Colorado Water

May/June 2018






STUDENT RESEARCH

Colorado State University

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Handies Peak Wilderness study area near Lake City, CO Photo by the Bureau of Land Management

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Cooperators include the Colorado State Forest Service, the Colorado Climate Center, and CSU's Water Resources Archive.

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Director's LETTER

This issue of Colorado Water contains the annual summaries of student projects competitively funded under the Colorado Water Institute (CWI) collaboration with the U.S. Geological Survey. The quality and value of these student projects is a reflection of the advising and mentoring they receive from their faculty advisors. The time-honored relationship between students and faculty teaches research skills and helps prepare students for their professions. What I find interesting as I review this issue is the juxtaposition of the student research projects and the past water leaders called out in the articles by CSU Professor Rob Ettema and Archivist Patricia Rettig.

Water issues are particularly complex, and understanding the nuances and multi-decadal time frame is critical for our leaders and decision-makers as Colorado continues to grow. Yet most of the big decisions that directly or indirectly affect water availability and quality are not made by water experts, but by elected and appointed leaders. Leadership skills, like in-depth knowledge of water management complexities, are earned in the trenches and over many years. We barely scratch the surface in higher education on teaching these skills, as experience is the true teacher. And in case you have not noticed, many of the leaders who have helped our communities make sound water decisions over the past decades are at retirement age. Colorado needs a new crop of water literate leaders!

The CWI has been facilitating a group called The Poudre Runs Through It Study/Action Work Group in Northern Colorado over the past seven years to find ways to help make a working river function better for all concerned. The group is made up of individuals who are in the know or are in the trenches of managing the water resources connected to the Cache la Poudre River, from the forested headwaters to Greeley, to the agricultural, urban, recreational, and environmental perspectives. As MaryLou Smith and I have worked to facilitate these dialogs and activities on the river, we have noted the loss of a number of former water savvy community leaders who had the knowledge and political ability to foster positive change in the watershed. To address that need, the CWI, in cooperation with Community Foundation of Northern Colorado, has launched a non-partisan Water Literate Leaders of Northern Colorado program. Modeled after highly successful programs such as Leadership Northern Colorado, this program is for those who hold or aspire to political office, or other roles, including boards and commissions, which can impact regional water policy.

We have just completed the first year of what we hope will be an annual nine-month educational program to gestate a new crop of water literate community leaders in the Greeley, Fort Collins, Loveland, and Windsor areas. The 20 applicants we chose this year included four city council members, a city manager, a mayor, Chamber of Commerce and economic development leaders, real estate folks, water utility staff and board members, business leaders, environmentalists and others. Our goal is to help these current and emerging regional leaders gain exposure to all things water in our region. Leaders want to do more than just learn—they want to act, and this first cohort has begun a regional dialogue about how we can cooperate across jurisdictional boundaries to create a better water future for Northern Colorado.

We have savvy and capable citizen leaders in Colorado; it is our responsibility as water professionals to provide them with an adequate understanding of Colorado water history, law, policy, and management so that they can make sound choices today for our collective future.

Reagan Waskom

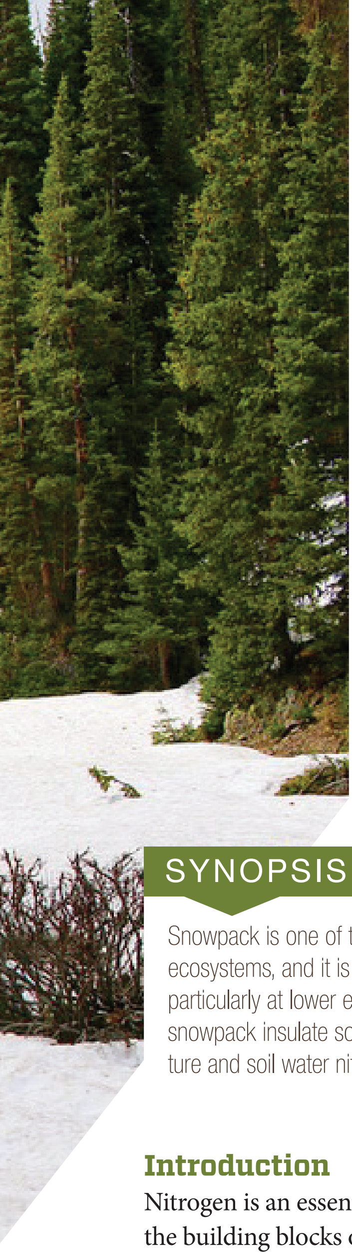
Director, Colorado Water Institute

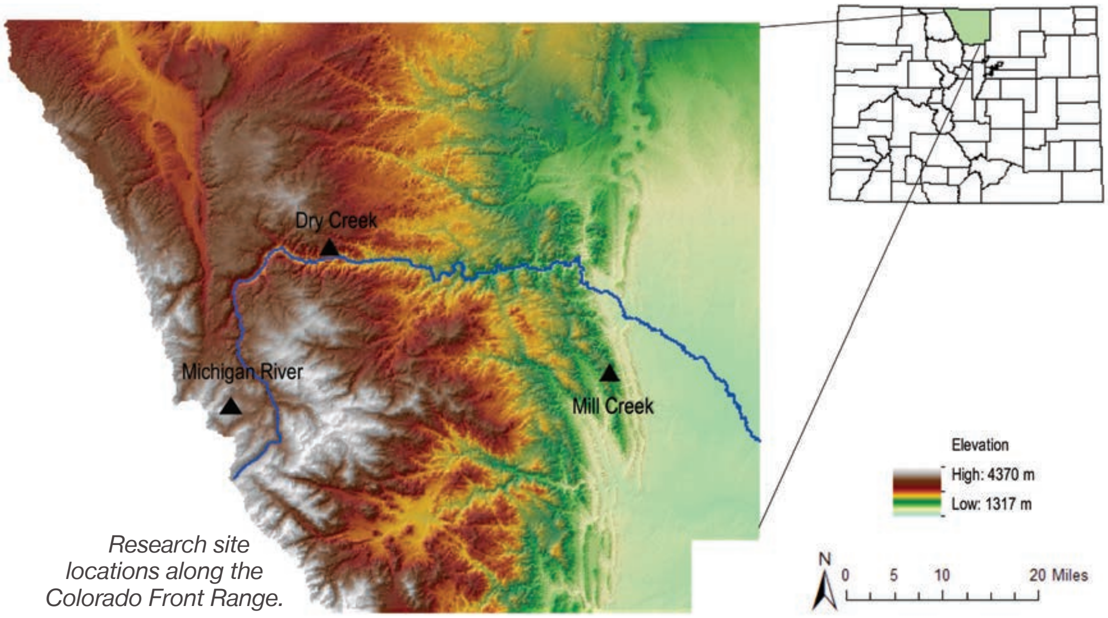
Handies Peak Wilderness Study Area
Bureau of Land Management

Michigan River, located in the persistent snow zone, in May 2017. Photo by John Hammond

Effects of Snow Persistence on Soil Moisture and Soil Water Nitrogen Along the Colorado Front Range

Alyssa Anenberg, Ecosystem Science and Sustainability, Colorado State University;
Stephanie Kampf, Ecosystem Science and Sustainability, Colorado State University;
Jill Baron, Natural Resource Ecology Laboratory, Colorado State University





Research site locations along the Colorado Front Range.

SYNOPSIS

Snowpack is one of the most important factors affecting mountain ecosystems, and it is highly sensitive to increasing temperatures, particularly at lower elevations. Increased duration and quantity of snowpack insulate soils throughout the winter and increase soil moisture and soil water nitrogen in the spring.

Introduction

Nitrogen is an essential nutrient for all life on Earth. It forms the building blocks of DNA and chlorophyll and is often the most limiting nutrient in crop and forest production. In most ecosystems, little soil water nitrogen is available for plant growth, constraining growth rates and primary productivity. Conversely, too much soil water nitrogen, while increasing growth rates and productivity, can cause adverse effects on the environment by changing biodiversity and leaching nitrogen from soils to streams. In the western U.S. mountains, the timing and magnitude of snowmelt is an important control on soil water and nutrient availability for plants. The broad goal of this study is to understand how the timing of snow accumulation and melt change soil moisture and soil water nitrogen concentrations. The specific objectives are to (1) manipulate snow depths at catchments in persistent, transitional, and intermittent snow zones along Colorado's Front Range, and (2) use the results to understand how snow accumulation and melt affect soil moisture and soil water nitrogen. This research is integrated into longer-term hydrologic monitoring examining how snow persistence affects soil moisture and streamflow generation from high to low elevations of Colorado mountains.

We hypothesize that higher elevations will accumulate deeper snowpack, causing increased spring snowmelt and elevated soil water nitrogen, whereas lower elevations will exhibit lower snow depths, snow moisture, and soil water nitrogen. Where winter snowpacks are deep and sustained throughout the winter, soils remain insulated from cold winter temperatures. If soil temperatures stay above freezing, this can allow winter microbial activity and retention of soil

Table 1. Study site name, snow zone, and elevation.

Study Site	Snow Zone	Elevation (m)	Elevation (ft)
Michigan River	Persistent	3,197	10,489
Dry Creek	Transitional	2,340	7,678
Mill Creek	Intermittent	1,784	5,854

A December 2016 snow event at Dry Creek (above) followed by a rapid snowmelt response (below).

Soil moisture sensors installed at 5 and 20 cm depth.

nitrogen. Concentrated melt of these deep snowpacks in the spring and early summer leads to elevated soil moisture and release of nitrogen in the soils. In contrast, low snow depths that are not sustained throughout the winter can cause soil water to freeze. This may trigger lysis of microbial cells, reduce nitrogen immobilization, and result in higher winter nitrogen export. Without the concentrated spring/summer snowmelt, low snowpack can lead to lower soil moisture to sustain plants through the growing season and a lower export of nitrogen in the spring.

Experimental Design

We monitor snow, soil moisture, and soil water nitrogen at three elevations in the Colorado Front Range. The highest elevation site, Michigan River, is located in the persistent snow zone at 3,197 m elevation. It has sandy loam soils that support vibrant wildflowers and dense fir trees throughout the summer growing season but is covered by a deep snowpack throughout the winter and a majority of the year. The middle elevation site, Dry Creek, is located in the Poudre Canyon, in the transitional snow zone. Snow persists throughout the winter, but at lower depths than Michigan River. This site sits at 2,340 m elevation and also has sandy loam soils. The low elevation site, Mill Creek, is located in Lory State Park, in the intermittent snow zone. The study site is in a small valley bottom at 1,784 m elevation, with sandy loam soils that support tall grasses and cacti.

To assess the effects of variable snow depth on soil moisture and soil water nitrogen, we constructed three plots at each study site, each 1.5 m x 1.5 m. One plot was a control, with no changes to snow; the other two were designed to increase and decrease snow depth. These latter two were constructed with PVC frames wrapped in either black or white canvas on three sides. The fourth side had a clear plastic side with visible depth increments facing a time-lapse camera used to document snow depth within the chamber. We hypothesized that the black canvas would decrease plot albedo and expedite snow melt while the white canvas would increase plot albedo and delay snow melt. Beneath each plot we installed two soil moisture probes (5 and 20 cm depth) and one soil temperature probe. To monitor soil water nitrogen, ion exchange resin probes (referred to as PRS™ probes / Plant Root Simulators) manufactured by Western Ag Innovations were installed in each plot. The resins attract nitrogen molecules that can be measured in the laboratory. Four sets of probes were inserted vertically into the soil for month-long burial periods between April and August. Once a probe was removed, a new probe was reinserted into the same location. Probes were cleaned with deionized water to prevent further ion exchange and refrigerated until shipped to the lab for analysis.

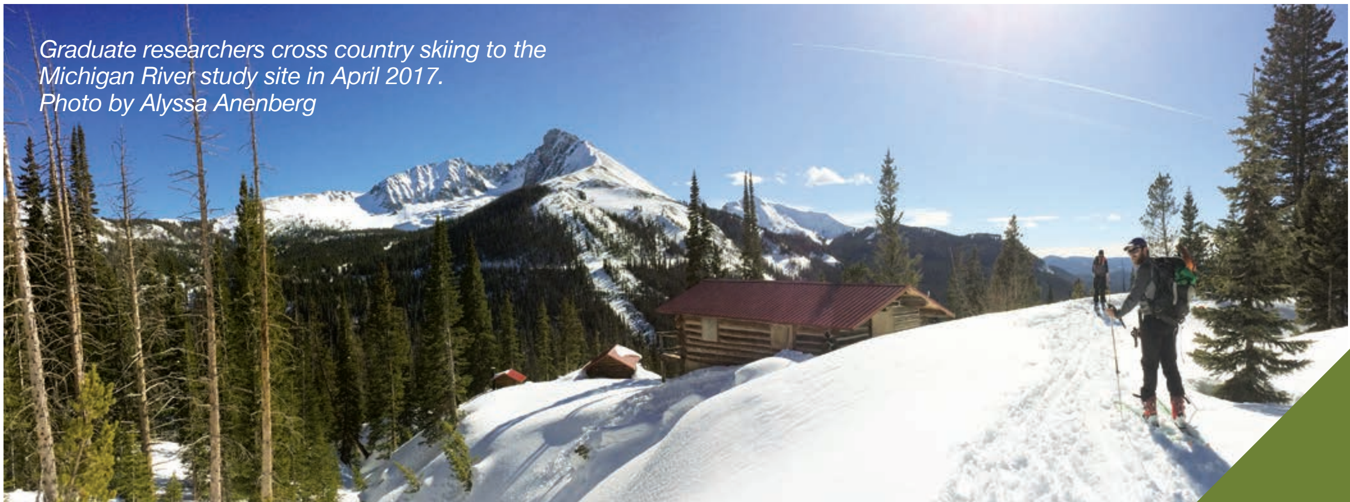
Alyssa Anenberg retrieving PRS probes during a May 2017 field visit to the Michigan River study site.

Preliminary Findings

During the 2017 water year, the high elevation Michigan River study site accumulated snow over several months, reaching peak snow depth (245 cm) in early May 2017. Soil moisture was relatively constant throughout the accumulation period and reached a maximum of 41% in June 2017 in response to spring snowmelt. Soil moisture gradually declined during the summer to a minimum of 15%. The middle elevation Dry Creek and low elevation Mill Creek study sites accumulated significantly less snow (75 and 35 cm, respectively) and experienced earlier mid-winter snowmelt, displaying the greatest magnitude of soil moisture following a late May storm event. Soil moisture at Dry Creek reached 49% while Mill Creek reached 43%. The snow accumulated and fully melted following each storm event, sending pulses of snow melt into the soil throughout the winter and spring. Soil moisture declined throughout the summer to a minimum of 8% at Dry Creek and 1% at Mill Creek.

Resin probes produce a nutrient supply rate based on the amount of nitrogen accumulated over the burial period. The highest nitrogen supply rates observed during the 2017 water year were at the high elevation site, Michigan River, during snowmelt, when soil moisture was high. These rates declined from June to August. Nitrogen supply rates at Dry Creek and Mill Creek were noticeably lower, with peak rates approximately one-third the magnitude observed at Michigan River. Rates were initially highest during snowmelt, declined in May, then increased again in July.

Results supported our original hypothesis that higher elevations would exhibit deeper snowpack and higher soil moisture. This high flux of water through the soil led to mobilization of nitrogen. Since the PRS™ probes simulate plant roots, they readily adsorb this available nitrogen following melt events. Traditionally higher elevation sites support a deep snow pack that would insulate the soils and reduce soil water nitrogen export, however during this water year, snow melted during October and increased soil moisture, which then froze during Novem-

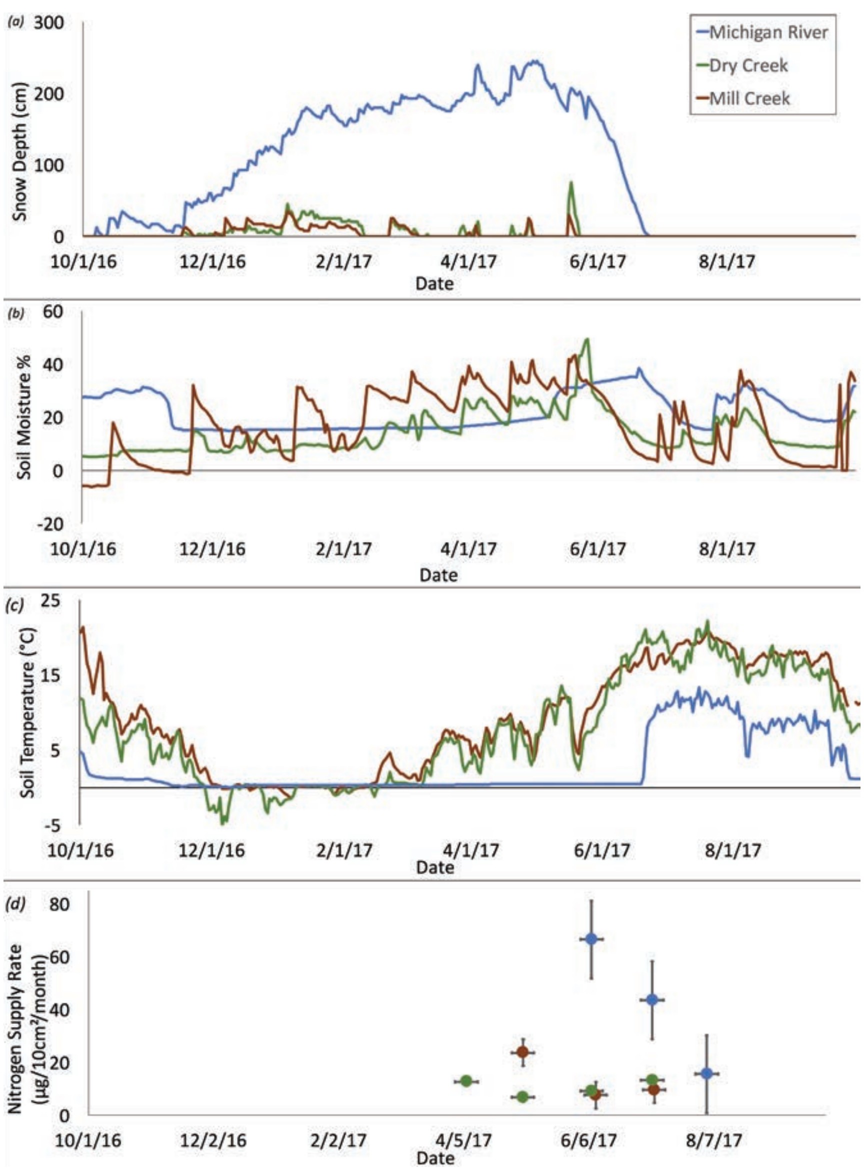


Graduate researchers cross country skiing to the Michigan River study site in April 2017. Photo by Alyssa Anenberg

Table 2. Mean snowpack and soil moisture properties

Study Site	Snow On-set Date	Snow Duration (days)	Peak Snow		Maximum Soil Moisture		Minimum Soil Moisture	
			Date	Depth (cm)	Date	%	Date	%
Michigan River	10/7/16	262	5/1/17	245	6/9/17	41	7/23/17	15
Dry Creek	11/17/16	188	5/19/17	75	5/27/17	49	7/4/17	8
Mill Creek	11/17/16	186	1/5/17	35	5/21/17	43	9/15/17	1

ber snow events and the winter season. Results for the lower elevation sites were consistent with our original hypothesis that lower snow depths would result in lower soil moisture and soil water nitrogen. These sites experienced freeze-thaw events that may have released nitrogen but not at the quantities observed for the deep snowpack site.



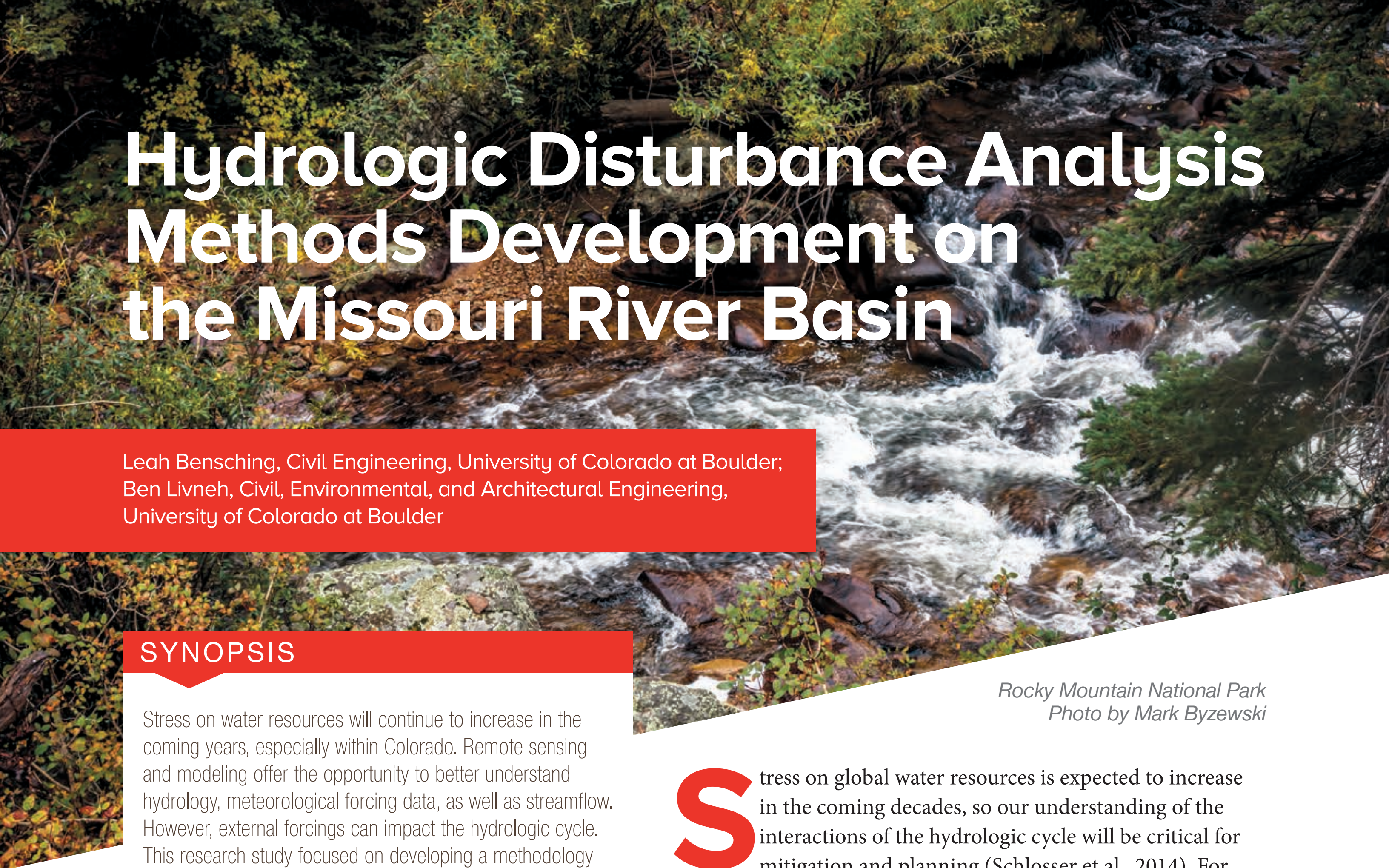
The graph above displays (a) snow depth, (b) soil moisture, (c) soil temperature, (d) nitrogen supply rates for all sites during the 2017 water year.

Future Directions

This first field season indicated that the snow manipulation approach within each study did not produce large differences in snow, and variability in soil water between plots was high. Therefore, for the second season, we are conducting more intensive monitoring on the low elevation site to better understand the effects of pulse-melt events and to increase the plot sample size. For 2018, we have (1) increased the number of plots to enhance statistical strength, (2) installed lysimeters to supplement seasonal data with more quantitative event data, and (3) increased snow manipulation by shoveling snow from black plots into white plots to amplify snow depth variability.

Conclusion

The timing and magnitude of snowmelt change soil moisture and nutrient dynamics. Understanding nutrient dynamics in this region is important for managing the health of ecosystems and water resources. This research provides preliminary data on the elevational response of soil moisture and nitrogen supply to changes in snow cover. Higher elevations with deep snowpacks resulted in a surge of early summer snowmelt that caused high soil moisture and flushing of soil water nitrogen. Lower elevations with smaller snowpacks experienced freeze-thaw events that released pulses of snowmelt throughout the winter and spring, and generated lower soil water nitrogen supply. As monitoring continues, we hope to gain a more detailed understanding of how these factors affect the supply of soil water nitrogen in these mountain regions.



Hydrologic Disturbance Analysis Methods Development on the Missouri River Basin

Leah Bensching, Civil Engineering, University of Colorado at Boulder;
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Rocky Mountain National Park
Photo by Mark Byzewski

SYNOPSIS

Stress on water resources will continue to increase in the coming years, especially within Colorado. Remote sensing and modeling offer the opportunity to better understand hydrology, meteorological forcing data, as well as streamflow. However, external forcings can impact the hydrologic cycle. This research study focused on developing a methodology for the Missouri River Basin to document external forcings and assess model performance.

Stress on global water resources is expected to increase in the coming decades, so our understanding of the interactions of the hydrologic cycle will be critical for mitigation and planning (Schlosser et al., 2014). For places like Colorado, this will be especially important given the over allocation of water resources. Currently, we rely on remotely sensed data and models to validate our understanding of hydrology. The assumption is that these models will transform meteorological forcing data (precipitation, evaporation, temperature, etc.) into streamflow. However, this transformation can be obscured by external forcings that may not be well documented or accounted for. External forcings are defined here as any human or natural changes in the environment that affects the hydrologic cycle. These forcings include, but are not limited to: land use change, land cover change, reservoir operations, and historically changing gaging protocols. The error due to these external forcings is often neglected and may even be erroneously attributed to model insufficiencies.

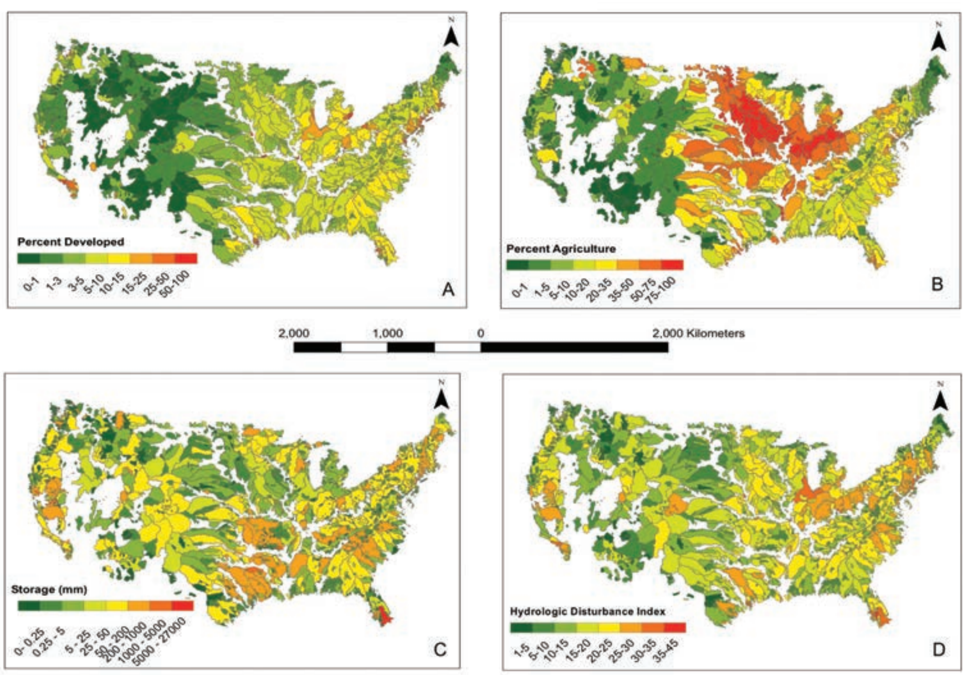


Figure 1. Maps displaying the following: A) Percent of developed land by area; B) Percent of area planted / cultivated (agriculture); C) Dam storage in watershed from the National Inventory of Dams (mm); and D) Hydrologic Disturbance Index; all values are as of 2006.

As seen in Figure 1, external

forcing magnitudes vary drastically across the continental U.S. In some cases, the disturbance is regional (i.e. agriculture in the Midwest and development along the East Coast), in other cases the disturbance is scattered across the country (i.e. reservoir storage). Identifying these continually changing disturbances and their influence on the hydrology can help improve model development and the appropriate use of model forecasts.

To develop the methods for this study, a preliminary set of seven Colorado basins were selected from the USGS GAGES II database to capture variations in size, streamflow magnitude and external forcing influences. The basins are shown in Figure 2. To overcome the problem that not all disturbances are well-documented, our first hypothesis is that a broad measure of disturbance can be obtained by comparing hydrologic model simulations representative of undisturbed conditions against gaged streamflow. The undisturbed model simulations and the gaged streamflow were compared using objective functions (bias, correlation, Nash score, and standard deviation ratio) that would capture the difference between the undisturbed model and the observed monthly streamflow. The analysis was then expanded for all streamflow gages in the Missouri river basin (HUC 2 basin scale). The VIC (Variable Infiltration Capacity) model was selected here since it balances both water and energy using physically-based equations of fluxes across vegetation, soil, and snow (Liang et al.,1994). Streamflow simulations from the Livneh et al. (2015) dataset were used as a baseline for undisturbed hydrologic response.

Table 1. Explanation of GAGES II classifications used to identify disturbance metrics.

External Forcing	Description
NID Storage	Dam storage in watershed as measured by the National Inventory of Dams in 2009 (megaliters total storage / km^2)
Fresh Water Withdrawal	Average freshwater withdrawal from 1995-2000 county-level estimates. (megaliters/ year/km^2)
% Irrigated Area	Percent of watershed in irrigated agriculture from USGS 2002 250-m MODIS data
% Developed Area	Watershed percent "developed" (urban), from 2006 era
% Cultivated Area	Watershed percent "planted/cultivated" (agriculture) from 2006 era
Road Density	Road density, km of roads per watershed km^2, from Census 2000 TIGER roads
Hydrologic Disturbance Index (HDI)	HDI aims to capture the total disturbance in a basin. It is comprised of Dam density, water withdrawal, change in dam storage from 1950-2009, streams classified as canals, ditches or pipelines, proximity of gage to dam, road density, and percent developed land.

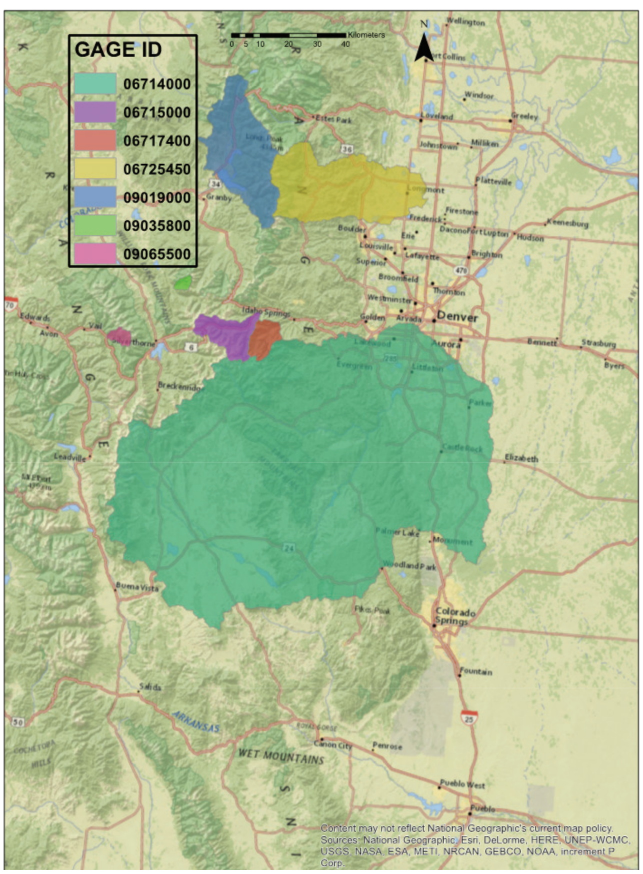


Figure 2. Basin areas corresponding to selected USGS streamflow gauges. The basin areas range from 25km² to 10,0000 km².

External forcings were obtained from the GAGES II database (Falcone et al., 2011). GAGES II provides characteristics of basins associated with a USGS monitored streamflow gage. Seven forcings were identified to capture common hydrologic disturbances, including: National Inventory of Dam storage, freshwater withdrawal, percent irrigated, percent developed, and percent cultivated areas, road density, and the Hydrologic Disturbance Index. The external forcings are described in table 1. Our second hypothesis was that objective functions such as bias, correlation, Nash score and standard deviation ratio would increase monotonically with the magnitude of each external forcing.

Findings

The scope of the findings are limited to a straightforward comparison between model performance and the degree of disturbance across seven basins with areas from 25 km^2 to 10,000 km^2. The Colorado basins are shown in Figure 3. In some cases (i.e. Hydrologic Disturbance Index versus Bias) there was a clear linear relationship between the external forcing and the calculated statistics. In others, (i.e. Hydrologic Disturbance Index versus Correlation), there was no clear relationship between the external forcing and the model performance statistic. Given the small sample size, our ability to assess the general pattern of disturbance response and to test our two hypotheses was limited. An ideal next step would be to increase the sample size (e.g. > 500 gaged basins) to understand disturbance impacts more broadly.

Preliminary analysis into a larger sample size was conducted by including the 924 gages in the Missouri River Basin, e.g. HUC 2 region 10. Following the same process as the seven Colorado basins, objective functions were calculated for each basin between the USGS observed streamflow and undisturbed baseline VIC model. The preliminary Missouri River Basin analysis did not reveal meaningful patterns when comparing the objective functions to the disturbance magnitude. A few examples are shown in Figure 4. These results reject the proposed hypotheses. Rejecting our hypotheses means we can learn from these results as to how to improve future analysis. Possible improvements include the following:

1) In retrospect, the Missouri River Basin was not the best choice for the large-scale disturbance analysis. Numerous hydrologic investigations have noted considerable challenges in realistically modeling the hydrology of the Missouri River Basin (e.g. Xia et al., 2012; Newman et al., 2015) due to problems with precipitation estimation, inadequate representation of surface water/groundwater interaction, and tile drainage. As such model errors could be due to factors other than the selected external forcings. A reasonable next step would be to analyze a basin such as the Sacramento, Columbia, or Ohio River Basins where model simulations are expected represent hydrologic processes with higher fidelity.

2) Most basins contained disturbances from more than one external forcing. This analysis did not distinguish between the mixed external forcings in the basins. Future studies should first identify basins with only one significant external forcing in order to isolate impacts.

3) The disturbance data from the GAGES II database provided stagnant external forcing magnitudes when many external forcings change over time. Results will be more meaningful if a time series analysis is done based off changed external forcings.

4) Models have a variety of strengths and weaknesses including the ability to capture streamflow peaks, snowmelt timing, and evaporation. Using an ensemble of hydrologic models will improve their role as an undisturbed proxy by identifying robust patterns across models and thereby decrease uncertainties.

This preliminary analysis generally rejected the proposed hypotheses about external forcings. Yet, it provided meaningful insight into the complexities of the problem at hand and leaves us with an important question: How do we consider the many changing variables in the hydrologic cycle?

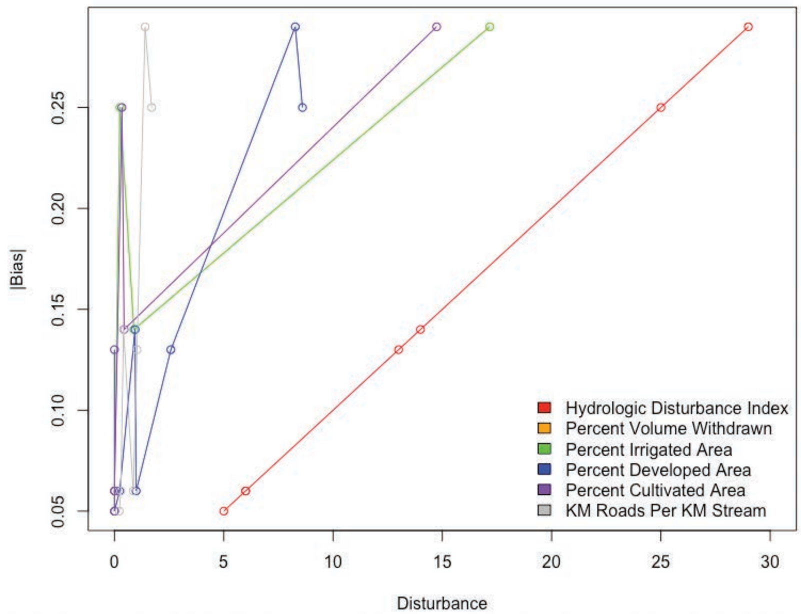
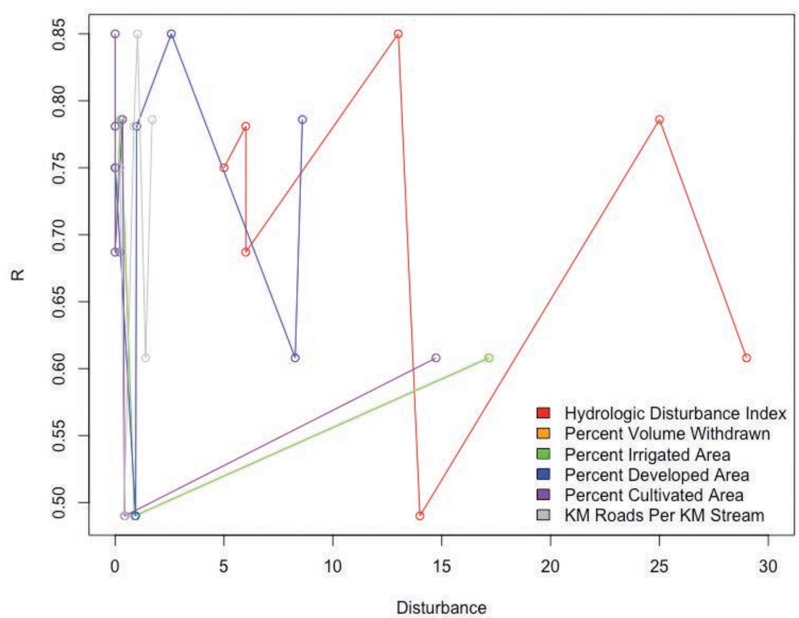


Figure 3. Absolute value of the model bias and correlation versus the magnitude of the disturbance for seven stream gauges in Colorado.



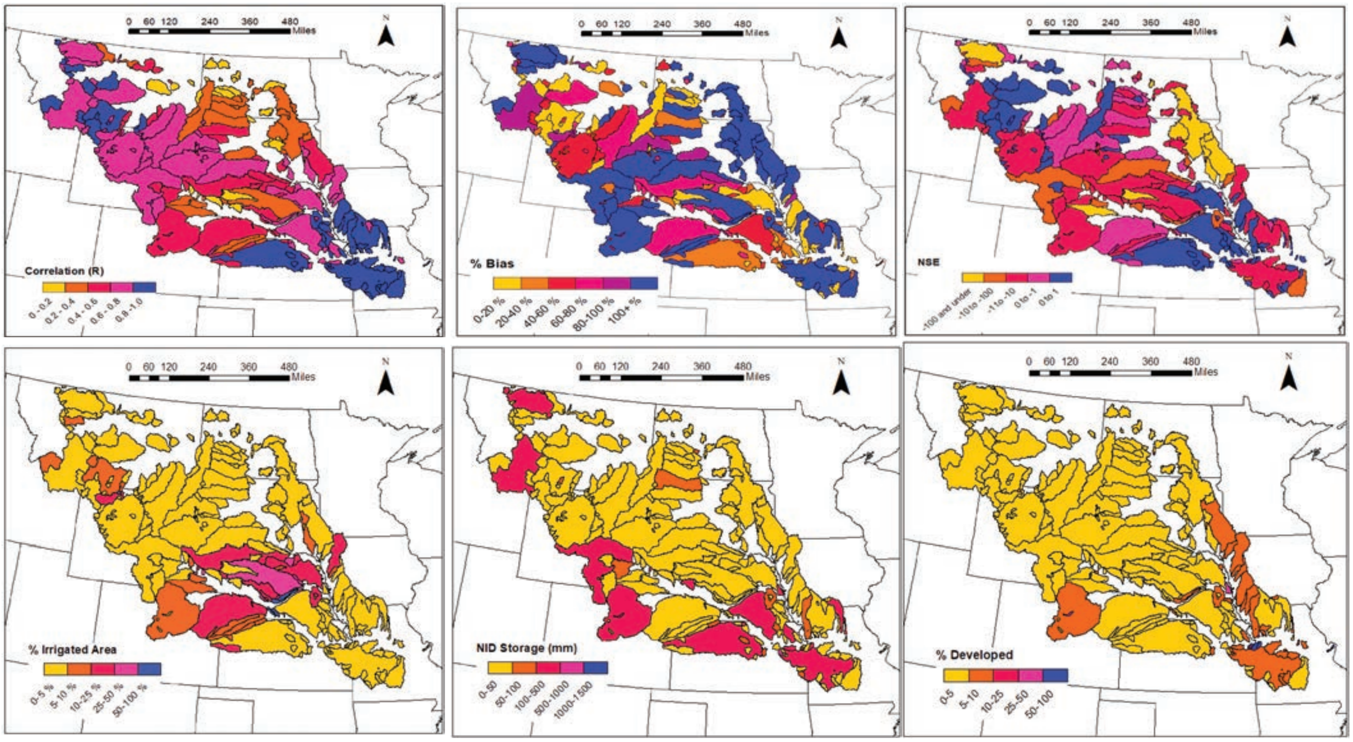


Figure 4. Spatial distribution of selected objective functions (Correlation, percent bias and Nash score) and external forcings (percent irrigated area, NID storage and percent developed area) for the Missouri river basin.

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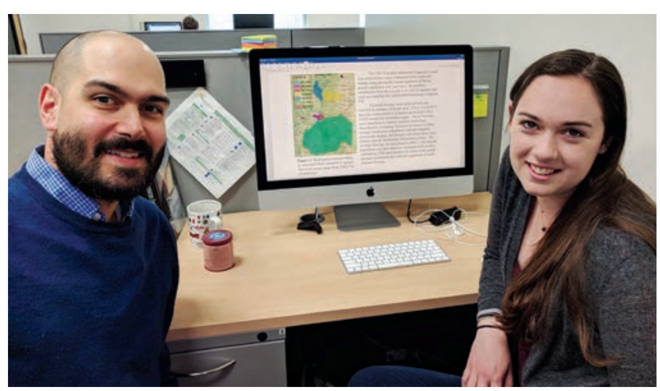
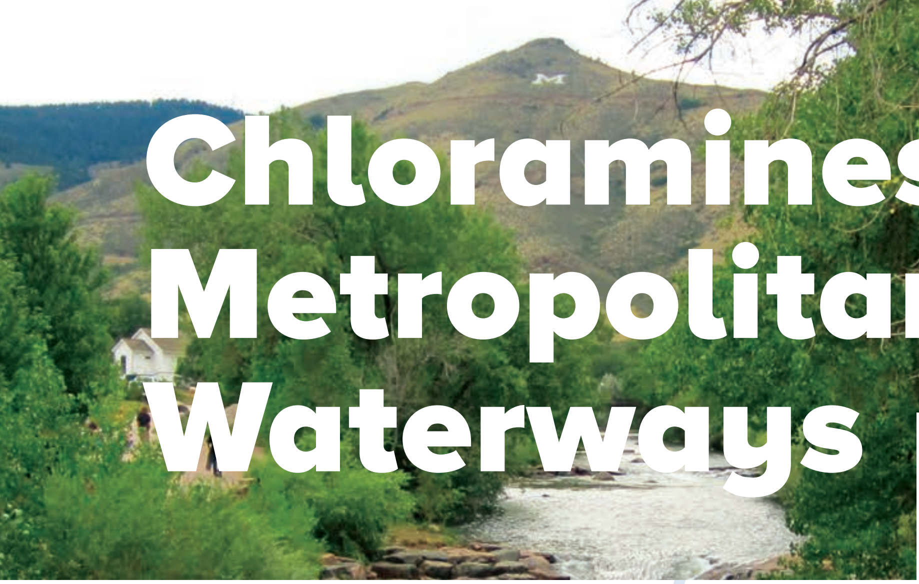


Ben Livneh (left) and Leah Bensching (right).

Chloramines in Metropolitan Denver Waterways



Daniel Clark, Geospatial Science, Metropolitan State University of Denver;
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SYNOPSIS

The South Platte River is an urban waterway that flows through the Denver metro area, which is impacted by elevated nutrient concentrations, pesticide residue, heavy metals, and halogens. As a result, this diminishes water quality, impacts the ecosystems along the river, and the fish community. This research project focused on assessing chloramine levels within the South Platte River, Clear Creek, as well as Sand Creek. The results indicated that each of these locations had chloramine concentrations that negatively impact invertebrate and vertebrate species.

Introduction

The Denver metro area is fully contained within the South Platte Watershed. Thus, the South Platte River can truly be classified as an urban waterway as it flows through the Denver Metro Area, highly impacted by urban runoff and stream modification. Elevated nutrient concentrations, pesticide residue, heavy metals, and halogens have been observed in the river (USGS, 1998; Health, 2014). This diminished water quality impacts the ecosystems along the river through the Denver Metro area including riparian wetlands that tend to have high proportions of non-native plants (Smith, 2015). The fish community of the South Platte River is also affected by the urban environment. The community changes dramatically from Denver, where Tate and Martin (1995) found low species richness (8 observed species, 3 non-native), to North Platte, Nebraska where the authors found higher species richness (15 species, 3 non-native). The authors theorize that the differences in the fish communities could be due to differences in water quality. Many urban factors can contribute to low species richness including the pollutants described above as well as sediment loading and thermal pollution. Colorado's Water Plan (2015) has acknowledged the degraded water quality throughout the South Platte River in the metro area and has "identified recovery of key species of trout and native plains fish as important."

(Above) Clear Creek in Golden. Photo by Wally Gobetz

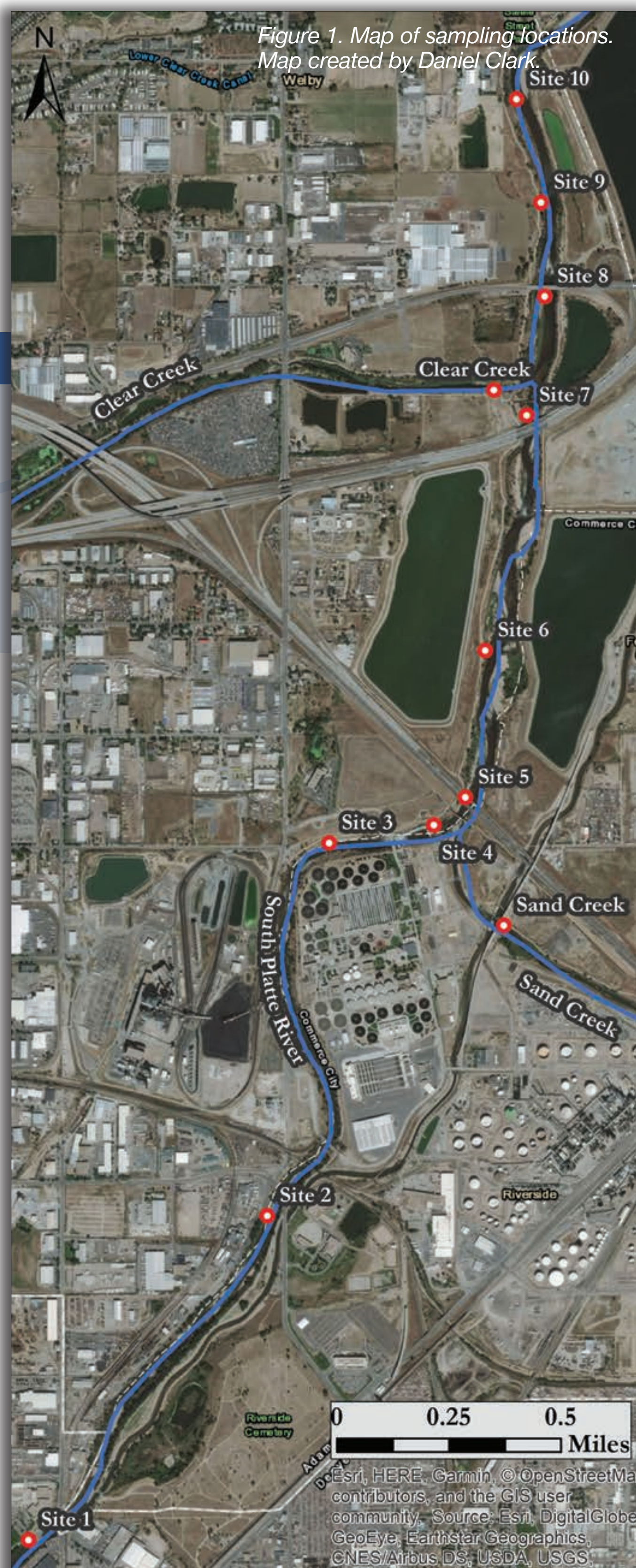

Figure 1. Map of sampling locations. Map created by Daniel Clark.

Chlorine is widely used as a disinfectant in water treatment because it is a strong oxidizer and will kill microbes as it reacts with cellular material. In the Denver metro area, two forms of chlorine are primarily used. Metro Wastewater uses sodium hypochlorite at the Robert W. Hite Treatment Facility as a final treatment before wastewater is discharged into the South Platte River. Sodium hypochlorite quickly reacts with organic material in the presence of oxygen and forms sodium or calcium chloride, rendering it less toxic. In contrast, chloramine is far more stable and will remain in water for long periods. Because of this persistence, it is often the preferred form of chlorine for drinking water disinfection, since the water will remain safe as it travels from the water treatment facility to the consumer (EPA, 1999). Denver Water currently uses chloramines in its disinfection process. While treated drinking water is not discharged directly into the South Platte River, some of this water does end up in the river when it flows through the hundreds of stormwater drains that deposit water originating from residential and commercial irrigated landscaping.

Figure 2. Sarah Schliemann and Daniel Clark collecting water samples from the South Platte River. Photo by Sara Jackson.

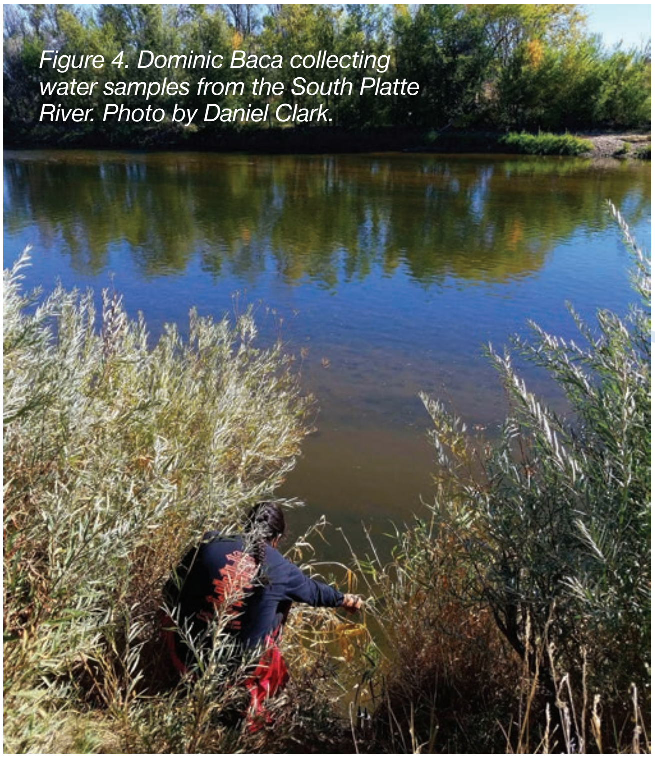

Figure 4. Dominic Baca collecting water samples from the South Platte River. Photo by Daniel Clark.

Figure 3. Deja Knox with water samples collected from the South Platte River. Photo by Daniel Clark.

Chloramines have been shown to causes adverse impacts on aquatic systems; causing mortality in invertebrates and vertebrates alike. The EPA has set the limit for chronic free chlorine expose to 0.011 mg/L. Above this level, biological organisms in the water body may be adversely affected (EPA, 1986). Chloramines can also react with organic matter to form disinfectant byproducts (DBPs) that can themselves be toxic. DBPs can be difficult to quantify due to the large number of chemicals that can form, however some of the more common DBPs include trihalomethanes, trihaloacetic acids, and dihaloacetonitriles (Du et al., 2017).

Because chloramines are not found in natural systems, they can also be used to gauge the total amount of municipal treated water that is found in a water body. The goal of this project was to investigate chloramine levels in the South Platte River and two of its main tributaries: Clear Creek and Sand Creek.

Methods

In the Fall of 2017, 12 sample sites were identified in the northern part of the Denver metro area including: ten along the South Platte River; one along Sand Creek, upstream of the confluence with the South Platte River; and one along Clear Creek, upstream of the confluence with the South Platte River (Figure 1). Samples were collected from the bank every two weeks from October 2017-February 2018 (Figures 2-4). In the lab, samples were prepared in accordance with Standard Methods for the Examination of Water and Wastewater and were pH buffered with sodium hydroxide and treated for hard water prior to analysis. Chloramine concentrations were subsequently measured using an indophenol colorimetric method on a Hach DR 900 colorimeter.

Results

Chloramine was present in 98% of the samples, with samples collected at sites along the South Platte River showing the highest concentrations (Figure 5). Over the course of the investigation, the measured concentrations ranged from a minimum of 0 mg/L to a maximum of 1.09 mg/L. There was a large amount of variability from one sampling period to the next and there were no temporal trends.

Conclusions

All the sites in this study had average chloramine concentrations that far exceeded the chronic exposure limit of 0.011 mg/L set by the EPA. At these levels, it is likely that invertebrate and vertebrate species are negatively impacted. Juveniles are often the most susceptible to elevated chlorine levels and so, there may be issues with recruitment of key fish, amphibian, and invertebrate species in these areas (Pasternak et al., 2003).

The high levels of chloramines found in this investigation are especially interesting given that the samples were collected during the winter. Presumably, a significant amount of municipal water runs from residential yards and ends up in the river during the summer. It is possible that, with every snowmelt, a flush of chloramines are moved from the soil or groundwater into the river, but that idea is impossible to confirm with the present data.

This project has initiated several new investigations that will begin this summer. We will widen our sampling area to include areas along the South Platte River upstream and downstream of the present sampling locations. In particular, we will include locations upstream of the city to measure the concentration before the water begins to accumulate inputs from storm drains. In our current area, we will also collect samples from storm drains to attempt to identify the sources of the chloramines. Moreover, we will expand our research to isolate other species of chlorine including chloride, chlorate, chlorite, free chlorine, and total chlorine. Using this information, we will attempt to identify sources of chlorine pollution in the South Platte River and its tributaries.

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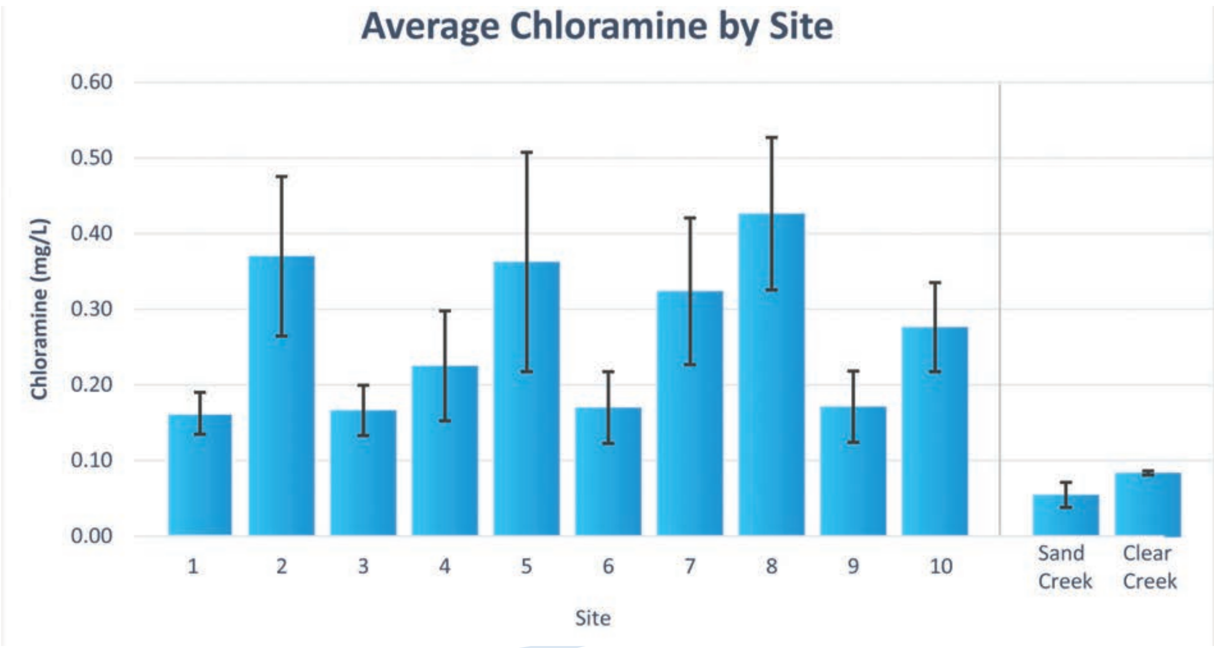

Figure 5. Mean chloramine concentrations at sample plots. Numbered plots are along the South Platte River. Error bars illustrate standard error. Figure created by Daniel Clark.

Effects of Water Velocity on Algal-Nutrient Interactions in Streams of the Poudre Watershed, Colorado

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SYNOPSIS

The Poudre River is an essential resource for freshwater within the Colorado Front Range for recreational activities and fisheries. Headwater mountain streams supporting the flow of the Poudre River help critical ecological functions, producing streambed algae as well as transporting organic matter to feed insects and fish. As a result, this research study assessed the influence of stream velocity on algal responses to nutrient additions and aquatic insect consumption.

Introduction and Background

The Poudre River provides an important source of freshwater to Colorado's Front Range, supporting recreational activities and fisheries. Headwater mountain streams that flow into the Poudre River serve important ecological functions, producing streambed algae and transporting organic matter that can feed insects and fish. Headwater streams also serve as refugia for cold water fish, which are being threatened by warming water temperatures across the state (Colorado Climate Plan, 2015). Finally, these smaller streams provide recreational opportunities for floating and fishing, and many of them lie adjacent to hiking trails. Clearly, these waters are of great value ecologically and for human use.

Headwater streams are being threatened by nutrient enrichment, which occurs when human-derived nitrogen and phosphorus enter the streams. Nutrients can come from grazing livestock, atmospheric deposition, or deforested lands in the mountains (Carpenter et al., 1998). Adding nutrients often increases algal biomass, and algae serve an important function of removing those nutrients from the water column so they are not transported downstream to larger rivers like the Poudre. However, under certain

(Left) Whitney Beck placing nutrient diffusing substrate experiments into Seven Mile Creek near Rustic, Colorado in the Poudre Canyon.
Photo by Mitch Ralson

Table 1. Study sites for experiments in the Poudre Watershed.

Site Name	Elevation (meters)
Elkhorn	1992
Seven Mile	2212
Little Beaver	2443
South Fork Poudre	2740
Killpecker	2798

conditions large algal blooms can form, and these produce detrimental effects on fish and insects by blocking sunlight, producing toxins, and lowering stream dissolved oxygen (Carpenter et al., 1998).

There is evidence that algal biomass in Poudre Watershed streams is responsive to increases in nutrients, particularly nitrogen. A study of 74 Colorado Front Range Streams showed that algal biomass was positively correlated with in-stream nitrogen levels (Lewis et al., 2010). If human activities continue to increase nitrogen, we are likely to see substantial increases in algal biomass. High elevation streams in the Poudre Watershed are particularly vulnerable because my research shows that they currently have high nitrogen levels and algal accumulation rates. This is surprising because high elevation sites have low summer temperatures (e.g., 4-6° Celsius) which would be expected to slow algal growth (Stevenson et al., 1996).

A little-explored research area is how stream water velocity can regulate the development of algae. Stream water velocity changes throughout the Poudre Watershed's snowmelt seasonal cycles, and also varies spatially in the riffle-pool sequences. Water velocity has been shown to a) influence algal uptake of nutrients (Stevenson et al., 1996), b) scour algae from rocks and other surfaces, and c) regulate insect grazing activity (Opsahl et al., 2003). In summer 2017, we completed field experiments in mountain streams of the Poudre Watershed to investigate how water velocity interacts with nutrient additions and aquatic insects to control algal biomass growth and accumulation. The five focal streams spanned an elevation gradient of 2,000 meters to 2,800 meters (Table 1). These small streams vary widely in temperature and have relatively low nutrient concentrations, making them ideal for answering questions about nutrient enrichment impacts.

Project Methods

Experiment 1: How does stream velocity influence algal responses to nutrient additions?

In August 2017, we deployed nutrient diffusing substrate experiments in fast (>40 cm second^{-1}) and slow (<15 cm second^{-1}) sections of five different streams. Nutrient diffusing vials were filled with just agar (control), agar + nitrate (N treatment), agar + phosphate (P treatment), and agar + nitrate + phosphate (NP treatment). Agar is a thick, gelatin-like substance from which nutrients are slowly released during the experimental period. The agar-filled vials were capped with porous glass discs, which served as a growth surface for algae in streams for a period of three weeks. Upon collection, the vials were analyzed for algal biomass (measured as the photosynthetic pigment chlorophyll a). ANOVA statistical tests were used to determine the effect of nutrients and velocity on algae.

Experiment 2: How does current velocity influence aquatic insect consumption of algae?

To answer this question, we completed experiments at the Colorado State University (CSU) Mountain Campus in August and September 2017. We built an underwater electric fence to exclude aquatic insect grazers and allowed algae to grow on the nutrient diffusing substrates within and outside the fence. Upon collection, the vials were analyzed for algal

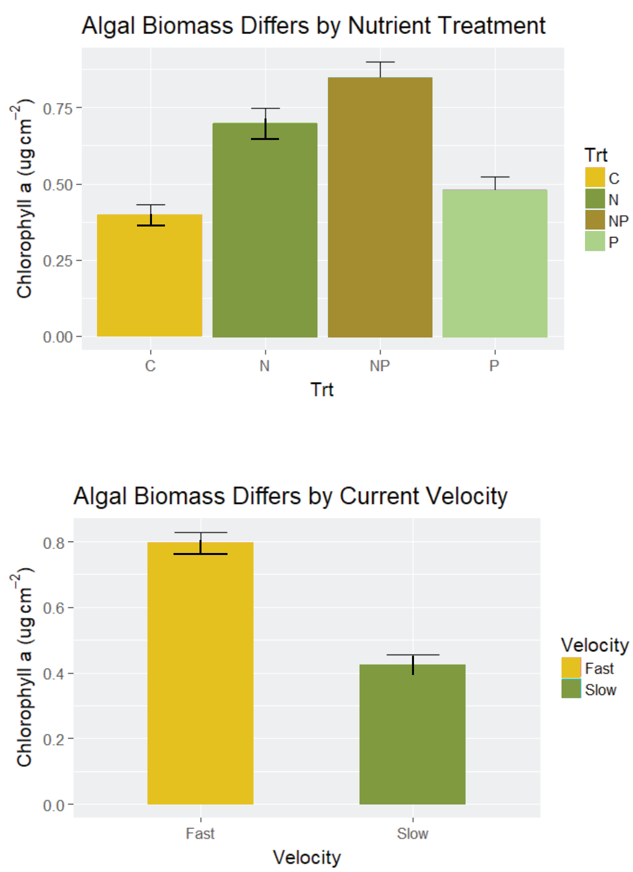

Figure 1. In Summer 2017, we deployed nutrient diffusing substrate experiments in two different velocities, within five streams of the Poudre Watershed. We found significantly higher algal biomass on the nitrogen and nitrogen + phosphorus treatments as compared to controls (top), and we found significantly higher algal biomass in fast velocities as compared to slow velocities (bottom).

biomass and organic matter, and ANOVAs were used to determine the effect of nutrient, velocity, and aquatic insects on these response variables.

How do stream background conditions vary during these experiments?

During each experiment, we completed in-stream surveys of physical, chemical, and biological parameters. These included in-stream nutrients (total nitrogen, nitrate, and phosphate), conductivity, pH, riparian canopy cover, discharge, plot-level velocity (measured at a fine, 1-cm scale), and aquatic insect densities.

Results & Discussion

In experiment 1, we found that algal growth in the Poudre Watershed streams was generally limited by the availability of nitrogen, which was evident from the strong response of algae to nitrogen additions (Figure 1). Algae also responded strongly to the nitrogen + phosphorus treatment. This is consistent with previous experiments we completed in summer 2015-2016, but is troublesome because we know nitrogen levels are increasing in nearby areas like Rocky Mountain National Park from atmospheric deposition. Indeed, we see an unexpected increase in stream nitrogen with elevation in the Poudre Watershed.

A novel conclusion from this study was that nutrient limitation changed depending on the velocity tested. For instance, at the South Fork Poudre River, we found nitrogen limitation in slow velocities (i.e., algae increased significantly with nitrogen additions) but phosphorus limitation in fast velocities (i.e., algae increased significantly with phosphorus additions). In Seven Mile Creek, we found no nutrient limitation in slow velocities (i.e., algae on nutrient treatments was similar to algae on controls), but nitrogen limitation in fast velocities. We recommend that researchers and managers consider the influence of current velocity when thinking about how to manage algae. Completing experiments in a single location will not help us understand the vulnerability of a stream to nutrient additions, and whole stream nutrient uptake experiments are likely more informative.

Elkhorn Creek in the Poudre Canyon, August 2017 (left). Algal communities change based on stream conditions. Rocks at Elkhorn Creek (right) are often covered with Nostoc spp., a cyanobacteria that can transform atmospheric nitrogen gas into a usable form when in-stream nitrogen is low. Photo by Whitney Beck.

We also found that algal growth was higher in faster velocities (Figure1). This may be counter-intuitive because in many streams, algal blooms form in slow pools. However, we hypothesize that faster current velocities support higher nutrient delivery rates in these low resource streams, allowing algae to thrive. Fast velocities may also decrease the mobility of aquatic insect grazers that consume algae.

In experiment 2, we found that aquatic insects depleted organic matter but not algal biomass (Figure 2). Organic matter consists of live and dead carbon, including algae, bacteria,

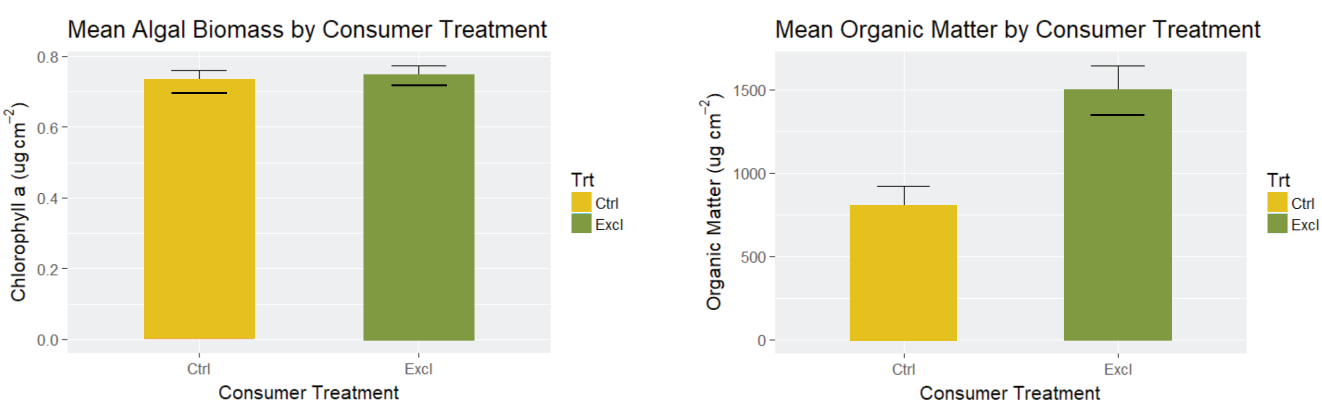

Figure 2. In Summer 2017, we built an underwater electric fence to exclude aquatic insects from algal growth plots. We found no difference in algal biomass between exclusion treatments and controls (left), but we did find a significant difference in organic matter (right). There was no interaction between current velocity and the influence of aquatic insects (data not shown).

Nutrient diffusing vials deployed in streams to determine whether more algae grows on nutrient-enriched treatments as compared to controls (left). The vials were filled with gelatin-like agar and nutrients, and capped with porous glass discs serving as an algal growth service. Aquatic insect larvae (Diptera, flies) colonized some of the vials and discs (right). Photo by Whitney Beck.

fungi, and detritus. This finding reflects the high abundance of Diptera (flies) and Coleoptera (beetles) present in the stream, which primarily consume and dislodge organic matter. Furthermore, there was no relationship between current velocity and insect consumption. This was likely because we tested a narrow range of velocities (2-30 cm second^{-1}) that the insects were already adapted to.

Conclusions and Future Directions

Taken together, these experiments have considered factors that increase algal biomass (in-stream nutrients and nutrient additions), factors that deplete algal biomass (aquatic insect consumers), and how they are mediated by current velocity. In general, nitrogen additions are likely to increase algal biomass in Poudre Watershed streams, and aquatic insects may not be able to consume algae quickly enough to compensate (especially in fast velocities).

These small-scale experiments are informing the design of a larger modeling study that will inform water quality policy and stream management programs. We plan to use Environmental Protection Agency (EPA) and United States Geological Survey (USGS) government datasets to model how algae respond to nutrients and insect grazers on a national scale, and whether those relationships changed based on streamflow disturbance metrics like flood frequency. These models will help inform when and where streamflow management could be used to control algal biomass in rivers and streams that experience harmful blooms.

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Tracking Post-Flood Channel Adjustments and Reservoir Sedimentation to Inform Water Management Practices

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Sara Rathburn, Geosciences, Colorado State University

SYNOPSIS

In September 2013, the Colorado Front Range experienced a >200-year flood, damage communities, infrastructure, water supply, and treatment facilities. Within the North St. Vrain watershed, 200-450 mm of precipitation fell and triggered over 100 landslides. This research study focused on understanding sediment fluxes from the North St. Vrain to the Ralph Price Reservoir. Specifically, the rate of delta progradation at the reservoir inlet from 2013-2017 was quantified, as well as we the volume and spatial distribution of sediment. Overall, this research study revealed that over 57,000 m^3 of sediment was remobilized and deposited within the delta.

Introduction

From September 9-15, 2013, a tropical storm swept across the Colorado Front Range, producing a >200-year flood (Yochum, 2015) that resulted in major damage to numerous Front Range communities. In its wake, eight lives were lost (Gochis et al., 2015), and homes, roads, bridges, buildings, as well as water supply and treatment facilities were damaged. Within the North St. Vrain (NSV) Watershed, the storm produced between 200 and

(Above) Surveying fieldwork at the North St. Vrain Creek approach channel, located approximately 800 meters upstream of the Ralph Price Reservoir in Lyons, CO. Photo by Sarah Rathburn.

Johanna Eidmann (Left) and
Sara Rathburn (Right)
Photo by Jamie Freel

450 mm of precipitation (Gochis et al., 2015) and triggered over 100 landslides. North St. Vrain Creek, which flows into Ralph Price Reservoir near Lyons, Colorado (Figure 1), experienced extensive flooding and channel change[1]. Over 10 m of aggradation occurred along an 800-m length of the channel, transforming the inlet into an approach channel (Figures 1B and 1C). In addition, over 300,000 m^3 of sediment was deposited in the reservoir, causing a 2-4% loss in reservoir storage capacity (Rathburn et al., 2017). The 2014 snowmelt runoff remobilized and deposited a volume of sediment to the reservoir that was comparable to the flood-derived deposition (Rathburn et al., 2017).

As the aggraded channel adjusts towards a state of equilibrium, sediment continues to be remobilized and transported into the reservoir. This research focuses on quantifying the ongoing channel change and sediment movement along NSV Creek into the reservoir, as well as the rate of the delta progradation caused by the remobilization of sediment. This research is a collaborative effort with the City of Longmont, which enables research results to inform future water management decisions.

Research Objectives

The primary goal of this research is to better understand and track continued sediment fluxes from the NSV into the Ralph Price Reservoir. For purposes of this paper, we focus on two objectives including: 1) quantifying the rate of delta progradation at the reservoir inlet between 2013 and 2017 and 2) quantifying the volume and spatial distribution of sediment that continues to be remobilized into the reservoir over time.

During our research, the reservoir was unexpectedly lowered to accommodate downstream post-flood bridge reconstruction. As a result, we took the opportunity to assess the impacts of this reservoir base level drop on channel erosion and associated deposition. An additional research objective is therefore 3) quantifying how post-flood (2014) rates of sedimentation and erosion compared to rates observed following a drop in reservoir base level (2016-2017).

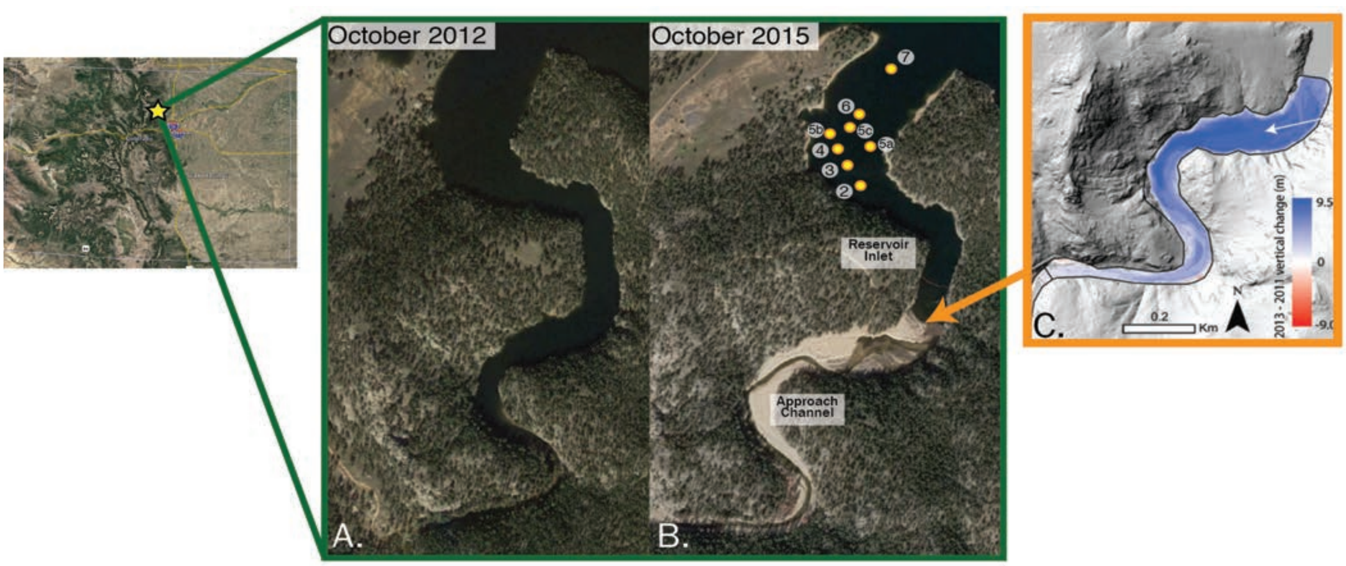

Figure 1. Google Earth images and DEM differencing showing significant sediment accumulation at the approach channel due to the flood. Figure 1B. shows the sediment core locations along the inlet.

Methods

To quantify the volume of sediment aggradation at the inlet and track delta progradation, we collected bathymetric surveys following the September 2013 storm. The sonar surveys were conducted at the reservoir inlet prior to snowmelt in April 2014, April 2016, and May 2017. Due to the low reservoir level in May 2017, an additional and more detailed bathymetric survey was also conducted in August 2017. Spatial statistical analyses were applied to create DEMs from the sonar tracks, and the DEMs were then differenced for volumetric change over time.

Eight sediment cores were collected from the reservoir inlet in April 2017 using a Livingstone surface corer (Figure 2A). To evaluate the spatial continuity of various sediment layers, six cores were collected near the center of the inlet along the long axis of the reservoir, and two cores were placed across the inlet (Figure 1B). Analyses on the collected cores include grain size analysis, bulk density, magnetic susceptibility, XRF analysis, and loss on ignition (LOI; for total organic carbon).

Results and Discussion

Four years after the flood, impacts to the reservoir are still being measured. Repeat bathymetry of the inlet reveals that the delta front has prograded over 170 m since the September 2013 flood (Figure 3). The rate of delta progradation (50 m/yr) has remained constant between April 2014 and April 2016 (post-flood), and between April 2016-May 2017 (the period associated with a 10 m drop in base level, Figure 4). However, the sub-annual rate of progradation between May 2017 and August 2017 (encompassing 2017 snowmelt) suggests a decrease in the progradation rate. An additional bathymetric survey in April 2018 will confirm this finding.

Volumetric differencing of bathymetric data indicates that, between 2014 and 2017, over 57,000 m^3 of sediment was deposited in the reservoir delta (Table 1). Net deposition occurred in the area of common bathymetry between 2014-2016, with up to 11 m of vertical aggradation (Figure 5). Net sediment erosion occurred between 2016-2017, associated with the drop in reservoir stage (base level), when up to 4 vertical meters of sediment was eroded from the inlet and transported into the deeper portion of the reservoir, possibly following the former NSV channel (Figure 5).

Since the 2013 flood, ten cores were collected at the reservoir inlet in the prodelta sediment, in front of the mapped delta front (Figure 3). The cores represent additional, not yet quantified deposition because they were collected in an area outside the common bathymetric surveys. As a result, our volumetric differencing represents a minimum amount of sediment remobilization and deposition into the reservoir inlet.

Cores collected at the reservoir inlet not only showed visually distinct sediment layers associated with pre- and post-flood sedimentation, but also depicted a post-flood (2014-

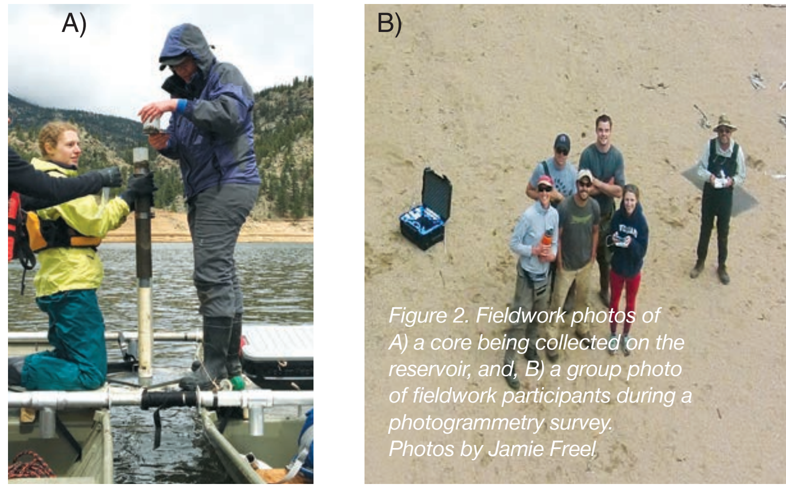

Figure 2. Fieldwork photos of A) a core being collected on the reservoir, and, B) a group photo of fieldwork participants during a photogrammetry survey. Photos by Jamie Freel

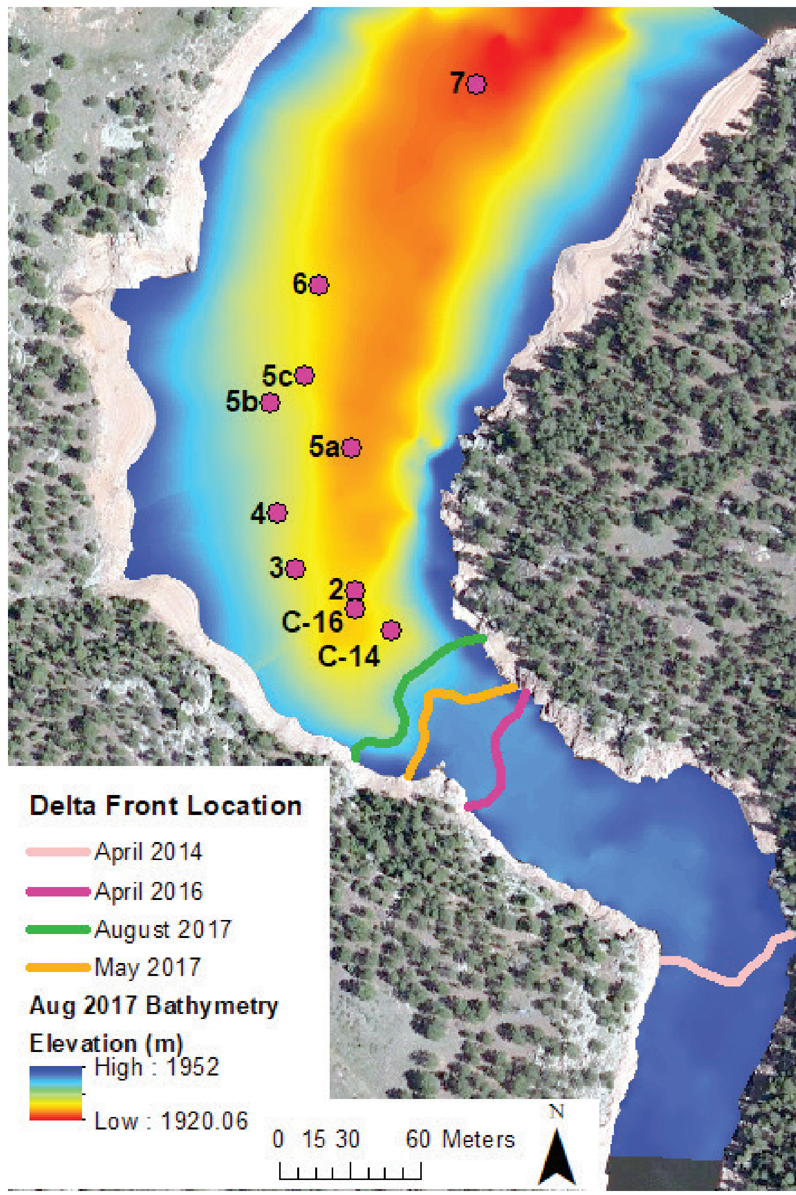

Figure 3. The August 2017 bathymetry of the reservoir inlet. Colored lines indicate the postion of the delta front with time, and points indicate coring locations.

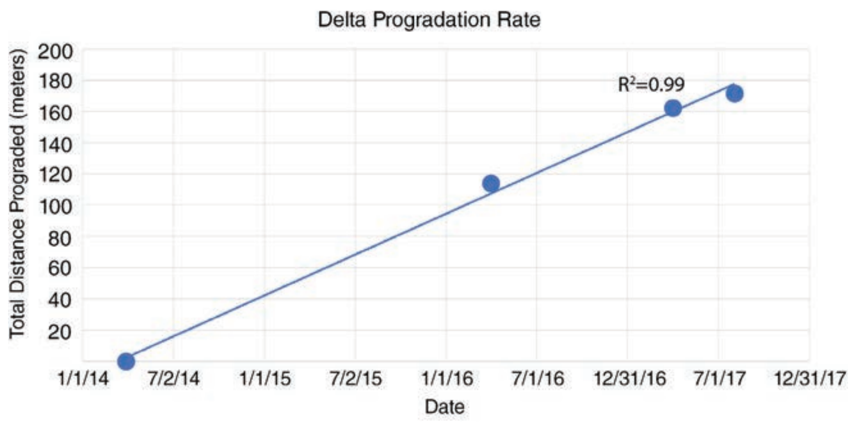

Figure 4. The distance of delta progradation relative to the location of the delta front in April 2014 with time.

2017) sediment accumulation of 20 cm to over 70 cm in thickness. Magnetic susceptibility, LOI, and grain size were further used to correlate the post-flood sediment layers between the cores (Figure 6). Cores showed that post-flood (Fall 2013 - Spring 2014) sediments include a laminated sand layer overlain by silty mud and organic layers present in almost all of the cores; sedimentation that is most likely associated with the initial flood event. A mud layer stratigraphically younger than the organic layer suggests the settling of fines during Winter 2014. Its occurrence as the top stratigraphic layer of a core collected in April 2014 further supports this conclusion. Remobilized sediment of coarser lenses of sand overlain by mud with organics is found at the top of a core collected in 2016, and is therefore most likely associated with the snowmelt runoff in 2015 and 2016. Unique to cores collected closest the approach channel in 2017 was a fine, silty layer, suggesting its recent deposition in winter or early spring of 2017. The pinching out of these layers with the progression to the more distal parts of the inlet (cores 5-7) corroborate that the top layers in the core are associated with lower-magnitude discharges than the flood.

A comparison between Cores 5a, 5b, and 5c shows a thicker lens of sand in Core 5a—the core closest to the inner bend of the former channel at the inlet. This suggests that coarser materials are preferentially deposited along the bend, whereas the outer bend is characterized by layers with a smaller median grain size.

Conclusions

Our research indicates that the effects of extreme floods on rivers are ongoing. On the NSV, post-flood snowmelt hydrographs influence the erosion, deposition, channel change, and resulting delta deposition. In 2014, an above average runoff hydrograph transported an additional volume of sediment comparable to the flood (Rathburn et al., 2017). Between 2014 and 2017, over 57,000 m^3 of sediment was remobilized and deposited in the delta, causing over 170 m of delta progradation. This represents a volume equivalent to 20% of the initial flood-derived sediment introduced into the reservoir in the four years following the flood. Core analysis of sediments collected at the prodelta further indicate widespread sedimentation associated with the flood and continued remobilization of flood sediments in the following years.

Table 1. The calculated volume of sediment eroded and deposited within the analyzed portion of the inlet between 2014 and 2017.

Time Interval	Volume Eroded (m³)	Volume Deposited (m³)	Net Volume Moved (m³)	Total Volume (m³)
April 2014 to April 2016	1,150	68,230	67,080	69,380
April 2016 to August 2017	15,660	5,550	-10,110	21,210
April 2014 to August 2017	65	57,040	56,970	57,100

Quantifying the sediment influx into Ralph Price Reservoir provides water managers with useful information pertaining to the lasting impact of the 2013 storm and consequences of lowering the base level on reservoir storage capacity. Our findings are relevant to communities in Colorado and elsewhere that face challenges in providing water in a region where water demand often exceeds supply and in planning for increased disturbances under a changing climate.

Future Research

Additional research will analyze recorded changes in the channel geometry of the approach channel, grain size, discharge, and sediment transport, to better predict future sediment influxes under various discharge scenarios. We specifically seek to understand: 1) whether the drop in base level (2016-2017) had a larger impact on channel morphology and recovery than other triggers such as high post-flood discharges, 2) whether the magnitude of overall channel response after the flood decreases with time, and, 3) whether erosion and deposition causing changes in channel geometry at the approach channel equate to sediment volume calculations in the delta to close our sediment budget.

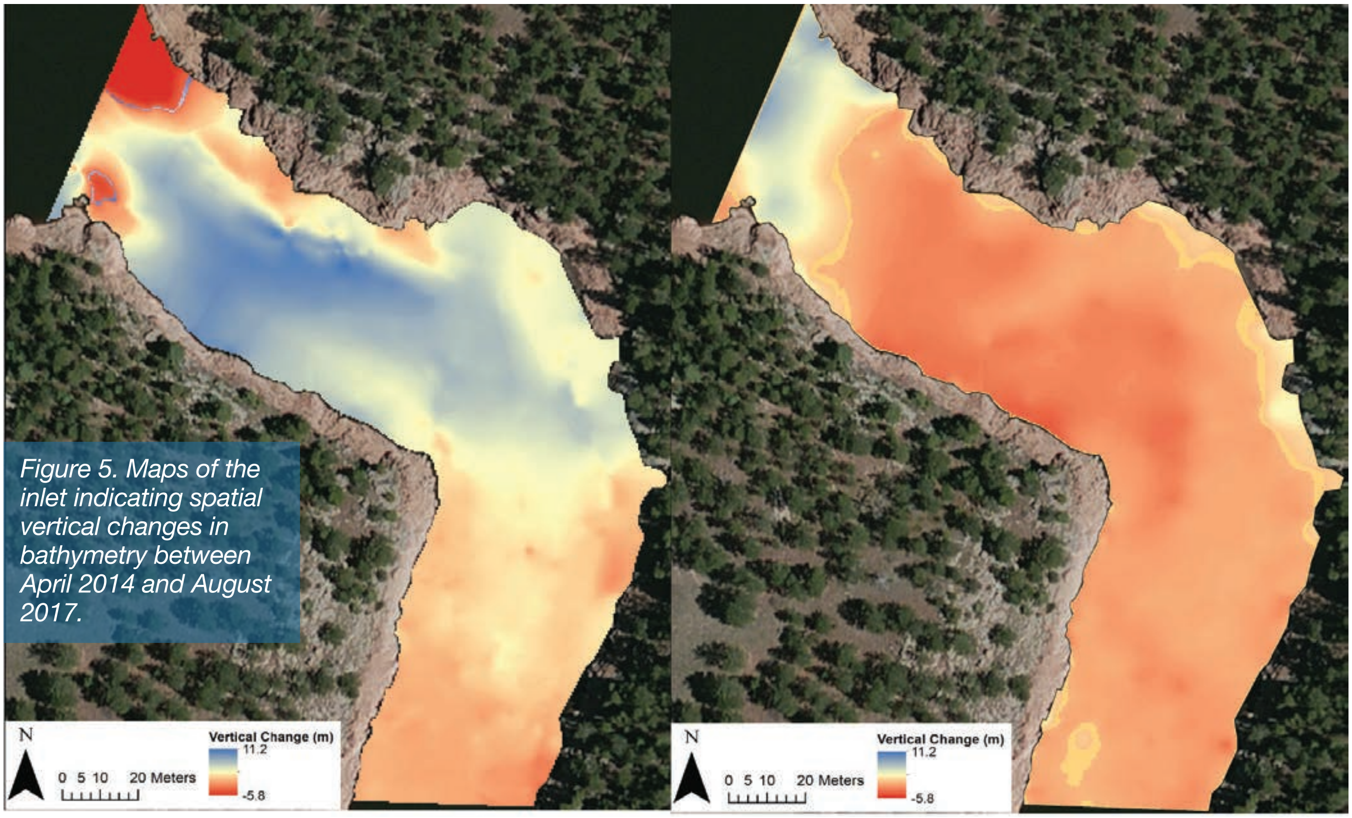

Figure 5. Maps of the inlet indicating spatial vertical changes in bathymetry between April 2014 and August 2017.

2014-2016 Difference

2016-2017 Difference

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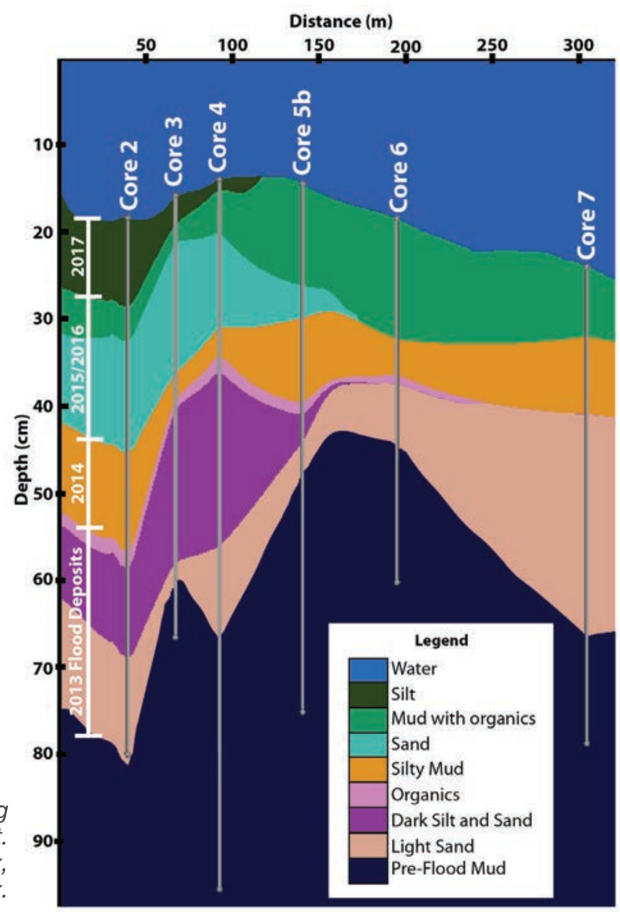


Figure 6. A cross section of core stratigraphy progressing from least distal (left) to most distal (right) parts of the inlet. Note that the surface topography is vertically exaggerated 5x, whereas the stratigraphic layers are exaggerated 50x.

WATER RESOURCES
ARCHIVE

TOPICS TO CONTEMPLATE

Student Research Opportunities

Patricia J. Rettig, Water Resources Archive, Colorado State University Libraries

Vecteezy.com

SYNOPSIS

The Water Resources Archive at Colorado State University offers several resources for student research focused on water resources. For example, there are resources related to dam construction, endangered species, borderlands, as well as an array of historical photographs, offering a glimpse into the past.

Graduate students in all disciplines have the opportunity to distinguish themselves through doing original research. An option that too few exercise is delving into the unique resources in archives.

Students at Colorado State University are fortunate to have the Water Resources Archive accessible in Morgan Library at the heart of campus. The Archive, which focuses on saving Colorado's water history, holds more than 100 collections documenting the numerous aspects of water across the state and beyond. Untold stories abound in the Archive, making it a wonderful resource available to curious graduate students eager to compose an outstanding thesis or dissertation.

Though many consider archival research only appropriate for history students, those in disciplines from engineering to political science, from art to biology, can benefit from diving in to knowledge from the past. Below are just a few topics that are ripe for research using collections in the Water Resources Archive.

CSU's Role in Water

The CSU's sesquicentennial is on the way, arriving in 2020! Prepare now by investigating the role CSU has played – institutionally and individually – in the water arena. Professors like Maury Albertson and Evan Vlachos were known around the world, through conducting significant research projects in Asia, Latin America, and the Middle East as well as shaping students who became international water leaders. Before them, early professors like Louis Carpenter and alumnus

CSU professor Maury Albertson (second from right) at a water resources conference in the Philippines, 1961. His colleague Hans Einstein (son of the famous Albert) is fourth from right. From the Albertson Papers, Water Resources Archive.

Ralph Parshall changed the course of irrigation-related instruction and research. Departments including Watershed Science and Fish, Wildlife, and Conservation Biology established groundbreaking programs.

Hot Topics

Taking a current events issue and delving into its background can be a good approach for a student research project. In the water world, some of the topics appearing in the media right now involve groundwater issues, river compacts, and interstate lawsuits. All of these have a wealth of background information available through the Water Resources Archive. One of our newest additions is an oral history interview with Bob Longenbaugh, who has 60 years of personal experience with Colorado groundwater issues. Such insights would make a valuable contribution to any study of groundwater. On the topic of river compacts, we are coming up on the 100th anniversary of the Colorado River Compact, which arose as a way to prevent interstate lawsuits over shared streams. With nearly 100 years of experience, now would be an apropos time to critically examine any number of compact and interstate lawsuit-related issues and assess their success.

Dam Construction

For those seeking a topic related to engineering, consider investigating one or more of the old dams in the state. Many are more than 100 years old and were built under varied circumstances and with different techniques than modern dams. Much more information about the construction of some of these structures has been surfacing in the Archive lately, including Halligan Dam on the North Fork of the Cache la Poudre River, the Rio Grande Reservoir in the San Luis Valley, and the Amity Dam on the Arkansas River. Beyond the actual construction, information exists on financing, the labor force, and management, providing a variety of aspects to investigate.

Endangered Species

A successful model of cooperation for the benefit of both water users and endangered wildlife originated in Colorado. The project focused on three fish species in the Upper Colorado River, and after years of negotiation with agencies and groups at all levels, a program was established to ensure sufficient water flows for those fish while maintaining water rights. Tom Pitts, the consultant who lead the effort, thoroughly docu-

Top of Halligan Dam, showing bedding of rubble stone, reinforcing iron, forms, concrete mixer, etc. Sept. 16, 1909. From the Records of the North Poudre Irrigation Company, Water Resources Archive.

mented his work, and it can all be reviewed at the Archive. Several other collections relate to Pitts' work, which extended to the Platte River, the San Juan, and the Middle Rio Grande as well. This significant story is waiting to be told and could benefit anyone seeking to understand endangered species issues.

Borderlands

Many people forget that the Arkansas River once formed the border between the United States and Mexico, meaning that the southern part of what is now Colorado used to be another country. The legacy of that continues to affect lives today. Studies of borderlands are a popular area of research, though not often in relation to water. At the Water Resources Archive, a donation from the Land Rights Council, based in San Luis, documents ongoing issues with land rights challenges tied to the former Mexican land grant system. Because different uses of the land in question affect the quantity and quality of the water in the creeks below, land issues become water issues and therefore livelihood issues.

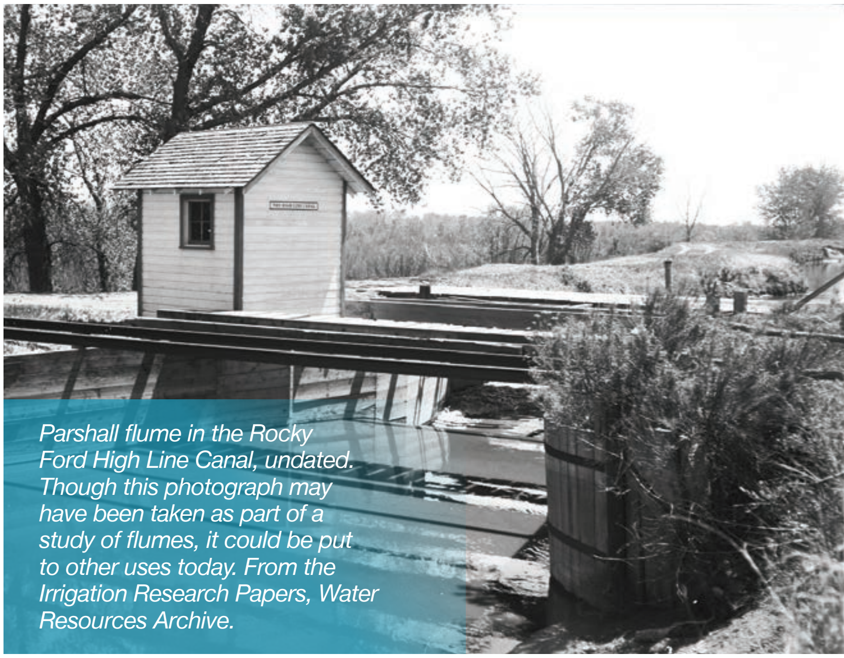
Photographic Analysis

Many researchers use historical photographs simply for illustrational purposes, but images can be used as the basis for research as well. Most of the thousands of photographs held in the Archive were created for research purposes or project documentation. Few could be considered artistic, but often they give an excellent glimpse of a setting or an event that cannot be adequately captured in words. The challenge is to find the right set of photographs, but with collections like the Irrigation Photograph Collection and the Photographs of the Arkansas Valley Sugar Beet and Irrigated Land Company, and many others, numerous offerings await!

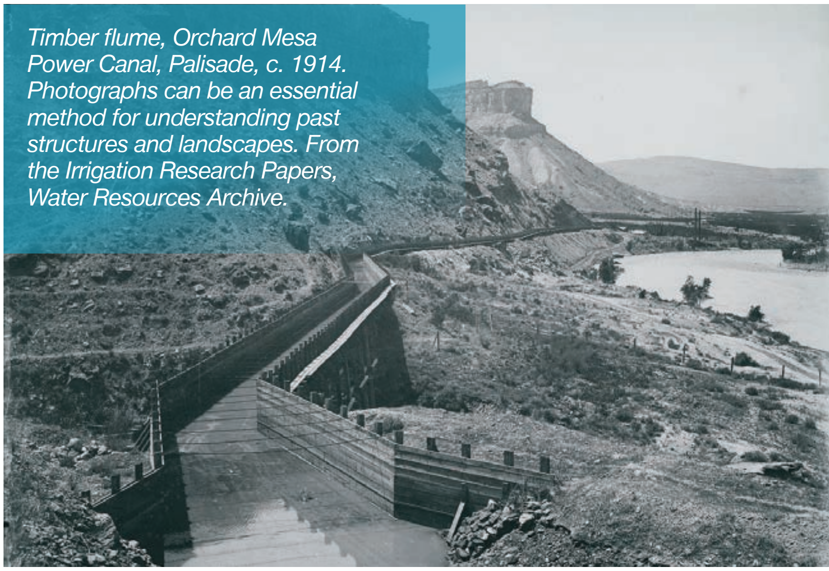
Students wanting to investigate any of the few topics discussed here, or wanting to explore their own avenues, should contact their advisors or the archivist for the Water Resources Archive. The archivist can also help students get started with the basics of archival research if they have not taken this approach before. Professors who want to know more should also contact the archivist.

Most of the Archive's materials are only accessible in its reading room in Morgan Library, though an increasing number of items are available online. The Archive is conveniently available for walk-in assistance during weekday hours, and access is open to anyone, free of charge.

For more information, consult the Water Resources Archive website (https://lib.colostate.edu/water) or contact the archivist (970-491-1939; Patricia.Rettig@ColoState.edu) at any time.



Parshall flume in the Rocky Ford High Line Canal, undated. Though this photograph may have been taken as part of a study of flumes, it could be put to other uses today. From the Irrigation Research Papers, Water Resources Archive.



Timber flume, Orchard Mesa Power Canal, Palisade, c. 1914. Photographs can be an essential method for understanding past structures and landscapes. From the Irrigation Research Papers, Water Resources Archive.

Water wheel in Grand Valley, undated. In a case like this, a photograph really is worth a thousand words. From the Irrigation Photograph Collection, Water Resources Archive.

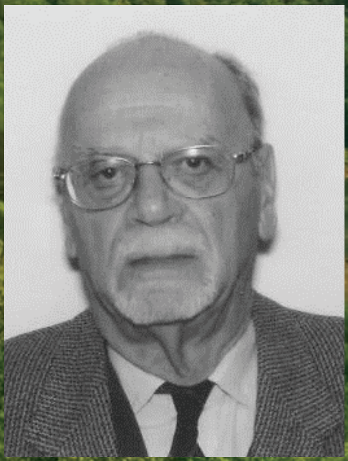
The Passing of Two Leaders in Hydraulic Structures Engineering

Robert Ettema, Civil and Environmental Engineering, Colorado State University

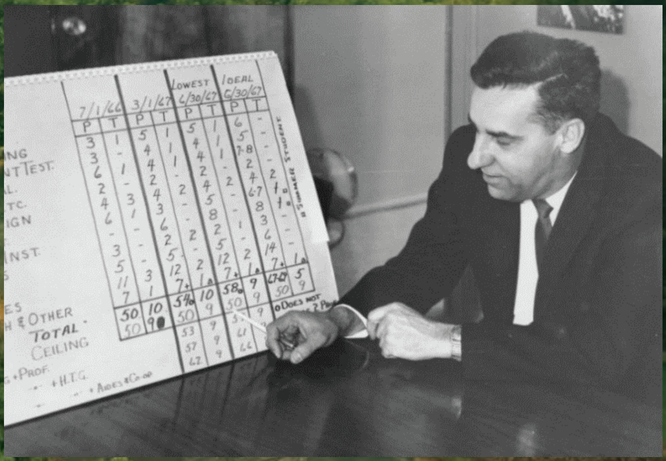
When water must be managed, moved, or used, some form of hydraulic structure is needed. This essential fact compels us to recognize the contributions of two leading figures in the design and operation of hydraulic structures—Rex Alfred Elder and Pavel Novak. Both men enjoyed remarkably long lives and passed away on the same day, this past February. Elder and Novak were exceptionally talented hydraulic engineers whose respective careers spanned decades of the 20th century critical to the development of hydraulic engineering.

Rex Elder was born on October 4, 1917, in the small town of Laquin, Pennsylvania. He grew up in a community centered on the regional lumber industry that was impacted by the Great Depression. After attaining a Bachelors and Masters degrees in civil engineering, Elder joined the Tennessee Valley Authority's (TVA) Hydraulics Laboratory as it was evolving to address major developments in water engineering.

While this article focuses especially on Elder's career, as he was extensively involved water use and engineering in the U.S., it also pays tribute to Pavel Novak, who was born on the September 7, 1918, in Stribro (now located in the Czech Republic). Novak lost family to the Holocaust and came to England during WWII, attaining a Bachelors degree in civil engineering. After the war, Novak returned to Czechoslovakia where in 1949 he attained a doctorate degree. From 1950 to 1955, he was the Deputy Director of the Water Research Institute in Prague and later Director of the Institute of Hydrodynamics, the Czechoslovak Academy of Sciences. When the Soviet army invaded Czechoslovakia in 1968, Novak returned to Britain where he was offered a faculty position at Newcastle University. By the time he retired, the water resources



Pavel Novak
Photo provided by Eric Valentine



Rex Elder
Photo provided by Will Elder

group at the University of Newcastle was the largest post-graduate group in the U.K. Novak wrote several noteworthy books, including the widely used book *Hydraulic Structures*, and is credited with making the *Journal of Hydraulic Research* an internationally leading publication.

Post-WWII expansion in hydro-research and developments impacted both Europe and the U.S. By the end of WWII, TVA had become the U.S.'s largest electricity supplier and was operating an important inland-navigation system along the Tennessee River. Elder's career spanned subsequent major developments at TVA, and generally in hydraulic engineering. During the years that Elder served as its director (1948-61), TVA's Hydraulics Lab became the U.S.'s leading non-university, hydraulics lab. In 1962, he was appointed Director of TVA's Engineering Laboratory.

During Elder's 31 years at TVA, it completed extensive studies for a series of hydropower dams, navigation locks, and other hydraulics structures facilitating its expanding operation. In 1952, TVA started on a huge program of power generation by coal-fired thermal-powerplants, such that by 1955 coal surpassed hydro as TVA's main power source. Economic and environmental challenges began to emerge with widespread coal use and energy demand was projected to keep expanding. Thus, in the mid-1960s, TVA began to develop the use of nuclear reactors for generating electricity. TVA undertook the construction of Browns Ferry Nuclear Powerplant on the Tennessee River in Alabama, one of few commercial nuclear powerplants in the U.S. TVA's growth in the use of thermal-power led Elder to conduct early studies regarding various aspects of the interdisciplinary field now known as environmental hydraulics. With colleagues, he investigated the hydraulics of thermally stratified reservoirs and the design of water intakes to withdraw cooler water; they also conducted pioneering work on density currents, and on the hydraulics of diffuser-pipes for managing thermal-effluent discharges.

Elder retired from TVA in 1973 and joined Bechtel in San Francisco, where he expanded and managed Bechtel's Hydraulics and Hydrology Group. In 1973, Bechtel had projects with approximately 20% of all of the U.S.'s new power-generating capacity and was extensively involved with overseas projects. Elder oversaw a sizeable number of engineers and hydrologists involved in a broad range of projects associated with hydro- and thermal-powerplants and hydraulics issues related to large-scale mining and industrial facilities.

Elder and Novak received extensive recognition for their work. For example, in 1978, Elder was elected to the U.S. National Academy of Engineering; and, in 2008, Novak was awarded the highest honorary medal, *De Scientia et Humanitate Optime Meritis*, of the Academy of Sciences of the Czech Republic. Both men leave lasting legacies to hydraulic-structure research and implementation.

Fontana Dam, one of Rex Elder's many notable projects. Photo by Chris Norrick

Forecasting

South Park Basin, Colorado. Photo by Rhonda Johnson

A CSU Student Researcher Advancing Rainfall Forecasting

Russ Schumacher, Colorado Climate Center, Atmospheric Science Department

SYNOPSIS

This article focuses on providing insight into the advancements for rainfall forecasts, opportunities for future research, and challenges presented with this area of research. Specifically, a forecast tool was been created to produce rainfall probabilities exceeding anticipated recurrence intervals.

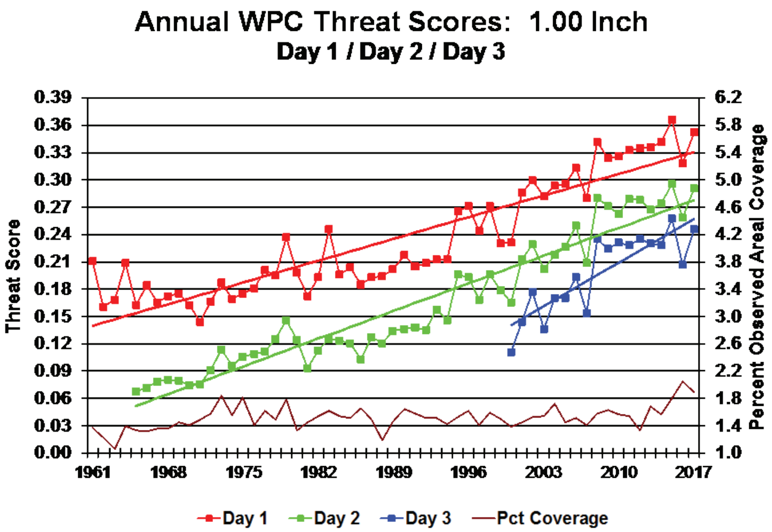


Figure 1a. Time series of Weather Prediction Center threat scores for 1" of rainfall in 24 hours for 1-day (red), 2-day (green), and 3-day (blue) forecasts. The percentage of area covered by 1" of rain each year is shown by the brown line and corresponds to the right-hand axis.

Rain is one of the most difficult things for meteorologists to predict. With the many advancements that have been made in atmospheric science, it is exceedingly rare to have the temperature forecast, even several days in advance, miss by more than a few degrees. But precipitation can still frustrate computer models and experienced forecasters alike. And the challenge is even greater in the summer. There are a number of reasons why this is the case. Most of the rain in the summer comes from deep convection (i.e., thunderstorms): these storms are often short-lived and relatively small in area, such that one side of town (or even one side of the street) can receive a downpour while the other side stays dry. Even if you know (or a supercomputer knows) the properties of a storm right now, predicting its exact motion and whether it will intensify or weaken is a daunting challenge. Furthermore, if the storm has yet to form, you also need to predict where and when that will occur. There are also some fundamental aspects of convective storms that remain poorly understood, including the details of rain and hail formation, and the development of the cold outflow that descends to the ground, spreads out, and can go on to initiate new storms. My graduate students and I, and many others within the Department of Atmospheric Science at Colorado State University (CSU), have been involved in intensive field research to observe these detailed aspects of storms and their environments, but that is not the focus of this particular article. Here, I will discuss some of our ongoing efforts to translate the results of research into advances in forecasts, and the opportunities and challenges associated with these efforts.

Although the previous paragraph may give the impression that forecasting rainfall is hopeless, great strides have been made over the years. The NOAA Weather Prediction Center (WPC), which is responsible for making rainfall forecasts across the United States (which are then fine-tuned and com-

Every Drop

South Park-Basin, Colorado
Photo by Flickr user Rhonda

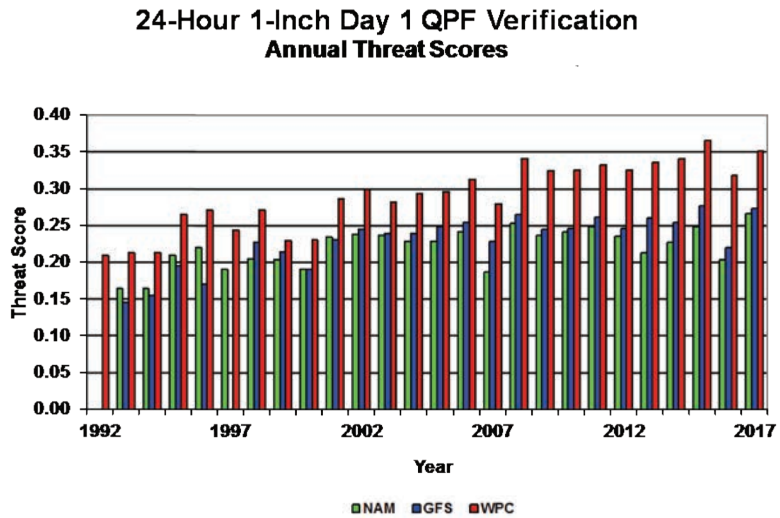


Figure 1b. Time series of threat score for the NAM (green) and GFS (blue) numerical models, and WPC human forecasts (red).

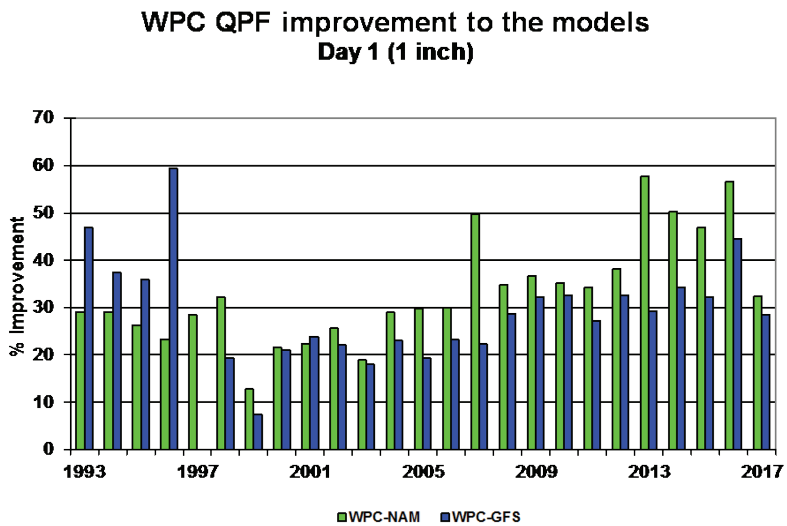


Figure 1c. As in (b), except for the percent improvement of the WPC human forecasts over the numerical models. A threat score of 1 indicates a perfect forecast; a score of zero indicates no correspondence between forecast and observation. From http://www.wpc.ncep.noaa.gov/html/hpcverif.shtml

municated by local National Weather Service forecast offices), has made steady progress, with a three-day rainfall forecast today being as good as a two-day forecast was about a decade ago, and as good as a one-day forecast fifteen years before that (Figure 1a). Much of this success can be attributed to improvements in the numerical weather prediction models that forecasters use (Figure 1b), but interestingly, human forecasters continue to outperform the models by a similar or even greater percentage (Figure 1c). Because the processes associated with rainfall are often poorly represented in these computer models, experienced human forecasters can use their knowledge of those processes to make substantial improvements. Yet another emerging way to combine this human expertise with advancing technology is through machine learning–replicating some of the ways that humans process complex information and training a computer to do something similar. CSU graduate student Greg Herman has been conducting cutting-edge research that uses historical information about where and when heavy rainfall occurs, information about how models typically perform in those situations, knowledge of the factors that contribute to heavy precipitation in the atmosphere, and machine-learning algorithms to help WPC forecasters produce even better predictions.

Specifically, the forecast tool that Greg developed generates probabilities that the precipitation will exceed a given expected recurrence interval for the local area (i.e., a so-called "1-year" or "10-year" rainfall). Our evaluation of its forecasts over a large number of cases was very promising, with the machine-learning algorithm producing substantial improvements over the "raw" model forecasts. As one example, Figure 2a shows the results of a retrospective forecast produced by the model for the September 2013 extreme rainfall and flooding in Colorado, with a broad swath of high probabilities both near the Front Range, on the plains, and into New Mexico. Such a forecast reflects what could be available about two days in advance, and the forecast probabilities were generally high in the same spots where heavy rain indeed fell on this day (Figure 2b). But the true test would be putting the model's forecasts in front of experienced forecasters each day.

Each summer the WPC hosts the Flash Flood and Intense Rainfall (FFaIR) experiment, which brings together researchers and forecasters to evaluate new technologies and techniques that might someday make it into everyday forecast operations.

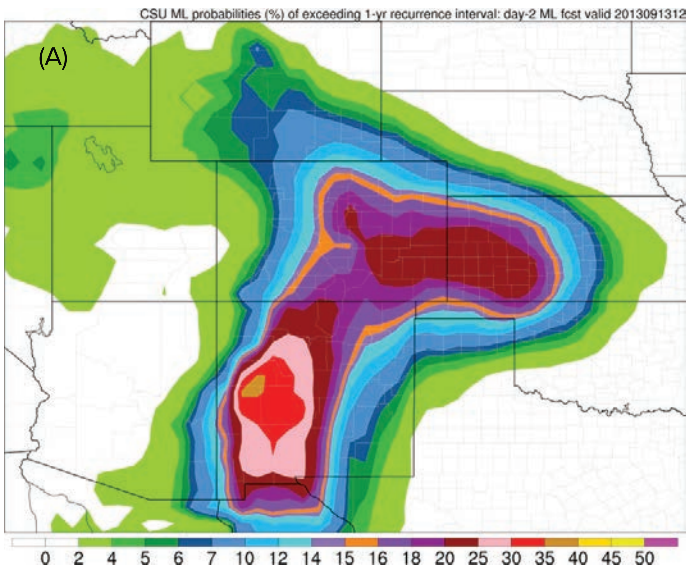
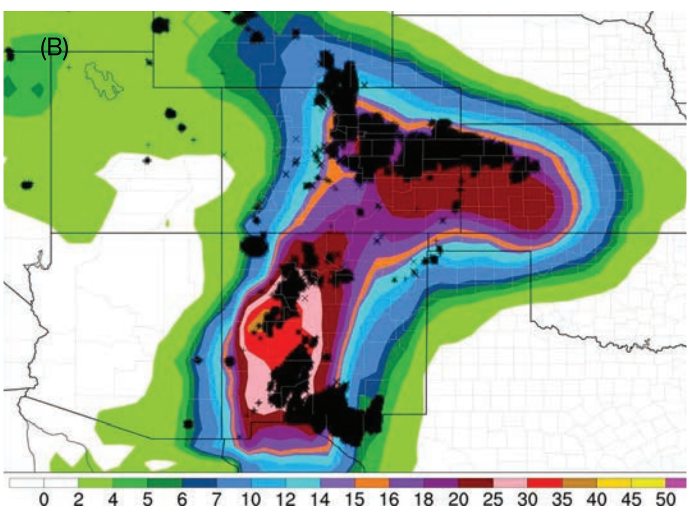


Figure 2: (A) CSU forecast of probabilities of exceeding the 1-year recurrence interval, for the forecast issued on the morning of 11 September 2013 for the 24-hour period ending at 1200 UTC 13 September 2013. (B) As in (A), except with markers at locations where this threshold was exceeded.



With support from NOAA's Joint Technology Transfer Initiative, our system was one of the tools being tested at FFaIR in 2017 (Figure 3). We were testing it as a potential "first guess" grid for the WPC's Excessive Rainfall Outlooks, their assessment of the potential for flooding rainfall over the next three days. Just like any model, it performed very well on some days and not so well on others, and there were some persistent issues that we are now working to remedy. But we were most encouraged by the positive reception that the tool received from WPC forecasters. Often (understandably) forecasters are skeptical of new techniques that have not yet been fully tested, especially when they are perceived as a "black box," where data goes in, results come out, and there is no way to interpret why the model did what it did. But one of the strengths of the methods we have used is that they also offer insights into what ingredients the model considers important for a given situation. Furthermore, the forecasters noted that it filled a gap in the tools that they currently have available to them: they regularly look at forecast precipitation amounts from models, but our tool highlights areas likely to receive rainfall that is unusually heavy for a particular area. Considering that the forecasters are responsible for predicting excessive rainfall, our framework is particularly helpful, and seeks to make the most of the information generated by the algorithm as well as the forecasters' experience and expertise.

Greg is continuing to develop this tool with an eye toward many further potential applications. We have been invited to test the product again at the FFaIR experiment in the summer of 2018, and we have already begun steps to transition the needed data and software into the operational environment at WPC. As this unique combination of research and applications continues to develop, we will still be limited by the challenges associated with forecasting precipitation, but hopefully these new advances will allow forecasters to identify the threat of extreme rainfall and flooding with a bit more precision and lead time.

Acknowledgments: The research described herein has been supported by NOAA grant NA16OAR4590238.

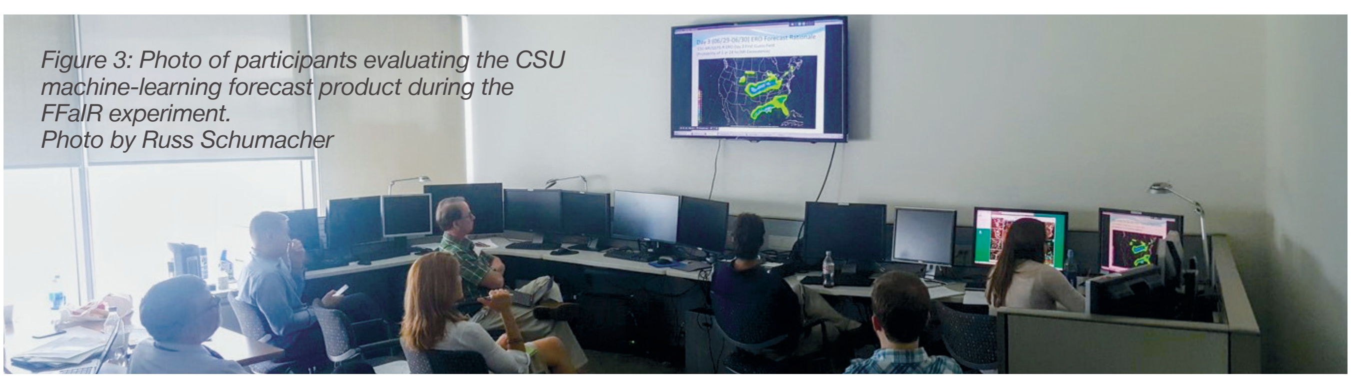


Figure 3: Photo of participants evaluating the CSU machine-learning forecast product during the FFaIR experiment.
Photo by Russ Schumacher

Dale Manning

Agricultural and Resource Economics, Colorado State University

In the Fall of 2013, I joined DARE at Colorado State University (CSU), where I teach and conduct research related to the management of scarce natural resources. Upon arrival in Fort Collins, Colorado, I quickly realized three things related to water: 1) a wide range of stakeholders care deeply about the use of our scarce water resources in Colorado, 2) CSU has a great community of researchers interested in water issues, and 3) the tools of resource economics can contribute to the discussion of water resource management by focusing on value and distributional outcomes across households, industries, and regions.

This led me to seek out policy-relevant research questions related to water use in Colorado, considering both agricultural and municipal water users. Water research fits within my broader interests related to economic development and natural resource use. In my research, I use optimization and econometric methods to examine energy and natural resource use, including groundwater management in the Ogallala region of the U.S., artisanal fisheries management in Honduras, solar minigrid adoption in Rwanda, and agricultural producer responses to climate change.

While I see economics as a valuable framework for studying natural resources, quality and relevant research in this area requires an interdisciplinary perspective. Therefore, I work closely with CSU faculty across many disciplines to integrate physical and economic models of coupled human-environmental systems that account for the feedbacks between natural resource dynamics and human economic decisions. Collaborators come from engineering, soil and crop sciences, ecosystem services and sustainability, epidemiology, and more. We also work closely with government agencies, including the U.S. Forest Service, ARS, and APHIS. Finally, the most innovative research often comes from interactions with graduate students, who I consider my most important collaborators.

Water Economics Research

In the area of water, I have worked in three general areas. First, I have examined the allocation of water between agricultural and municipal/industrial (M&I) uses. For example, we have demonstrated that the value of additional water storage depends on how managers balance agricultural and M&I values. Also, with colleagues in the Economics department, we developed an economic model of water use in the South Platte River Basin (SPRB) to examine the impacts of urban population growth on the distribution of water value across space and uses.

Next, I worked closely with colleagues in DARE and engineering to examine the impacts of water conservation policies on farmers. We developed a hydro-economic model of the Republican River Basin to quantify the agricultural impacts of groundwater conservation policies (e.g., a cap on the annual volume of water used per well). Members of the Water Preservation Partnership in Eastern Colorado used this information to propose a resolution that encourages producers across the region to reduce groundwater use by 25% by 2025. We are currently improving and expanding this modeling approach as part of The Ogallala Water Coordinated Agriculture Project (http://ogallalawater.org/).

Finally, I have examined the impacts of climate change on agricultural producers. For example, with co-authors in DARE, we demonstrated that surface water producers in the SPRB use information about changing water availability to adjust planting decisions. The use of information in this way can help producers mitigate the negative impacts of a changing climate.

I hope to continue to build relationships with researchers and policymakers interested in using economics to improve the management of scarce natural resources. CSU students interested in natural resource economics could enroll in one of the three courses I teach in this area: Environmental Economics (300 level), Environmental and Natural Resource Economics (500 level), and Natural Resource Economics (700 level).

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Water Calendar

June

24-28 9th International Congress on Environmental Modelling and Software (iEMSs); Fort Collins, CO

The 2018 congress is themed "Modelling for Sustainable Food-Energy-Water Systems" with an objective to foster the exchange of ideas and solutions leading to methods and techniques for managing these systems effectively and efficiently.
iemss2018.engr.colostate.edu/

26-28 Universities Council on Water Resources/ National Institutes for Water Resources Conference; Pittsburgh, PA

This joint-annual conference offers the opportunity for participants to learn how water is constantly changing the environment.
ucowr.org/conferences/2018-ucowr-conference

July

9-11 2018 AWRA Summer Conference: The Science, Management & Governance of Transboundary Groundwater; Fort Worth, TX

This conference will provide the opportunity for participants to learn about and engage in discussions about innovative approaches for identifying transboundary groundwater resources and the methods to develop sustainable governance and management agreements.
awra.org/meetings/FortWorth2018/index.html

10-12 One Water Summit; Minneapolis, MN

Participate in a national summit regarding the sustainability of water in the future.
uswateralliance.org/summit/one-water-summit-2018

August

22-24 Colorado Water Congress Summer Conference; Vail, CO

This conference is an opportunity to stay informed about water issues in Colorado.
cowatercongress.org/summer-conference.html

For more events, visit www.watercenter.colostate.edu

The Uncompahgre Wilderness
Photo by the Bureau of Land Management

Water Research Awards 11/6/17 — 5/2/18

Cheng, Antony, S., City of Boulder, Risk Analysis Decision Support for Boulder Watershed, $49,626.69

Cooper, David, J., Colorado Department of Transportation, Summit Lake Wetland Study, $90,000

Covino, Timothy, P., National Aeronautics and Space Administration, Using Landsat Imagery to Monitor the Effects of Landscape Recovery on Nutrient Export in Fire-Affected Watersheds, $45,000

Dell, Tyler A., Colorado Department of Transportation, CDOT Permanent Stormwater BMP Inspection and Maintenance Training, $26,265

Ippolito, J., City of Littleton, Biosolids Land Application Research Program, $122,322

Kampf, Stephanie K, The Nature Conservancy, Changes in Snowmelt and Rainfall Runoff in the Salt River Watershed, $19,365

Lemly, J., Colorado Division of Parks and Wildlife, Data Analysis and Programmatic Support for the Wetland Wildlife Conservation Program, Phase 2, $112,220

McGrath, Daniel, Department of the Interior—U.S. Geological Survey, Resolving Spatial and Temporal Variability of Snow Accumulation in Mountain and Glacier Environments RMCESU, $10,000

Myrick, Christopher, A., Colorado Division of Parks and Wildlife, Triploid Walleye: A New Frontier for Managing Cool Water Predators in the West, $78,471

Ode, Paul, J., Department of the Interior—U.S. Geological Survey, Improving Methods for Anticipating the Impacts of Invasive Insects, Plants, and Biological Control Agents, $91,971

Ronayne, Michael, J., Town of Castle Rock, Colorado, 2018 Studies Supporting Sustainable Use of the Denver Basin Aquifers in the Vicinity of Castle Rock, $25,000

Sale, Thomas, C., CH2M Hill, Services Supporting Aquifer Storage and Recovery Analyses for the City of Fort Collins, $5,500

Sharvelle, Sybil, E., Oregon Environmental Council, Development of a Database to Support Decentralized Non-Potable Water Systems, $7,046

Wohl, Ellen E., National Geographic Society, Ephemeral Debris Accumulations in Puerto Rican Streams Following Hurricanes, $7,650

USGS science for a changing world

USGS Recent Publications

Changes in biological communities of the Fountain Creek Basin, Colorado, 2003–2016, in relation to antecedent streamflow, water quality, and habitat; 2017, U.S. Geological Survey Scientific Investigations Report 2017–5162, 20, James J. Roberts, James F. Bruce, Robert E. Zuellig

Characterization of water quality and suspended sediment during cold-season flows, warm-season flows, and stormflows in the Fountain and Monument Creek Watersheds, Colorado, 2007–2015; 2017, U.S. Geological Survey Scientific Investigations Report 2017–5084, 47, Lisa D. Miller, Robert W. Stogner

Disentangling the effects of low pH and metal mixture toxicity on macroinvertebrate diversity: 2018, Environmental Pollution, 235 (2018), 889-898, Riccardo Fornaroli, Alessio Ippolito, Mari J. Tolkkinen, Heikki Mykrä, Timo Muotka, Laurie S. Balistrieri, Travis S. Schmidt

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The Animas River outside of Durango, Colorado
Photo by Flickr user Adifferentbrian