

# Colorado Water

September/October 2018



CSU  
**WATER CENTER**  
PROJECTS

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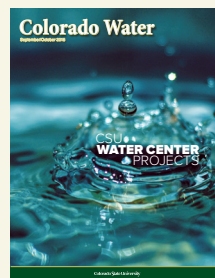
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A falling droplet piercing vibrant blue waters.

Photo by Deven Dadbhawala

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# COLORADO WATER

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Melissa Mokry

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Ethan Worker

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Nancy Grice

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## Director's LETTER



Colorado State University continues to expand the reach and impact of its programs and leadership in water research, education, and outreach, through both the CSU Water Center and a variety of other initiatives and water programs underway here at Colorado State. The depth and breadth of water activity at CSU is remarkable. The University currently offers 28 undergraduate majors, minors, and graduate degrees related to water. We have 44 water-related organizations and 17 student clubs and offer 183 water-related courses (69 at the undergraduate and 113 at the graduate level). If you want to learn more about these many programs and offerings, visit: <https://watercenter.colostate.edu/directory/>

2018 was another successful year for our water faculty and student research program. In this issue of Colorado Water, you will learn about some of their recent research projects and activities. Student inclusion is a key aspect of these research endeavors, as the process of conducting research deepens and solidifies theoretical knowledge and practical skills. The process of working closely with a faculty mentor helps prepare students for their careers as water managers, scientists, and leaders. One of the most important things we can impart to students through their classroom and research activities is a solid foundation for lifelong learning and inquiry so that they can grow and take on future challenges we have yet to even contemplate today.

Looking ahead, we expect CSU to remain at the forefront of water scholarship, advancing as a center of excellence and a leader in research, education, and outreach. This year, we are uniting the CSU Water Center and the Colorado Water Institute under one organizational unit to gain operational efficiencies and reduce internal or external confusion on how to access CSU expertise, networks, and resources. New water programs and opportunities are emerging around the development of a Water Building at the National Western Stock Show. Construction of the Water Building is slated to begin at National Western in early 2020, and water-related research, education, innovation and policy programs are already under development in partnership with Denver Water.

The future challenges we face will require water professionals who can work across disciplines to solve intertwined human and technical problems. To serve this need, the Water Center at Colorado State University will continue to foster collaborations among our water faculty, staff, students, and community partners to address the increasingly complex water challenges of today and tomorrow. 

*Reagan Waskom*

Director, Colorado Water Institute

*Photo by  
Flickr User Christine  
und David Schmidt*

# The Integration of **Green Infrastructure** in Land-Use and Water Planning

Kelly Curl, Horticulture and Landscape Architecture,  
Colorado State University



## SYNOPSIS

The integration of land-use planning and water planning is a critical need as our urban, exurban, and rural environments continue to be developed. The installation of green infrastructure within the planned communities can be a social, economic, and environmental benefit for our larger ecosystems and overall increased groundwater recharge. This research study focused on the benefits of Native Grass landscape installed in the Bucking Horse neighborhood of Fort Collins, Colorado.

### Introduction

Human population growth leads to the loss of biodiversity. Population growth and low-residential housing are causing more damage than the environment can sustain. The impact of our continuously increasing population proves that the integration of land-use-planning and water planning is even more critical. Colorado's Water Plan (CWP) states that by 2025, 75% of Coloradans will live in communities that have

“water-saving actions” in their land-use planning. The CWP recognizes the need for a strong partnership between the local water providers and the communities. The Colorado Water Conservation Board (CWCB) also plans to begin connecting “Department of Local Affairs, local governments, water providers, Colorado Counties Inc., Colorado Municipal League, the Special District Association, councils of governments, and homebuilders to examine and strengthen the tools they collectively possess to help Colorado reach this objective”.

As land is developed, it disrupts the regional ecosystems. It is critical for land-use planning to integrate green infrastructure within our designed environments. Green infrastructure planning is a strategic landscape approach to open space conservation, whereby local communities, landowners, and organizations work together to identify, design, and conserve their local land network in order to maintain healthy ecological planning. As natural areas or agricultural lands become developed, habitat diversity diminishes. Increased impervious land cover increases the risk of flooding. Green infrastructure reduces a community's susceptibility to floods, fires, mudslides, and other natural hazards.

My research focused on the economic, social, and environmental benefits of installed green infrastructure within a local community neighborhood, Bucking Horse. “Bucking Horse is an infill, mixed-use neighborhood on 160 acres in Fort Collins, Colorado. The goal of the project is to “buck” the system and demonstrate a financially successful, agriculture-oriented neighborhood centered on the values of community and quality of life. This new neighborhood will promote a triple bottom line of sustainability considering environmental, social, and financial outcomes”. Bucking Horse was also selected to be part of Fort Collins’ Nature in the City plan. Nature in the City’s vision is a “...connected open space network accessible to the entire community that provides a variety of experiences and functional habitat for people, plants, and wildlife.” Bucking Horse was selected to install a native grass restoration project within the neighborhood. It was calculated to save 55 million gallons of water each year. This native landscape also prevents 6,000 pounds of CO2 from being emitted per year by lawn maintenance equipment. It provides excellent habitat for rabbits, deer, birds, insects, and small mammals that rely on grasses for food, nesting, and coverage.

## Methods

My research began with reviewing specific case study projects within the Landscape Architecture Foundation’s Landscape Performance Series. I selected nine regionally local case studies to review how each performed with documented stormwater management techniques. The projects were:

1. *Phoenix Civic Space Park, Phoenix, Arizona; AECOM*
2. *George “Doc” Cavalliere Park, Scottsdale, Arizona; JJR | Floor*

3. *Yuma East Wetlands, Phase 1 and 2, Yuma, Arizona; Fred Phillips Consulting*
4. *Riverside Ranch, Colorado; Design Workshop, Inc.*
5. *Capitol Valley Ranch, Colorado; Design Workshop, Inc.*
6. *Cascade Garden, Aspen, Colorado; Design Workshop, Inc.*
7. *Charles City Permeable Streetscape Phase I, Charles City, Iowa; Conservation Design Forum*
8. *Cherry Creek North Improvements and Fillmore Plaza, Denver, Colorado; Design Workshop, Inc*
9. *Daybreak Community, South Jordan, Utah; Design Workshop, Inc.*

Next, I designed and distributed a survey that was sent out to the Bucking Horse residents who were on a newsletter e-mail list. I was unable to reach all residents for this research. The survey was designed to inquire about the economic, social, and environmental benefits of the neighborhood. The online survey was live for a two-week period.

## Results

A sample analysis and review of the case studies on Landscape Performance are as follows:

*George “Doc” Cavalliere Park, Scottsdale, Arizona; JJR | Floor*

- Captures and infiltrates 100% of stormwater generated on-site from a 100-year, 2-hr storm event. The site also manages runoff from several upstream developments with a storage capacity of 49.5 acre-feet.



*George “Doc” Cavalliere Park, in Scottsdale, Arizona, is a case study project representing beneficial landscape performance metrics with environmental, social, and economic benefits. These images show the site before and after the construction of the park. On the left, a view of the existing basin displays overgrown invasive species, while on the right, the core park elements, basketball courts, restrooms, shaded playground, and turf area are carefully sited in the gabiion lined basins.*

- Saves 88% of potable water use for irrigation by limiting turf areas and utilizing a native plant palette.
- Reduces hardscape surface temperatures under tree shade and structured shade by 30 and 45 degrees, respectively, when compared to unshaded areas of the site. The steel canopy helps to maintain playground surface temperatures under 82 degrees.
- Reduces air temperatures on the natural turf field and the playground by 3.3 and 2.3 degrees, respectively, when compared to air temperatures in the undisturbed desert areas.

Capitol Valley Ranch, Colorado; Design Workshop, Inc.

- Saves over 1,000,000 gallons of irrigation water and 400 lb. of fertilizer annually by limiting lawn area to 5,440 sf, 7% of the total planted area on the entire 35-acre site.
- Reduces atmospheric carbon by more than 8.7 tons annually through 137 trees planted on the property, approximately the same amount of CO2 released by burning 884 gallons of gasoline.

Cherry Creek North Improvements and Fillmore Plaza, Denver, Colorado; Design Workshop, Inc.

- Reduces annual water consumption for irrigation by 3,376,000 gallons, saving \$17,600 annually, by replacing over half of the spray-irrigated turf with drip-irrigated, water-wise perennials and shrubs.
- Removes up to 80% of solids in the stormwater runoff from Fillmore Plaza using an underground water treatment vault.

The Bucking Horse survey consisted of 40 questions inquiring about the social, environmental, and economic benefits of the neighborhood native landscape. A summary of the survey results demonstrates that the majority of the residents surveyed favor the neighborhood park and pool and Jessup Farm Artisan Village. The maintained manicured spaces were more favorable in comparison to the natural landscapes. Figure 1 displays a graphic showing favorable topics. Figure 2 displays a graphic of landscapes that residents did not favor. Residents were also asked to rank their favorable type of landscape when given the following options (Figure 3). The majority of residents favored rain gardens and rainwater harvesting. Additional results are as follows:



Figure 3. Residents were asked which green infrastructure practice they would prefer to have installed in their neighborhood; rain garden, wetland, permeable paving, rainwater harvesting, planter boxes, and vegetated swale.



Figure 1. Word cloud illustrating resident's least favorite landscapes within their neighborhood. Created by Megan Ruxton.

Figure 2. Word cloud illustrating resident's favorite landscape in the neighborhood. Created by Megan Ruxton.





*The Bucking Horse Neighborhood. Photo by Kelly Curl.*

- 83% use the neighborhood community gardens and trails;
- 100% are aware of the Native Grass Restoration Project;
- 93% do not like the aesthetics of the native grass landscape;
- 57% purchased their property not knowing their neighborhood was conducting the Native Grass Restoration Project;
- 53% do not currently or ever plan to capture rain water;
- 63% are unknowledgeable of the neighborhood landscape goals to improve water quality; and
- 61% are unknowledgeable of the neighborhood landscape goals to conserve water use.

## Conclusions

The results showed that the majority of residents did not have much knowledge about the installed native landscape, they did not favor the aesthetics of the landscape, and thought it was very messy and unkempt. Many admitted that they did not know the ecological and hydrological benefits of the native landscapes. In conclusion, this neighborhood is an excellent example of testing out and installing a native grass landscape. This landscape type was seeded and takes years of

maintenance to ensure its success. In the early years before the meadows are established, it looks like an unplanned landscape. I believe with further maintenance, and continued education on the benefits of this landscape type, communities will understand the remarkable benefits that green infrastructure has on larger city ecosystems and watersheds.

## Next Steps/Further Research

Given time, I did not obtain as much environmental and economic data on the water saving benefits of the native green infrastructure within Bucking Horse. I would like to continue this research and work more closely with others who are also researching this neighborhood. I also hope to work with other neighborhoods within the Front Range of Colorado in order to build a comparison among size, urban and rural, and residence with varying economic status. I greatly appreciate the opportunity to receive this grant to conduct this research this past year. It has connected me to many people within the community who have the same passion for sustainability around water-saving techniques in our built environment. With more time, I will continue my research focus on land planning efforts related to water conservation.

*This project was funded by the Colorado State University Water Center.* 



# Modelling Commercial Demand for Water

Matthew Flyr, Agricultural and Resource Economics,  
Colorado State University;  
Jesse Burkhardt, Agricultural and Resource Economics,  
Colorado State University

## SYNOPSIS

In this paper, we evaluate the determinants of commercial water demand in Fort Collins, Colorado. We present evidence that firms are more responsive to one period lagged average price than marginal price. We also find notable differences in price responsiveness across different categories of businesses. The findings in this paper are particularly important as water utilities consider how to maintain revenue while coping with limited water supplies and increasing commercial demand.

## Introduction

According to the Colorado Water Conservation Board's (CWCB) 2010 Colorado Statewide Water Supply Initiative, Colorado will face a gap between industrial/municipal water

supply and water demand of between 190,000 and 630,000 acre-feet by 2050 (CWCB, 2011). This problem is not limited to Colorado. The United States Bureau of Reclamation's (USBR) Colorado River Basin Water Supply and Demand Study projects the gap in the Colorado River Basin (including Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming) to reach 3.2-million-acre-feet by 2060 (USBR, 2012).

Growing municipal and industrial demand is a major contributor to this problem. The USBR report noted that this sector is expected to have the largest demand increase of any sector in Colorado River Basin, and the CWB report projects this sector's demand to nearly double in Colorado by 2050. As a result, municipal and industrial water conservation has





become a major focus for utilities and policymakers. Both the USBR and CWB reports identified conservation in this sector as one of the key strategies to close the gap. Commercial users are an important area of concern, as they demand 30-40% of total public water supply on average across American cities (Renzetti, 2015).

Despite the growing need to manage commercial demand, little is known about commercial responsiveness to utility policies, especially relative to the wealth of knowledge on residential water demand. As a result, it is difficult for utilities and policymakers to anticipate the effectiveness of pricing policies on this important group.

## Study Objectives

In this study, we focused on improving the knowledge of commercial water demand in several ways. First, we tested which water price businesses were responding in Fort Collins, Colorado. Economic theory suggests businesses respond to marginal price or the price of their last gallon of water. However, calculating marginal price can be difficult in an increasing block rate pricing schedule, a type employed by many utilities across the country. Calculating marginal price in this situation required routinely checking the water meter, which can be difficult and time-consuming. When the marginal price is costly to ascertain, consumers often look for a proxy, like the average price of water from the previous bill (Nieswiadomy and Molina, 1991). To see if this is the case in the commercial sector, we formally tested whether businesses responded more to contemporaneous marginal price, previous period average price, or a series of other price terms.

Second, to help utilities anticipate whether price increases are an effective method to limit commercial demand in the future, we estimated the price responsiveness of water demand for several categories of commercial users.

*Horsetooth Reservoir.  
Photo by Fort Collins Utilities.*



## Data and Sources

Firm-level monthly water consumption data was provided by Fort Collins Utilities. The dataset included total water consumed, total bill, rate type, billing period dates, and premise and customer code for all commercial users from January 1, 2001 to December 31, 2016. After data was quality controlled, our dataset consisted of 330,065 observations across 2,956 commercial premises.

In Fort Collins and in many utilities across the U.S., businesses face (1) a base charge and (2) a marginal rate per 1,000 gallons (kgal) consumed, both varying by water meter size. All meter sizes except the 6" and 8" meters face increasing block rate pricing, where the firm pays a lower per-kgal price until they hit a certain threshold of water consumption and jump to a higher price for the remainder of the period. In the summer, both the lower and higher price tiers are increased. During our study period, the utility implemented nine increases in fixed rates and price tiers for all meter sizes.



*Profile of the Fort Collins Foothills.  
Photo by Fort Collins Utilities.*

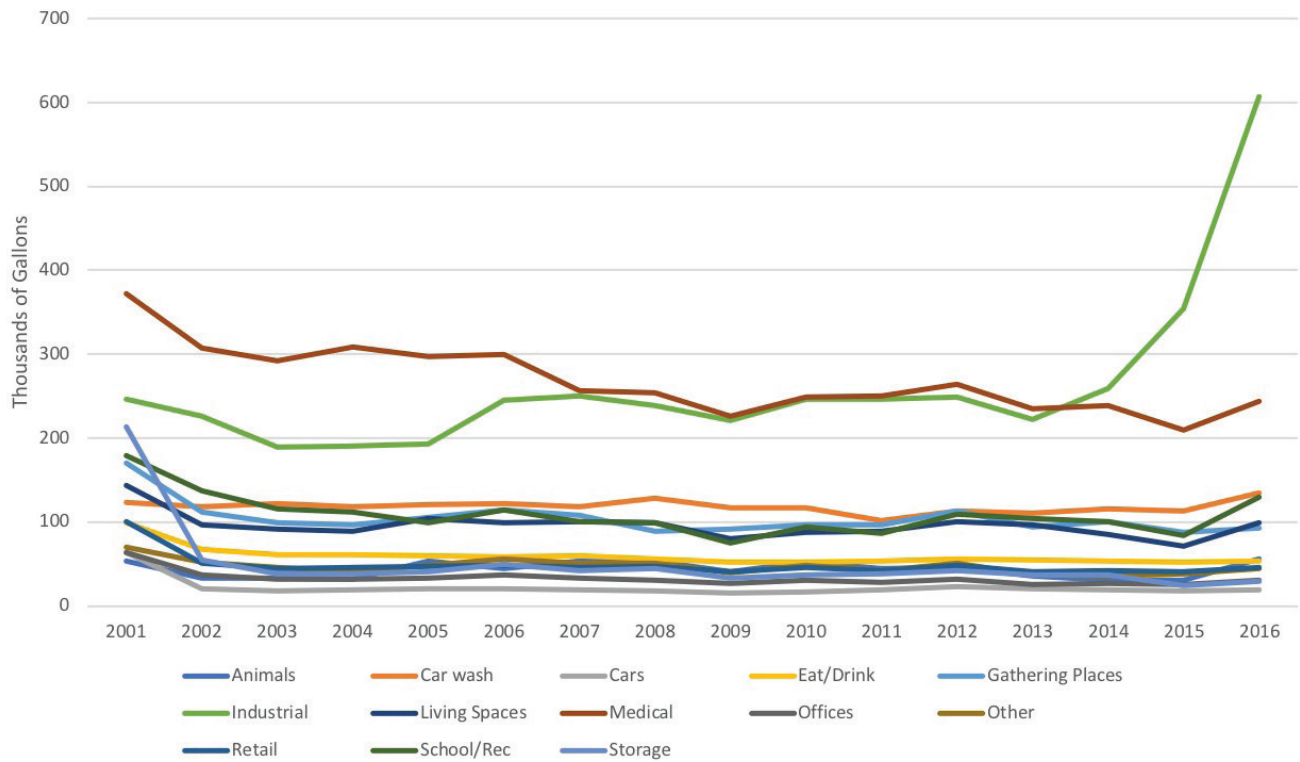


Figure 1. Average billed consumption (gallons) by commercial category.

In order to estimate price responsiveness across different commercial categories, we merged Assessor data, which includes a variable for business type. We were able to match a business type to 1,633 of 2,956 commercial premises or 251,721 observations. This yielded 99 different business types, from which we created 13 broad commercial categories. We based these groups primarily on similarities in characteristics of their water use as similar water uses often place similar demands on the system.

We also matched the water data with climate data from the National Oceanic and Atmospheric Administration (NOAA). This data included maximum/minimum temperature and total precipitation from several climate stations throughout Fort Collins. All temperature and precipitation readings were averaged by month and assigned to a water consumption observation based on the meter read date. Finally, we matched each observation with the percentage of Fort Collins land under a level 3 drought at the meter read date according to the United States Drought Monitor.

## Results and Discussion

In our first price test, we considered whether businesses respond more to contemporaneous (current period) marginal price or previous period (lagged) average price. We discovered evidence that businesses respond more to lagged average price than marginal price. This is not a surprising result as businesses face the same difficulty in determining their marginal

price as the average homeowner. Ascertaining marginal price requires reading the meter and a full knowledge of the pricing schedule, whereas calculating average price only requires a basic understanding of the last water bill received.

There are other prices that businesses may be responding to outside of marginal price and lagged average price. We also tested how businesses respond to three other pairs of prices: (1) contemporaneous marginal price or contemporaneous average price, (2) contemporaneous average price or lagged average price, and (3) the average monthly price over the previous 12 months or lagged average price. We found weak evidence that businesses responded more to contemporaneous average prices than contemporaneous marginal prices. While further evidence indicated that businesses responded more to lagged average prices than contemporaneous average prices and responded more to lagged average price than the average price over the past 12 months. These test results combined with our first price test provided evidence that businesses responded more to lagged average price than a number of other prices available to the firm.

This result has important implications for utility pricing. Utilities and policymakers can increase marginal prices without affecting the average price. If utilities believe that businesses respond to marginal price, they would expect this type of price change to elicit demand reductions. However, if businesses respond more to average price than marginal price, there would likely be very little, if any, reduction. Instead, util-


ities and policymakers would have to increase average price by simply raising the fixed cost faced by each firm. This type of price change may also be more politically palatable than an across-the-board increase in the marginal rates.

Next, we estimated the price responsiveness of water demand for our thirteen commercial categories. In our demand equation, we included the lagged average price (our preferred price from the price tests), climate and weather variables, and other controls to capture time-invariant firm characteristics that could impact consumption.

In seven of our thirteen commercial groups, we found statistically significant price responses. In each of these groups, the price response was negative, meaning an increase in lagged average price induces a decrease in water demanded. Our least responsive categories were retail and office, where a 10% increase in price led to around a 1% decrease in consumption. Our most responsive groups were car wash and industrial, where a 10% decrease in price led to a 16% and 20% reduction in price, respectively. We found it unsurprising that car wash and industrial businesses were more price responsive because their primary business involves water use. Likewise, we found it unsurprising that retail and office business were less price responsive because water use likely accounts for very little of their primary business. There are several factors that may contribute to insignificant price response estimates in the other categories. For example, we may expect non-responsiveness in categories where water use is essential, like the Medical category. For other categories, the reasons are less evident.

In summary, our study found that businesses responded more to lagged average price than contemporaneous marginal price or a number of other prices. Furthermore, we discovered that price responsiveness varied among different commercial categories, with some categories like retail and office proving far less responsive than others.

This latter result has particularly important implications for utilities and policymakers facing the municipal and industrial water supply and demand gap. Utilities spend considerable energy planning for future growth in their customer base. If a utility predicts most growth will come from more price responsive categories like car wash and industrial, they can utilize price policies to manage future demand and minimize the gap. However, if the growth is expected primarily in less responsive categories, the utilities will need to plan and test the effectiveness of their non-price conservation policies.

*This project was funded by the Colorado State University Water Center.* 

*The Poudre River.  
Photo by Fort Collins Utilities.*



An aerial photograph of a stream flowing through a snowy, forested landscape. The stream is surrounded by dense evergreen trees and patches of snow. The water is clear, and the surrounding terrain is rugged and rocky.

# **Stream Habitat Mapping Using Unmanned Aerial Vehicles**

Yoichiro Kanno, Fish, Wildlife, and Conservation Biology, Colorado State University;  
Christopher Post, Forestry and Environmental Conservation, Clemson University



## SYNOPSIS

Habitat degradation and loss is a primary cause for imperilment of freshwater biota, and thus inventorying and monitoring stream habitat is paramount to aquatic sustainability. Traditionally, stream habitat has been characterized using a tape measure and other devices on foot, which prohibits sufficient spatial coverage in an efficient manner. In this study, we tested the utility of Unmanned Aerial Vehicles (UAV: a.k.a. “drone”) in mapping two streams in Colorado. The technology allowed spatially continuous mapping of stream habitat, and features such as substrate and channel drying could be identified on photographs. The use of UAV can be a powerful tool for characterizing stream habitat beyond local pools and riffles without sacrificing resolution at such a local scale.

### Introduction

Growing demand for freshwater has proved challenging for sustaining aquatic ecosystems in Colorado and across the globe. Many freshwater species (e.g., fish and insects) are imperiled - the major cause of which has been habitat degradation and loss due to anthropogenic activities. Conserving freshwater habitats and the processes that create them is widely recognized as a requirement for aquatic biodiversity. For

example, a set of “critical habitats” need to be designated for endangered or threatened species under the U.S. Endangered Species Act, which plays a key role in the recovery efforts of these species. States similarly emphasize the importance of stream habitat protection and restoration in their legislation and management action plans. Accordingly, measuring and inventorying stream habitat at multiple spatial and temporal scales provides background information for planning aquatic conservation.

Stream habitat has been traditionally measured on foot. A tape measure and meter stick are simple but useful tools for measuring habitat volume (e.g., stream width and depth). Stream ecologists also visually assess habitat conditions, such as riparian cover, substrate size, and stream intermittency. These types of habitat measurements continue to be trustworthy friends for stream ecologists, but it can be time-consuming and labor-intensive to walk along a few kilometers and measure local pools and riffles in such a manner. However, measuring aquatic habitat beyond local pools and riffles (tens of meters) is important because aquatic species typically

*(Above) Figure 2. A vertical view down from UAV at Dry Gulch. Individual cobbles and boulders can be seen on the image. White areas are the stream bank covered with snow. Photo by Christopher Post.*



*Figure 1. An image of Dry Gulch taken from the air by an UAV. Photo by Christopher Post.*

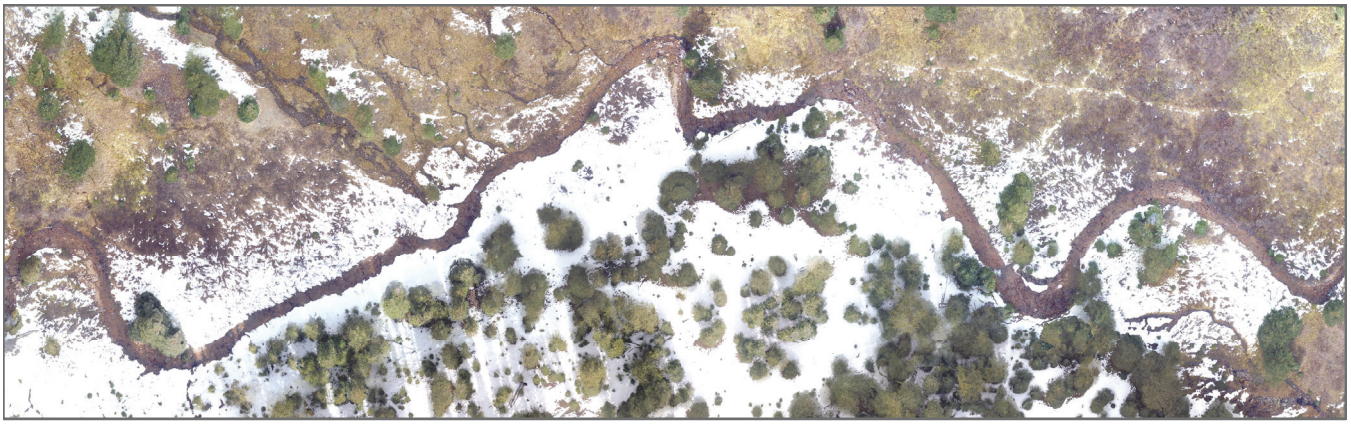


Figure 3. Mosaic showing stream area surveyed at Dry Gulch. Photo by Christopher Post.

disperse as they grow, and their habitat needs to be characterized to encompass the spatial extent of movement over their life history. In many instances, stream habitat connectivity by itself is of great interest.

In this study, we used Unmanned Aerial Vehicles (UAV: a.k.a. “drones”) to map a 1.6-km habitat stretch in two streams within Colorado. The two streams were located in contrasting geographies (Dry Gulch in the Rocky Mountains and Arikaree River in the Great Plains) to assess the applicability of the technique in a range of conditions.

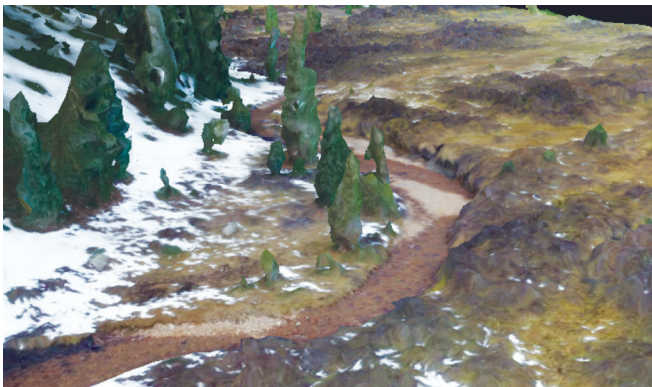


Figure 4. Example of 3D information available from mosaiced photos at Dry Gulch. Photo by Christopher Post.

## Methods

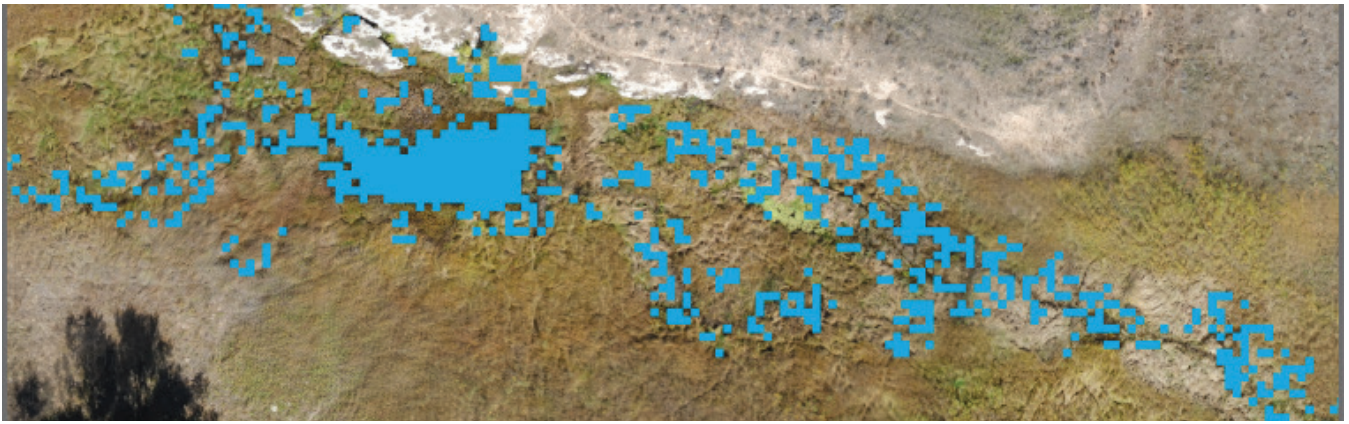
This study was conducted at two streams in Colorado, Dry Gulch, and Arikaree River. Dry Gulch (39.698111, -105.878264) is a headwater stream located in the Rocky Mountains at an elevation of approximately 3,200 m at the most downstream location of the study area. A reintroduction effort of greenback cutthroat trout (*Oncorhynchus clarki stomias*) is underway by the Colorado Parks and Wildlife Service, and juvenile greenback cutthroat trout were reintroduced

to the study site in July 2017 after removing existing cutthroat trout. If successful, the reintroduction effort will establish one of few wild-reproducing populations of the state fish of Colorado. Arikaree River (39.760300, -102.464257) is a low-gradient, soft-bottom Great Plains stream located in Yuma County, eastern Colorado. The study site was located on the Fox Ranch owned by The Nature Conservancy. Arikaree River maintains a relatively intact native fish assemblage composed primarily of minnows and darters, but the river has been literally shrinking due to a declining water table from groundwater pumping for agricultural irrigation. A good portion of the river stretch at the study site becomes intermittent as agricultural irrigation intensifies through summer.

In both study streams, a 1.6-km segment was surveyed by UAV from the air, taking hundreds of individual images at approximately 60m above the stream channel. Dry Gulch was surveyed on October 5-6, 2017 and Arikaree River on October 7, 2017. Two types of UAVs were used: a quadcopter and a fixed-wing UAV, each with a 20-megapixel camera. Individual photos were combined into mosaics to provide a seamless image of the habitat, which also provided 3D information for the stream and surrounding vegetation.

## Results and Conclusions

UAVs provided high-resolution images of stream habitat at Dry Gulch and Arikaree River. Stream sinuosity and substrate was quantifiable at Dry Gulch, and individual cobbles and boulders could be identified in some instances (Figure 1-4). Stream sinuosity affects pool-riffle formation, which affects cutthroat trout distribution and abundance, and substrate composition influences habitat selection by stream fish. Thus, mapping these features from the air is a key technological advance in stream fish ecology. At Arikaree River, dry stream reaches could be spotted on UAV-taken images (Fig. 5). Streamflow is diminished in late summer through early fall due to groundwater pumping at Arikaree River, which results in a series of pools remaining between dry reaches. Computer vision algorithms are being developed to automatically identify and quantify water locations (Figure 6). These remaining




*Figure 6. Example of computer vision algorithms being developed to automatically identify wet channels. Photo by Christopher Post.*

pools become key refugia for native Great Plains fishes at Arikaree River. Accordingly, mapping the chain of fish habitat along the river corridor is important for understanding habitat connectivity and dynamics.

Results of this study show a promise in more widespread applications of UAV technology in stream ecology and conservation. The technology makes it possible to inventory stream habitat over a few kilometers without walking along the stream, and in fact, without walking a step once the operator is set on the bank. In recent years, the use of UAV has increased in natural resources management; examples include

abundance surveys of large-bodied marine mammals, stream temperature measurements, and invasive bird eradication by dropping dry ice onto tree-top nests. Further research is warranted to assess the utility of UAV technology in advancing aquatic ecology and sustainability by expanding spatial coverage without sacrificing resolution at the finer scale.

*This research was supported by a Water Faculty Fellow grant from the Colorado State University Water Center.* 

*Figure 5. A bird's eye view of the Arikaree River and its riparian area taken from an UAV at the Fox Ranch owned by The Nature Conservancy. Photo by Christopher Post.*





# Does Long-Term Exposure to Metals Permanently Alter the Structure of Benthic Food Webs in Stream Ecosystems?

William H. Clements, Fish, Wildlife, and Conservation Biology, Colorado State University;  
Brian Wolff, Fish, Wildlife, and Conservation Biology, Colorado State University;  
Edward K. Hall, Natural Resource Ecology Laboratory, Colorado State University;  
Katy A. Warner, Natural Resource Management Field Institute, Colorado Mountain College

## SYNOPSIS

Failure to implement pre- and post-restoration monitoring is a serious impediment to our ability to assess the effectiveness of stream restoration programs. The objective of our research is to test the hypothesis that improvements in water quality, habitat, and riparian vegetation in the Arkansas River (Colorado) will result in improvements in macroinvertebrate and other prey resources for brown trout. Our results support the hypothesis that aquatic communities in this system have shifted to an alternative stable state that may not return to pre-disturbance, reference conditions.

## Introduction and Background

The likelihood that degraded ecosystems can recover following the removal of a stressor and the length of time required for these systems to return to pre-disturbance conditions

remain critical questions in applied ecology (Millennium Ecosystem Assessment, 2005). However, long-term monitoring programs that evaluate recovery of degraded ecosystems following restoration are relatively rare. Failure to implement effective pre- and post-restoration monitoring remains a serious impediment to our ability to assess the effectiveness of stream restoration programs (Bernhardt, 2005). Mining in the Upper Arkansas River Basin began in the 1800s, resulting in significant degradation of water quality and aquatic communities. In 1983, the Yak Tunnel and California Gulch (CG) were placed on the U.S. Environmental Protection Agency (EPA) National Priorities (“Superfund”) list. A large-scale restoration program is currently underway in the upper Arkansas River Valley near Leadville, Colorado (Figure 1). For the last 29 years, (1989-present) our laboratory has monitored responses of benthic macroinvertebrate communities, the primary prey of brown trout, to improvements in water





Figure 1. Photos of the Arkansas River immediately below the California Gulch Superfund site. Photos were taken before and after completion of water treatment and habitat restoration operations.

quality and habitat. These data represent the longest continuous record and most comprehensive quantitative assessment of benthic communities and water quality in North America. The primary objective of our research is to test the hypothesis that improvements in water quality, habitat and riparian vegetation will result in improvements in macroinvertebrate and terrestrial prey resources for brown trout. The second objective of our research is to determine if exposure to metals alters the macromolecular composition of bacteria in ways that affect food quality for invertebrate consumers.

## Materials and Methods

**Field Monitoring-** Routine physico-chemical (pH, specific conductance, temperature, hardness, and alkalinity) and metals analyses were conducted at 4-8 stations in May, August, and September 2017. To estimate transfer of metals to higher trophic levels, biofilm, seston, and macroinvertebrates were collected from five stations and analyzed using atomic adsorption spectrophotometry. To quantify responses of macroinvertebrate communities to metals and restoration treatments, replicate (n = 5) benthic macroinvertebrate samples were collected from sites upstream and downstream from the California Gulch Superfund site.

**Mesocosm Experiments-** To quantify responses of benthic communities to long-term improvements in water quality, a stream mesocosm experiment was conducted in October 2017 using a technique previously developed in our lab (Clements et al., 2002; Clements et al., 2013). Briefly, benthic communities were collected in the

field using trays (10 x 10 x 6 cm) filled with small cobble placed at stations AR1 (reference) and AR5 (impacted). After 35 days colonization, trays from each station were placed into individual coolers (four trays per cooler) filled with ambient stream water and transported to CSU's Stream Research Laboratory. The four trays within each cooler were placed in stream mesocosms using a 2 X 2 factorial experimental design with four treatments: 1) control AR1; 2) control AR5; 3) metals AR1; and 4) metals AR5. Peristaltic pumps delivered metals from 20-L carboys at 10-mL/min to

obtain nominal concentrations of 25- $\mu\text{g/L}$  Cu and 650- $\mu\text{g/L}$  Zn in treated streams. After 10 days, trays from each stream were collected, and contents were sieved to remove surviving organisms. Samples were preserved in 80% ethanol and all organisms were identified to the lowest practical taxonomic level (genus for most taxa; family for chironomids). To test the hypothesis that downstream, metal-tolerant communities are more sensitive to novel stressors, a second mesocosm experiment was conducted in which organisms were exposed to diesel fuel.

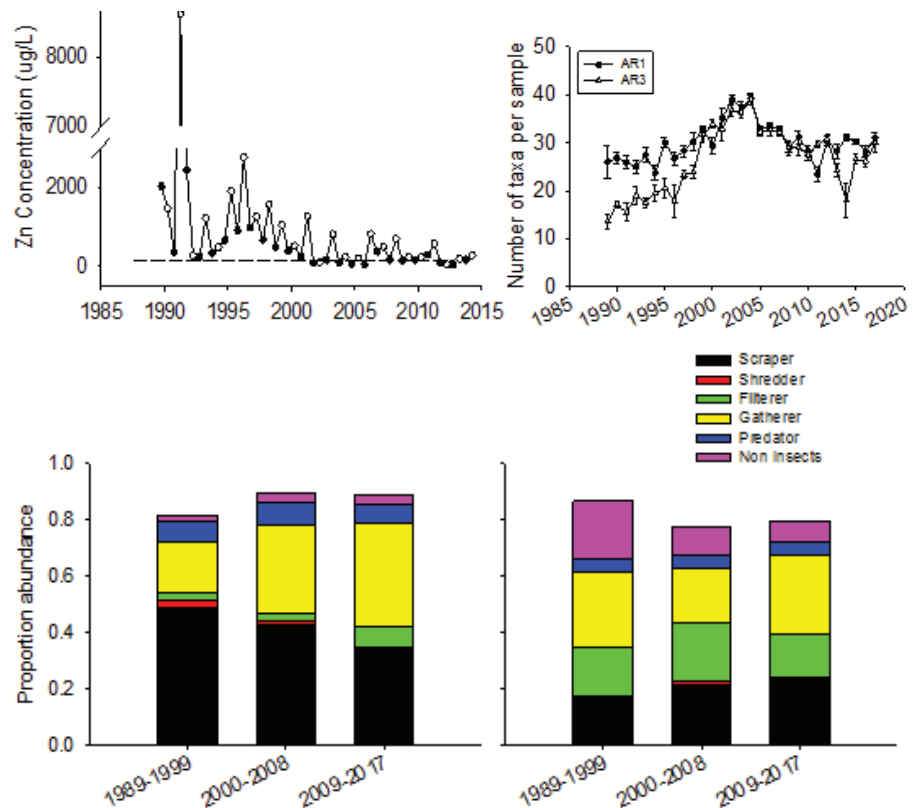


Figure 2. Long-term changes in the concentration of Zn, number of taxa (upper panels), and food web composition (lower panels) at upstream and downstream stations in the Arkansas River, Colorado.

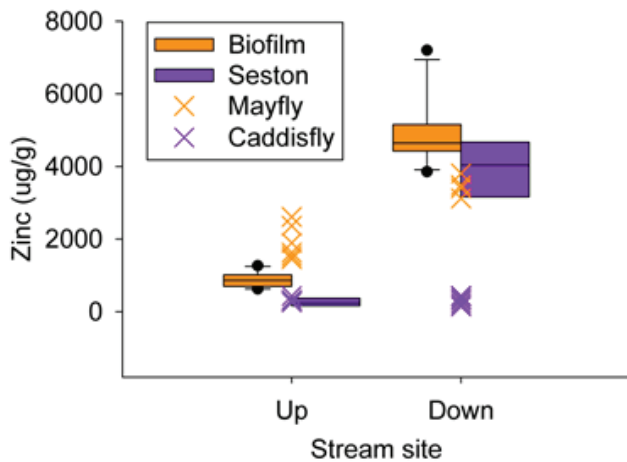


Figure 3. Concentrations of Zn in biofilm, seston, and macroinvertebrates collected from upstream and downstream stations in the Arkansas River.

**Microbial Community Analyses**-Microbial samples were taken at field sites upstream and downstream for CG in the summer of 2017 (August 8, 2017). Microbial biofilm samples included sediments, epilithon (biofilm scraped from river cobblestone), and seston (suspended particles in the river column). Additionally, biofilm was collected in spring and fall as part of our routine monitoring of the microbial communities in our study area. From each site, we extracted DNA and sequenced the V4 region of the 16S rRNA gene to identify members of the extant community. An in-vivo field fluorometer (BenthoTorch; bbe Moldaenke, Kiel, Germany) was used to estimate biomass of the dominant microbial communities

upstream and downstream of CG. Differences in bacterial communities were compared using non-metric multidimensional (NMDs) scaling.

## Results and Discussion

Metal concentrations measured downstream from the CG Superfund site have decreased significantly following completion of water treatment facilities in 2000 (Figure 2). Although some measures of ecological integrity (e.g., species richness and diversity) have recovered following these improvements in water quality and habitat, community composition and the structure of benthic food webs have remained significantly altered. In particular, downstream benthic communities were characterized by fewer grazing organisms, more filter-feeders, and were dominated primarily by taxa known to be tolerant to metals.

The composition of autotrophic communities in biofilm differed between upstream and downstream sites, with a greater abundance of diatoms at upstream sites and greater cyanobacteria ('blue-green' algae) below CG. Interestingly, we found very low (< 0.5%) biomass of green algae at downstream sites, whereas green algae comprised ~8% of the algal community at the upstream reference sites. Because cyanobacteria are thought to be a relatively poor resource for benthic macroinvertebrates compared to diatoms and green algae, the increase of cyanobacteria supports our hypothesis that nutritional quality downstream from CG is poor compared to upstream reference sites.

Biofilm and seston are the primary routes of dietary exposure of metals to mayflies and caddisflies, respectively. Concentrations of Zn were significantly greater in biofilm and

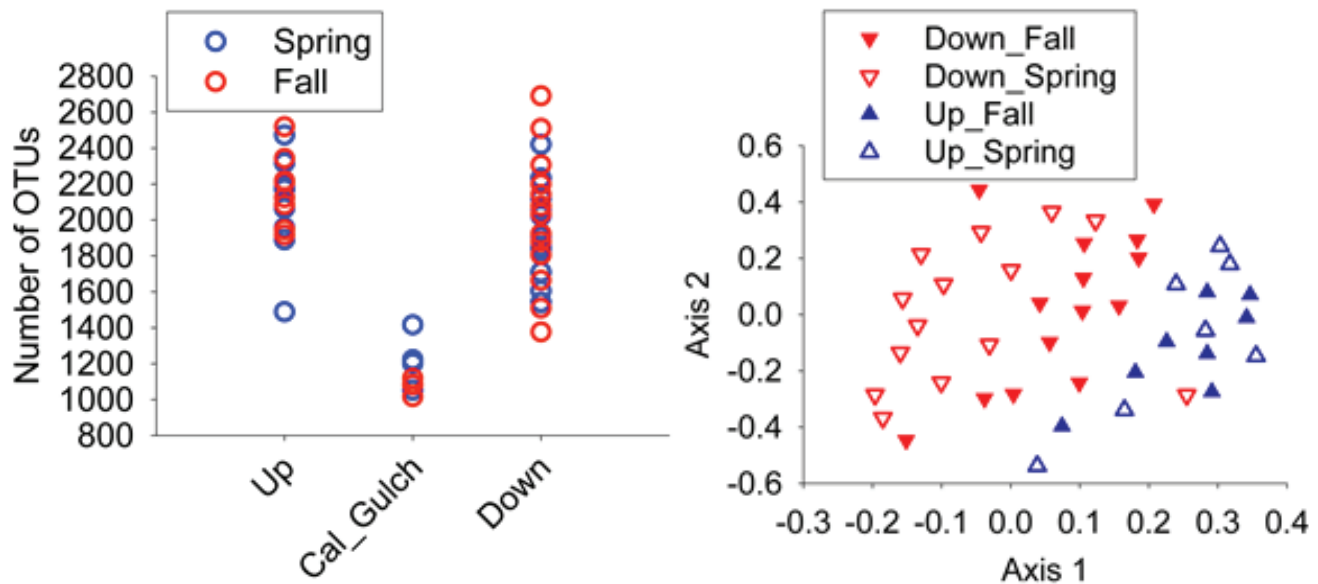


Figure 4. Taxonomic richness (defined as operational taxonomic units, OTUs; left panel) and similarity (right panel) in bacterial community composition upstream and downstream from California Gulch in the Arkansas River.

seston collected downstream from CG, demonstrating that exposure to metals remained elevated at these sites (Figure 3), despite improvements in water quality. Interestingly, only mayflies, organisms known to be highly sensitive to metals, showed significantly elevated levels of Zn at the downstream sites.

Microbial richness, defined as the number of operational taxonomic units (OTUs), was similar at upstream and downstream stations but significantly lower in CG (Fig. 4). Consistent with patterns observed in macroinvertebrate communities, the membership of microbial communities was strikingly different between upstream and downstream sites. We also observed that bacterial isolates (representing a diverse set of phyla) grown in the presence and absence of Zn differed in both biomass stoichiometry (an indicator of resource quality) and metal content. These changes in microbial community composition in response to metals have the potential to alter stream food webs through dietary exposure pathways.

Results of the mesocosm experiment comparing responses of communities from upstream and downstream stations to metals were remarkably consistent with those of experiments conducted in 2009, 2014, and 2016 (Figure 5). These experiments showed that aquatic macroinvertebrates from the downstream station (AR5) remained significantly more tolerant to metals, despite improvements in water and habitat quality over the past 15 years. More importantly, our results showed that metal-tolerant communities from station AR5 were more sensitive to diesel fuel compared to those from the reference site.

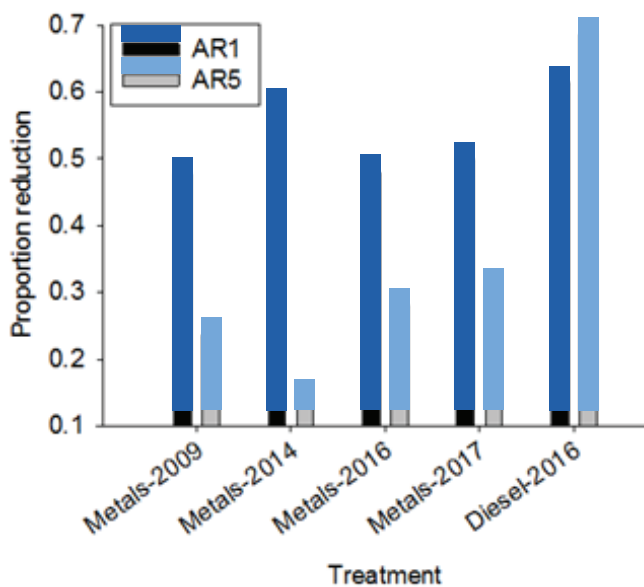
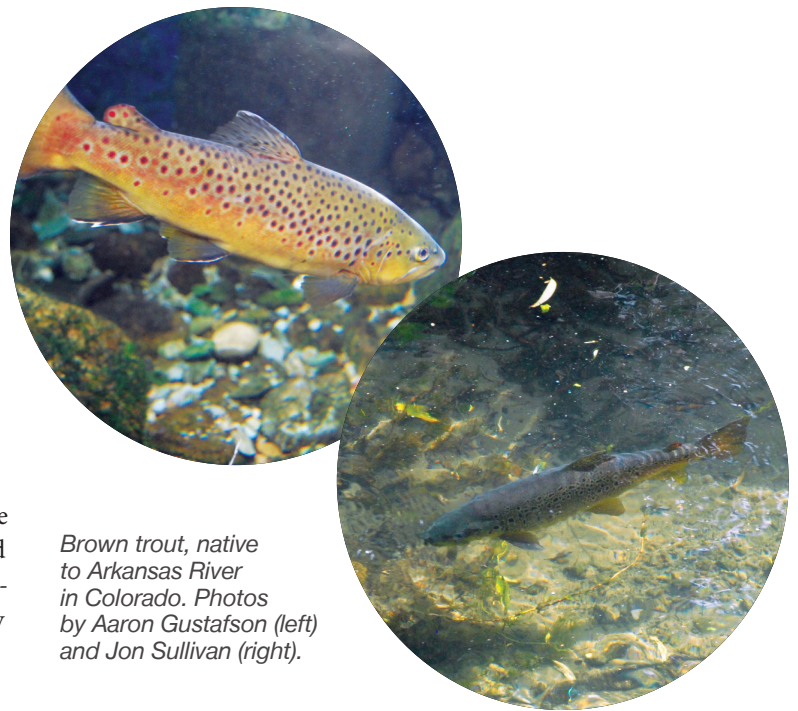


Figure 5. Results of mesocosm experiments conducted in 2009, 2014, 2016, and 2017 showing effects of metals or diesel fuel on total abundance of Ephemeroptera, Plecoptera, and Trichoptera (EPT). The figure shows the proportion reduction at upstream (AR1) and downstream (AR5) stations in the Arkansas River.

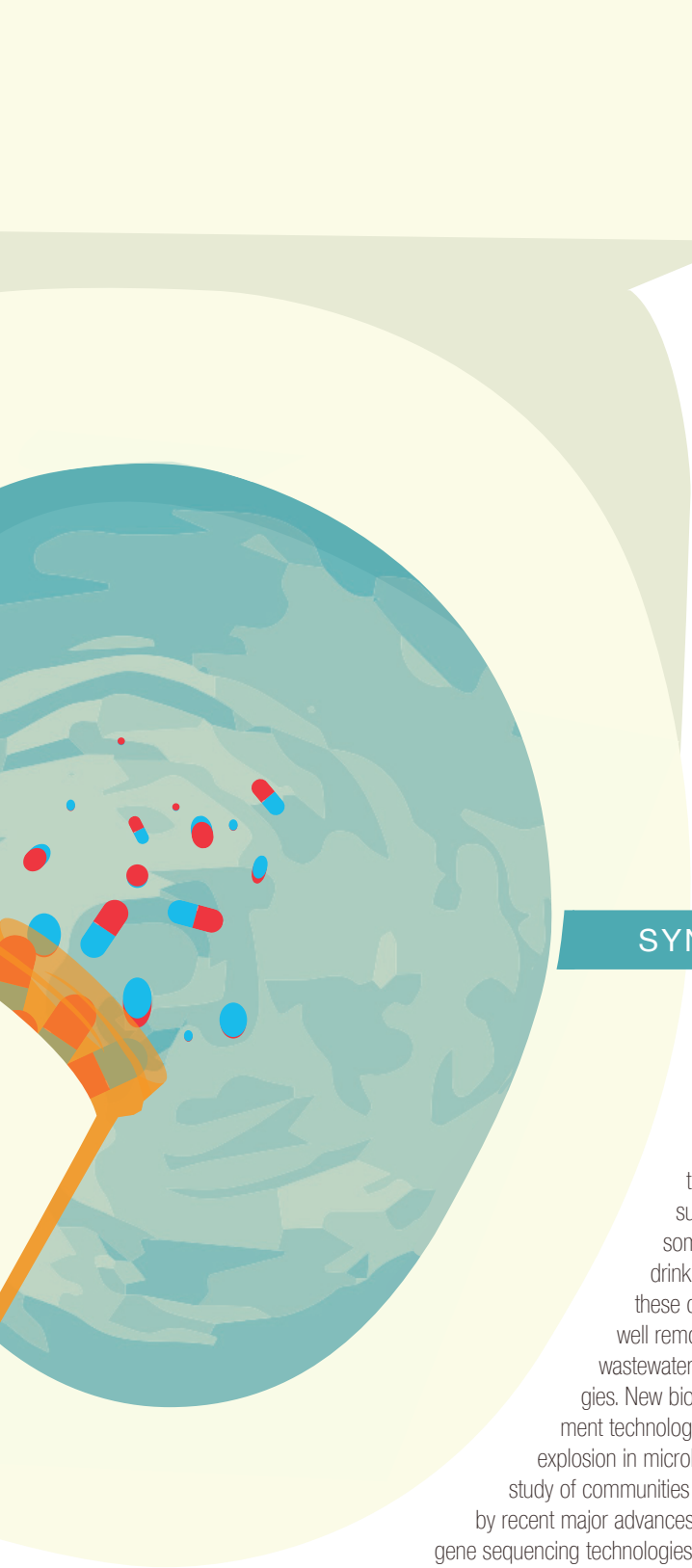


Brown trout, native to Arkansas River in Colorado. Photos by Aaron Gustafson (left) and Jon Sullivan (right).

## Conclusions and Future Research

The most significant finding of our research is that despite reductions in aqueous metal concentrations and improvements in habitat quality over the past 15 years, benthic communities (macroinvertebrate and microbial) downstream from the California Gulch Superfund site remain impaired and dominated by metal-tolerant species. Concentrations of metals in biofilm and seston were also elevated, resulting in greater exposure to some organisms. Results of our mesocosm experiments demonstrate that, despite greater tolerance to metals, these communities were more sensitive to diesel fuel. These findings are consistent with our previous experiments conducted with other novel stressors (acidification; UV-B radiation) and suggest a potential cost to metal tolerance in downstream communities (Courtney and Clements, 2000; Kashian et al., 2007). Our results support the hypothesis that benthic communities in the Arkansas River have shifted to an alternative stable state (Scheffer, 2001) and are part of a “novel” ecosystem (sensu Hobbs et al., 2009) that may not return to pre-disturbance, reference conditions. The structure and composition of autotrophic producers and microbial communities were also significantly different downstream. These results support our hypothesis that the failure of benthic communities in the Arkansas River to recover is partially a result of alterations in basal food resources and poor food quality downstream from CG. Future studies will focus on improving our understanding of the mechanisms that are responsible for the failure of these communities to recover.

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# Getting Pharmaceuticals and Personal Care Product Chemicals Out of Our Water

Susan K. De Long, Civil and Environmental Engineering, Colorado State University;  
Karen Rossmassler, Civil and Environmental Engineering, Colorado State University;  
Corey Broeckling, Proteomic and Metabolomics Facility, Colorado State University;  
Jessica Prenni, Proteomic and Metabolomics Facility, Colorado State University

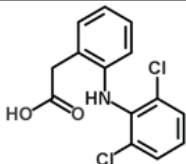
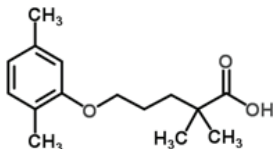
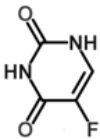
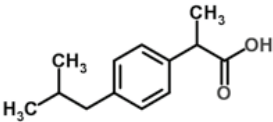
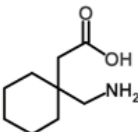
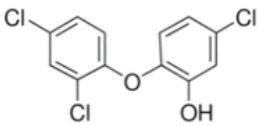
## SYNOPSIS

Pharmaceuticals and personal care products (PPCPs) are now routinely detected in treated wastewater, surface water, and sometimes even treated drinking water because these chemicals are not well removed by conventional wastewater treatment technologies. New biologically based treatment technologies are promising. The explosion in microbiome science (the study of communities of microbes), enabled by recent major advances in next-generation gene sequencing technologies, is providing an unprecedented opportunity to advance our understanding of microbes that degrade PPCPs. Herein, a technique called metagenomics, which involves sequencing the genomes of a whole community of microbes, was used to probe microbes involved in degrading PPCPs. Our work has helped identify types of microbes that may be particularly useful to cultivate for applications in PPCP treatment. Additionally, we have identified a suite of genes that may prove to be useful biomarkers for PPCP degradation; that is, these genes can be tracked to monitor the health of PPCP treatment reactors and guide the development of a new generation of microbiome-science-enabled water treatment technologies.

**P**harmaceuticals and personal care products (PPCPs) are now routinely detected in treated wastewater, surface water, and sometimes even treated drinking water. We take medications and use other chemicals routinely, such as antimicrobials found in soaps or in toothpaste, or fragrances in shampoos. These chemicals enter the municipal wastewater stream; only a fraction of medications consumed are metabolized in the body, while the remainder end up in the wastewater. PPCPs are present in treated wastewater due to minimal removal by existing wastewater treatment technologies, and thus PPCPs are released into the environment, albeit at very low concentrations. Discharged PPCPs can sometimes reach drinking water sources, presenting the risk they will ultimately be ingested by consumers. Due to advances in analytical chemistry, these chemicals can now be detected at incredibly low concentrations (ng/L or less), which has allowed for tracking of these chemicals through the water system. PPCP ingestion through drinking water represents a potential human health risk, although human toxicological studies following populations chronically exposed to realistic (extremely low) levels of these compounds are lacking. However, if we are to follow the precautionary principle, treatment technologies are needed to remove these chemicals from the water system.

Physical/chemical water treatment technologies exist, including advanced oxidation processes and reverse osmosis, but these technologies are expensive, have high energy needs, and can produce problematic waste streams. These challenges limit the use of physical/chemical treatment technologies. To date, these treatments are only being implemented for potable water reuse projects. Water treatment engineers and practitioners desire new treatment technologies that are low cost and avoid the aforementioned pitfalls of existing technologies. Biological PPCP treatment technologies, including biofiltration and soil aquifer treatment (SAT), are promising because they can potentially achieve treatment cheaply and sustainably (e.g., with a minimal carbon footprint). In biological treatment, bacteria break down contaminants into innocuous substances resulting in their removal. These beneficial bacteria can be grown in engineered filters (e.g., sand filters) or within ecological treatment systems (e.g., the soil in an aquifer recharge basin). This approach is well documented for removal of more conventional contaminants (nitrate biofiltration) but has yet to be developed for PPCPs. PPCP biodegradability has been documented in laboratory studies, and both biofiltration and aquifer treatment have been investigated among other technologies. However, reported PPCP removal efficiencies vary widely, for reasons that have been poorly understood. The key microbes that can be used to remove PPCPs in water treatment systems, and the biochemical mechanisms, remain poorly understood, despite decades of study, because PPCP biodegradation is highly complex, involving dozens of compounds and probably an equally long list of the types of microbes. Although biological PPCP treatment technologies have been researched for many years, we still do not have a sufficient fundamental understanding of the biology to design robust treatments.

Table 1. Chemical structure and therapeutic class of the target compounds.

Compound (Therapeutic class)	Structure	Compound (Therapeutic class)	Structure
Diclofenac (NSAID)		Gemfibrozil (Lipid regulator)	
5-Fluorouracil (Anticancer drug)		Ibuprofen (NSAID)	
Gabapentin (Anticonvulsant)		<u>Triclosan</u> (Antiseptic agent)	

Simultaneously, we are seeing an explosion in the study of microbiomes - communities of microbes, or bacteria forming microbial ecosystems - including gut microbiomes, soil microbiomes, and even water treatment microbiomes. The field of microbiome science is enabled by recent major advances in gene sequencing technologies. These big data approaches appear well poised to help tackle the questions of which microbes will be the most useful for PPCP treatment and what mechanisms and genes are involved. Specific types of microbes or genes involved in PPCP treatment could be tracked as useful indicators of process health both for technology development and for eventual monitoring of full-scale systems. So identifying a broad range of microbes or genes that can be linked with degradation covering the myriad classes of PPCP compounds would enable a novel, and exceptionally powerful, toolbox for probing the microbiomes underpinning a promising new “green” PPCP treatment technology.

Thus, in our study, we leveraged cutting-edge metagenome sequencing and analysis methods to probe different microbiomes capable of degrading a range of model PPCPs.

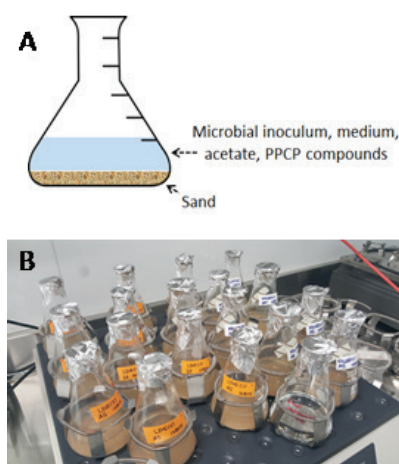


Figure 1. Diagram (A) and photo (B) of the biodegradation tests. Sand is added for the bacteria to grow on (i.e., produce biofilms) as they would in the biotreatment processes being developed.

Table 2. Enzymes found that may be involved in degrading PPCP chemicals.

Enzyme	CA	HP	ML	OA	PN
Cytochrome p450 (hydroxylase)	++	++	++	++	++
Cytochrome b	+++	+++	+++	+++	+++
Catechol 2,3 dioxygenase	++	++	-	-	++
Aromatic dioxygenase IpfA (large subunit)	++	++	++	++	++
Aromatic dioxygenase IpfB (small subunit)	++	++	++	-	++
Catechol 1,2 dioxygenase	++	++	++	-	-
Ammonia monooxygenase	-	-	-	-	+

CA = casamino acids, HP = humic acids and peptone, ML = molasses, OA = organic acids, PC = Phenol.  
 +++ Abundant, ++ Present, + Rare, - Absent

The effective microbiomes were developed, via acclimation, from three sources: wastewater treatment activated sludge, ditch sediments that historically received wastewater effluent, and aquifer soils used in a short-term PPCP treatment study. PPCP biodegradation tests were previously conducted with these microbiomes for a suite of model compounds (Figure 1, Table 1). Secondarily, we have tested the impact of microbial carbon sources (feed sources) on PPCP removal, including casamino acids, phenol, organic acids, molasses, and humic acid-peptone mixtures.

Results showed that the carbon sources available to the microbes play a major role in determining the success of PPCP treatment (Figure 2). Then, we characterized the microbiomes for each of these carbon sources, by applying next generation sequencing technologies to the 16S rRNA gene, a “fingerprinting” gene used to identify the types of microbes present, much like a human fingerprint is used to identify an individual by pattern matching. Statistical analysis of this dataset allowed us to link specific types of microbes with favorable trends in PPCP removal within the context of the very complex micro-

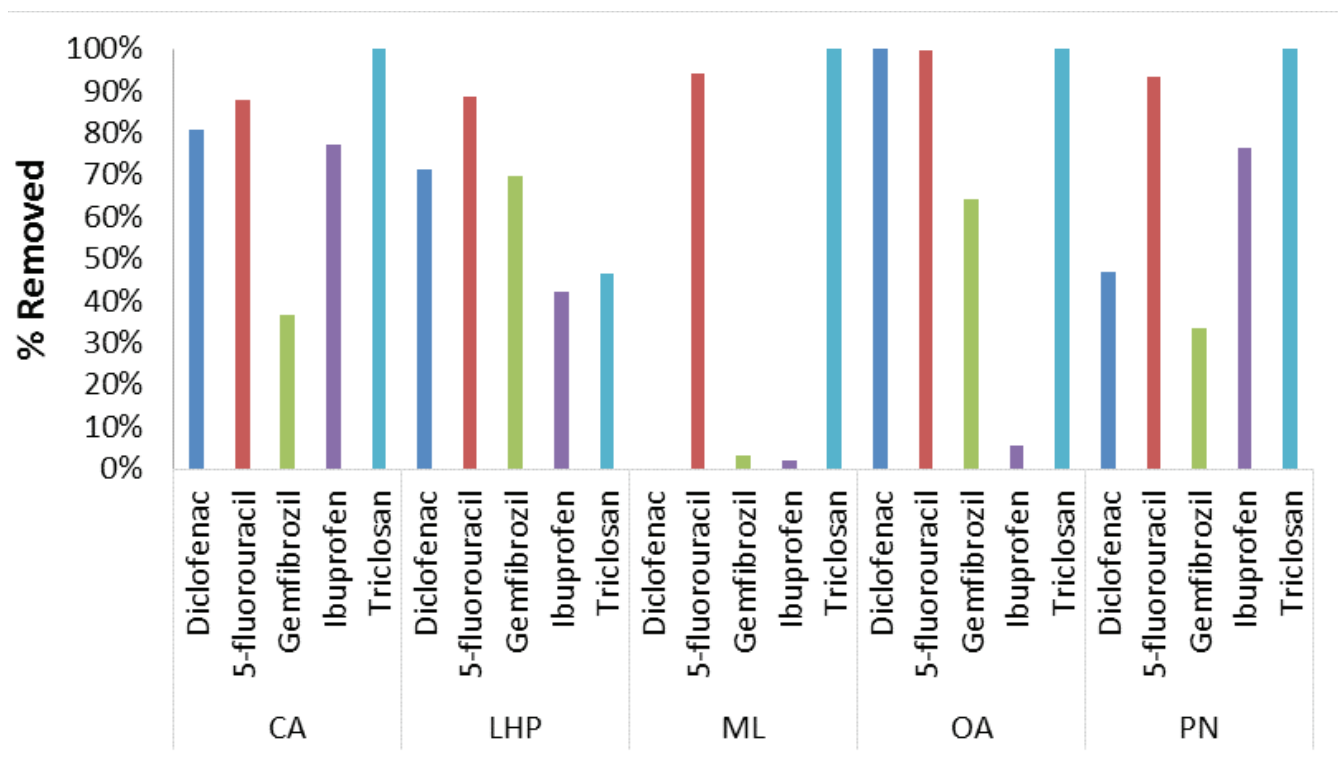


Figure 2. This graph shows the amount of each PPCP that could be removed by the bacteria within 4 days for each of the carbon feeds tested: casamino acids (CA), phenol (PN), organic acids (OA), molasses (ML), high levels of humic acids and peptone (HHP), and low levels of humic acids and peptone (LHP).

biomes found in reactor systems (Figure 3). We found that *Sphingomonas*, *Methylophilus*, and *Beijerinckia*, among other microbial types, could be linked with successful degradation of a range of PPCPs.

Next, we selected the five most promising or potentially informative samples for application of full metagenome sequencing and analysis using next-generation sequencing technology. Via a hypothesis-driven metagenome analysis approach, we found that cytochrome p450 hydroxylases, cytochrome b, a range of dioxygenases, and monooxygenase enzymes were present in our PPCP-degrading cultures and these may play a role in the PPCP degradation (Table 2). Future studies of the enzyme activities are needed to validate a role for these enzymes in PPCP degradation. However, identification of potentially critical enzymes within our metagenomes sheds light on mechanisms of PPCP removal for biologically based water treatment. Further, these data provide a first step in the development of molecular water treatment process monitoring tools that can guide technology development, process optimization, and field operation, because these tools can be used to track levels of required microbes.

To conclude this project, we plan to complete analysis of the metaproteomes (which involves identifying all of the enzymes or proteins produced by a whole community of

microbes) for the five microbiomes subjected to metagenomic analysis. These analyses will provide another line of evidence regarding whether the enzymes identified (Table 2) are likely involved; not all enzymes encoded in a genome are produced all the time, so if we find those enzymes are produced during PPCP degradation, we will be one step closer to learning whether they can play a critical role.

In summary, our investigations used cutting-edge microbiome science tools to advance the development of sustainable bio-based water treatment technologies. This project furthered our understanding of which types of microbes can play a role in successful treatment of PPCPs in water and completed the first step in developing advanced molecular monitoring tools—identifying genes linked with PPCP removal via metagenomics. Although there is still a long way to go, given the power of the “meta-omic” tools applied here, if we see a sufficient investment of resources, we will undoubtedly see rationally designed, robust, biologically-based PPCP treatment technologies being applied in the field in the not too distant future.

*This project was funded by the Colorado State University Water Center.*

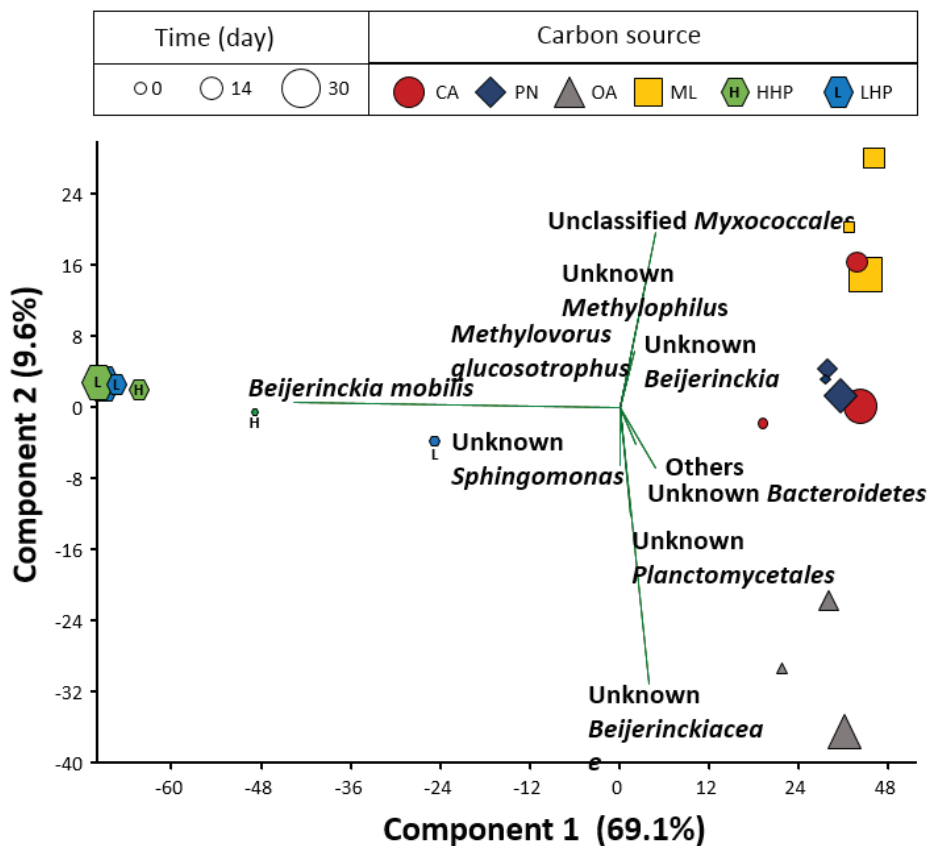


Figure 3. This figure shows a principal component analysis of all the sequencing data generated to determine the types of bacteria that could be linked with successful degradation of PPCP chemicals. The different carbon feeds provided to the bacteria to stimulate their growth and activity include: casamino acids (CA), phenol (PN), organic acids (OA), molasses (ML), high levels of humic acids and peptone (HHP), and low levels of humic acids and peptone (LHP). The symbols on the graph that are close together have similar types of bacteria in them and the symbols that are far apart on the graph have very different types of bacteria in them. The green lines show the types of bacteria that were important for each carbon source; in the cases that the carbon sources supported PPCP degradation of a given model compound these bacteria could be linked with successful treatment of PPCPs.



# LIVING WITH FIRE & WATER

Ben Gannon, Colorado Forest Restoration Institute, Forest and Rangeland Stewardship, Colorado State University;  
Stephanie Kampf, Ecosystem Science and Sustainability, Colorado State University;  
Codie Wilson, Geosciences, Colorado State University;  
Kelly Jones, Human Dimensions of Natural Resources, Colorado State University;  
Yu Wei, Forest and Rangeland Stewardship, Colorado State University;  
Lee MacDonald, Natural Resource Ecology Laboratory, Colorado State University;  
Katherine Mattor, Forest and Rangeland Stewardship, Colorado State University;  
Peter Nelson, Civil and Environmental Engineering, Colorado State University;  
Tony Cheng, Colorado Forest Restoration Institute, Forest and Rangeland Stewardship, Colorado State University;  
Brett Wolk, Colorado Forest Restoration Institute, Colorado State University

## SYNOPSIS

Wildfire is considered a critical risk to community drinking water supplies in the western U.S. Our team integrates research from the physical and social sciences to better characterize wildfire risk to water supplies and to evaluate the effects of pre- and post-fire risk mitigation approaches.

### Introduction

Recent wildfires in Colorado and other western states demonstrate the vulnerability of community drinking water supplies to wildfire. The removal of ground cover and changes in soil properties can lead to very large increases in surface runoff and erosion that detach and convey ash, soil, and debris into rivers and reservoirs. The increased organic material, sediment, and debris can increase the cost and complexity of water conveyance, treatment, and storage. For example, post-fire erosion following the 1996 Buffalo Creek and 2002 Hayman Fires resulted in 500,000 m<sup>3</sup> of sediment deposition in Denver Water's Strontia Springs Reservoir. Ash and sediment inputs following the 2012 High Park fire prevented the Cities of Fort Collins and Greeley from using water from the Cache la Poudre River for over three months and necessitated shifts to alternative water sources to meet basic demands (Figure 1).

Although Colorado communities have identified wildfire as a critical risk to their water supplies, they have limited tools to evaluate which risk mitigation strategies would be most effective. Possible strategies include reducing fuels in source watersheds, fire suppression, infrastructure improvements, developing alternative supplies or water intakes, and post-fire

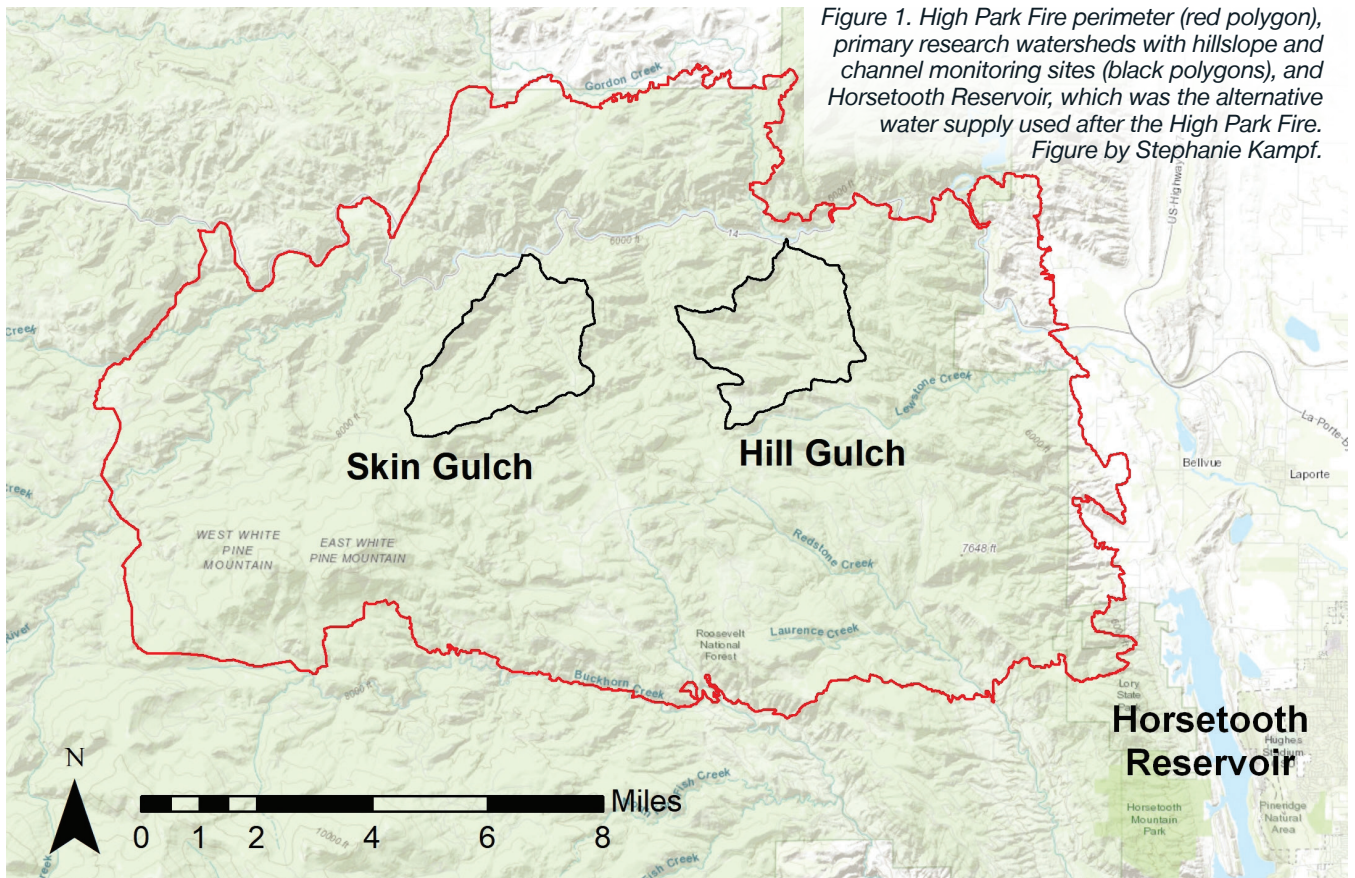
watershed rehabilitation. Our team is conducting a range of research studies and analyses to help communities predict the magnitude of potential fire effects and evaluate the costs and benefits associated with different management alternatives. Here, we present on recent efforts to improve predictions of post-fire physical processes, increase understanding of social and economic factors that influence wildfire risk mitigation and financing, and deliver locally-relevant decision support tools to land and water managers.

### Watershed Research and Modeling

Models are increasingly being used to predict post-fire erosion. Models help assess the benefits of pre-fire mitigation treatments, such as fuel reduction, and post-fire watershed rehabilitation activities, such as mulching. The most prevalent models are the Water Erosion Prediction Project (WEPP; Flanagan and Nearing, 1995) and the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997). These models were developed primarily from observations on small agricultural plots with gentle slopes. Model predictions, therefore, come with considerable uncertainty when applied to steeply forested watersheds, especially when combined with imperfect spatial data used to approximate topography, soil, ground cover, and rainfall. We used field data, a local empirical model, and evidence of erosion from aerial photographs to evaluate the performance of WEPP and RUSLE at hillslope to watershed scales (~0.1-1,500 ha).

We compared the predicted erosion from RUSLE and WEPP to sediment yield measurements from convergent hillslopes after the 2012 High Park Fire (HPF; Figures 1 and 2) to evaluate model performance at the hillslope scale. To assess





the value of RUSLE and WEPP for prioritizing management activities across larger watersheds, we compared the erosion predictions from RUSLE and WEPP to a local empirical model (Schmeer et al., 2018) applied to the hillslope portions of Hill and Skin Gulches (Figure 1). The local empirical model was developed from measured hillslope erosion rates following the High Park Fire, which related post-fire sediment production to rainfall depth, slope length, and percent bare soil (Schmeer et al. 2018). As an additional test, we compared erosion predictions from RUSLE, WEPP, and the local empirical model to the density of channel head locations in Hill and Skin Gulches mapped from high-resolution aerial photography. Channel head locations indicate where erosional features such as rills and gullies initiate.

Compared to field measurements of hillslope erosion, neither WEPP nor RUSLE represented erosion accurately ( $R^2=0.00$  and  $0.05$ , RMSE 20.4 and 2.8, respectively). Hillslope erosion rates were better correlated with observed erosion for the empirical model ( $R^2=0.60$ , RMSE 5.2), which makes sense as this was locally derived and calibrated using the measured HPF data. We also found that the empirical model correlation with observations declined when used with radar-derived rainfall and bare soil estimates from satellite imagery ( $R^2=0.14$ ), highlighting the importance of accurately characterizing these variables. We are also comparing the erosion model predictions across two watersheds within the

High Park Fire, Skin Gulch, and Hill Gulch. The location of channel heads across watersheds were most correlated to the erosion patterns simulated by the empirical models ( $R^2=0.54-0.75$ ), however, erosion patterns from WEPP and RUSLE also compared favorably ( $R^2=0.47-0.52$  for WEPP and  $0.15-0.33$  for RUSLE). This is encouraging because even if the models

*Figure 2. Sediment fence used to measure erosion after the High Park Fire. After rainstorms, researchers dug out and measured the accumulated mass. These are placed in small convergent hillslopes as indicated by the small rill leading into the sediment fence, indicating significant post-fire overland flow. Photo by Sarah Schmeer.*



do not predict the actual amounts of erosion accurately at a given location, they are likely reliable for identifying areas of high erosion (Figure 3).

### Social and Economic

Because wildfire impacts rarely stop at jurisdictional boundaries, both proactive fuels management and post-fire rehabilitation efforts require collaborative watershed management. This collaborative effort needs to include diverse stakeholders, ranging from water utilities to non- and for-profit organizations and land management agencies. We are conducting structured interviews and surveys to determine what motivates stakeholders to collaborate, how they participate in different stages of risk mitigation (e.g., planning, funding, and implementing), and what information they need to make better decisions. Risk-based decision making is now used by federal fire and land managers, but we know little about why and how other stakeholders, such as water utilities and private industry, are engaging in wildfire risk mitigation. Hence, we

are testing: (1) the role of scientific information in prioritizing and assessing outcomes within collaborative partnerships, and (2) the influence of different factors on participation in collaborative partnerships. Future research will focus on how communicating information on risk and uncertainty influences stakeholders' contributions to these groups and their perception of wildfire risks. Many of these collaborative watershed management groups are still developing, and we anticipate that this research will identify information needs and barriers that can better facilitate stakeholder participation and the development of policy tools and funding for watershed management.

### Development of a Decision Support System

We are integrating our work on erosion modeling with our social and economic findings to help stakeholders identify types and locations of pre- and post-fire management activities to reduce wildfire risk to water supplies. We quantify wildfire risk as a function of fire likelihood and intensity and the

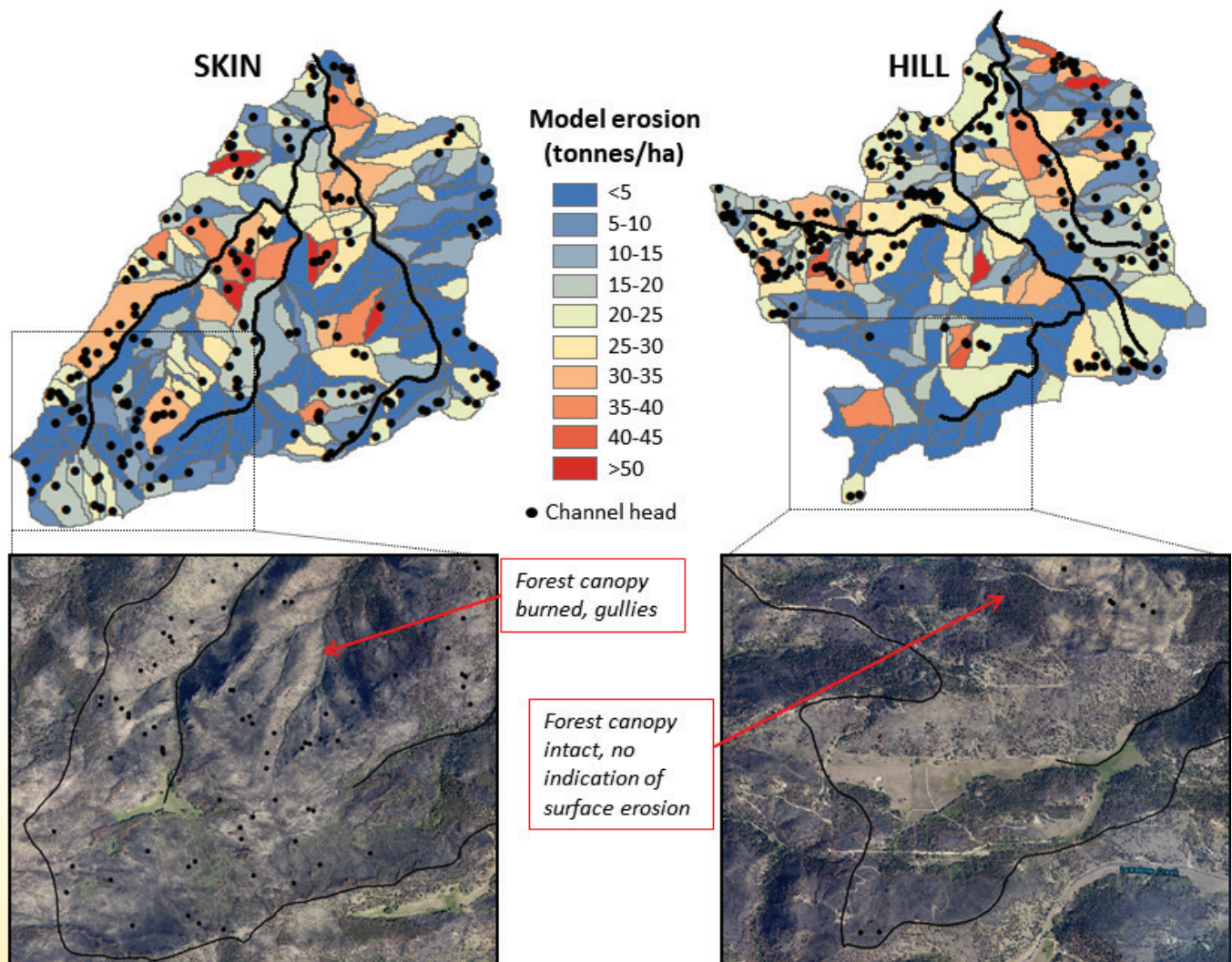


Figure 3. Upper: simulated patterns of erosion from WEPP for Skin and Hill Gulch overlain by post-fire channel heads; Lower: indications of surface erosion in Pictometry air photos from 2012. Figure by Stephanie Kampf.

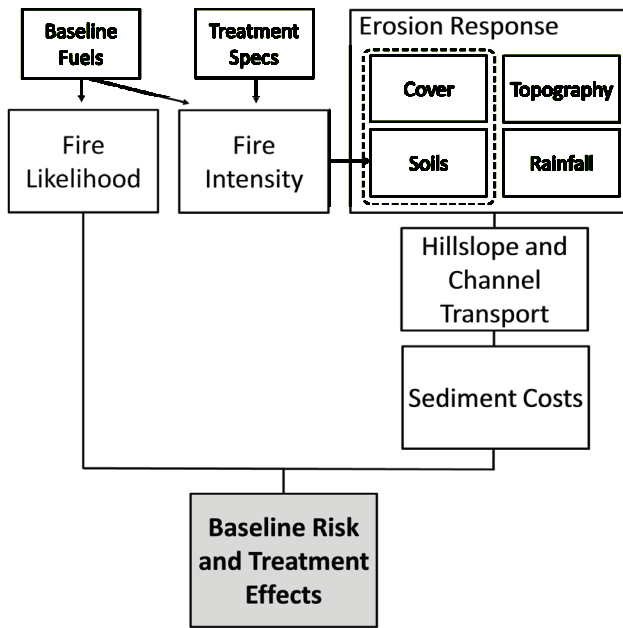


Figure 4. Schematic of our wildfire risk assessment methods. Current vegetation (fuel) conditions determine the likelihood of fire and fire intensity. Post-fire hillslope erosion is controlled by fire intensity. This eroded sediment is then routed downstream to water infrastructure locations, which are assigned sediment impact costs that reflect their importance and vulnerability. Risk is then calculated as the product of wildfire impact costs to water supplies and the probability of experiencing fire. Different fuel treatment scenarios such as forest thinning or prescribed fire can be tested to determine how they modify fire intensity, erosion, and sediment delivered to water infrastructure. Figure by Ben Gannon.

potential for post-fire erosion to impact water supplies (Figure 4). Fire likelihood and intensity vary across large watersheds due to fuels, weather, topography, and ignition sources. There is also considerable spatial variability in the potential for wildfire to impact water supplies due to biophysical controls on erosion and sediment transport and the locations of water infrastructure. By linking wildfire, erosion, and sediment transport models (Figure 4), we can produce spatially-explicit and locally-relevant wildfire risk assessments for large water collection systems (Figure 5).

We can also test the effects of management by simulating pre-fire fuel reduction and post-fire watershed rehabilitation treatments (Figure 4). With additional information on treatment constraints, it is then possible to optimize treatment type and placement to minimize water supply risk. Priorities are refined by considering constraints on management including land management designations, operability, costs, and social and ecological values. Decision tools like this can support strategic risk management by explicitly considering the spatial distribution of risk on the landscape and the ability to mitigate it with different management approaches. Source water systems are diverse, so it is likely that optimal risk reduction

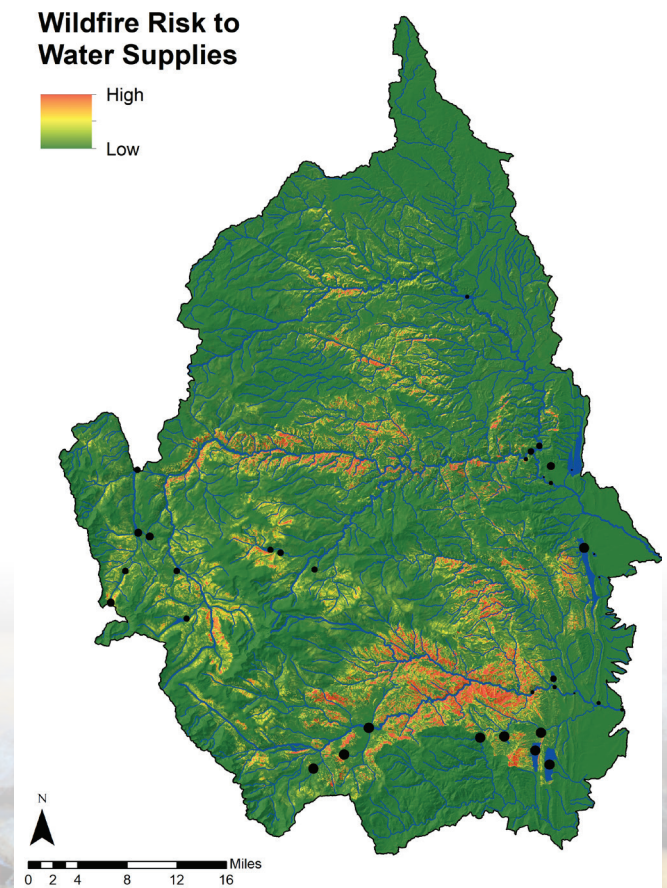
strategies will also vary by community. Using consistent and quantitative approaches for assessing risks and risk mitigation effects can help communities decide what strategies are most appropriate for them.

## Conclusions

We found that popular erosion models do not accurately predict post-fire erosion from small hillslopes, but they do have acceptable accuracy for mapping the relative erosion potential across large watersheds. We are working to understand the roles of risk, risk perception, and other social and ecological factors in motivating stakeholders to engage in watershed protection efforts. Our decision support tools provide spatially-explicit measures of wildfire risk in meaningful terms for water management and powerful methods to evaluate and prioritize risk mitigation actions.

*This project was funded by the Colorado State University Water Center, Peaks to People Water Fund, and the City of Boulder.*

Figure 5. Wildfire risk to water supplies across interconnected source water systems in the Cache la Poudre and Big Thompson Basins of Northern Colorado. Black dots indicate locations of water infrastructure such as pipelines or reservoirs, and the size of the black dot represents the relative importance for water supply. Figure by Ben Gannon.





## **Quantifying the Scope and Regional Economic Impact of Permanent Agricultural Dry-Up Due to Rural to Urban Water Transfers**

Michael Falkowski, Ecosystem Science and Sustainability, Colorado State University;  
Dale Manning, Agricultural and Resource Economics, Colorado State University;  
Jillian LaRoe, Ecosystem Science and Sustainability, Colorado State University;  
Drew Bennett, Haub School of Environment & Natural Resources and Ruckelshaus Institute, University of Wyoming;  
Keith Carlisle, Human Dimensions of Natural Resources, Colorado State University;  
Kevin Crofton, Agricultural and Resource Economics, Colorado State University;  
Chris Goemans, Agricultural and Resource Economics, Colorado State University

*Farmland in Boulder County, Colorado.  
Photo by Flickr user Let Ideas Compete.*



## SYNOPSIS

Increasing demand for water in urban areas of Colorado's Front Range is typically met through transfers of water previously used for agriculture. These transfers may result in the permanent dry-up of irrigated agricultural land and have consequences for local economies. We used an interdisciplinary approach to examine the extent, timing, and economic consequences of agricultural dry-up in Colorado's South Platte Basin. We estimate that approximately 19 percent of irrigated lands were dried between 1984 and 2016, but the drying process may still take decades to fully unfold. Economic modeling suggests that requiring land to return to irrigated agriculture would increase irrigated agricultural production but have small negative impacts on the regional economy.

## Introduction

Water right transfers from agriculture to municipal uses is a primary way urban areas meet growing urban water demand across the American West. These transfers typically result in the permanent dry-up (i.e., "agricultural dry-up" or "buy-and-dry") of previously irrigated agricultural land and may ultimately have a significant impact on the economic viability of rural communities. Agricultural dry-up is especially prevalent in Colorado's South Platte River Basin (the Basin), which is now home to over 3.5 million people. The Basin's population is projected to be 6 million by 2050. Municipal water managers have responded to increased demand by acquiring water rights from surrounding rural areas. Despite increases in agricultural dry-up, many questions remain about the phenomenon, including how much land has been dried, the process and timing of dry-up, and the economic implications of dry-up. This research helps fill these gaps by addressing the

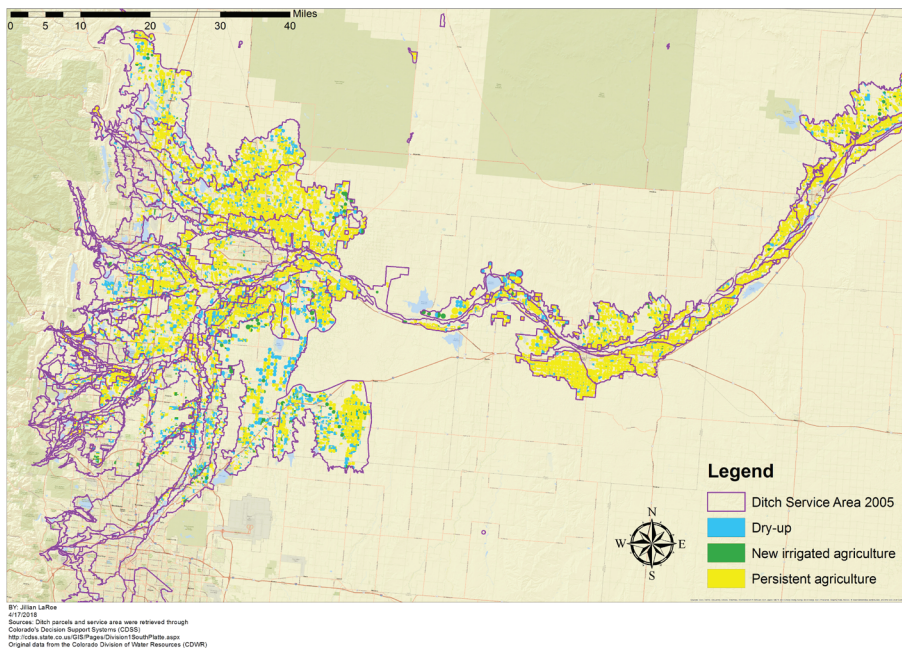


Figure 1. Map of the study area in the South Platte River Basin showing the service area of the ditch system and the estimated dry-up area.

following objectives: 1) estimate the magnitude of agricultural dry-up in the South Platte Basin via remote sensed data, 2) trace the legal process through which dry-up takes place, and 3) assess the regional economic consequences of dry-up.

## Methods

The extent of agricultural dry-up was estimated through a remote sensing analysis that used annual Landsat satellite images from 1984–2016. The analysis area was limited to the land irrigated from surface water delivered by ditch systems in the Basin. These images were leveraged to identify: (1) agricultural land that was irrigated throughout the study period (i.e., persistent agriculture), (2) land that became irrigated during the time period (i.e., new irrigated agriculture), and (3) land that was historically irrigated but dried between 1984–2016 (i.e., dry-up).

Table 1. Results from the remote sensing and court decree analyses.

	Acres
<b>Remote Sensing Results</b>	
Dry-up	99,876
New Irrigated Agriculture	16,406
Persistent Agriculture	400,297
Total in Study Area	516,580
<b>Results from Analysis of Court Decrees</b>	
Potential Dry-up from All Changes of Use	94,157
Potential Dry-up from Changes to Municipal Water Uses	86,389

To trace the legal process behind agricultural dry-up, we analyzed the change of use decrees issued by the Colorado Water Court that were associated with the major ditch systems in the Basin. We searched for a change of use decree using the Colorado Division of Water Resources Decision Support System on water rights transactions. For each decree authorizing a change from agriculture to municipal water use, we extracted information on the acreage of land historically irrigated by the changed water rights, the municipality receiving the water, and other attributes such as required revegetation or dry-up covenants. Although the water rights were changed to include municipal uses, the land changed to dry-land agriculture, rural residential, urban, and industrial uses. We

note that the Basin also receives a sizable percentage of its water volume from water diverted from the Colorado River Basin through the Colorado Big Thompson Project (CBT). This CBT water is traded through shares that do not require a water court decree to change their beneficial use or location of use and we were unable to account for dry-up due to changes in CBT water ownership and use.

Finally, we used an economy-wide, general equilibrium model of the Basin (excluding High Plains counties) to examine the impact of reversing the land use changes that occurred through buy-and-dry over a 5-year period. The model was calibrated to 2013 and corresponded to the economy we observe today. Simulations provided measurements of both costs *and* benefits of moving land and water back to irrigated agriculture under several simplifying assumptions (e.g., land use changes were evenly distributed over the study period, total land area in the model was held constant). To

better understand the impacts of the estimated land use changes associated with dry-up in the Basin between 1984 and 2016, we simulated the impact on today's economy of a requirement that agricultural and urban land use return to previous levels and compare outcomes to those that resulted through dry-up. We report the impact of *reversing* dry-up on water use, economic activity, and per-household income across the Basin.

## Results and Discussion

We conservatively estimate that 99,876 acres of the 516,580 acres of land irrigated by ditch systems

Table 2. Impact of Land and Water Remaining in Agricultural Production in the South Platte River Basin of Colorado.

Panel A: Simulation	Levels	Percent Change
<b>Change in Land (Acres):</b>		
Irrigated Agriculture	36,520	4.16%
Dryland Agriculture	-34,856	-7.13%
Urban	-1,664	0.00%
<b>Panel B: Results</b>		
<b>Change in Water (Acre-feet)</b>		
Agriculture	67,539	0.04%
Non-agriculture	-67,539	-0.09%
<b>Change in Gross Output Value (Million dollars)</b>		
Agriculture	-\$13.29	-1.44%
Non-agriculture	-\$263.99	-0.08%
<b>Change in Real Income (Million Dollars)</b>		
Total	-\$74.70	-0.05%
Per Household	-\$0.0003	-0.01%
Note: simulation is a change in land use to 5-years prior to 2013 (base), representing a policy to reverse agricultural dry-up.		

were dried between 1984-2016 (Table 1). A majority of the dry-up was located in the western portion of the Basin near urban areas (Figure 1). Some dry-up was observed lower in the Basin, but this was largely associated with changes in use to augment wells using groundwater for irrigation. We also observed 16,406 acres of new irrigated agriculture. This new irrigated agriculture is likely receiving CBT water leased back from municipal water providers with surplus supplies.

The court decree analysis identified 79 change of use decrees for municipal water uses. Changed rights historically irrigated 86,389 acres (Table 1). Municipal water providers have been active in acquiring shares of CBT water. In 1984, agricultural uses accounted for 61% of CBT share ownership and 83% of deliveries. By 2012, this dropped to 34% of ownership and 57% of deliveries. Dry-up due to changes in CBT ownership likely explains a large proportion of observed dry-up. Significant additional acreage is likely to be dried in the future due to rights changed through a change of use decree even if municipal water providers acquire no additional rights.

The dry-up process will likely play out over multiple decades. We observed cases taking from one to eight years from when an application for a change of water right was submitted to when the water court issued a decree allowing for changes in beneficial use and location of use of water rights. Once a municipal water provider is granted a change of water right, it may take a decade or more before water is transferred out of agriculture and put to municipal use.


Table 2 presents the simulated 5-year land use changes in levels and as a percent change (Panel A), as well as the economic impacts of these changes (Panel B). The economic impacts of undoing dry-up are small relative to the overall Basin economy. The simulation requires land to return to its original use, leading to more land in irrigated agriculture and

less in urban uses and dryland agriculture (Table 2, Panel A). Associated with this change is an increase of 67,000 acre-feet of water in agriculture. Dry-up leads to an increase in non-agricultural economic activity of more than \$250 million (Table 2, Panel B demonstrates the negative impact of reversing dry-up), though this is less than 0.1% of the current non-agricultural economy. Counterintuitively, the value of (dry and irrigated) agricultural output also falls. While forcing land into agriculture causes an increase in production, local demand for output falls, driving prices down. Ultimately, less urban water means fewer people living in urban areas. The net effect is a decrease in agricultural output value of over 1%, despite increases in production from irrigated agriculture. Taken together, reversing dry-up leads to a decrease in real income across the Basin of \$70 million, though this represents just 0.05% of base incomes.

## Conclusions

A significant proportion of irrigated agricultural land was dried between 1984-2016. We estimate that a significant amount of land has already gone through the legal process to allow for its transfer to municipal use and this water will be diverted from agriculture as cities grow into their supplies, although this process may take several decades to unfold. The economic analysis highlights the complicated relationship between population growth and the agricultural economy. Reallocation of land and water from agricultural to meet municipal demands negatively impacts agricultural production. However, increases in local demand for agricultural products associated with urban population growth increases prices for agricultural products. In our simulation, the latter effect dominates, suggesting that requiring agricultural land to remain in irrigation could negatively impact producers through the lower prices that result.

The majority of the dried land and change of use decrees were located in the western portion of the Basin near major urban areas. While irrigated agriculture in the western part of the Basin will continue to decline, it is likely to persist downstream in the foreseeable future. Dried land near rapidly growing urban areas presents restoration opportunities. While net impacts of buy-and-dry have been positive in the Basin, it has created both winners and losers. Therefore, policy can play a role in mitigating losses to affected sectors. For example, the promotion of non-agricultural industries supporting urban growth could allow rural communities to benefit from urban growth. Finally, policies that facilitate the conversion of dried land to valuable uses, such as recreation, would broaden the benefits of population growth and economic development in the Basin (Figure 2).

Funding for this project was provided by a Colorado State University Water Center Research Team Grant. 



# Estimating Agricultural Consumptive Use for Grass and Hay Pasture Fields on Colorado

Christopher Pack, Environmental Science and Technology, Colorado Mesa University;  
Christopher Louie, Environmental Science and Technology, Colorado Mesa University;  
Gigi Richard, Geosciences, Colorado Mesa University;  
Perry E. Cabot, Colorado Water Institute

## Introduction

More sophisticated evaluation of agricultural consumptive use (CU) on the Western Slope of Colorado is needed for evaluating the delivery requirements for improved infrastructure, contending with recurrent drought and water shortages, and assessing the amount of water potentially available for water sharing arrangements. Given that only the CU fraction of a Colorado direct diversion rights can be transferred or leased to other uses, a method for accurate estimation of the amount

of CU occurring on agricultural parcels will ensure that water sharing programs are executed fairly. Measures of actual consumptive use (ACU) or actual evapotranspiration ( $ET_a$ ) on parcels that are and are not enrolled in water sharing programs will also help to account for the conserved consumptive use (CCU) that resides elsewhere in the delivery system when diversions are foregone in order to conserve consumptive uses.

Grass and hay pasturing for animal feeding is by far the largest agricultural endeavor on the Western Slope of Col-





(Left) Cattle grazing in a field.  
Photo by the U.S. Department of Agriculture.

imagery and multi-spectral observations are available free of cost through Landsat on an 8-day basis. These observations may occasionally suffer from interference from cloud coverage, so the measurements needed to make regular CU estimates can be improved using ground-based multispectral remote sensing surface reflectance data.

This project was conducted to 1) estimate CU from ground-based multispectral remote sensing surface reflectance data; 2) create spatially-averaged GIS maps of CU at these locations; and 3) compare ground-based CU estimates performed using reflectance data in order to determine the utility of ground-based methods to fill in data gaps resulting from the infrequent Landsat passes. The project tested the hypothesis that a vegetation index derived from ground-based multispectral remote sensing surface reflectance data can be related to grass pastures in the Western Slope of Colorado.

### Methods

Measurements of surface reflectance were taken on separate visits using an MSR5 multispectral radiometer at two grass hay/pasture locations in Hotchkiss, Colorado. The data used for this project was obtained in 2016 and collected under a project done for the Colorado River District. This device is housed in an 80 x 80 x 100 mm casing, made from anodized aluminum, consisting of an upward and a downward facing sensor to measure both incoming solar radiation and reflected radiation from the canopy surface. As indicated by the name of the device, the MSR5 measures five bandwidths corresponding to blue (450–520 nm), green (520–600 nm), red

orado, on the basis of acreage. The Colorado Water Bank Workgroup estimates a potential 1,069,759 acre-feet of CU occurring in this land use sector. These estimates were derived from generalized empirical approaches for predicting CU, but more advanced methods are available for these same assessments. In particular, remote-sensing approaches using energy-balances or reflectance-based models will help improve estimates of ACU on a more accurate spatio-temporal basis. Satellite

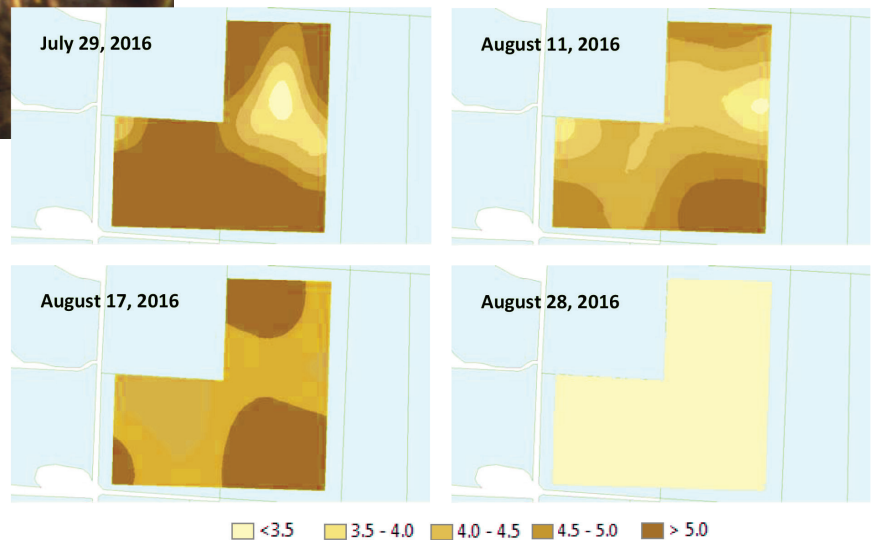


Figure 1. Evotranspiration estimates (mm/day) for a grass pasture field in Hotchkiss, Colorado during the 2016 growing season. Estimates made using methods developed by Gautam (2018).

(630–690 nm), near infrared (760–900 nm) and short-wave infrared (1550–1750 nm). The field of view of the sensor is 28 degrees, and measurement is taken on the field diameter equal to half the height at which the radiometer is held from the ground. The data collected are stored in a data logger in millivolt format, which is later processed using the CropScan software to obtain the percent reflectance data. Because the MSR5 is a handheld device, the instrument is easier to use, and data processing is simple as opposed to the other satellite-based methods, which are more time consuming and complex to process the satellite images. In addition, useful readings can be obtained by the MSR5 even during cloudy conditions (Cropscan, 2011).

A small subset of soil moisture measurements was taken in 2017 using Watermark™ sensors manufactured by Irrometer® (Riverside, California). Chávez et al. (2011) reported accuracies of ±11% for soils of Eastern Colorado using Watermark™ sensors to measure soil moisture. Rather than measuring soil moisture directly, the Watermark™ sensor effectively measures the soil matric potential ( $\psi_m$ ), or soil tension, by monitoring water movement through the porous granular matrix when in good contact with the soil. Therefore, soil tension must be related to volumetric water content using a soil water characteristic curve, which was developed for the project site using standard methods (Saxton and Rawls, 2006) and existing soils data. Data was collected from the sensors every 30 minutes using an industry-supplied data logger for comparison with  $ET_a$  rates

The Normalized Difference Vegetation Index (NDVI) was calculated from the surface reflectance data. The NDVI is the mathematical combination or transformation of surface reflectance in different spectral bands. They are derived

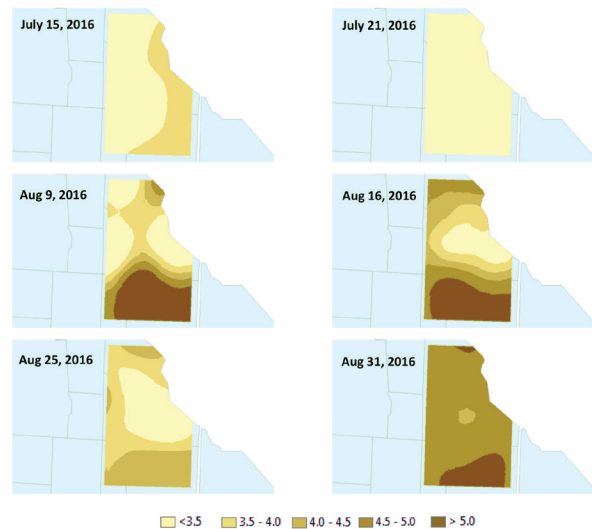


Figure 2. Evapotranspiration estimates (mm/day) for a grass pasture field in Hotchkiss, Colorado during the 2016 growing season. Estimates made using methods developed by Gautam (2018).

using reflectance properties of the vegetation. Usually, the visible to near-infrared bands are used to calculate vegetation indices. The differences in reflectance values at different bandwidth from typical multispectral signatures help to determine current or actual canopy properties. There are several vegetation indices developed to date, ranging from very simple to very complex band combinations, but the NDVI is the most widely used vegetation index to study the plant biophysical properties (Jiang et al., 2006). NDVI uses the surface reflectance readings of near-infrared (NIR) and Red bandwidths of the electromagnetic spectrum and is calculated by the following equation, where the units of NIR and Red are nanometers:

Cows grazing in Longmont, Colorado.  
Photo by Flickr user Let Ideas Compete.



The NDVI can range from -1.0 to 1.0, but generally, for sparse vegetation, values range from 0.2 to 0.5 while denser vegetation ranges from 0.6 to 0.9.

Using an empirical regression model ( $K_{ca} = [1.12 \text{ NDVI}] - 0.08$ ) developed by Gautam (2018), the NDVI was related to a quasi-crop coefficient ( $K_{ca}$ ) to estimate the actual crop evapotranspiration ( $ET_a$ ) rate.

Where  $ET_a$  = actual ET estimate (assumed as a proxy for CU) and  $ET_{ref, alfalfa}$  = a reference ET calculated from the ASCE Standardized Equation using data measured at the nearby CoAgMet Station located on Rogers Mesa Agricultural Experiment Station. The quasi-crop coefficient estimated here is a single crop coefficient, which is the sum of basal crop coefficient ( $K_{cb}$ ) and soil evaporation rate ( $K_e$ ).


## Results

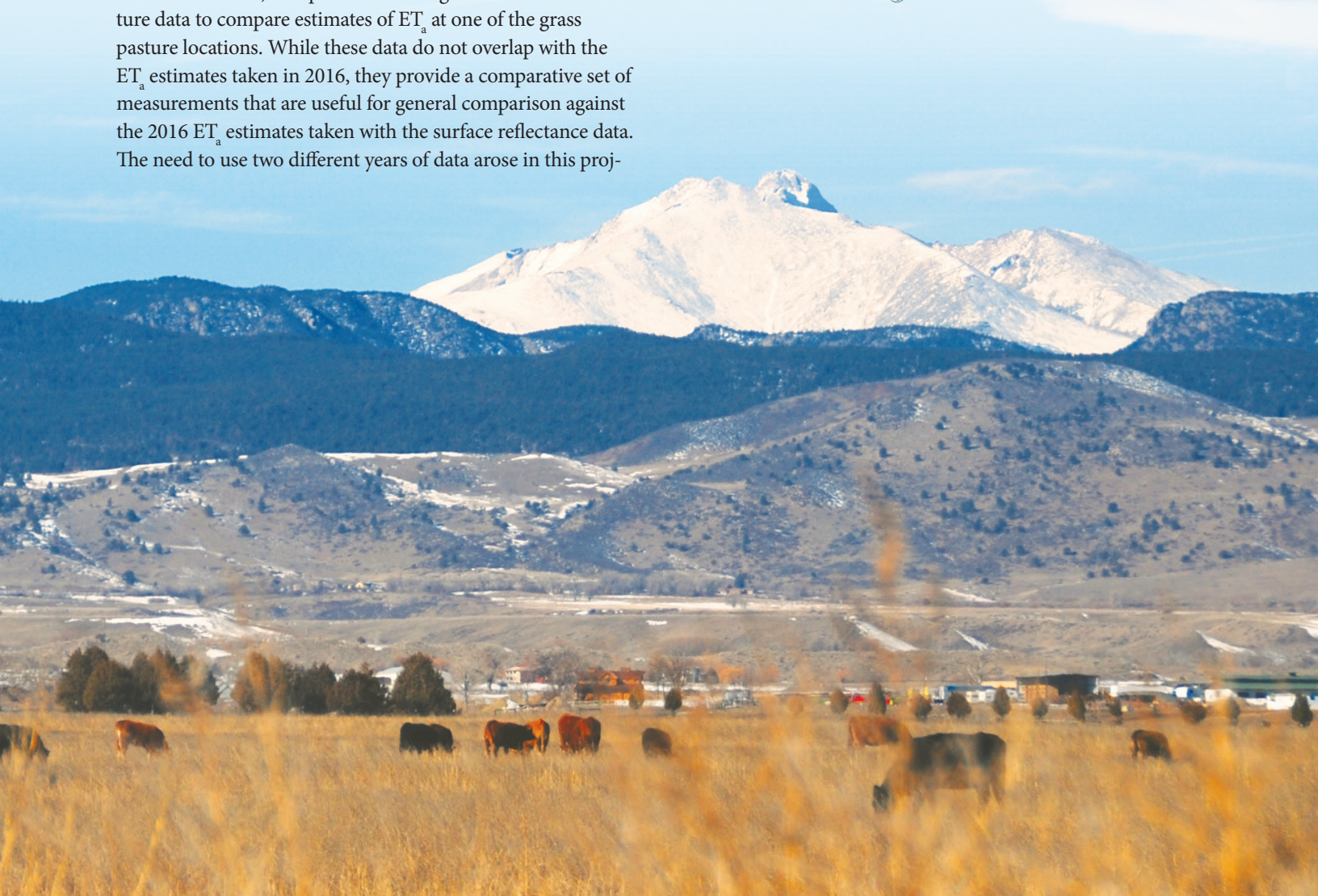
The surface reflectance data taken with the MSR5 was applied to the empirical regression model to derive  $K_{ca}$  and applied to  $ET_{ref, alfalfa}$  for the given day of each visit. The maps of  $ET_a$  are shown in Figure 1 and Figure 2 for each of the two evaluated sites. The calculated values of  $ET_a$  for these locations correspond reasonably well to published values for grasses (Romero and Dukes, 2016).

A one-dimensional soil water balance (assuming a root zone of 36 inches) was performed using the 2017 soil moisture data to compare estimates of  $ET_a$  at one of the grass pasture locations. While these data do not overlap with the  $ET_a$  estimates taken in 2016, they provide a comparative set of measurements that are useful for general comparison against the 2016  $ET_a$  estimates taken with the surface reflectance data. The need to use two different years of data arose in this proj-

ect due to several changes in the student participants during the 2017 year of the study. The most reliable subset of soil moisture data obtained from the one-dimensional soil water balance is shown in Figure 3.

## Discussion

Surface reflectance readings from a hand-held multispectral radiometer were processed and related to a quasi-crop coefficient to develop from calculated NDVI. An NDVI based model has high potential to be used to estimate locally calibrated quasi-crop coefficient and grass evapotranspiration rates at near-real-time as well as on the seasonal scale. The results from this evaluation indicate that further investment of time for research would be beneficial to continue evaluating this inexpensive and faster method to estimate evapotranspiration rates for grass hay/pastures of western Colorado. While this research has shown positive results, further evaluations should be performed with more sophisticated and lengthy soil water balances at greater depth, using instruments such as a neutron probe or a weighing lysimeter. The results from this evaluation do suggest, however, that further effort with remote sensing models should be applied to the Western Slope of Colorado used as an inexpensive and faster method to estimate evapotranspiration and consumptive use rate under a variety of irrigated conditions. 



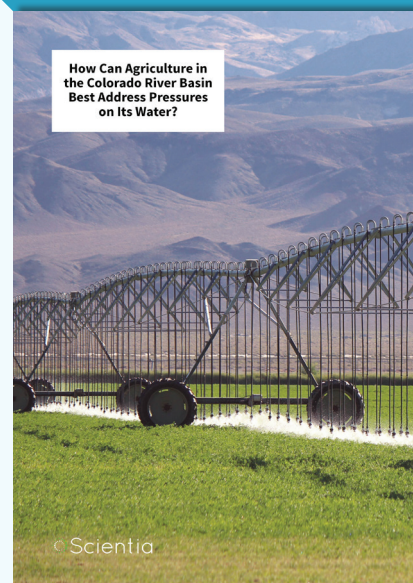
# Team Led by the Colorado Water Institute Completes Second of Two USDA Research Projects on Agriculture in the Colorado River Basin

MaryLou Smith, Colorado Water Institute

Everyone knows the Colorado River has a big task to provide water for people, crops, and the environment in seven states and part of Mexico. Most everyone knows that the policymakers responsible for making sure the river can do that have a huge challenge on their hands. Likely, at no time since the 1922 Colorado River Compact was crafted has the Colorado River had more attention. Most every-

one paying attention to the challenge agrees that agriculture is the sector that has the most to lose from conflict. Most individuals agree that collaboration is the best approach for tackling the challenge.

Colorado Water Institute (CWI) researchers have for the past seven years had their hat in the collaboration ring, seeing what they might do to support those in the agricultural sector who



are experimenting with the idea of “sharing” agricultural water for other purposes such as urban growth and environmental health, while protecting the long-term security of that water to provide food for growing worldwide demand, the viability of rural culture, and the environmental benefits irrigated agriculture provides.

Two U.S. Department of Agriculture (USDA) grants—both part of the National Institute of Food and Agriculture program—supported CWI in this effort. The first of the two grants included researchers from other water resources research institutes in the seven Colorado River Basin states.

The work has not been an easy ride, as agricultural producers and those who manage their water in the Colorado River Basin states have many different opinions about such “water sharing” efforts. Some want nothing to do with even a drop of water leaving agriculture temporarily; others believe agriculture will be the loser if the sector is not proactive about participating in cooperative agreements.

Read about their work and findings in this recently released document from Scintia (<http://www.scintia.global/wp-content/uploads/CSU.pdf>).

## Quantification

Tackle the science, data and modelling needs to quantify consumptive use and return flows on a parcel basis that can be spatially scaled through remote sensing.



## Irrigation Efficiency Measures

Take a close look at the irrigation efficiency improvements recommended under the Regional Conservation Partnership Program of the USDA's Natural Resources Conservation Service. To what extent will irrigation efficiency improvements affect return flows, delivery patterns, junior water rights holders, and the ecosystem services of the impact areas?

## Markets

What market-based conditions could incent farmers to conserve, reduce or forego diversions, and engage in short or long-term transfers? Are water market solutions (temporary and permanent transfers) more cost-effective than spending funding on irrigation system improvements (looking at long-term agricultural and food security?)

## Shepherding

The problem of shepherding conserved water from the point of conservation to an intended use elsewhere (up or down) on the stream is a major obstacle. This requires consideration of hydrological, legal and social-organisational factors.



## Legal / Institutional

Investigate the challenges and possibilities of legally and politically institutionalising the conservation of water as a formal beneficial use by a user and therefore, protecting the conserving water user's existing water right.



# Voices of Experience

Patricia Rettig, Water Resources Archive, Colorado State University Libraries

**F**ew people beyond his immediate associates may have known Peter Van Putten, the long-time ditch rider for the Water Supply and Storage Company on the Cache la Poudre River. But those who knew him certainly recognized his extensive knowledge of the ditch system and Colorado water rights as implemented by irrigators on the ground. His recent passing has removed his specialized knowledge from the world.

This is true for others in the Colorado water community who have also recently passed, including Jerry Kenny, the Executive Director of the Platte River Recovery Implementation Program, and Dr. Norm Evans, a retired CSU Professor and former Director of the Colorado Water Institute (CWI). The loss of life is inevitable, but the loss of knowledge, to some extent, need not be.

Fortunately, Dr. Evans sat down in 1988 for an oral history interview, which was recorded and transcribed. He spoke for more than two hours about his background and

work experiences, sharing his insights and opinions. When he talked about the Colorado General Assembly passing a bill that authorized the Water Institute as a state agency in 1981, he included the reason why the bill had no appropriation attached to it: the legislature was short on funds.

“The income to the state was inadequate to meet the needs, and there were high priorities everywhere, and so water research wasn’t considered a high priority and never has been, and I don’t know if it ever will be. I think the time it would be is whenever there is a severe drought. About the only time when people get serious about water is when there isn’t any” (Dr. Evans interview transcript p.25 <http://hdl.handle.net/10217/172799>).

Later in the interview, Dr. Evans turned to think about the future. “I don’t see how the state cannot put emphasis and funding in water research. But that’s been the case for about that many years, so I may be wrong in forecasting a change. But I do believe the state will begin to put more money into water research in the near future, maybe not immediately this year, but in the next few years” (Dr. Evans transcript p. 38-39).

“About the only time when people get serious about water is when there isn’t any.”  
 -Norman A. Evans

*(Above) c. 1978, Norm Evans (middle) with two other members of the Water Quality Control Commission. From the Colorado Water Resources Research Institute Records.*



*Cache la Poudre River, 1903. Capturing images and stories of how things used to be help us to understand our present and future. From the Irrigation Research Papers, Water Resources Archive.*

The Evans interview is part of the CSU Water Resources Archive's Water Oral Histories Collection. This collection, containing just ten interviews done between 1986 and 1996, is one of several in the Archive that contains oral histories. Two such collections relate to area ditch companies. These are the collections of the Water Supply and Storage Company, with interviews dating between 1973 and 1991, and the North Poudre Irrigation Company, with interviews dating from 1992 to 1994. Each set generally focuses on company leaders or employees.

We also have two collections of oral histories focused on floods. One of these, the David McComb Big Thompson Flood Collection, contains interviews done with survivors, first responders, and officials just months after the July 1976 event. The other, the Northern Colorado Flood Oral History Collection, holds interviews conducted primarily with water managers who had some role or responsibility for planning or recovery in the wake of the 2013 floods.

Two additional collections containing oral histories are based on different topics. The collection from the Colorado

Association of Soil Conservation Districts includes about twenty tapes and transcripts from interviews recorded in 1983 and 1984. This is a small subset of their overall collection, but the interviews share varying perspectives from people involved in the soil conservation movement. The Cache la Poudre Oral History Project Collection originated with a 2002-2004 project funded by the local office of the National Park Service (NPS). The area residents, professors, water organization administrators, policymakers, and lawyers interviewed discuss their views on and interactions with the river.

The Poudre project also interviewed Dr. Evans, focusing for an hour on his role on the Fort Collins Water Board and the Colorado Water Quality Control Commission, in the context of the Poudre River. Dr. Evans was an original appointee when the water board was formed in 1963, and he stayed on for 25 years. The board took important steps to secure a water supply for the city, and Dr. Evans was quite proud of how they accomplished that in cooperation with other cities. He stated, "So the idea of cooperation then in the '60s and '70s was not a common thing, but it was something that most who were

sensible would recognize as it's better to cooperate than it is to try to force through legal actions. And I'm delighted to say that the City of Fort Collins, through its water board, was a leader in advocating and moving in a cooperative way. (Dr. Norm Evans oral history interview transcript p. 4 <https://hdl.handle.net/10217/188061>).

Beyond the Water Resources Archive, two other groups have conducted substantial water-related oral history interview projects. In the mid- to late-1990s, the U.S. Bureau of Reclamation's history program interviewed prominent people in the Bureau and has since distributed the transcripts to a handful of institutions across the country, including the Water Resources Archive. The digital versions can be found online (<https://www.usbr.gov/history/oralhist.html>). Also, the Colorado River Water Users Association conducted a number of oral histories with people across the basin between 2001 and 2009, and these are online as well (<http://www.crwua.org/about-us/oral-histories>).


This listing of water-related oral histories might make it seem like sufficient work has been done. But most of these interviews were recorded more than a decade ago, and the experiences, insights, and opinions of the current generation of retiring water leaders have largely not been captured. Many in the water community believe we should not let the present opportunity get away.

To that end, the Water Resources Archive is partnering with the Poudre Heritage Alliance in the interest of initiating an oral history project. We are aiming to record at least twenty interviews with Colorado water leaders across the state who have recently retired or who are nearing the completion of

their careers. We expect to have broad representation across the basins, water sectors, and professions.

All interviews will be transcribed, with the recordings and transcriptions made available through the Water Resources Archive. The Poudre Heritage Alliance will further utilize the recordings to make educational video clips available to the public. Other organizations, educators, the media, and any researchers will be able to similarly use the information to create presentations, films, articles, and books, or to simply listen and learn from those who have created our water future by their decades of work.

We have all lost someone in our lives whose voice we would like to hear again. If there is a person in the Colorado water community who should be recorded sharing their wisdom for posterity, please e-mail me with their name and contact information. While the project is aiming for twenty interviews, we can accomplish as many as funding allows. Donations to the Poudre Heritage Alliance, specifying the "Water Legacy Heritage Video Series," will be much appreciated. Donate through their website at <https://poudreheritage.org/donate/>.

For more information about the collections mentioned, visit the Water Resources Archive website (<https://lib.ColoState.edu/water>) or contact me (970)-491-1939; [Patricia.Rettig@ColoState.edu](mailto:Patricia.Rettig@ColoState.edu)) at any time. 

*(Below) Car parked next to Jackson Ditch headgate and Bellvue Hydraulic Laboratory, 1919. Pete Van Putten lived near this location on the Poudre River and could explain the changes that happened over the years. From the Irrigation Research Papers, Water Resources Archive.*



# Using CoAgMET, “Colorado’s Mesonet”, to Analyze Our State’s Weather and Climate

Russ Schumacher, Colorado Climate Center,  
Atmospheric Science, Colorado State University;  
Peter Goble, Colorado Climate Center;  
Zach Schwalbe, Colorado Climate Center;  
Becky Bolinger, Colorado Climate Center

**W**e know the climate across Colorado is highly variable: from the near-desert of the San Luis Valley, to the super-snowy mountains, and everything in between. And the weather is highly variable too: the eastern plains often go from severe thunderstorms to a blizzard on the same day in the spring. The key to analyzing and understanding this variability is sufficient weather observations, something of which we can never have enough. The routine networks managed by the National Weather Service (NWS) are critical for observing current weather conditions, but they may not always have the detailed information needed for applications like agriculture and water resources. To fill this gap, many states have developed their own “mesoscale networks” or “mesonets”. In meteorology, “mesoscale” refers to processes

at scales in the middle, too big to be seen by a single station or radar display, but too small to be seen on a national-scale weather map. The most prominent of these is the Oklahoma Mesonet, which provides high-quality data every 5 minutes from at least one station in every county of the state. Since I took over as state climatologist, given my background in mesoscale meteorology, people often ask me “When is Colorado going to get its own mesonet?” To which I can respond: we already have one!

The Colorado Agricultural Meteorological Network (CoAgMET) originated in 1992, when two different groups at CSU, Plant Pathology Extension specialists, and USDA’s Agricultural Research Service Water Management Unit realized they needed localized weather data for research and decision-making related to agriculture. With additional support and sponsors, the network grew (<http://coagmet.colostate.edu/about.php>), and there are now 85 stations across the state (Figure 1).

One of the primary purposes of CoAgMET has been to provide timely, accurate measurements of reference evapotranspiration (ET: hence those letters are capitalized in the network’s name). This is the amount of moisture that a plant (with adequate water) loses to the atmosphere, and is based on temperature, humidity, wind, and incoming solar radiation. Accurate knowledge of reference ET, in conjunction with detailed rainfall data, allows growers to irrigate just the right amounts, at just the right times. Providing an accurate and locally relevant estimate of ET to Colorado’s farmers remains the most important goal of CoAgMET.



A COAGMET station.  
Photo by The Colorado Climate Center.





Yet a network like CoAgMET can also do so much more. High-quality data from individual stations are, of course, invaluable to users near those individual stations. But putting those data on a map reveals a true “mesonet” across Colorado, indicating some of the fascinating variability around the state. Furthermore, over half of the stations currently report data every 5 minutes, which allows for the documentation of rapid changes in the weather. One interesting example occurred in late June 2018, when a “heatburst” – a rapid rise in temperature and drop in humidity associated with decaying thunderstorms, usually overnight—occurred in northeast Colorado. A map of CoAgMET observations at that time (Figure 2a) shows how out of place a temperature of 92°F is at 2:25 am, and the five-minute data shows the heatburst in a way that data at hourly intervals could not.

CoAgMET data can also tell the story of the water balance in a given location over time. With the combination of precipitation and reference ET data, we can track the gains and losses of surface water for various crop types and do our favorite thing as climatologists: see how it compares to other years. We see this in Figure 3 for the Fort Collins (FTC01) station. Sudden shifts from warm to cool colors show heavy rainfall events that shifted the water balance from drier to wetter than normal. Slower progressions from cool to warm colors indicate years in which warmer, drier conditions prevailed over the course of the summer.

They can also be used to show the details of why a particular growing season had higher or lower than average evaporative demand. At seven stations with over 30 years of observations, we have constructed interactive summaries that show the drivers of water balance: the daily evapotranspiration, temperature, wind, solar radiation, and precipitation. A user can visualize either the ‘absolute’ values or the differences from the long-term average. An example at Avondale (Figure 4) illustrates that 2017 was a rather cool and wet summer, and accordingly the accumulated ET was lower than average. Based on the observations so far in 2018, these graphs will look quite different when they are generated, and we hope to start gener-

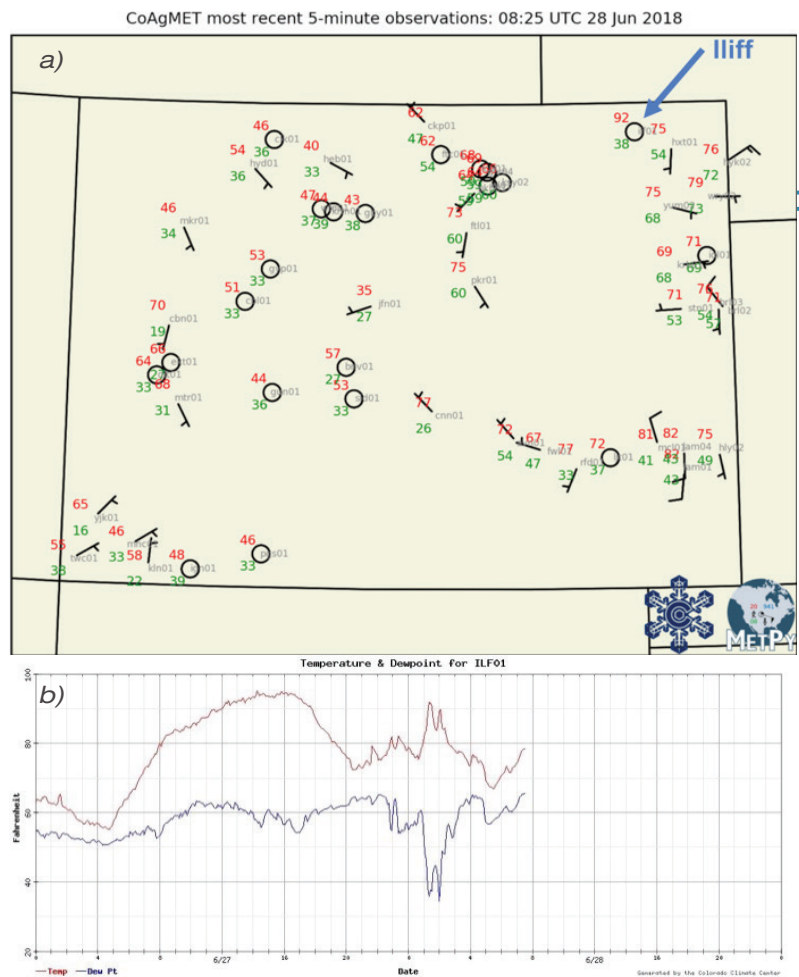


Figure 2. (a) Map showing CoAgMET weather observations at 2:25am local time, 28 June 2018. (b) Time series of 5-minute data at the Iliff station, illustrating the rapid warming and drying associated with a heatburst in the early morning of 28 June 2018.

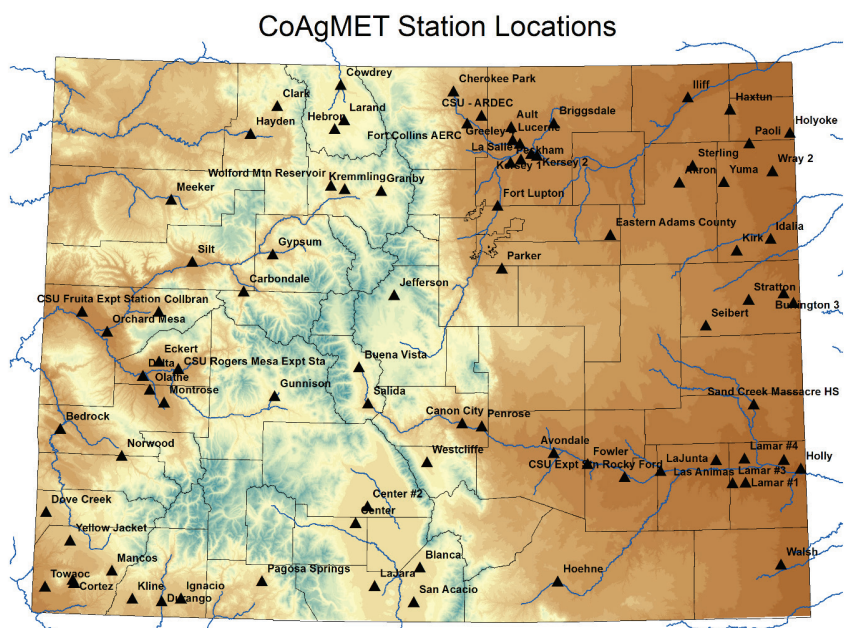


Figure 1. Map of current CoAgMET stations, as of July 2018.

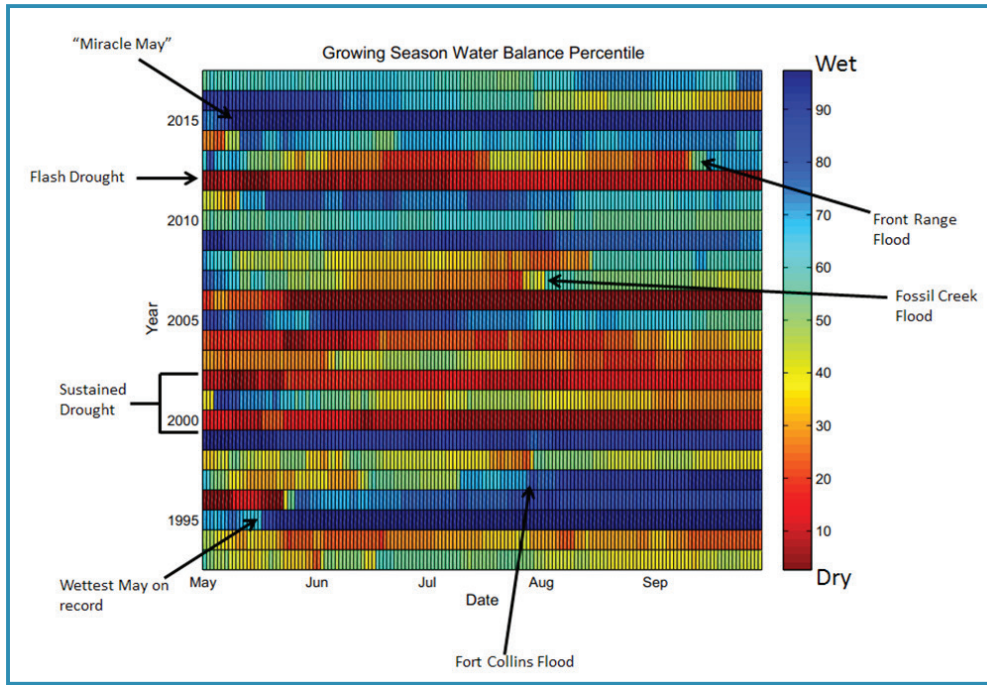



Figure 3. Water balance (precipitation minus reference evapotranspiration) at the Fort Collins CoAgMET station for May through September, 1993-2017. Color shading indicates the percentiles of water balance over the period of record, and several notable time periods are annotated on the image.

ating them in near-real-time for our long-term stations.

Now, for a state as complex as Colorado, even a network like CoAgMET cannot address every question related to our weather and climate. For example, our network is not designed for high mountain environments, but in combination with other networks like SNOTEL (which measures precipitation and snowpack at high elevations) and RAWS (which provides observations in mountainous terrain prone to wildfires), we can obtain a fairly complete picture of the variability across the state.

And the topics described here only scratch the surface of the potential of CoAgMET as “Colorado’s Mesonet.” In the coming years, we intend to continue maintaining the network, expanding its use in monitoring Colorado’s weather and climate, and making the data easier for a wide variety of users to access and analyze. We greatly appreciate the Colorado Water Conservation Board, the National Mesonet Program, the CSU Agricultural Experiment Station, and the many sponsors of stations around the state for their support of the network, and we welcome your ideas for improving what we can do in the future. Visit [coagmet.colostate.edu](http://coagmet.colostate.edu) for more information.

*Acknowledgments:* CWCB, National Mesonet Program, Agricultural Experiment Station, and our partners in CoAgMET. 

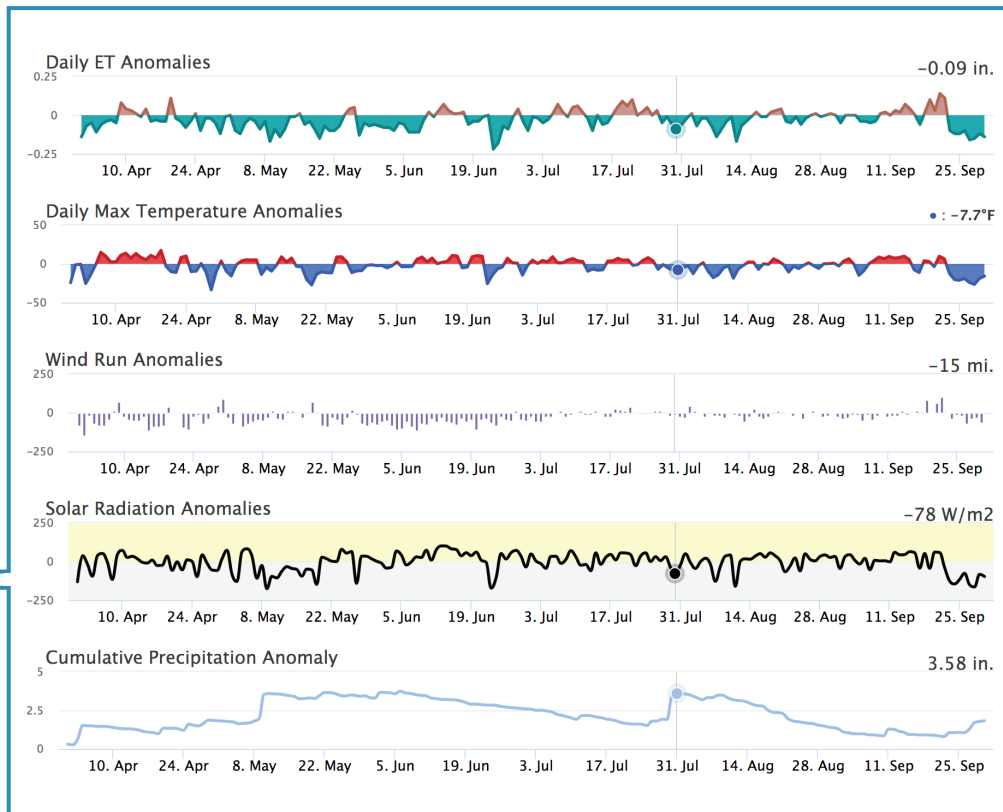


Figure 4. Example of an interactive growing season summary for the Avondale station in 2017, showing the differences in 2017 from the long-term average.

Obtained from: [http://climate.colostate.edu/2017ET/et\\_summary\\_avn\\_anom.html](http://climate.colostate.edu/2017ET/et_summary_avn_anom.html)

# John Fetcher Scholarship Award

The Upper Yampa Water Conservancy District John Fetcher Scholarship provides financial assistance to a committed and talented student who is pursuing a water-related career in any major at a public university within the state of Colorado. Congratulations to this year's scholarship recipient, Marissa Karpack.

**Name:** Marissa Karpack

**University:** Colorado State University

**Anticipated Graduation:** May 2019

**Major:** Masters of Science in Civil and Environmental Engineering

**Minor: Area of Interest:** Hydrology and hydraulics, with an emphasis on river and floodplain processes

While at Colorado State University, Karpack has been a graduate teaching assistant for undergraduate civil engineering courses. She was the 2017-2018 Walter Scott, Jr. Graduate Fellow and plans on pursuing a career in river engineering. More specifically, Karpack hopes to pursue hydraulic engineering, incorporating 2D and 3D numerical river modeling. She has previously worked for the Engineers Without Borders chapter at Colorado State University as a Design Engineer and as the International Projects Director during her undergraduate time at the University of Washington. The ultimate goal of her education and work experience is to develop effective long-term solutions to river and floodplain issues.



Photo by Chelsey Heiden.

# Colorado Water Congress Honorary Lifetime Membership Award

This year, Nolan Doesken received the Honorary Lifetime Membership Award. This award recognizes individuals whose careers in the water-related industry exemplify vision, creativity, and excellent professional performance over a long and productive career. Colorado Water Congress Life Membership honorees receive dues-free membership and waived conference fees for the balance of their lives.

Doesken recently retired as the Colorado State Climatologist for the Colorado Climate Center (CCC) after a 40-year career. He also served as the Assistant State Climatologist, prior to being the State Climatologist. During his time at the CCC, he led a profound career, conducting climates studies and providing educational outreach. In particular, he created the Community Collaborative Rain, Hail, and Snow network, commonly known as CoCoRaHS. Doesken is currently working for the Colorado Water Institute (CWI) in support of climate initiatives in the Office of Engagement.

During the presentation of Doesken's award, Colorado Water Congress President Erin Wilson mentioned that, "We were unable to precisely determine how many times Nolan stood on this stage but can definitely say that he presented more times than anyone else in the Water Congress history. The honorary membership award means we won't have to miss out on Nolan's wonderful enthusiasm and humor".



Photo by Henry Reges.

# Jesse Burkhardt

Agricultural and Resource Economics, Colorado State University



Photo by Adrienne Cohen.

I joined the Department of Agricultural and Resource Economics (DARE) at CSU in the fall of 2016. I am also part of the interdisciplinary research group, The Partnership for Air Quality Climate and Health. Since joining CSU, my research has focused on a variety of topics within environmental, energy, and resource economics.

My recent work bridges disciplinary boundaries. I am currently working with atmospheric scientists, environmental engineers, and statisticians at CSU to understand the short-term effects of pollution on aggressive behavior. To identify this relationship, the team is using extremely detailed daily data on pollution, wildfire smoke, and crime from across the United States. Preliminary findings indicate a strong positive effect of increased pollution on violent crimes within households, suggestive of increased domestic violence. Our results suggest that more research needs to be done to understand the short-term physiological impacts of pollution.

I also have a growing portfolio of water-related research. I was awarded the 2017-2018 CSU Water Center Faculty Fellow grant, which I used to fund two graduate students in DARE on collaborative projects with the Fort Collins Utility. The work has resulted in two important papers and internships for the students. First, my coauthors and I explored the drivers of commercial water demand in Fort Collins. Fort Collins is a dynamic city and is expected to grow. For planning purposes, the Utility needs to know how businesses respond to water price changes, drought conditions, and general weather patterns. The Utility can then use this information to predict future water demand and revenue as well as to identify outliers in water use. Second, the Utility has implemented several

experiments with residential customers. For this grant, we evaluated the effect of receiving a Home Water Report (HWR) on residential water consumption. HWRs rate a customer's consumption relative to one's neighbors. A customer receives a smiley face if they consume less than their neighbors, a neutral face if they consume about the same as their neighbors, and a frowny face if they consume more than their neighbors. We find that receiving a HWR reduces residential water consumption by approximately 2% on average. This effect would result in substantial water savings if applied across the population of Fort Collins or a larger city.

I am also currently working with the City of Phoenix Water Department to identify peer effects in landscape changes for residential customers. Landscaping is one of the largest sources of water use in arid environments. In this study, we use highly detailed remote sensing images, combined with water consumption data to generate robust measures of landscape greenery for nearly all households in Phoenix over a 10 year period. We can use this information to determine whether landscape transitions (conversion to dry landscaping) is contagious. This work has several important implications for water saving strategies in arid landscapes. For instance, if utilities provide subsidies to households to convert to dry landscaping, our research quantifies the water savings they can expect from the household that received the subsidy and the savings from the surrounding neighbors.

My future goal as a professor at CSU is to continue to build relationships with local policymakers and practitioners to answer questions important to Colorado. To do so, I plan to develop cross-disciplinary partnerships within the University and with outside research groups such as the United States Forest Service (USFS), U.S. Geological Survey (USGS), and the Fort Collins Utility. CSU students interested in environmental, energy, or climate change economics or econometrics can enroll in one of the two courses that I teach: Econometrics (300 level) and The Economics of Energy Resources (300 level).



**Jesse Burkhardt**

Assistant Professor

Agricultural and Resource Economics

Colorado State University

jesse.burkhardt@colostate.edu

Work: (970) 491-6951

# Water Calendar

## December

### 10-14 2018 AGU Fall Meeting; Washington D.C.

The AGU Fall Meeting is the best place to present your research; hear about the latest discoveries, trends, and challenges in the field; and network and make connections that can enhance your career.

[fallmeeting.agu.org/2018/](http://fallmeeting.agu.org/2018/)

### 12-14 Colorado River Water Users Association Annual Conference; Las Vegas, NV

This conference will provide the opportunity to hear an array of informative speakers, panel discussions, and other meetings. The conference is a significant meeting for key decision makers from the Colorado River Basin states.

[cvent.com/events/2018-crwua-annual-conference/event-summary4edc04ef36a64246bc6df659297ee093.aspx](http://cvent.com/events/2018-crwua-annual-conference/event-summary4edc04ef36a64246bc6df659297ee093.aspx)

[prti.colostate.edu/](http://prti.colostate.edu/)

### 5-7 2019 Riparian Restoration Conference; Phoenix, AZ

This year, the 17th annual RiversEdge West's conference will focus on innovative ideas, challenges, adaptive management techniques, and policy updates related to riparian restoration.

[riversedgewest.org/events/2019-riparian-restoration-conference](http://riversedgewest.org/events/2019-riparian-restoration-conference)

### 11 Colorado Rural Water Association Annual Conference and Exhibition; Denver, CO

This conference will provide the opportunity to participate in training sessions related to wastewater, distribution, collection, management, and water resources, in general.

[crwa.net/events/crwa-annual-conference-exhibition/](http://crwa.net/events/crwa-annual-conference-exhibition/)

## January

### 6-10 99th Annual Meeting American Meteorological Society; Phoenix, AZ

Join fellow scientists, educators, students, and other professionals from across the weather, water, and climate community to learn about societal impacts of extreme weather, hydrology, and the history of satellites.

[ametsoc.org/index.cfm/2019/](http://ametsoc.org/index.cfm/2019/)

### 30-2.1 Colorado Water Congress Annual Convention; Denver, CO

This annual convention is the premier water industry event in the state, providing an opportunity for networking and collaboration related to important water issues.

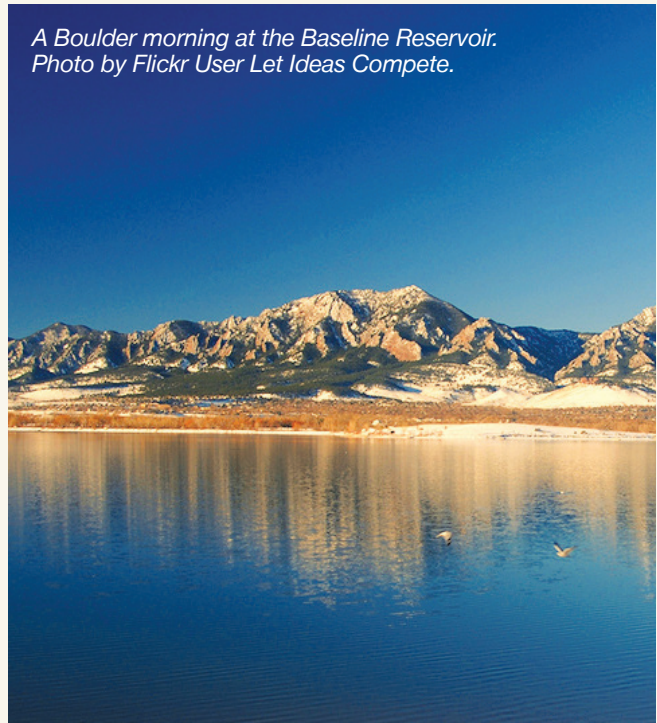
[cwatercongress.org/annual-convention.html](http://cwatercongress.org/annual-convention.html)

## February

### 1 Poudre River Forum; Fort Collins, CO

Save the date for this engaging forum that will bring together stakeholders and water resource professionals from an array of sectors including agriculture and urban water.

For more events, visit [watercenter.colostate.edu](http://watercenter.colostate.edu)



*A Boulder morning at the Baseline Reservoir.  
Photo by Flickr User Let Ideas Compete.*

# Water Research Awards 5/2/18 — 8/1/18

**Bailey, Ryan T.**, Colorado Water Conservation Board, Investigating Major Influences on Groundwater Levels in the LaSalle/Gilcrest Area, \$47,610

**Bauder, Troy A.**, Colorado Department of Agriculture, Training and Education for Agricultural Chemicals and Groundwater Protection, \$225,004

**Borch, Thomas**, Environmental Defense Fund, Irrigation with Produced Water: Impact on Crop and Soil Health, \$95,000

**Chavez, Jose L.**, Colorado Water Conservation Board, Assessing Temporal and Spatial Crop Water Consumptive Use with Unmanned Aerial Systems, \$49,999

**Covino, Timothy P.**, U.S. Department of Agriculture-U.S. Forest Service-Rocky Mountain Research Station, Post Wildfire Watershed Nitrogen Retention Processes, \$75,000

**Dell, Tyler A.**, Colorado Department of Public Health and Environment, E. Coli Sampling in the Cache la Poudre River, \$205,154

**Engle, Terry E.**, Climax Molybdenum Company, The Effects of Chronic Molybdenum Exposure in Drinking Water on Molybdenum Metabolism and Production Performance of Gestating and Lactating Beef Cattle Consuming a High Forage Diet, \$147,792

**Ettema, Robert**, Ayres Associates, Revised Clear-Water and Live-Bed Contraction Scour Analysis, \$95,074

**Gates, Timothy K.**, Colorado School of Mines, Lower Arkansas Natural Uranium Project: Finding Ways to Mitigate Irrigation-Induced Uranium Contamination in Colorado's Lower Arkansas River Valley, \$10,000

**Laituri, Melinda J.**, Department of the Interior-National Park Service, Make Federal Water Data Available to States and the Public, \$184,300

**Manning, Dale T.**, U.S. Department of Agriculture-National Institute of Food and Agriculture, Crop Insurance and Groundwater Consumption in the Ogallala Aquifer Region, \$499,785

**Mooney, Daniel F.**, Platte River Water Development Authority, Arid Climate Water Management Strategies, \$276,785

**Myrick, Christopher, A.**, Colorado Division of Parks and Wildlife, Native Fish Passage in Front Range Transition Zone Streams, \$68,148

**Rhoades, Ryan D.**, Texas A&M University-Kingsville, Training Wicked Problem Solvers to Use Systems Approaches to Address Contemporary Food, Energy, and Water Issues, \$15,518

**Schipanski, Meagan E.**, U.S. Department of Agriculture-National Institute of Food and Agriculture, Sustaining Agriculture Through Adaptive Management to Preserve the Ogallala Aquifer Under a Changing Climate, \$2,401,617

**Schook, Derek M.**, Department of the Interior-U.S. Geological Survey, Effects of Drought and Flow Regulation on Growth of Plains Cottonwood Along the Wind River, Wyoming, \$17,627

**Shaw, Jeremy R.**, Department of the Interior-National Park Service, Ecohydrological Impacts of Roads in Arid Environments: Interruption of Sheetflow Pathways, \$46,804

**Stevens-Rumann, Camille S.**, City of Boulder Open Space and Mountain Parks, Forest Vulnerability to Climate Change, \$14,871

**Sueltenfuss, Jeremy**, Department of the Interior-National Park Service, Assessing Baseline Riparian Conditions Prior to Any Future Work Aimed at Facilitating Willow Growth and Beaver Habitat Restoration in Rocky Mountain National Park, \$20,008

**Cinnamon Gulch revisited: Another look at separating natural and mining-impacted contributions to instream metal load;** 2018, Applied Geochemistry, 95, 206-217, R.L. Runkel, P.L. Verplanck, B.A. Kimball, K. Walton-Day

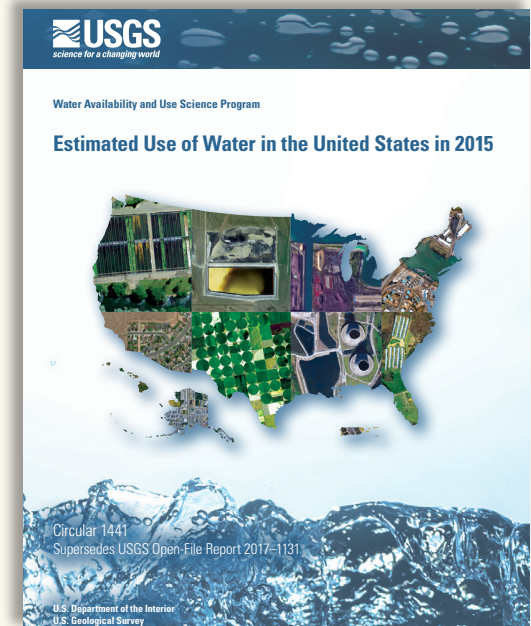
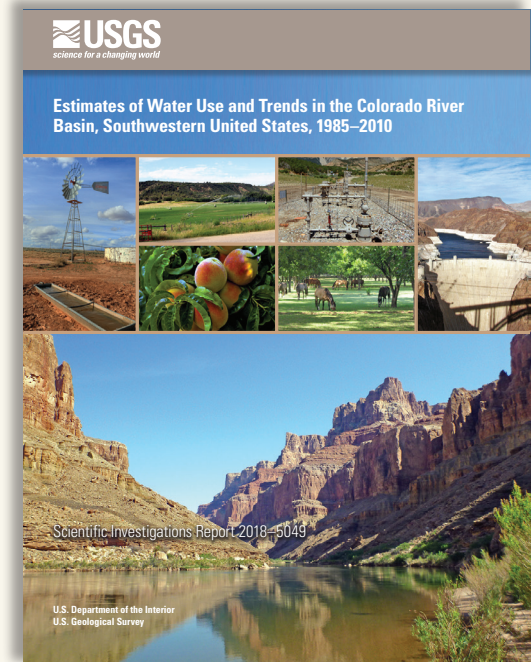
**Dataset of estimated use of water by subbasin (HUC8) in the Colorado River Basin, Southwestern United States, 1985-2010;** 2018, U.S. Geological Survey data release; T. Ivahnenko, M.A. Maupin

**Estimates of water use and trends in the Colorado River Basin, Southwestern United States, 1985–2010;** 2018, U.S. Geological Survey Scientific Investigations Report 2018–5049, 61; M.A. Maupin, T. Ivahnenko, B. Bruce

**Estimated use of water in the United States in 2015;** 2018, U.S. Geological Survey Circular 1441, 65; C.A. Dieter, M.A. Maupin, R.R. Caldwell, M.A. Harris, T.I. Ivahnenko, J.K. Lovelace, N.L. Barber, K.S. Linsey

**Pharmaceuticals, hormones, pesticides, and other bioactive contaminants in water, sediment, and tissue from Rocky Mountain National Park, 2012–2013;** 2018, Science of The Total Environment, 643, 651-673; W.A. Battaglin, P.M. Bradley, L. Iwanowicz, C.A. Journey, H.L. Walsh, V.S. Blazer

**Streamflow and selenium loads during synoptic sampling of the Gunnison River and its tributaries near Delta, Colorado;** 2018, U.S. Geological Survey Scientific Investigations Report 2018–5029, 17; M.R. Stevens, K.J. Leib, J.C. Thomas, N.J. Bauch, R.J. Richards



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*Chatfield State Park.  
Photo by Michael Levine-Clark*

