nunn station is located is 0.113, which is exactly the same as the soil moisture observed at the station. This is an encouraging sign for the second stage of downscaling. The 1-km resolution soil moisture data of July 13, 2008, was also downscaled to the 250-m resolution. But because the downscaling was based on the only available ASTER data of August 19, 2008, large amounts of error can be expected. Therefore, validation has not yet been executed.

Conclusion

The developed downscaling algorithm seems satisfactory, based on the limited analyses conducted. The problem of AMSR-E indicating soil moisture that is too dry compared to reality during the wet phase suggests that AMSR-E data are not adequate for downscaling. However, this deficiency can perhaps be overcome by integrating SMOS data, because

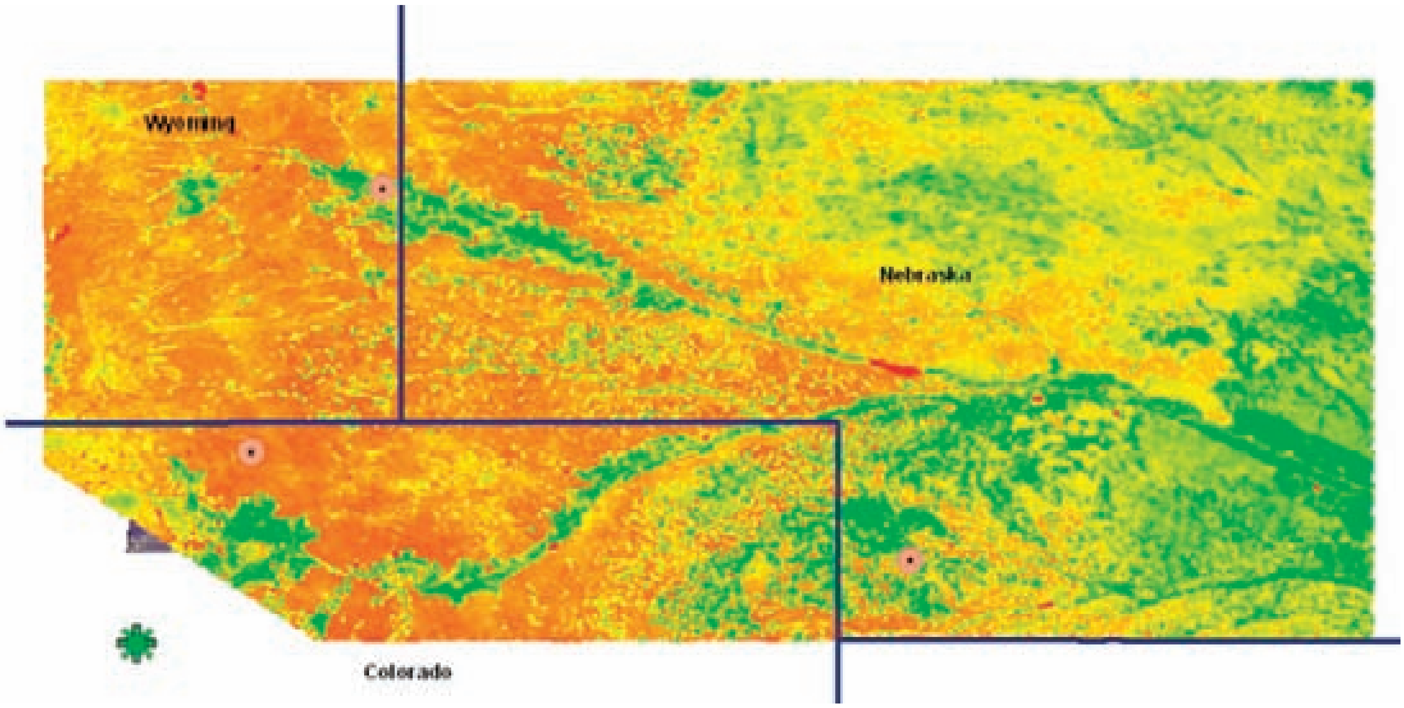

Figure 3: The EVI of the period between July 27, 2008 and August 11, 2008 represents the factional vegetation cover of that period of time. The greener the color is, the higher the percentage of vegetation cover.

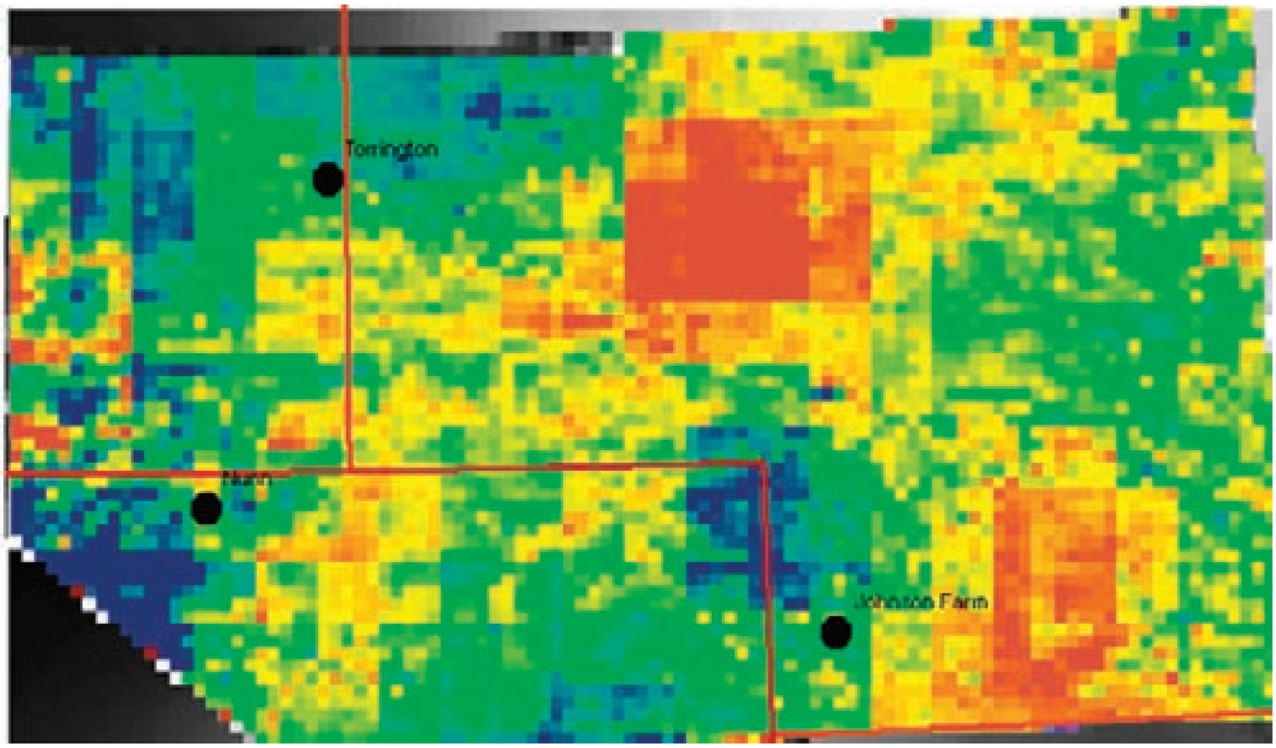

Figure 4: The downscaled 5-km resolution soil moisture data on August 1, 2008.

the SMOS satellite equips sensors that can detect L-band energy emitted from the Earth. This will reduce the problem of vegetation canopy forming an opaque layer that hinders the signal from the soil as detected by AMSR-E sensor. Another way to improve this downscaling model is to make adjustments to the second stage. In this research, a constant value of 0.025 was used. In fact, it can be shaped as a parameter integrating the dynamics of precipitation. Improvement of the second phase of the downscaling algorithm deserves additional attention.

References

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Merlin, O., Walker, J. P., Chehbouni, A., & Kerr, Y. (2008). Toward deterministic downscaling of SMOS soil moisture using MODIS derived soil evaporative efficiency. *Remote Sensing of Environment , 112*, 3935-3946.

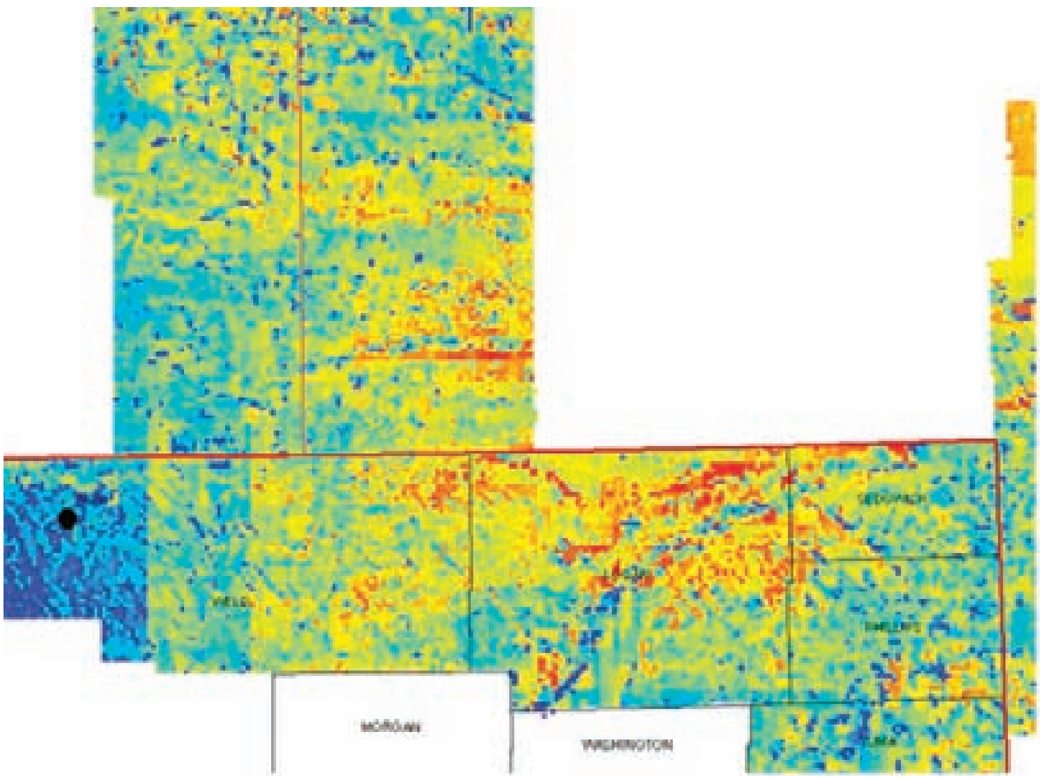

Figure 5: The downscaled 1-km resolution soil moisture data of July 13, 2008. The black spot in the left corner is the Nunn station of the Soil Climate Analysis Network.

Potential Changes in Groundwater Acquisition by Native Phreatophytes in Response to Climate Change

by Julie Kray, MS Candidate, Forest, Rangeland, and Watershed Stewardship, Colorado State University
Faculty Sponsor: David J. Cooper

Introduction

Across the arid intermountain regions of western North America, precipitation is limited, yet much of the natural landscape supports plant communities. Some plants in these near-desert environments are able to thrive in spite of drier surface soil conditions by developing roots deep enough to tap into a more stable water source: groundwater.

Phreatophytes, or plants that can use groundwater, cover vast areas of our western landscape. Native plant communities dominated by phreatophytes are ecologically valuable for soil stabilization, wildlife habitat, and forage for domestic livestock. However, phreatophyte communities can substantially influence total water outflow on a basin scale through groundwater evapotranspiration (ET). Groundwater resources in the West are essential to human populations, sustaining regional agriculture and municipalities by providing a reliable water supply in arid regions with unpredictable climates. Accurate estimates of groundwater use by native phreatophyte communities are therefore critical to managing groundwater in arid intermountain basins. Additionally, we need to understand how phreatophyte water use may change in response to climate variability. Changes in the timing and amount of precipitation are likely throughout western North America, and warming temperatures are expected to increase ET by native plant communities and agricultural crops. It is unknown whether different species of phreatophytes will vary in their sensitivity to altered precipitation patterns, and how these differences will affect groundwater use at the plant community scale. Changes in plant community composition and water acquisition patterns may in turn influence water availability for agriculture and other human uses.

Study Area and Questions

This study took place in the San Luis Valley (SLV), a high-elevation intermountain basin located in southern Colorado. The SLV is the most arid region in Colorado, receiving only 180-250 mm of precipitation annually; yet, a shallow unconfined aquifer recharged by snowmelt runoff from the surrounding mountains supports over 600,000 acres of irrigated agriculture, substantial water transfers out of the valley, and more than 1.2 million acres of native rangeland plant communities (Figure 1). The dominant native plant species in the SLV are phreatophytes, and evapotranspiration by phreatophyte communities accounts for nearly one-third of the total annual groundwater consumption.

The four most common native plant species in the SLV are the shrubs greasewood (*Sarcobatus vermiculatus*) and rabbitbrush (*Ericameria nauseosa*), and the grasses alkali sacaton (*Sporobolus airoides*) and saltgrass (*Distichlis spicata*). These four species are generally regarded as facultative phreatophytes, able to acquire both groundwater and soil water recharged by precipitation.

Between 50-70% of the total annual precipitation in the SLV occurs from mid-July through September, through rain events generated by the North American monsoon system. Some SLV phreatophytes may be adapted to use predictable pulses of late summer monsoon precipitation to reduce or supplement their groundwater consumption. However, current precipitation patterns are likely to vary with climate change. Existing climate model projections for the SLV are inconclusive, with some suggesting an increase and others projecting a decrease in monsoon rainfall. The goal of our study was to understand the interactions between precipitation and plant water use patterns for both wetter and drier futures.

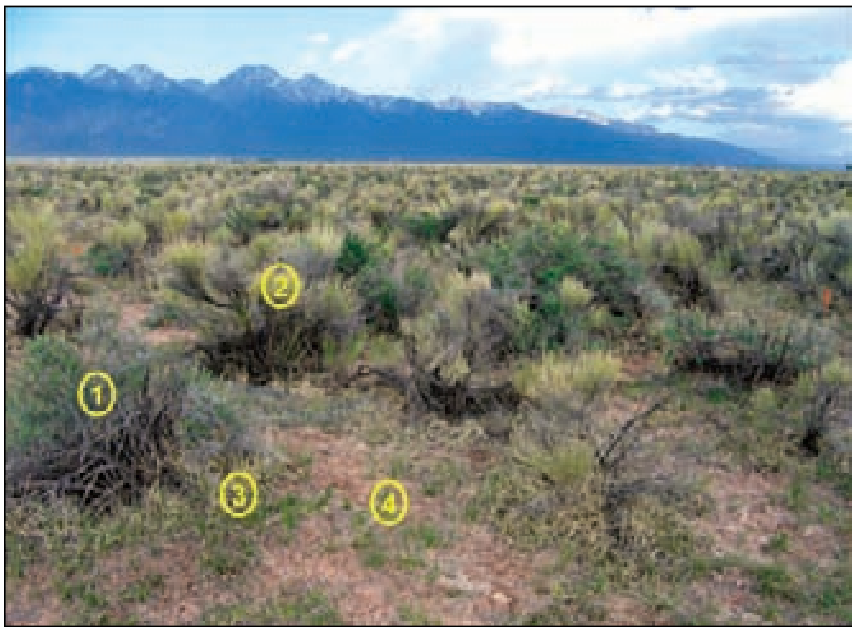

Figure 1: Native phreatophyte communities occupy over 1.2 million acres in the San Luis Valley, Colorado. These include the shrubs Sarcobatus vermiculatus (1) and Ericameria nauseosa (2), and the grasses Sporobolus airoides (3) and Distichlis spicata (4). (Courtesy of Julie Kray)

Figure 2: The rainfall manipulation experiment compared control plots receiving ambient rainfall with one of two treatments: (a) decreased rainfall using rain-out shelters and (b) increased rainfall through addition of rain captured by shelter roofs. (Courtesy of Julie Kray)

Our study addressed the following questions:

- How do water acquisition patterns (groundwater versus rain-recharged soil water) vary among native phreatophyte species under the current climate? Are some species more dependent on groundwater than others?
- How will phreatophyte water acquisition patterns respond to a change in growing season precipitation? Will increased monsoon rainfall lead to increased plant use of soil water and reduced use of groundwater?
- Conversely, if growing season precipitation decreases, will plants become more reliant on groundwater?

Methods

We conducted a rainfall manipulation experiment at our long-term study site near Crestone, Colorado. The experiment compared plants in control plots receiving natural rainfall with plants receiving one of two treatments: (1) decreased rainfall using rain out shelters ("rain out"), and (2) increased rainfall by applying rain captured from shelter roofs ("rain add") (Figure 2).

To identify plant water sources, we compared the stable oxygen isotope signature of water taken up by each plant species with soil water from 0-15 cm and 15-30 cm depths, and groundwater. The isotopic signature (the ratio of ^{18}O to ^{16}O, or $\delta^{18}O$ value) of water in plant xylem tissue reflects the signature of the water source(s) a plant acquires. In the SLV, groundwater carries the isotopic signature of winter precipitation and varies little over time. Soil water picks up the signature of rain immediately following an event, but as rainwater evaporates, heavier isotopes are concentrated in the soil, and the signature of soil water becomes more enriched. We used these naturally occurring differences in source water isotopic signatures to determine the relative contributions of soil water and groundwater to total plant water uptake.

Results

Precipitation during the 2008 growing season followed a typical pattern, with minimal rainfall in June and early July (Figure 3). The majority of the rainfall occurred in August during the peak of the monsoon season, including one large event of 42 mm on August 6. In the top 15 cm of the soil profile, our rainfall manipulation treatments effectively altered mean volumetric soil water content. Pre-treatment soil water content was similar in all plots (7-8%) (Figure 3). After treatments took effect in early August, mean soil water content increased to 15% in control plots and 18% in rain addition plots, but was limited to 7% in rain out plots. In the 15-30 cm soil layer, treatment effects were reduced, and soil water content in all plots was both higher and more stable than in the 0-15 cm layer throughout the growing season (Figure 3b). Water table depth increased during the growing season, dropping from 119 to 143 cm below the soil surface.

The isotopic signature of groundwater ($\delta^{18}O$ = -14.2 ‰) did not change over the growing season, while soil water $\delta^{18}O$ values in the upper 30 cm varied from -9.9 ‰ to -2.3 ‰, as a function of rain inputs or evaporation. Comparing the mean stable oxygen isotope signatures of plant xylem water with these potential sources showed clear differences in water acquisition patterns between the four phreatophyte species. Both grasses (*Sporobolus* and *Distichlis*) used water only from the upper 30 cm of the soil profile and accessed little or no groundwater. Grasses that received rain (control and rain add treatments) acquired water from both sampled soil layers, while grasses in rain out plots relied heavily on soil water in the 15-30 cm layer.

The two shrubs (*Sarcobatus* and *Ericameria*) had different water acquisition strategies. Early in the growing season, *Sarcobatus* used primarily groundwater.

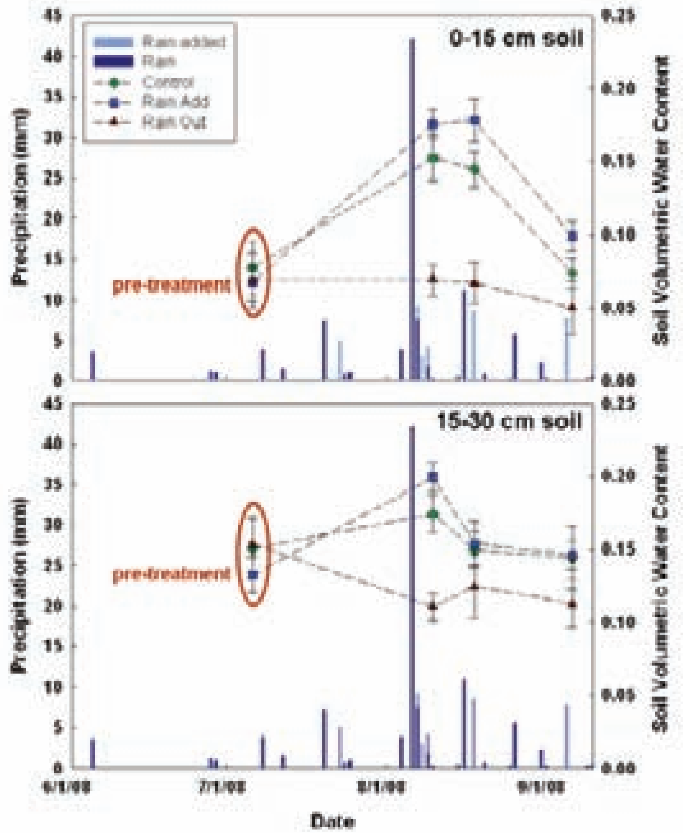

Figure 3a & b: This graphic illustrates growing season precipitation in 2008 and comparison of treatment effects on mean volumetric soil water content in: (a) the 0-15 cm soil layer and (b) the 15-30 cm soil layer.

However, as monsoon rain events recharged the upper 30 cm of the soil profile, *Sarcobatus* responded by increasing its uptake of water from this source. This pattern suggested that while *Sarcobatus* may be able to persist using groundwater exclusively, it also responds rapidly to acquire precipitation inputs to surface soil. In contrast, *Ericameria* primarily acquired groundwater throughout the growing season, including periods when soil water was abundant. *Ericameria* plants did incorporate some surface soil water in plots that received rain, though much less than *Sarcobatus*. Of the two shrubs, *Ericameria* relied more heavily on groundwater and was relatively insensitive to precipitation inputs in the surface soil.

Implications and Future Research Directions

Our results indicate that distinct differences occur in the water acquisition patterns of four common native phreatophytes in the SLV. These phreatophytes will vary in their sensitivity to changes in soil water availability, which may affect basin-scale groundwater use by native plant communities over time. An increase in rainfall may benefit both grass species and *Sarcobatus*, as these plants are either partly or entirely dependent on rain-recharged surface soil water. However, it does not appear that a moderate increase in rainfall will dramatically change current plant water acquisition strategies or greatly alter plant community composition and groundwater ET. Conversely, a decrease in rainfall will likely increase water stress in grasses, which could lead to a reduction in grass cover and a plant community dominated by shrubs over time. Because both shrub species use groundwater, a slight increase in both abundance and individual plant use of groundwater could result in a large increase in groundwater ET on a watershed scale. This may further alter the balance of groundwater available to sustain regional agriculture and other human uses in the SLV.

Future research should focus on quantifying the total annual groundwater use by each phreatophyte species and understanding how variations in soil water availability affect plant production. Results from our work and future research on phreatophytes in the SLV will be incorporated into the Rio Grande Decision Support System (RGDSS) groundwater model that is used to manage the SLV aquifer.

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Relative Costs of New Water Supply Options for Front Range Cities

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Introduction

Ensuring an adequate water supply for the growing municipal population of Colorado's Front Range is an ongoing challenge. The Statewide Water Supply Initiative in 2004 (SWSI) projects that Colorado's population will grow 65 percent between 2000 and 2030, resulting in an increasing municipal and industrial (M&I) water demand of 630,000 acre-feet. The majority of this demand (507,700 acre-feet) will occur along the Front Range in the South Platte and Arkansas River Basins.

As each city charts its own course in seeking to eliminate a potential water supply gap, water utilities normally explore three general (and non-exclusive) strategies:

(1) increase water supplies through new projects (and/or the rehabilitation or expansion of existing projects);
(2) purchase and transfer water rights from the agricultural sector; and/or
(3) reduce demand through conservation and efficiency projects.

In this research project, we are reviewing the efforts of each of the three types on Colorado's Front Range, comparing the approaches based on one simple criterion: average cost per acre-foot ($/AF). In this comparison, we are not simply assuming that the best choice is always the lowest-cost option. Determining which options are "best" is a complex matter, as it entails an assessment of highly case-specific opportunities, constraints, trade-offs, and risks, all overlain by value choices. Nonetheless, $/AF provides an obvious starting point for making comparisons among broad categories of options.

In the paragraphs and tables that follow, we present our preliminary compilation of cost data, focused primarily on the upfront capital expenditures associated with the three previously mentioned categories of supply options. Over the next year (in phase two of research), we plan to supplement this data on capital expenditures with an assessment of ongoing, operating expenses, especially as they relate to energy costs. Looking forward, this figures to be an increasingly important consideration for Front Range water utilities, as the era of supply projects powered by gravity and delivering clean mountain snowmelt is quickly giving way to projects requiring extensive pumping and advanced water treatment.

Data and Methodology

Case studies and data sources varied widely for our three categories of supply options. For new projects, we selected prominent options spread across the northern, central, and southern Front Range for which detailed public documents exist. This yielded 28 different water development options associated with three main efforts: the Northern Integrated Supply Project (NISP) with 6 variations, the South Metro Water Supply Authority (SMWSA) Master Plan with 15 variations, and the Southern Delivery System (SDS) with 7 variations. For water transfers, we relied on information compiled from a privately published newsletter, the *Water Strategist*, focusing on agriculture-to-urban transfers from 1990 to 2009 of at least 100 acre-feet or 100 shares in the case of the Colorado-Big Thompson (CBT) project. This yielded 121 transactions, of which 113 involved CBT shares. Finally, for water conservation, we relied on data drawn primarily from reports by the Conservation and Efficiency Technical Roundtable (established as part of Phase 2 of the SWSI exercise in 2007), an analysis by Denver Water (*Solutions: Saving Water for the Future,* 2009), and a yet unpublished analysis of Water Conservation Implementation Plans prepared by the Great Western Institute for the Colorado Water Conservation Board (CWCB). We chose these reports because they are recent, they provide credible sources, and they include a mix of both actual and theoretical (projected) savings.

We found it challenging in many ways to compile and present data in a way that supports meaningful comparisons among the three supply options. The simplicity of our $/AF criterion hides many challenges, assumptions and ambiguities. For example, while the numerator in our $/AF metric has been standardized in 2010 dollars, it is worth considering that our dataset has options with widely variable temporal qualities. The water projects reviewed are primarily still in the planning stage; the transfers reviewed have all been consummated (often several years ago); and the conservation programs typically describe programs that are highly incremental and multi-faceted in application (e.g., ongoing appliance retrofit programs), as opposed to the big, one-time expenditures associated with bringing a new project online or completing a water rights purchase. More challenging are issues surrounding the denominator in the $/AF metric, as not every acre-foot is created equal in terms of reliability, quality, location, and so on. Limiting our focus to the reliability criterion only partially simplified our task, as procedures for defining and measuring reliability vary across our three strategy types, and between options within each category. In this report, every effort has been made to provide data that are accurate and fair, but complete standardization of results is impractical, and comparisons should be made carefully.

Findings

New Projects

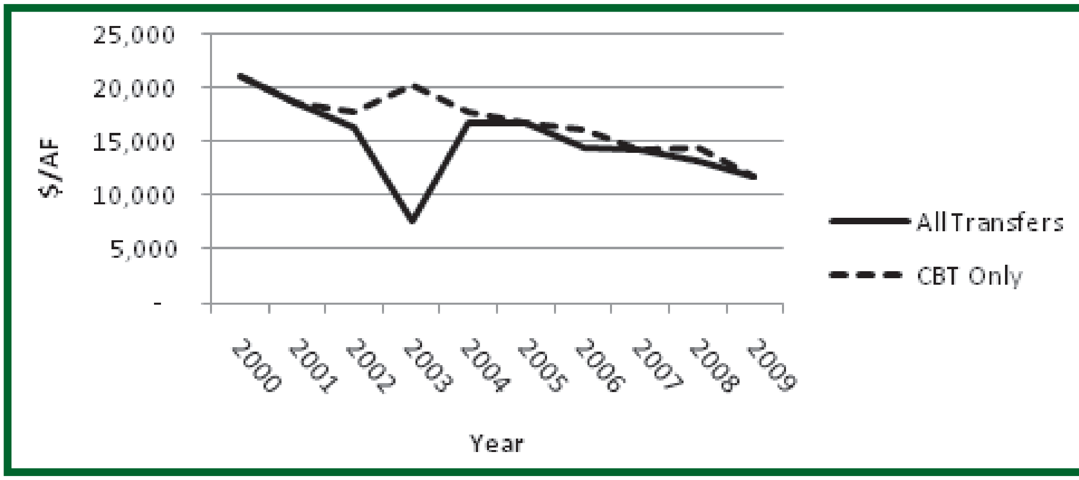
Table 1 provides a summary of firm-yields, total costs (converted to 2010 dollars), and unit costs, $/AF, for the 28 new project options grouped into four sub-categories: (1) NISP (6 options); (2) SMWSA: S. Platte (9 options); (3) SMWSA: Arkansas (6 options); and (4) SDS (7 options).

For the 28 projects reviewed, the average cost of a new acre-foot of firm yield is $20,764. This figure changes slightly (to $20,482) when calculated as a weighted average (total costs/total yields). These values are consistent with numbers commonly quoted in the water management community. However, a significant reduction in cost estimates can be achieved by taking the least-cost option in each of the four sub-groupings on the grounds that, in practice, only one option within each grouping (maximum) is likely to ever be pursued, although there are no guarantees that the least-cost options would be selected. Using that approach, average costs are reduced to $15,932, or $16,282 if using a weighted average. In this report, for purposes of comparison to the other categories of new supply options, the value $16,200 is utilized.

Table 1. Potential Costs of New Water Supply Projects Serving the Front Range.

Project: Option	Firm Yield (acre-feet/year)	Cost (2010 dollars)	Average Cost ($/AF)
NISP (Northern Integrated Supply Project)			
Average of Alternatives 3, 4.1a, 4.1b, 4.2, Proposed 1, Proposed 2	40,000	$544,038,650	$13,601
Lowest Cost Option: Proposed 1	40,000	$458,900,100	$11,473
SMWSA (South Metro Water Supply Authority Master Plan): South Platte River Options			
Average of alternatives based on Split, Single or Shared Pipelines, with diversions at Greeley, Sterling or Weldona	47,800	$942,776,967	$19,723
Lowest Cost Option: Shared-Greeley	47,800	$789,856,800	$16,524
SMWSA (South Metro Water Supply Authority Master Plan): Arkansas River Options			
Average of alternatives based on Split, Single or Shared Pipelines, with diversions at Avondale or La Junta	42,783	$1,023,041,150	$23,912
Lowest Cost Option: Shared-Avondale	47,800	$877,490,700	$18,358
SDD (Southern Delivery System)			
Average of Alternatives 1 through 7	55,257	$1,288,453,157	$23,317
Lowest Cost Option: Alternative 3	74,900	$1,301,211,600	$17,373
Averages			
Average (all 28 projects)	46,918	$960,951,557	$20,764
Weighted Average (all 28 projects) (total costs/total yields)			$20,482
Average of Lowest Cost Options (4 projects)	52,625	$856,864,800	$15,932
Weighted Average (4 projects) (total costs/total yields)			$16,282

Figure 1. *Cost trends in water transfers: 2000-2009 (2010 $/AF).*



Water Transfers

Results compiled from the review of water transfers are presented in Figure 1 and Table 2. The dataset contains information from each of the past ten years (2000-2009) as well as three points in the 1990s. This was done to help illuminate trends and averages.

Prices for water transfers have shifted over time. Prices jumped sharply to start the new millennium (to over $21,000/AF in 2000), but the rest of the decade featured a steady decline. The only interruption in this steady trend was in 2003, which saw a slight jump in CBT prices, but this rebound in price was modest and short-lived and was more than offset in our dataset by an unusually inexpensive and large non-CBT transfer. The average cost per acre-foot in the past 5 years (2005-2009) is $13,996; consequently, for purposes of comparison to the other categories of new supply options, the value $14,000 is utilized.

Water Conservation

The three studies consulted for water conservation data utilized very different approaches. The SWSI study reviewed a variety of municipal water conservation strategies that could be applied statewide, estimating a potential savings by 2030 of 286,900 to 458,600 acre-feet/year at an average cost of $11,098 (once converted to 2010

Table 2. Summary of Major Front Range Water Transfers.

Year	Number of Transactions	Total Yield (acre-feet/year)	Total Price (2010 dollars)	Unit Cost ($/acre-foot)
1990	12	2,857	$8,171,047	$2,860
1994	13	1,957	$6,315,488	$3,227
1999	21	2,699	$22,345,051	$8,278
2000	11	2,146	$45,242,631	$21,080
2001	3	932	$17,289,153	$18,557
2002	8	2,141	$34,803,342	$16,259
2003	12	8,882	$68,069,282	$7,664
2004	8	1,811	$30,409,665	$16,795
2005	6	1,289	$21,556,085	$16,727
2006	7	1,188	$17,249,732	$14,515
2007	5	940	$13,423,692	$14,279
2008	12	4,022	$52,709,074	$13,106
2009	3	378	$4,466,541	$11,816
Totals and Weighted Averages (total costs/total yields)				
Total	121	31,241	$342,050,782	$10,949
Sub-Total: 2005-2009	33	7,817	$109,405,124	$13,996

Table 3. Summary of data from 22 water conservation implementation plans.			
All Programs	**Total Cost (over planning horizon)**	**Total Water Savings (in acre-feet, over planning horizon)**	**Average Cost ($/AF)**
Total	$328,648,807	63,534	$5,173
Cities and Districts: Arapahoe County Water and Wastewater Authority, Aurora, Boulder, Brighton, Castle Pines North, Castle Rock, Centennial, Colorado Springs, Denver, East Larimer County, Evans, Fort Collins Loveland Water District, Firestone, Greeley, Left Hand Water District, Longmont, Fort Lupton, Northglenn, North Table Mountain, North Weld County, Parker Water and Sanitation District, and Windsor.			

dollars). However, by focusing solely on turf replacements (at the lowest rebate level), leak reductions, toilet rebates, washer rebates (at the lowest rebate level), and conservation-oriented pricing regimes, these data suggest it may be possible to achieve roughly 300,000 acre-feet/year of these savings at costs no higher than $7,000 per acre-feet.

Water supplies, like this canal that delivers Horsetooth Reservoir water to the Front Range, will need to grow to meet rising population demands.
Photo by Lindsey A. Knebel.

This number is consistent with the other two studies focused on planned and implemented Front Range conservation programs. The Denver Water study reports efforts already implemented in 2008 costing an average of $5,861 per acre-foot (in 2010 dollars), while the plans of 22 Front Range utilities covered by the data compiled by the Great Western Institute (for the CWCB) suggest a value of $5,173 per acre-foot. This is shown in Table 3. This value drops further, to $4,572 per acre-foot, if the major outliers (i.e., the 3 most and 3 least costly programs) are removed from the dataset. Given these considerations, we have chosen to use the value of $5,200 acre-feet as a fair estimate of the average cost of conservation on the Front Range.

Summary and Conclusions

Three major themes emerge from the compilation and comparison of cost data. First, cost data are extremely difficult to find. Given the magnitude of the dollars involved, and the fact that the money spent and the obligations incurred belong to the public, we found this to be both odd and troubling. Second, the values we have compiled are deficient in many ways, as they are not produced using standardized assumptions, and in most cases they are confined to upfront capital expenditures. By using the $/AF metric across all categories, we standardized the data to the extent possible; nonetheless, the numbers presented should be considered as generalizations. And third, despite our concerns about the availability and quality of information, the data are sufficient to indicate that water obtained via conservation is, by far, the cheapest option. To review, our estimates of representative costs (in $/AF) are as follows: new projects, $16,200; water transfers, $14,000; and conservation, $5,200.

This is a highly condensed version of the full Phase 1 report. That report can be viewed online at www.waterpolicy.info or by contacting the lead author at douglas.kenney@colorado.edu. This research was supported by a grant from the Colorado Water Institute.

The Costs and Benefits of Preventative Management for Zebra and Quagga Mussels

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Craig Bond, *Assistant Professor, Colorado State University*

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*) are invasive mollusks native to an area in the Ukraine and Russia near the Black and Caspian Seas. Introduced to the Great Lakes in the late 1980s, Dreissena mussels rapidly spread throughout the Mississippi River Basin and the eastern U.S. These mussels currently cost the nation an estimated $1 billion per year, mostly in damages and control costs associated with electric power plants and water supply facilities. Western waterways were believed to be free of Dreissena mussels until 2007 when Lake Mead in Nevada became the first water body west of the 100th Meridian to have a confirmed Dreissena population.

Until recently, many scientists believed that the Colorado environment was unsuitable for mussel invasion. Nevertheless, juvenile mussels (called veligers) were identified in Colorado waters in January of 2008, with Pueblo Reservoir, Grand Lake, Jumbo Lake, Lake Granby, Shadow Mountain Reservoir, Tarryall Reservoir, and Willow Creek Reservoir all testing positive in the past two years. The presence of mussels in Colorado waters is a major concern due to potentially severe economic and ecological damage. Adult mussels attach to all types of structures and form dense mats up to one foot thick. These mats can clog water pipes and damage hydrologic infrastructure. Dreissena also affect natural ecosystems through their feeding behavior; they are filter feeders and process up to one gallon of water per mussel per day, thus drastically altering the food web and negatively affecting fisheries and biodiversity. In response to these threats, the Colorado Division of Wildlife (CDOW) has implemented a mandatory boat inspection program that requires trailered boats to be inspected before launching in Colorado waterways.

This study builds a bioeconomic simulation model to predict the intertemporal and spatial spread of mussels in a case study water delivery and storage system, the Colorado-Big Thompson (C-BT) system. The objective of this analysis is to compare the costs of implementing the CDOW boat inspection program to the benefits of the program. For this analysis, program benefits are assumed equal to the expected reduction in control costs to water conveyance systems, hydropower generation stations, and municipal water treatment facilities (see Table 1 for a complete list of program benefits).

Table 1. Benefits of preventative management for zebra and quagga mussels.

Reduced costs to infrastructure	Possible costs to infrastructure include:
	Costs to hydropower facilities, water treatment facilities, dams, and pump plants
	Costs to manually clean pipelines, tunnels and canals in the Colorado-Big Thompson system
Reduced control costs to industrial users	Industrial users that could be affected include:
	Fossil-fuel fired power plants
	Any industry using raw water as an input to production
Reduced control costs to irrigators	Affected irrigators include:
	Farmers using sub-irrigation or overhead sprinkler irrigation
	Parks and golf courses using raw water
Reduced ecological damages	Possible ecological damages include:
	Food chain depletion
	Long term negative effects to fisheries
	Severe reduction in populations of native mussels
	Noxious weed growth and associated control costs
	Algal blooms and associated control costs
Reduced human and animal health concerns	Human and animal health concerns include:
	Accumulation of organic pollutants that are passed up through the food chain
	Foul tastes in drinking water and associated costs to mitigate this in drinking water supplies

Mussels in Colorado and the West

Western water systems are very different from those found in the East. The rapid spread of mussels through the eastern system was facilitated by connected and navigable waterways. Western water systems are less connected, making overland transport by recreational boats the most important vector of spread in the region. This gives western water managers and policy makers a unique opportunity to slow or prevent invasions by implementing policies, such as the CDOW program, that reduce the probability that mussels are introduced by recreational boats.

A Colorado Department of Wildlife officer decontaminates a boat hull for zebra or quagga mussels at Granby Reservoir. Photo by Elizabeth Brown.

Very few mussel studies have focused on western water systems and the effect of preventative management programs, and only a few studies have analyzed the potential threat, including the economic impacts, of invasive mussels at a water system level. This study considers the potential spread of mussels in a connected western water system and the corresponding economic damages of an invasion. The study highlights how the spatial layout of a system, the type of infrastructure and level of control costs associated with a system, and the risk of invasion within a system affect the benefits of preventative management.

Model

The developed model simulates an invasion in the C-BT system (Figure 1) over a 50-year time horizon based on the probability of colonization for each reservoir in each year. The probability of colonization is derived based on two factors: (1) the suitability of the receiving environment, and (2) the ability of the species to reach the receiving environment. Dreissena mussels can be transported to new environments on boats or via downstream flows. The number of invaders that reach a new location via these pathways determines propagule pressure, an important predictor of invasion success. Once veligers are introduced to a new environment, their ability to persist depends on the suitability of the new environment for survival. Thus, the probability that a water body will become colonized is

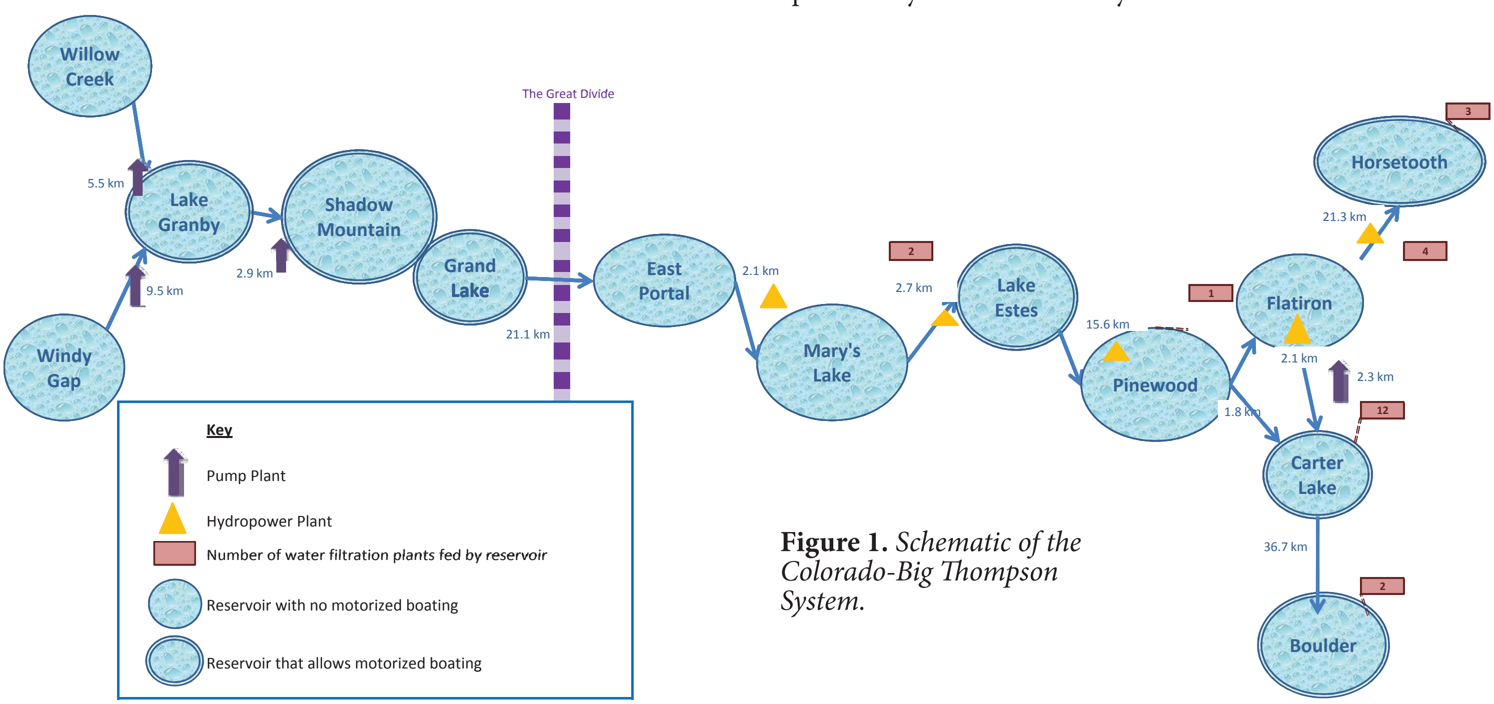


Figure 1. *Schematic of the Colorado-Big Thompson System.*

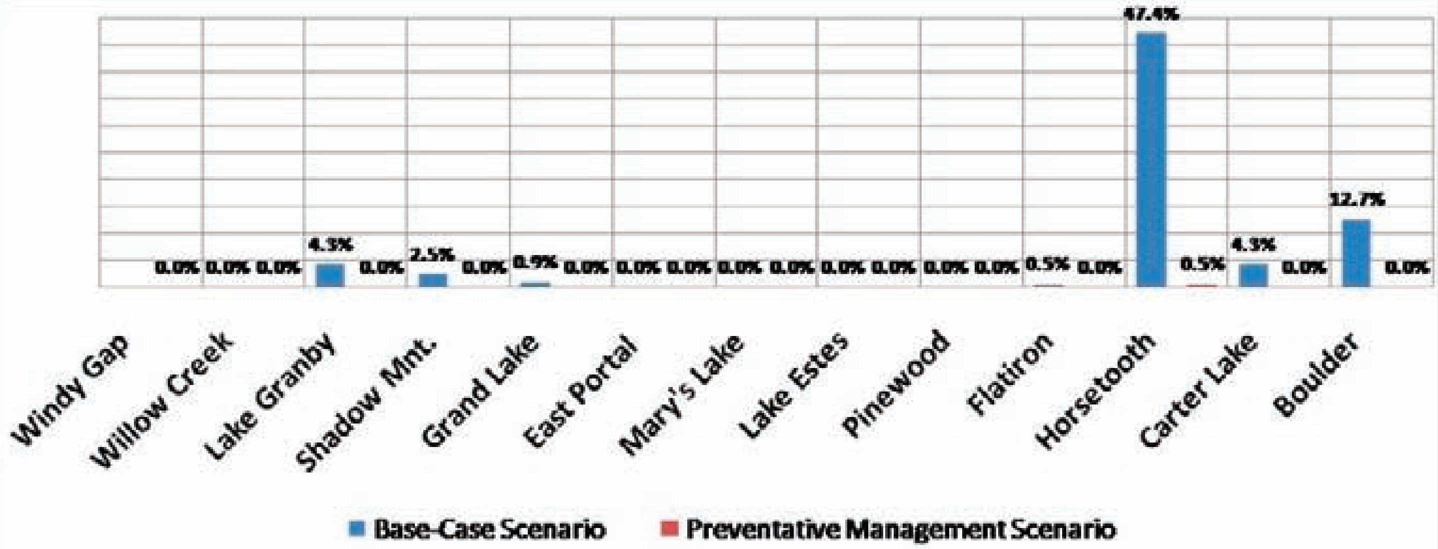


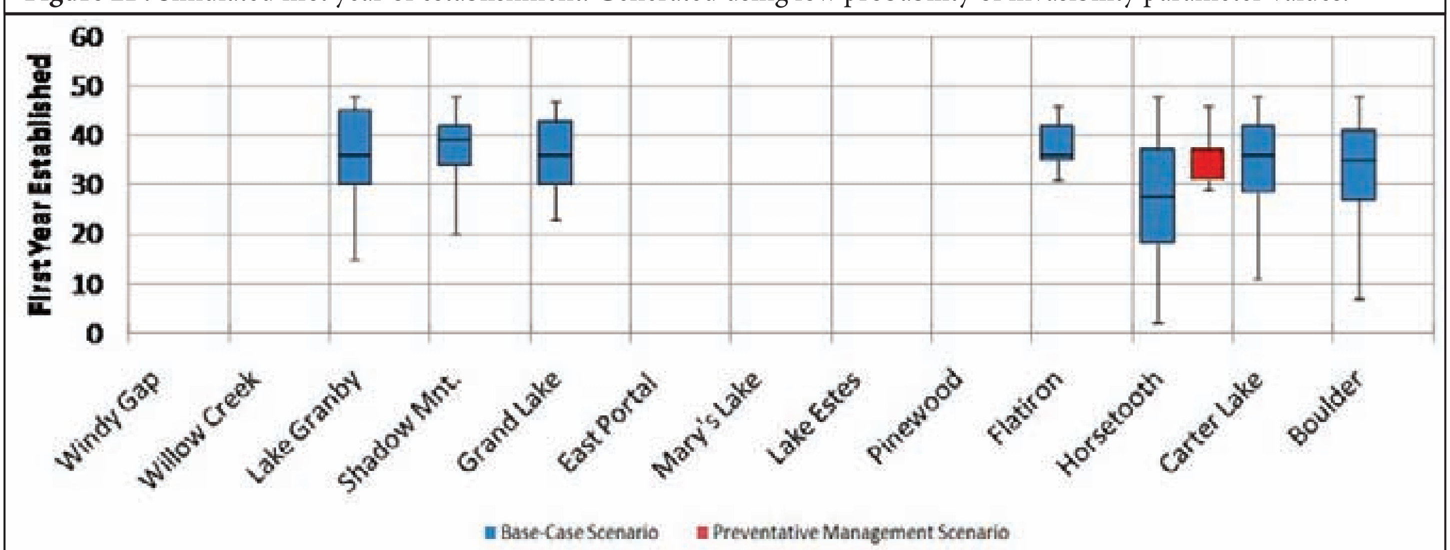
Figure 2A. Percent of runs that result in establishment. Generated using low probability of invasibility parameter values.

jointly determined by the probability that the water body is invasible (i.e., provides a suitable environment for mussels to survive and reproduce) and the probability that the water body becomes established (i.e., the probability that a sufficiently large number of propagules are introduced to the water body). Together, these probabilities determine the likelihood that a reservoir will become colonized by a given period in time.

Facilities and infrastructure below colonized reservoirs are assumed to incur mussel-related control costs. Cost schedules were developed for all of the water treatment plants, hydropower facilities, dams, and pump plants in the C-BT system and include yearly capital and variable costs associated with mussel mitigation. Other system infrastructure such as pipelines, tunnels, canals, and gauging stations are also likely to incur minor damage costs if mussels are present, but these costs are not included in the analysis. Unique control cost schedules are developed for each type of infrastructure and are based on published mussel control cost survey results and unpublished cost estimation studies. Control cost schedules only account for mussel-related costs incurred by facilities experiencing settling mussels, with facility costs assumed to be zero prior to settling. Boat inspection costs are based on budget data provided by CDOW.

The simulation model predicts spread and control costs in the system under a base case scenario if no preventative management takes place, then under an alternative scenario in which the boat inspection program is in place. The key difference between the two is the probability that reservoirs become established by propagules introduced by boats. By slowing the rate of invasion and catching and

Figure 2B. Simulated first year of establishment. Generated using low probability of invasibility parameter values.



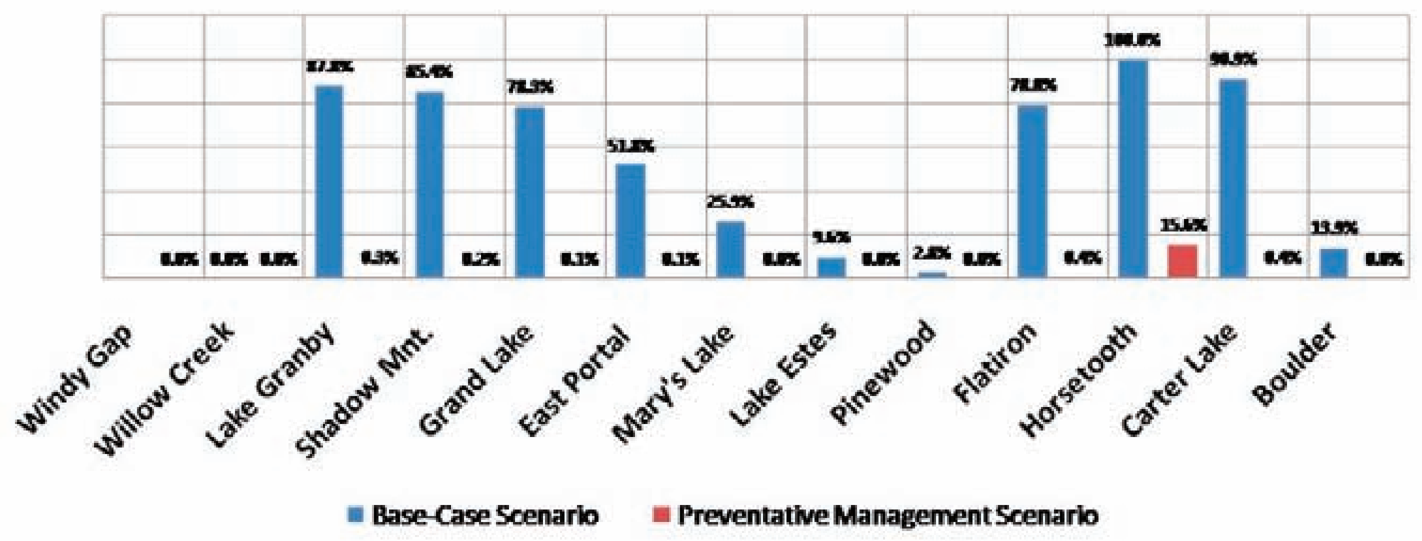


Figure 3A. Percent of runs that result in establishment. Generated using high probability of invasibility parameter values.

cleaning a large percentage of boats that are potentially carrying mussels, the boat inspection program reduces the probability of colonization.

Program benefits are measured as the difference in the net present value of expected control costs for the base case scenario and for the preventative management scenario, and program costs are measured as the net present value of the direct costs of implementing the program. Net program benefits are equal to program benefits less program costs.

The model is run 1,000 times per simulation and uses randomly-drawn numbers to determine the state of nature in each year. The resultant output characterizes the distribution of mussel establishment and net program benefits over the 1,000 runs.

Results

Establishment patterns and associated control costs are simulated using two levels for the probability of invasibility. The probability that a reservoir is invasible is a function of many variables, some known and some unknown. For the simulation of invasion in the C-BT system, parameter estimates for the probability of invasibility are assigned based on the calcium risk level for each reservoir. Calcium level is a key indicator in determining the suitability of a water body for Dreissena survival. With the exception of Boulder Reservoir, calcium levels in the C-BT reservoirs are very low, and many experts would consider these reservoirs to have very low probabilities of invasibility. Results for contrasting levels of invasibility are presented for two reasons: (1) the CDOW boat inspection program is a statewide mandate, and it could have different effects

Figure 3B. Simulated first year of establishment. Generated using high probability of invasibility parameter values.

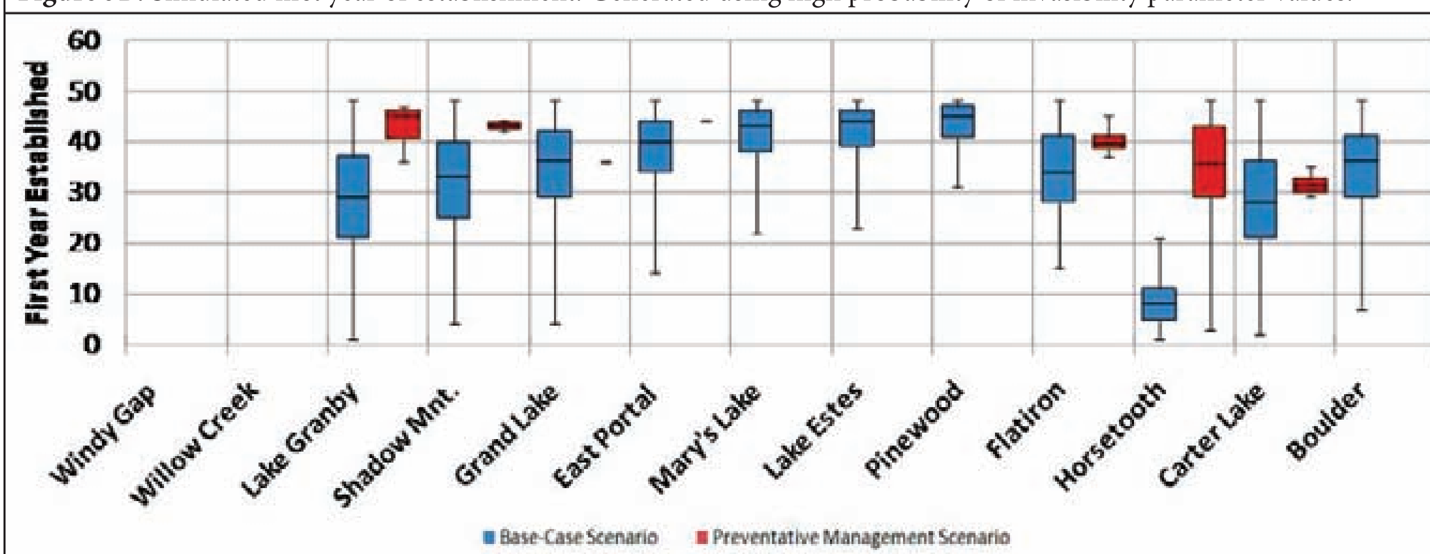


Table 2. Simulated mean costs and benefits of the CDOW boat inspection program on the reservoirs of the Colorado-Big Thompson (C-BT) system over a 50-year time horizon. Simulation results are presented based on parameter values that represent a system with low probabilities of invasibility and low mussel densities and a system with high probabilities of invasibility and high mussel densities. Net present values (NPV) are calculated using a discount rate of 2.65%.

System-wide Probability of Invasibility	Low	High
Program Cost		
NPV Direct Costs	$23,450,768	$23,450,768
Program Benefits		
Average NPV Control Costs (Base-Case Scenario)	$10,110,108	$62,384,958
Average NPV Control Costs (Preventative Management Scenario)	$34,215	$1,515,144
Average Program Benefits	$10,075,893	$60,869,815
Average Net Benefits	($13,374,875)	$37,419,047
Benefit-Cost Ratio	0.4297	2.5956

in other water bodies in the state that have higher probabilities of invasibility, and (2) the actual environmental probabilities of invasibility in the C-BT waters are extraordinarily uncertain. The identification of mussels in the low-calcium waters of Grand County reservoirs is a sign that the system may be more susceptible to invasion than expected.

Figures 2 and 3 (pages 12-13) provide simulated establishment patterns in the system under low and high probabilities of invasibility, respectively. In both cases, the simulated results suggest that the boat inspection program is very effective at reducing the probability that reservoirs in the system become established and almost entirely eliminates the possibility of invasion in the system over the 50-year horizon.

Table 2 provides the simulated net present values (NPV) of program costs and program benefits over the 50-year horizon using a discount rate of 2.65 percent. These results suggest that the benefits of reduced control costs to infrastructure are less than the costs of the boat inspection program in a system with low invasibility. In a highly invasible system, the benefits are over 2.5 times the costs of the program, and it would be reasonable to spend as much as $2.1 million per year on preventative management.

If the system has a low probability of invasibility, then the simulated gap between the NPV of the costs and benefits of the program there is about $13 million. This gap is driven by three factors: (1) the probabilities of colonization in the system are low; (2) once established, facility control costs in the system are relatively low compared to program costs; and (3) program costs are incurred every year whereas program benefits are realized 30 to 40 years in the future.

Furthermore, as measured in this analysis, benefits only include reduced control costs to infrastructure and facilities in the system. Non-market benefits such as the prevention of ecosystem disruption, reductions in ecosystem services, and diminished recreational opportunities are not included in the benefit calculation. Also omitted from program benefits are reductions in control costs to irrigators and industries using raw C-BT water. The boat inspection program is cost effective if all of the omitted program benefits exceed the cost-benefit gap.

Within the system, Horsetooth Reservoir and Boulder Reservoir have the greatest risk of establishment. Horsetooth Reservoir has nearly 50,000 boat visits each year, making its probability of establishment by boats very high. Boulder Reservoir has relatively low boat pressure, with about 1,500 boat visits each year, but has a high probability of invasibility due to high calcium levels. The majority of the control costs incurred in the system are incurred by facilities below these reservoirs. The spatial layout of the system also plays a role in the cost-benefit results. All of the hydropower facilities in the system are located between East Portal Reservoir and Flatiron Reservoir. With the exception of Lake Estes, which has a very small number of trailered boat visits each year, the reservoirs in this central stretch are closed to trailered boats. Thus, probabilities of colonization in the central reservoirs are almost entirely driven by flows. Simulation results suggest that if the probability of invasibility and the overall density of mussels in the system are low, then the probability that the central reservoirs become established by flows is close to zero, which results in zero control costs to hydropower facilities.

Conclusions

Preventative management is a valuable option for dealing with irreversible invasions that have the potential to cause severe ecological and economic damages; however, the costs of proactively slowing an invasion can be large. Results of this analysis suggest that preventative management programs designed to slow the spread of mussels over land on recreational boats are effective at preventing mussel invasions. However, the market benefits of these programs are highly dependent on the environmental suitability, the spatial layout, the type of infrastructure, and the level of control costs associated with the managed system. Lower risks of invasion and a smaller industrial presence in the West suggest that invasion and the associated control costs in western states are likely to be less severe than they were in the East, which may make the market benefits of slowing an invasion smaller than anticipated.

The results of this study identify several areas for future research. To fully address the costs and benefits of preventative management for mussels in Colorado, valuation of the non-market benefits and costs of the program and the regional economic impacts of the program are needed. In addition, a statewide analysis that captures positive spillover effects of management between systems will give a more accurate estimate of the net benefits of preventative management. Overall, the probability of invasibility and the magnitude of control costs in the system are the most important drivers in the cost-benefit analysis, and further research is needed to reduce uncertainty around these values.

The Excel-based model is available at http://dare.colostate.edu/tools/index.aspx, where users can test the effects of varying model parameter values on the establishment patterns and associated distributions of control costs.

A sign stops lake visitors from putting in their boats because of mussel contamination. Photo provided by Elizabeth Brown.

A User-Centered Approach To Developing Decision Support Systems For Estimating Pumping And Augmentation Needs In Colorado's South Platte Basin

Luis Garcia and David Patterson
Integrated Decision Support Group, Colorado State University

Throughout the United States, new models for computing augmentation requirements are being developed and applied. For the past twelve years, the Integrated Decision Support Group (IDS) has had the opportunity to study the data and modeling needs of water users in the Lower South Platte River region in Colorado. With the active participation of the water users, IDS has prioritized needs and then collected or generated the data and modeling tools necessary to meet these needs. This approach to decision support system (DSS) development is based on the premise that the user has a good understanding of what their current and future needs are, and with this in mind, we have developed an interactive and dynamic development process in which the users play an integral part. This what we call a "user-centered approach" to developing DSS tools. As part of this approach, several data-driven tools have been identified and developed that are widely used in the South Platte Basin and other parts of Colorado. These tools are collectively called the "South Platte Mapping and Analysis Program" (SPMAP) (www.ids.colostate.edu/projects/splatte). The project has been funded by water users, the Colorado Water Institute, Colorado Cooperative Extension, Colorado Agricultural Experiment Station, the Division One Office of the Colorado State Engineer, and the United States Bureau of Reclamation.

Introduction

In Colorado there is increased scrutiny of the amount of groundwater depletions caused by well pumping in alluvial aquifers. The impact of these depletions on river flows has prompted renewed interest in the methods used to calculate them.

Prolonged, severe drought and rapidly growing urban populations have exacerbated conflicts between ground and surface water users. Water managers are attempting to reconcile the desire to make use of the large amount of storage in the alluvial aquifer with the need to protect Colorado's Doctrine of Prior Appropriation and more senior surface water rights. In order to manage conjunctive use of surface and groundwater, four components need to be evaluated: 1) water demands, 2) water supplies, 3) depletions of groundwater, and 4) impacts to rivers due to depletions of groundwater and resulting augmentation requirements. SPMAP tools have been developed to deal with each one of these components.

Quantifying Water Demands

In many instances, groundwater in the South Platte Basin in Colorado is used as a supplemental water supply: groundwater is pumped when surface water supplies are unable to meet demand. Therefore, one of the first steps in modeling a groundwater/surface water system is calculating the water demand for the system. In agricultural systems, the demand is normally determined using either crop evapotranspiration (ET) or an estimate derived from multiplying well pumping by a factor (normally referred to as a presumptive depletion factor - PDF). In order to quantify consumptive use, the IDS Group developed two consumptive use models, one called IDSCU, and the other called Remote Sensing of ET (ReSET). The IDSCU Model allows users to determine crop consumptive use, irrigation water requirements, and depletions of groundwater using both traditional ET methods (Penman Monteith, ASCE, Blaney Criddle, etc.) and PDF methods. In addition, IDS had developed the ReSET model, which is an energy balance model that uses remote sensing to determine the "actual" ET. The IDSCU allows the user to choose between traditional ET methods, ReSET, or PDFs to estimate ET as part of the water balance.

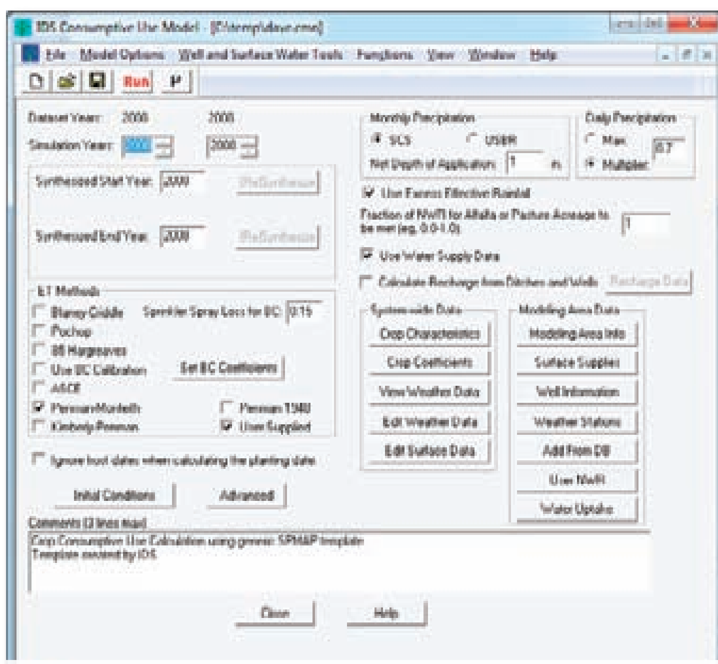


Figure 1. *IDSCU Main Interface Window.*

The IDSCU model enables water managers to estimate the consumptive use (CU) of groundwater based on surface water supplies and crop consumptive use estimates. Surface water supply information and information collected by local weather stations can be imported from the Colorado State Engineer's Office database, HydroBase, or manually entered by the user. Weather station information can also be imported from the Northern Colorado Water Conservancy District weather stations or from the Colorado Agricultural Meteorological Network (CoAgMet), or users can manually enter data. The IDSCU Model can compute monthly CU using the SCS Blaney Criddle, Calibrated Blaney-Criddle, Hargreaves, and Pochop methods. Daily CU estimates can be computed by the model using the Penman-Monteith, Kimberly-Penman, the new ASCE standardized reference evapotranspiration equation, or user-defined ET such as the one estimated using the ReSET model. The IDSCU Model graphical user interface (GUI) main window is shown in Figure 1. On the lower right hand side of the main screen, a number of buttons are displayed that allow the user to access pop-up screens for entering or modifying data pertaining to: crop characteristics, crop coefficients, weather data, surface water supplies, modeling area information, well information, and modeling area weather station weighting.

The IDSCU Model allows users to generate input data before (pre) or after (post) the historical data period. The user may select to generate pre- or post-historical data by averaging selected years, repeating a selected year, or repeating a sequence of years and computing the CU for them. The model is also capable of formatting input and output displays for all year types (calendar, irrigation, and water).

The model can calculate CU or Irrigation Water Requirements (IWR) with or without using soil moisture. The model does a water budget and determines the times when crops might be water short as well as the amount of CU met from both surface and groundwater. The GUI allows users to compare the CU computed with different methods and computes ratios between the different methods. This allows users to evaluate the difference between ET methods and provides some guidance for users if they are interested in calibrating a monthly method based on the differences between the monthly aggregated values of daily ET methods and computed monthly ET values.

Quantification of Water Supplies

Water supplies normally come from surface water supplies and groundwater pumping. The model allows users to query HydroBase in order to generate a set of diversion records for different ditches or diversion structures. Users may also build a set of diversion records for different

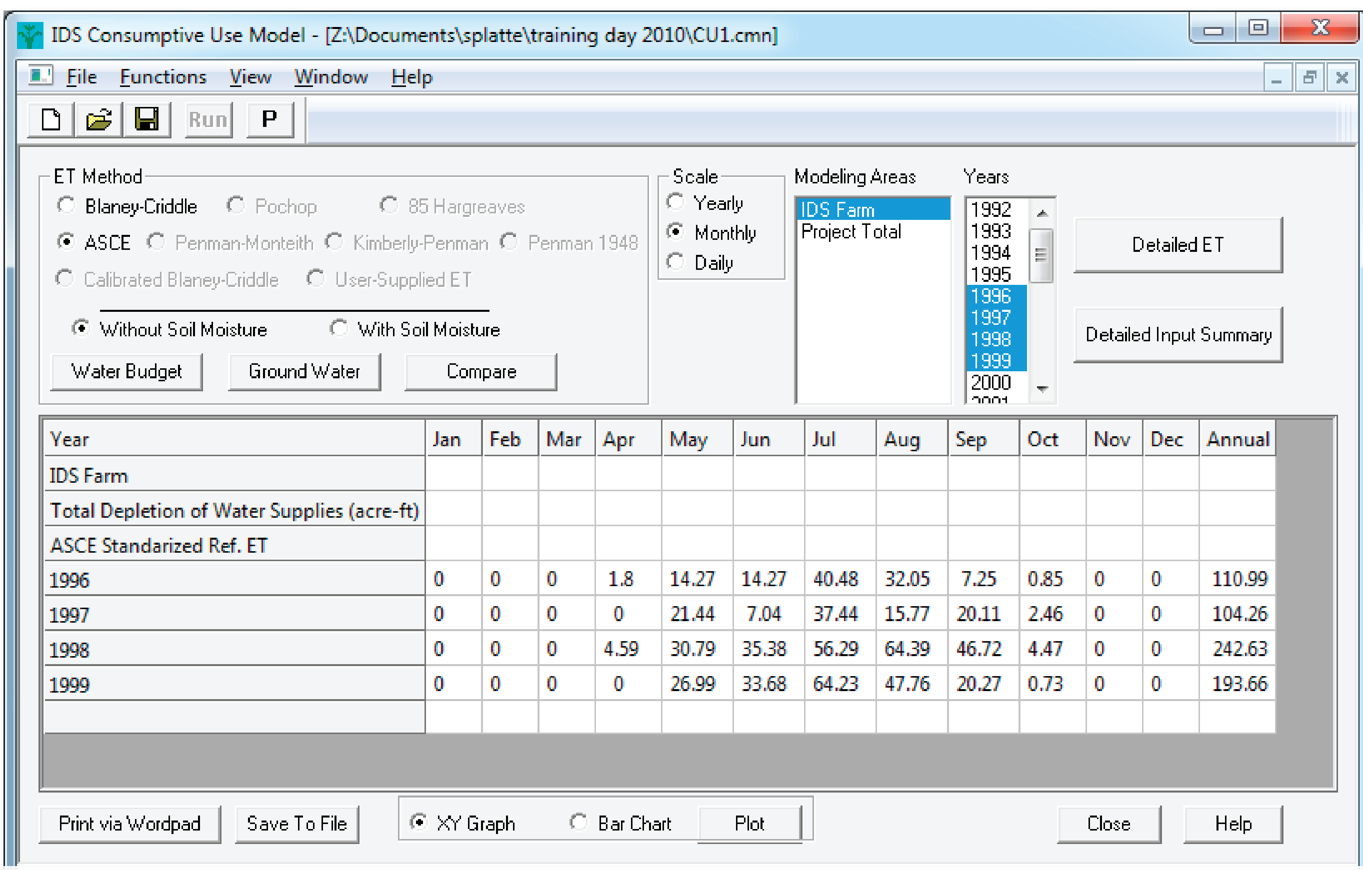


Figure 2. *IDSCU GUI General Output Screen.*

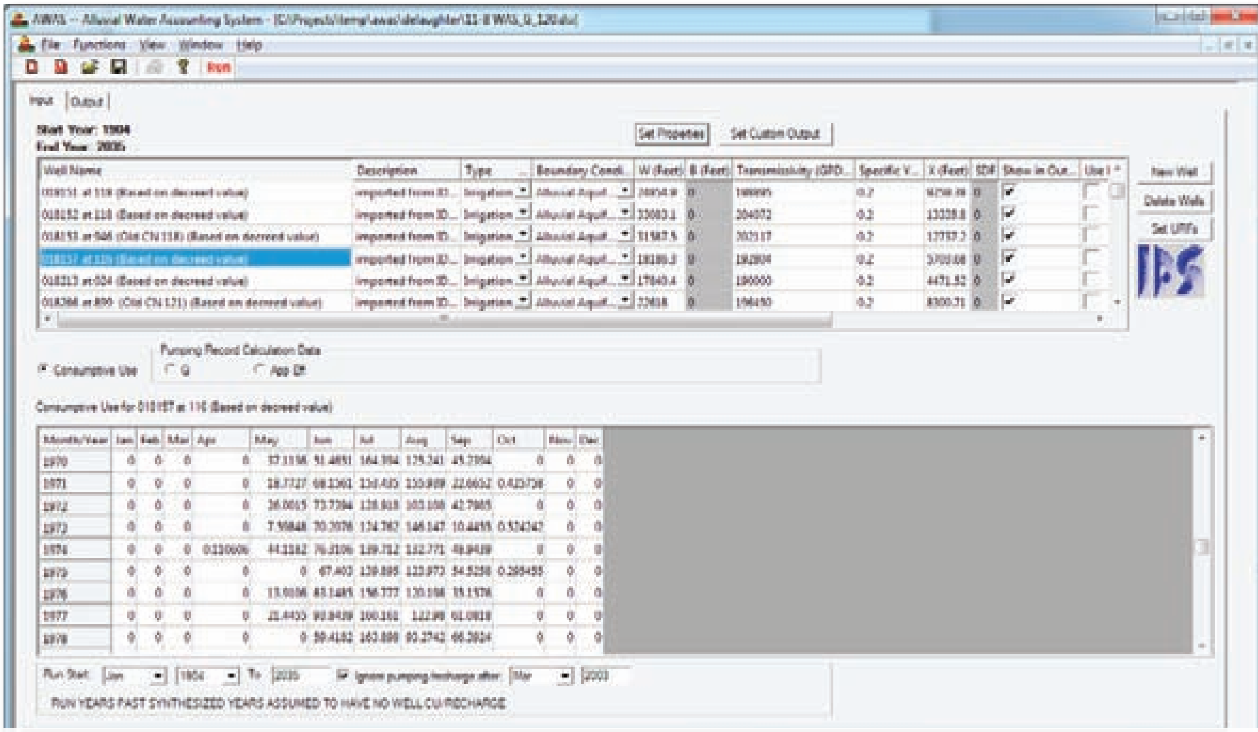


Figure 3. *IDS AWAS GUI Input Screen.*

ditches or diversion structures by entering the diversion records manually. The surface supply for each modeling area is then calculated by assigning one or more surface supply ditches or structures to it. The IDSCU Model requires users to enter the shares for each ditch or structure owned by each modeling area. The amount of shares for a particular ditch that are assigned to a modeling area can vary from year to year, enabling users to evaluate the impact of leasing water in certain years. In the event that the user has headgate diversion records, these can be entered for each modeling area.

For groundwater pumping, users may enter monthly groundwater pumping, or if the user only has total annual pumping, the model can distribute annual pumping into monthly values for agricultural and non-agricultural wells.

Quantification of Depletion of Groundwater

After obtaining an estimate of the water demand and supply, the IDSCU model can compute depletions of both surface and groundwater. Users may evaluate the impacts of the groundwater depletions by examining whether the groundwater is a primary or supplemental source of water and by examining well efficiency using a PDF. The model also can compute groundwater depletions based on a water budget. Results may be plotted with the click of a button using the IDSCU model's built-in graphics package. Users may compare the results of CU of groundwater based on a water budget versus well efficiency multiplied by well pumping to evaluate if the two results are in general agreement.

Quantification of Augmentation Requirements

Colorado water managers need to determine the lag time from when a well is pumped or water is recharged to a recharge site and when a depletion or accretion happens in the river. A model based on HydroBase was implemented by the IDS Group and is called the IDS Alluvial Water Accounting System (IDS AWAS). Figure 3 shows the IDS AWAS input screen.

IDS AWAS provides users with the option of calculating river depletions using The Analytical Stream Depletion method developed in 1987 by Dewayne R. Schroeder. This method uses analytical equations described by Glover (Glover, 1977) and others. The model allows users to calculate depletions using daily or monthly time steps. The user may evaluate a number of different boundary conditions (alluvial, infinite, no flow and effective SDF). IDS AWAS can create model input in two ways: 1) each well can have a list of pumping records consisting of a pumping rate and duration (original mode), or 2) input records consisting of net consumptive use or recharge in a daily or monthly time step can be used. Year type can be set to calendar, irrigation, or U.S. Geologic Survey (USGS). Data can be projected into the future or past based on historical data, and the effect of turning off the well by specifying an end date beyond the period of record can be simulated.

The IDS Group's work in the South Platte is one framework for the development and implementation of decision support tools to assist water managers. There continue to be opportunities for updating the current methodology used for calculating augmentation requirements. Fertile areas for ongoing research include developing, maintaining, updating, and deploying DSS.

Software Development Approach

Building on good communication with water users, the IDS Group adopts a user-centered approach to DSS development. Using this approach, we have developed several data driven tools that are widely used in the South Platte and other parts of Colorado. These tools are collectively called the SPMAP (www.ids.colostate.edu/projects/splatte).

The SPMAP tools include a GIS tool that calculates CU, and a tool for calculating depletions to an aquifer. The GIS tools can be used to determine the location and size of irrigated lands, groundwater wells, weather stations, and other data important for determining consumptive use for an area. This data can then be used to run the IDSCU Model to estimate CU as well as groundwater withdrawals to meet crop water needs. The CU withdrawals by pumping can then be exported to IDS AWAS, which can estimate the impact that groundwater pumping will have on the river. IDS AWAS can also be used to determine the effects of groundwater recharge on the river. They provide a comprehensive and flexible approach to meeting the modeling needs of water managers on the South Platte River.

At each major stage of development, the software is provided to the participating organizations via the Web along with online documentation and hardcopy documentation that can be downloaded and printed.

To make the programs easier to use and provide new options for building input files and viewing output, GUIs are constructed in Visual C. The development and user platform is a PC running Windows 95/98/NT/2000. Development has proceeded by using a "modular" approach, meaning tools can be used as stand-alone components or used in tandem. New components and tools can be substituted or added to the system with minimal changes to the other components or the data storage.

User documentation for the software is available on the Internet and can be accessed from help menus in the model interfaces. The combination of using developed models, building graphical interfaces, using Avenue scripts, following a modular approach, and developing good documentation makes this software flexible, generalized, and easy to use.

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The Complexities of Conservation: Identifying Conservation Research Needed to Incorporate Conservation Savings Into Utility Water Supply Planning

Janine Stone, Graduate Research Assistant, Department of Agricultural and Resource Economics, CSU
Christopher Goemans, Assistant Professor, Department of Agricultural and Resource Economics, CSU

"Conservation." Intuitively, this word has a simple definition: use less. In the context of water resources planning, conservation is a way to decrease residential consumers' water use so that utilities don't need to further augment water supplies to meet demand. The Colorado Legislature, Colorado Water Conservation Board (CWCB), and municipalities throughout the state all agree that water conservation needs to play a major role in the state's future. However, to effectively incorporate conservation savings into long-run planning efforts, an understanding of the effectiveness of particular conservation measures is necessary. One needs information regarding the effectiveness of demand management to not only identify which policies to implement, but also to determine the extent to which conservation can be counted upon to reduce future demand.

For most of the past 50 years, literature on water demand has focused on estimating consumer responsiveness to changes in price, while analyzing the effectiveness of non-price policy measures has only gained prominence in the past ten or fifteen years. In part, this is because non-price policies (and their impacts) are more difficult to measure given the data typically available. Nevertheless, several themes have emerged from the water use literature on non-price policies. First, research has found that policies aimed at promoting conservation do not always have the effects we expect or intend. Furthermore, communities themselves have unique baseline water demands and water supply portfolios, so a policy aimed at increasing conservation will have a differing impact depending upon where it is implemented, the characteristics of its service population and other demand-reduction policies that are in place. For example, informational campaigns have been found to increase the effectiveness of price increases. Lastly, researchers note that the short-term impact of a policy may differ from its long-term effects, though few studies have looked at the long-term impact of conservation policies. The combination of these factors makes it difficult for an individual utility to incorporate conservation into water planning efforts.

> "To Resident X of Colorado Springs, "wise water use" might mean watering three times a week instead of every day; however, he now waters for twice the time."

Early-morning watering, as this site in Greeley, Colo., demonstrates, is an example of individual efforts to conserve water. Photo by Lindsey A. Knebel.

The CWCB defines "conservation" as "water use efficiency, wise water use, water transmission and distribution system efficiency, and supply substitution." What does this mean to the typical consumer? To Resident X of Colorado Springs, "wise water use" might mean watering three times a week instead of every day; however, he now waters for twice the time. And to Resident Y in Aurora, "water use efficiency" means Y installed a low-flow showerhead; the only problem is she now runs the water longer to rinse her hair. Resident Z of Fort Collins, on the other hand, took "water distribution efficiency" to mean he should perform a home water audit and fix all leaks; however, he uses a portion of his savings for watering new plants.

Uncertainty regarding how consumers will react to conservation policies complicates estimating potential conservation savings. For example, estimating the demand impact of, say, a low-flow showerhead incentive program is not just simple accounting. We can't merely add the number of residents who installed the devices and multiply that number by average water savings for that specific device, and this is true for one major reason: the "Resident Y" factor. Like this hypothetical Aurora resident, some consumers who install water-efficient appliances or take other actions to "conserve" end up using more water as a result of behavioral changes made in conjunction with the conservation action. Thus, we use regression analysis to estimate these behavioral responses, to examine how consumers think, and to tease out how policies like price increases, water-use restrictions, and informational campaigns impact consumers' choices and actions. This approach utilizes data to compare household behavior before and after a particular policy has been implemented.

As the above paragraphs explain, totaling the impact of a conservation policy is difficult because it depends on two factors: consumers' initial reaction to the policy, and how those reactions/behaviors change over time. Figure 1 shows a timeline of water demand before and after a conservation policy is put into place. As illustrated, research has found that water demand typically falls when a conservation policy is implemented. However, consumer behavior may change—and resulting water savings erode—over time, as can be seen by the increase in demand in the post-conservation period in Figure 1.

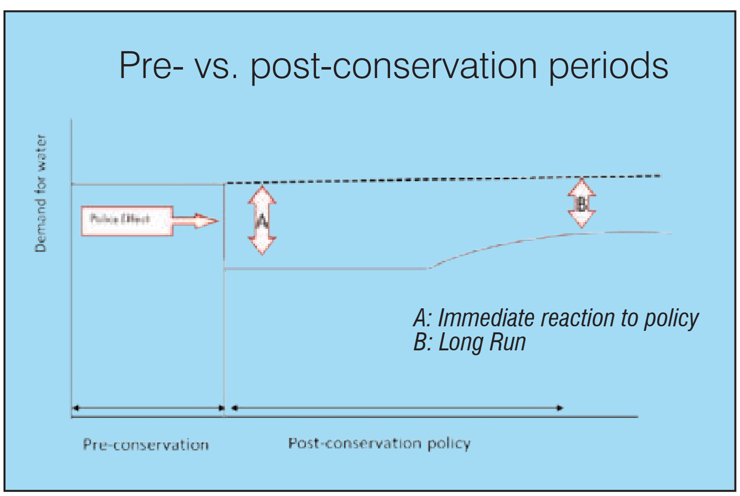

Figure 1. The chart indicates that initial response to conservation policy may be greater than long-run response and that long-run demand is more elastic, as households can switch to low water usage technologies and landscapes.

In order to incorporate savings from conservation into water supply plans and policy, utilities need to know both the short and long-run impacts of conservation policies. Thus, the data we use needs to span a long enough time horizon to capture these changes.

Lastly, we must consider the impact of drought. Previous research has found that consumers are more responsive to utility policies when they perceive a crisis situation. For this reason, using data from a drought period to estimate the impact of a conservation policy may overestimate that policy's effects. Second, Colorado utilities have observed decreases in demand in the post-drought period, and these decreases have remained even after temporary drought programs ended. The question is, will those demand reductions become permanent, or are they merely a "drought shadow," the lingering impact of the drought on consumer behavior? If the drought inspires consumers to adopt more water-efficient technologies, how far can we expect such technology to penetrate (i.e., how many total households can be induced to install low-flush toilets, drip irrigation systems, and so forth in any given community)?

Researchers at CSU are teaming with the Colorado Water Conservation Board and Colorado water providers to assess the feasibility of future research into the permanency and penetration rates of water conservation savings and measures. This research project is designed to jump-start the process of collecting the information utilities needed to build conservation into water supply plans. We are working with both large and small utilities throughout the state to identify the information they require and to determine what types of data need to be collected in order to obtain this information. Specifically, we will examine existing data and processes of providers; examine data needs and processes needs; examine constraints and barriers to assessing water conservation potential; and create a needs/opportunities matrix which highlights current informational shortcomings. This will be followed by a demonstration analysis in which we work with utilities to illustrate the types of analysis that can be done given the data they currently collect, and what could be done if more data were available.

We expect to find large differences in the types of data collected by different utilities, as well as differences in the types of conservation programs currently used and/or integrated into present water resources planning. However, these differences between utilities are not necessarily negative; they are merely the result of the fact that every community has a unique mix of water supply resources, and its residents hold varying preferences for water consumption. As such, studying these differences—and seeing what utilities can learn from each other—is an integral first step in incorporating conservation into Colorado's water supply future. To use a metaphor, studying the policies and data collection policies used by utilities is like staring at the drifts of snow that supply the Front-Range's water—at first glance, it all looks the same, yet if you look closer, every flake is different. Our goal is to look closely at these differences and, in doing so, add new dimension to the process of incorporating conservation into water supply planning.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	6	0	0	0	6
Masters	4	1	0	0	5
Ph.D.	3	0	1	0	4
Post-Doc.	0	0	0	0	0
Total	13	1	1	0	15

Notable Awards and Achievements

- Lohman Receives NPS Lifetime Achievement Award
- Dr. Jose Salas Awarded the Prestigious Ven Te Chow Award
- Archivist Patricia J. Rettig Receives Faculty Award for Excellence
- CSU Professor Receives Two Awards
- Former CWI Director Robet Ward Receives Elizabeth Jester Fellows Award

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Awards and Achievements

Lohman Receives NPS Lifetime Achievement Award
Early in the day, before most people have even thought of the news or what it holds concerning water, articles are being reviewed, categorized, and stored for retrieval by water professionals across the state and beyond. Loretta Lohman accomplishes this task, placing the articles under the Current News link at www.npscolorado.com. Lohman serves as the nonpoint source (NPS) information and education coordinator for the Colorado NPS program. She has held this position for over 10 years, providing consultation and resources to spread the message about managing NPS. Lohman, who oversees the NPS Colorado Web site, is quick to tell anyone using the site, “If something is needed or not working right, just let me know and I’ll work it out.” That dedicated, “can-do” spirit was recognized at the Sustaining Colorado Watersheds conference in October, when Lohman received the 2010 NPS Lifetime Achievement award. Managers, colleagues and family were present to offer perspectives and congratulations on her professional accomplishments. Annually, individuals and organizations are recognized for exceptional water quality accomplishments that address NPS pollution. The Colorado NPS program, which is part of the Colorado Department of Public Health and Environment’s Water Quality Control Division, presents this award. Lohman was the sole recipient this year. “Information and education efforts have a critical role in meeting the state’s needs of NPS management,” says Lucia Machado, Colorado NPS coordinator. “Loretta’s valued background and dedication has provided the program with a solid foundation over the years.” Lohman completed bachelor and doctorate degrees in political science and American History, respectively, at the University of Denver. Her master’s is in social science from the University of Northern Colorado. Lohman applied her education to consulting, teaching and research. Much of her work has focused on the state’s water issues. She has authored over 60 publications and articles throughout her career; most deal with water reuse, economics, and the Colorado River. Lohman Receives NPS Lifetime Achievement Award Colorado NPS Program Staff The oldest of three, Lohman was raised in a home that valued education – from regular trips to

the library to the expectation of earning a college degree. Her parents also instilled the importance of valuing diversity and assisting those less fortunate. At the recent award presentation, Lohman's brother and his wife described instances that typify how Loretta cares and appreciates others. In accepting the award, and in true fashion, Lohman quickly turned the spotlight to the many volunteers who play key roles managing Colorado's water resources, especially in the fields of water quality and NPS.

Dr. Jose Salas Awarded the Prestigious Ven Te Chow Award

Dr. Jose 'Pepe' Salas, a Colorado State University civil and environmental engineering professor, was recently awarded the prestigious new Ven Te Chow award from the American Society of Civil Engineers. The award is presented annually to individuals in recognition of a lifetime spent on "...exceptional achievement and significant contribution in research, education, and practice" in the field of hydrologic engineering. The award, which will be presented May 16-20 in Providence, Rhode Island, is the most visible and prestigious award given in Salas' chosen field of hydrology. Salas is being recognized for his 35 years of experience and significant contributions to hydrology in the areas of probabilistic and stochastic characterization of hydrologic processes, flood forecasting, regional drought analysis, frequency analysis, and education efforts through books and publications, as well as his modeling of the Colorado River, the Nile, and the Great Lakes Basin

Archivist Patricia J. Rettig Receives Faculty Award for Excellence

Colorado State University Libraries Assistant Professor Patricia J. Rettig has been selected as the recipient of the 2010 Colorado State University Libraries Faculty Award for Excellence. This award recognizes a member of the Libraries faculty for outstanding contributions to the Libraries, to the University, and/or to the library profession. Rettig, the Head Archivist for the Water Resources Archive since 2005, has been recognized not only for her practice of librarianship, but also for her many scholarly and creative contributions to the profession. Rettig joined the University Libraries as a Project Cataloger in 2000 and became an Archivist in 2001. During her years of service with University Libraries Archives and Special Collections, she has built the Water Resources Archive from a small assortment of boxes to a premier collection of archival records documenting all aspects of water in the Rocky Mountain West. Following her initial efforts to arrange and describe the existing archival collections, Rettig created a display to showcase the Water Resources Archive and took it on the road to water conferences, ditch company meetings, and other gatherings, introducing Colorado's water community to the Archive's holdings. Through careful cultivation of relationships with civil engineers, historians, water lawyers, and other key individuals in the water community, Rettig has facilitated the donation of dozens of new collections to the Archive, most notably the highly significant Papers of Delph E. Carpenter and Family. She has worked tirelessly to make these unique materials available to a worldwide research community through online finding aids and digitized materials In addition to her articles for peer-reviewed journals, Rettig has contributed to the Colorado Water newsletter on a regular basis, educating members of the water community about the holdings and activities of the Water Resources Archive. Finally, her thorough planning, visually pleasing and informative exhibit design, and successful execution of the annual Water Tables fundraising event have resulted in higher visibility for the Water Resources Archive, donation of new archival collections, and funding to assist in the preservation of these collections. Rettig deserves recognition for excellence in building and making accessible unique holdings of the CSU Libraries to water researchers throughout the world. Rettig is a member of the American Library Association, the Society of American Archivists, and the Society of Rocky Mountain Archivists.

CSU Professor Receives Two Awards

Dr. Kurt Fausch, professor in the Department of Fish, Wildlife, and Conservation Biology at CSU, was recently honored with two awards for lifetime achievement. Fausch won the Award of Excellence from the Colorado-Wyoming Chapter of the American Fisheries Society and the 2010 Outstanding Alumnus Award awarded by the College of Agriculture and Natural Resources at Michigan State University, where he earned his M.S. and Ph.D. Fausch is internationally known for his research, teaching, and outreach on stream ecology, with an emphasis on conservation and management of stream fishes. His work with students and colleagues was recently chronicled in the documentary film RiverWebs, which aired on PBS to more than 70 million homes in 2009 and is currently showing again

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Former CWI Director Robert Ward Receives 2010 Elizabeth Jester Fellows Award

Dr. Robert C. Ward, retired professor and director of the Colorado Water Institute at Colorado State University, is the recipient of the 2010 Elizabeth Jester Fellows Award. This award recognizes individuals for outstanding achievement, exemplary service, and distinguished leadership in the field of water-quality monitoring. Dr. Ward is dedicated to improving the state of the science of water quality monitoring through the delivery of quality education, development of coherent water monitoring systems, and promotion of the development of water quality information that the public and decision makers can understand, trust, and use to further improve water resources. He taught two generations of students in operations research, engineering design, and water quality monitoring during his 35-year tenure at CSU and through his "Short Course on Water Quality Monitoring Network Design." His seminal text on this topic and the monitoring network design he helped develop in New Zealand stand as testament to his work. His profession of goal-oriented monitoring was reflected in the Interim Task Force on Monitoring products, as well as the National Water Quality Monitoring Council's (NWQMC) Framework for Water Quality Monitoring. Internationally he has served on the scientific Organizing Committee for four Europe-wide conferences on water quality monitoring.