Colorado Water

May/June 2017

STUDENT RESEARCH

Colorado State University

On the cover: (Background) Trout Lake, Photo By Alex Berger. (Students, Clockwise from Top Right) Allen Gilbert, Brian Wolff, John Hammond, Dan Scott, Amber Childress-Runyon, DeAnna Laurel, and Haley Sir

Features — Student Research 2017

From our Cooperators

In Every Issue

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

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Director's LETTER

The paradox of change is that although we occasionally proclaim out of frustration that "nothing changes around here," we know that nothing stays the same for very long. While change is inexorable, progress is another matter altogether. The passage of time alone causes change, but there is more afoot. Heraclitus famously insisted on ever-present change as being the fundamental essence of the universe, as he stated sometime in the 4th century B.C., "No one steps in the same river twice." The river (or more generally, time) has moved on, being inherently dynamic. Interestingly, Albert Einstein, in his theory of relativity postulated the seemingly contradictory idea that time is a result of change, not the converse.

While we accept change as an all-pervasive phenomenon, it does seem to occur at an inconsistent pace. From this vantage point, 2017 seems to be a year of accelerated change. Last year's election promised changes that are still unfolding, some of which will have implications for water, as agency personnel, policies, and funding formulas are in flux. Our state is in a period of rapid change as well, with burgeoning population putting increasing pressure on resources and infrastructure. Significant changes of leadership are occurring at the Colorado Water Conservation Board, State Engineer, the Colorado Foundation for Water Education, and other organizations. And we witness the passing of distinguished water leaders such as former U.S. Representative Ray Kogovsek of Pueblo, Colorado.

Global change forces are usually viewed from negative lenses. Climate warming, nonstationary hydrologic conditions, changing land use, growing population, and urbanization, declining resources such as groundwater, and involuntary mass human migrations, are all components of global change and are mostly seen as negative. The other side of the coin is that humanity is making rapid progress, particularly in science and technology, but there is some evidence (in spite of the daily news) that we are in the midst of rapid socioeconomic progress as well. While the second law of thermodynamics states that the natural progression is towards greater entropy, change in human social systems can be a source of rejuvenation and renewal. Indeed, the ability to adapt to change is the key to evolutionary survival.

This issue of Colorado Water newsletter focuses on the student water research projects funded through the Colorado Water Institute. In the reports from these student projects, we see the next generation of water scientists, managers, and leaders already emerging and we expect they will replace us in due time. The connection of these students with academic faculty is key to their success and we acknowledge the important role of faculty in training these students for water careers. We also appreciate the connection with practicing water managers and leaders as students find their way from academia to practice.

And speaking of change, State Engineer Dick Wolfe, will retire in June, leaving a legacy of steady leadership at the Colorado Division of Water Resources. Dick's farewell article in this issue calls for the continued application of good science in the stewardship of our water resources and the need for a water-literate citizenry. We have greatly appreciated Dick's sterling character and leadership, as well as his support and encouragement for faculty and students here at Colorado State University.

Reagan Waskom
Director, Colorado Water Institute

Bear Lake, Rocky Mountain National Park

Yuya Sekiguchi

Comparing Fine Scale Snow Depth Measurements Using LiDAR and Photogrammetry

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SYNOPSIS

Snow dominated watersheds rely on coarse resolution measurements to model and forecast annual water yields for agricultural and municipal use. This study endeavors to quantify vertical differences associated with photogrammetric methods by comparing terrestrial LiDAR scanned surfaces to those generated with commercial off-the-shelf photographic equipment and processing software. We describe techniques for use at the operational management level that may refine products used to estimate snow coverage across large spatial domains.

Introduction

Snow is important to a number of interests in Colorado and techniques to measure its extent, depth, and density are technologically limited. Until the late 1970s, snow measurements were accomplished regularly through periodic manual point measurements of snow depth and snow water equivalent, and the data are used to estimate runoff volumes. The Intermountain West is now populated by the automated snow telemetry (SNOTEL) network of remote stations to provide daily snowpack measurements, but the network is still at a coarse resolution. Finer resolution direct data collection is often done manually but requires much effort, and are typically only collected over short distances.

Light detection and ranging (LiDAR) is a proven technology that provides accurate sub-meter snow depth data at landscape scales. Current aerial and terrestrial LiDAR products require equipment and practices that are expensive and may not be used with enough frequency to justify their purchase. Recent efforts to measure snow depth on low relief areas at landscape scales using aerial photogrammetry in Alaska have shown promise in providing results similar to those produced using LiDAR but at reduced cost. Although aerial platforms can provide data across a much larger extent, it is possible to use these technologies terrestrially with great success. This study endeavors to quantify vertical differences between photogrammetric methods and terrestrial LiDAR scanned surfaces using commercial off-the-shelf photographic equipment and processing software. The overall effect of this study is to describe techniques for use at the operational level that may refine products used to estimate snow coverage across large spatial domains. Our ultimate determination is that both technologies are viable when properly scoped and produce better products than current spatial interpolation techniques allow.

Research Design

Two sites were selected to provide

Figure 1. Data Collection
1A: Allen (right) and Allis (left) Gilbert establishing ground control at Joe Wright during the initial data collection event on November 13, 2016. 1B: Allen Gilbert using the FARO LiDAR unit to collect data on January 29, 2017.

variety in terrain and data collection variables. A nearly 3,000 m^2 site was selected at the CSU Agricultural Research Development and Education Center's southern area (ARDEC-South). It is located along Interstate 25, is mostly flat with plowed rows, and is relatively devoid of vegetative cover. A 900 m^2 plot near the Joe Wright SNOTEL (# 551) station was chosen to represent montane conditions (Figure 1a). This plot is in a sloped clearing dominated by woody shrubs and surrounded by trees at various stages of growth.

Data collection for this study occurred during the 2016 – 2017 snow season. Each site was scanned using a FARO Focus3D LiDAR, and a series of approximately evenly spaced camera stills using a Nikon D810 digital single lens reflex (DSLR) camera with a Nikkor 24 mm fixed focal-length lens were taken along each of the plot's edges. Snow on the images were captured as bracketed sets adjusting time settings so when one image was properly exposed, a second was one stop overexposed, and a third image was two stops overexposed. Although when previewed, overexposed image highlight areas appeared not to contain usable data. This study found that post-processed overexposed images produced the best photogrammetric results by equalizing their histograms.

Spherical reference points made of 6 in (15 cm) Styrofoam spheres were set at each corner (Figure 1), approximately 1 m above the surface, and were used to align point clouds within a survey and between survey sessions. LiDAR scans were processed using CloudCompare open sourced software. Images were processed using the commercially available Agisoft

Table 1. Summary Statistics
Assessment statistics, recorded in centimeters, of the vertical difference between LiDAR and photogrammetric 1-m surfaces.

Date	Site	Min Difference	Mean Difference	Max Difference	Standard Deviation
20161112	ARDEC-South	-4.9	6.6	18.9	3.5
20161217	ARDEC-South	-23.7	-4.7	14.7	6.6
20170104	ARDEC-South	-25.1	8.2	39.6	6.3
20170105	ARDEC-South	-24.6	-2.1	14.6	4.2
20161113	Joe Wright	-7.5	6.6	159.4	7.3
20161224	Joe Wright	-61.9	-3.1	109.1	5.7
20170101	Joe Wright	-9.9	-1.5	87.6	5.0
20170129	Joe Wright	-38.5	3.2	30.7	2.4

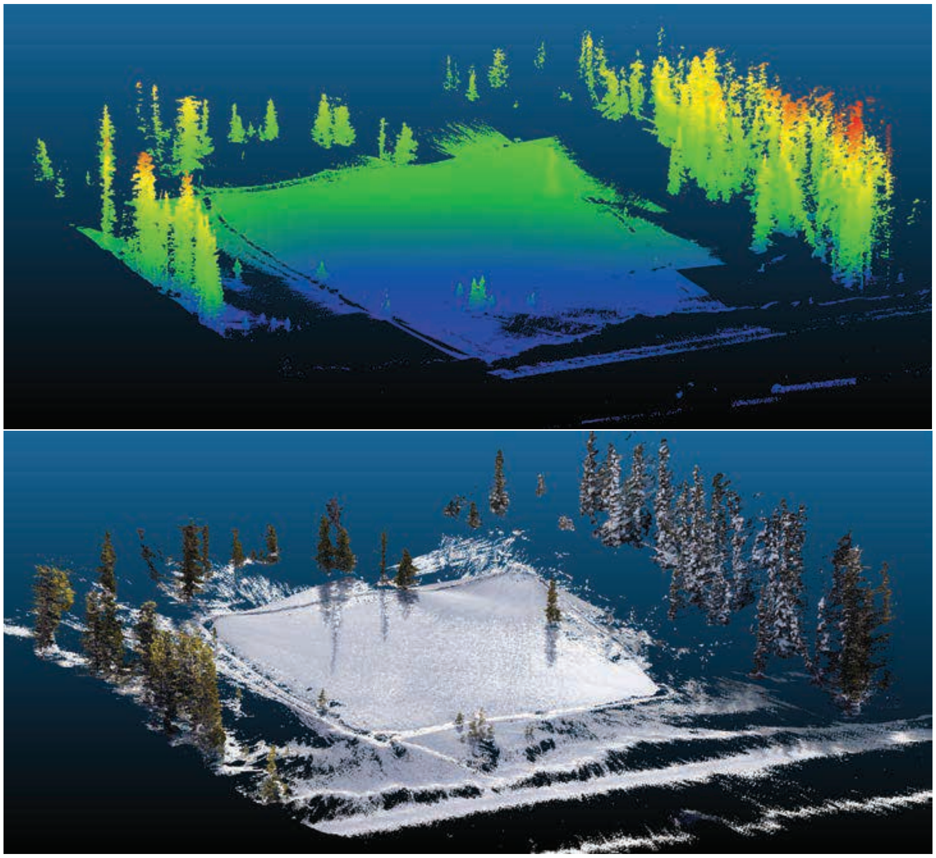


Figure 2. Point Clouds
(2a: Top) LiDAR point cloud displayed as a height color ramp. (2b: Bottom) Photogrammetric point cloud displayed as real color captured in photographic images. These data are from the Joe Wright study site recorded on January 29, 2017. Although these images are from an aerial perspective, the underlying data to create their point clouds was taken at ground level.

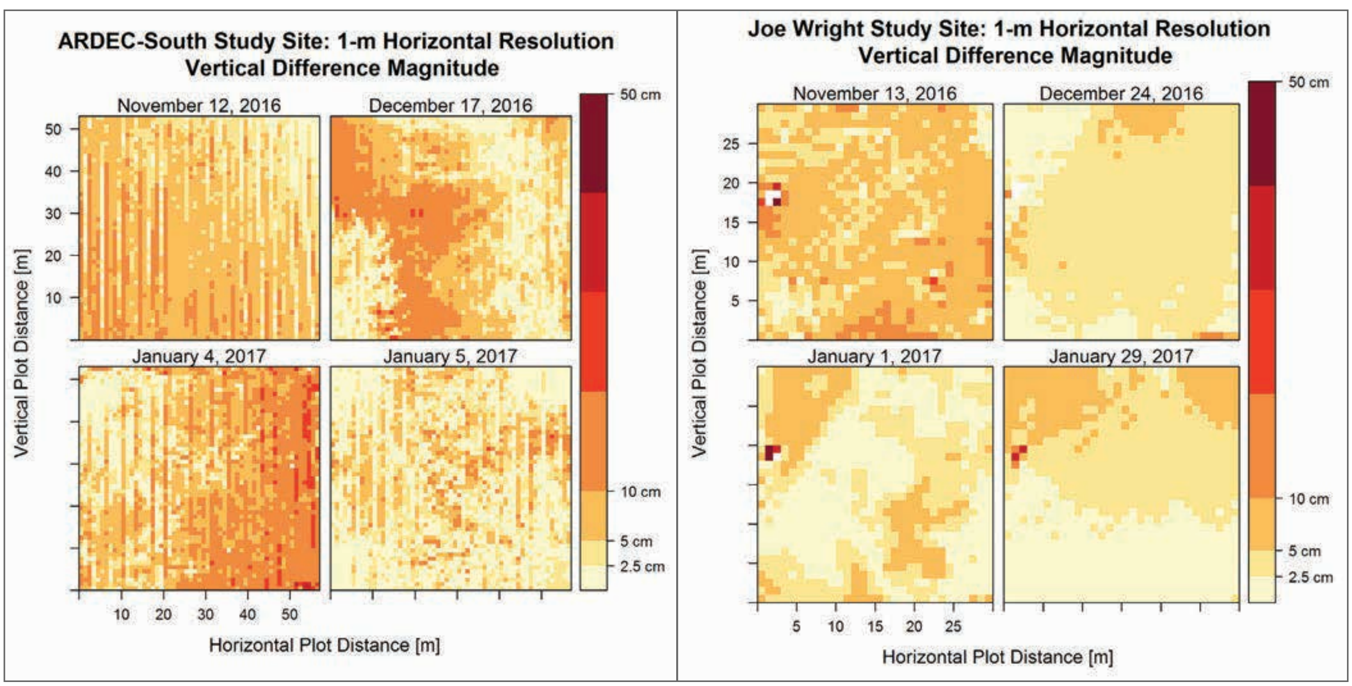


Figure 3. Vertical Difference Surfaces
These plots visualize the magnitude of error between photogrammetrically derived surfaces when compared to LiDAR derived surfaces by record date. (3a: Left) ARDEC-South generally experienced more error and a mottling artifact best observed on Dec. 17th, 2016 suggesting the photogrammetric software had difficulty identifying similar objects between images. (3b: Right) Joe Wright differences are more evenly distributed throughout the surface allowing for a more direct comparison between surface types.

Photoscan software to produce dense point clouds (Figure 2a), which were then imported into CloudCompare and aligned to LiDAR point clouds (Figure 2b). Digital surface models (DSM) for each cloud were created at 1-m and 10-cm resolutions. A lens calibration was created for the DSLR using a feature present in the Photoscan software.

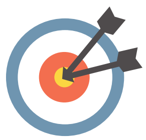
Comparison

This study considered LiDAR surfaces as the actual snow surface. Photogrammetrically derived surfaces were subtracted from the LiDAR surface and the absolute value was computed to provide an overall magnitude of vertical difference between surfaces (Figure 3 at a 1-m horizontal resolution). No obvious spatial patterns, except the vertical lines present at ARDEC-South (Figure 3a), were observed in the surface differences. It should be noted that aligning surfaces proved more difficult than originally anticipated and likely exacerbates our observed difference. Further alignment of surfaces may reduce the overall error, but the potential time dedicated to those refinements may only prove marginally beneficial.

Average overall vertical difference was within 10 cm between surfaces. Table 1 summarizes the vertical difference of the photogrammetric surface from the LiDAR surface for each site by record date. Photogrammetric surfaces recorded at the Joe Wright study site (Figure 3b) agreed with their corresponding LiDAR surfaces more often than those at ARDEC-South (Figure 3a). The obvious differences between these sites is the variation in topography and different lighting conditions common during collection events. The results in Figure 3 may suggest, not surprisingly, that lighting is the dominant factor to successfully record snow using photogrammetry. All images were taken at about solar noon. The final day at ARDEC-South (January 5th) was brighter than the others and all the days at Joe Wright were clear and bright. Those recorded differences have the smallest difference magnitudes and appear more evenly distributed throughout the entire surface.

Discussion and Recommendations

Photogrammetry can substantially reduce the cost of equipment and data acquisition without substantial reduction in data quality. The collection process described in this study used a professional DSLR, but the technique is able to use almost any photographic image, making its incorporation into other data acquisition or management activities a viable solution for agencies interested in three-dimensional imaging at increased frequency. This study recommends three metrics be used when comparing these methods:



1. Measurement accuracy and precision - LiDAR will almost always result in better vertical accuracy and finer resolved precision, but geographic accuracy is more reliant on the quality of ground control and influences both techniques. Imaging equipment should be considered part of the entire package which, combined with a survey grade GPS, can create highly accurate products.

2. Time and monetary costs - Photographic equipment is much more affordable than LiDAR equipment. It may be able to maintain that price gap in the future even though LiDAR is becoming smaller to meet other commercial demands. An element that was not shown in this study, but is worth mention, is that digital imaging equipment can include spectrum beyond the visible and could be used to enhance already high resolution photogrammetric products with multispectral output. Data collection time for each technique is substantially different, wherein LiDAR required approximately an hour to record a moderate resolution point cloud but photographic images were recorded in about fifteen minutes. Processing times varied, but all data were processed on a higher end four-year-old home desktop computer, suggesting viability for both at the small office operational level.

3. Integration into existing workflows - Each method has its learning curve and both may be automated to some degree. Photogrammetry's ability to use most images allows an agencies existing infrastructure to be included as potential data collection assets. The determining factor is performing the steps to develop a lens calibration.

It is becoming more common to find versions of both technologies that are small enough to fit on unmanned aerial systems (UAS) or that could be fitted to mobile terrestrial platforms. Some commercial survey firms are already using such technologies and techniques to produce centimeter resolution surfaces over extents covering hectares.

This study described a means of implementing photogrammetric snow measurement into existing operational workflows. Camera equipment and photogrammetric software were the most expensive investments; both are consistently being improved. It is recommended to use a camera with the ability to manually control exposure settings, but this research team has had some success with cell phone and GoPro cameras shooting subjects other than snow. The recent increased interest in photogrammetry may also result in open source or other freely available software. VisualSFM, for example, is freely available and a promising alternative. Ultimately, the core elements of this study comparing LiDAR and photogrammetric techniques and outputs should remain relevant beyond technological advances.

Watershed Monitoring Across the Intermittent Persistent Snow Transition Zone

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Craig Moore, BS Student, Environmental Science and Technology, Colorado Mesa University;
Dr. Stephanie Kampf, Ecosystem Science and Sustainability, Colorado State University;
Dr. Gigi Richard, Geosciences, Director of the Water Center, Colorado Mesa University

SYNOPSIS

Snowmelt water is the largest contribution to runoff in Colorado's major rivers, and the loss of snow can have consequences for downstream water users throughout the state. This study develops a monitoring network that tracks changes in snow, soil moisture, and streamflow across the intermittent-persistent snow transition.

Monitoring the Snow Transition

In mountainous regions, both snowpack trend analyses and modeling studies suggest that snowpacks are most sensitive to drought and temperature at lower elevation boundaries. In a cold region like Colorado, high elevations have persistent snow that lasts throughout the winter, whereas low elevations have intermittent snow that falls and melts several times over the winter season. Most watershed monitoring in Colorado does not include areas where the snowpack transitions between intermittent and persistent seasonal snow. Snow monitoring is concentrated at high elevations, and most streamflow monitoring is at low elevations. Expanded hydrologic monitoring that spans the gradient of snow conditions in Colorado can help improve streamflow prediction and inform land management in potentially sensitive areas near the intermittent-persistent snow transition.

This study (1) established hydrologic monitoring watersheds in intermittent, transitional, and persistent snow zones on the east and west slopes of the Rocky Mountains within Colorado, and (2) used this monitoring network to improve understanding of how snow accumulation and melt impact soil moisture and streamflow generation under different snow conditions.

The Monitoring Network

Six small watersheds (three west slope, three east slope) were monitored ranging in size from 0.8 to 3.9 square kilometers that drain intermittent, transitional, and persistent snow zones. Each of the six watersheds (Figure 1, Table 1) was equipped with the following instrumentation: one

(Images at Left)
(Top) John Hammond conducting a snow survey during May 2016 in the Michigan River watershed. (Center) Craig Moore taking notes during a soil moisture survey at the transitional Grand Mesa site. (Bottom) Gigi Richard at the intermittent Grand Mesa site.

Table 1. Watershed name, snow zone, mean annual precipitation, and mean watershed elevation.

Watershed	Snow Zone	Region	Precipitation (mm)	Precipitation (in)	Mean Elevation (m)	Mean Elevation (ft)
Michigan River	Persistent	Front Range	1087	43	3437	11273
Lazy D	Transitional	Front Range	507	20	2702	8863
Mill Creek	Intermittent	Front Range	462	18	1947	6386
Ward Creek Trib 1	Persistent	Grand Mesa	1028	40	3019	9902
Ward Creek Trib 2	Transitional	Grand Mesa	877	35	2939	9640
Shirtail Creek Trib	Intermittent	Grand Mesa	415	16	2189	7180

Table 2. Front Range watershed peak streamflow (Q), date of peak Q, peak snow depth (D), date of peak D, peak snow water equivalent (SWE), date of peak SWE, and date of snow disappearance.

Watershed	Q (l/s)	Date Q	D (cm)	Date D	SWE (cm)	Date SWE	Date no snow
Michigan R.	963	20-Jun	243	17-Apr	80	17-Apr	23-Jun
Lazy D	245	9-May	95	23-Mar	35	17-Apr	12-May
Mill Creek	463	3-May	43	2-Feb	6.5	24-Mar	28-Mar

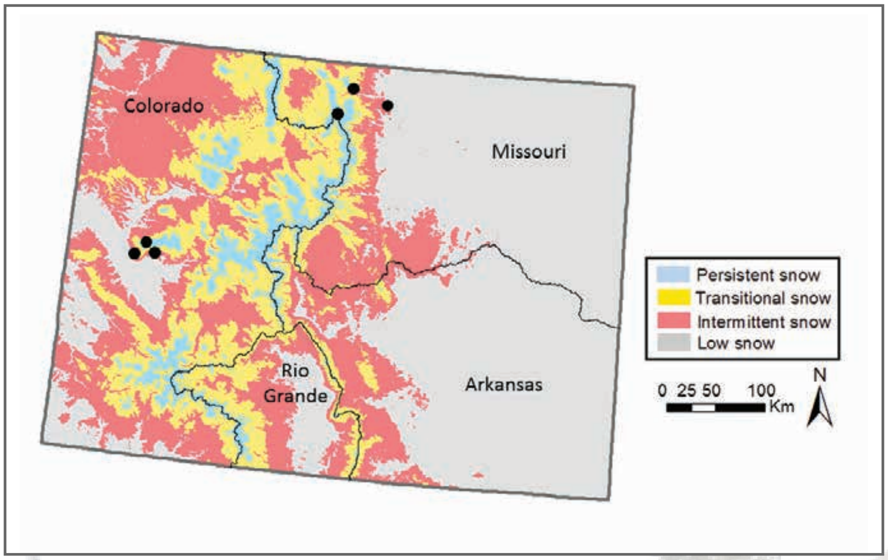


Figure 1. Study watersheds in the Front Range and Grand Mesa regions of Colorado displayed as black points on top of snow zones generated by Moore et al. (2015).

Figure 2. Precipitation and soil moisture instrumentation at Mill Creek (left), water level instrumentation at Lazy D (center), and snow poles for time lapse camera measurements of snow depth at Mill Creek (right).

tipping bucket rain gauge, three snow depth poles monitored by a time-lapse camera, one pressure transducer and/or capacitance rod to monitor stream stage, three soil moisture probes (5, 20, 50 cm) and one soil temperature probe (Figure 2). Snow depth and snow water equivalent were also measured during winter snow courses, and after the snow melted. Soil moisture along transects in each study watershed was also monitored using a handheld time-domain reflectometry (TDR) instrument.

Preliminary Findings

During the 2016 water year, the Front Range sites generally had deeper snowpack and longer snow duration than the Grand Mesa sites (Figure 3). Snow cover remained at the Front Range persistent site into June on the Front Range (Table 2), whereas much of the snow at the persistent site on the Grand Mesa had already melted by early June. Instrument failures at some of the Grand Mesa sites lead to some data loss, so here we focus on summarizing the 2016 water year at the Front Range sites.

Persistent Snow Zone

The Michigan River watershed retained snow from the onset of accumulation to the date of snow disappearance. As expected, peak snow depth and peak SWE were highest at this site (Table 2). While snow accumulated over a period of several months, snowmelt was considerably quicker (Figure 4). North-facing slopes and valley bottoms retained snow from the onset of snow in the fall to melt in the spring while south-facing slopes and ridgetops behaved more like areas in the intermittent snow zone where snow completely melted out several times throughout the fall, winter and spring months (Figure 5). Soil moisture values were elevated during and following snowmelt (Figure 4), displaying the greatest magnitude of volumetric water content (VWC) increase in response to snowmelt of all

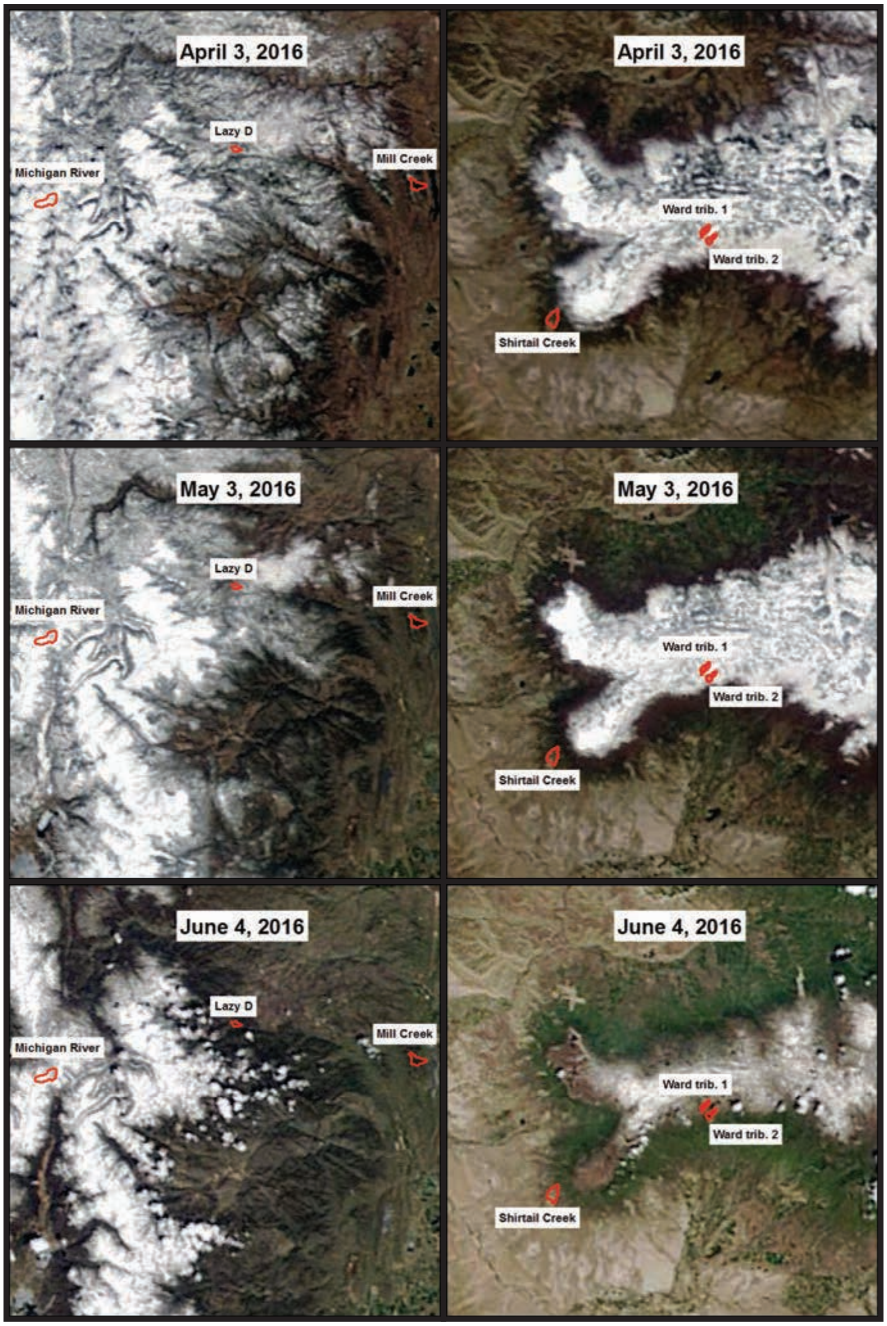


Figure 3. MODIS satellite imagery showing changes in snow at Front Range (left) and Grand Mesa (right) study watersheds from April to June 2016.

John Hammond

John Hammond, Alyssa Anenberg, Stephanie Kampf and Chenchen Ma on an October 2016 field visit to the Michigan River watershed.

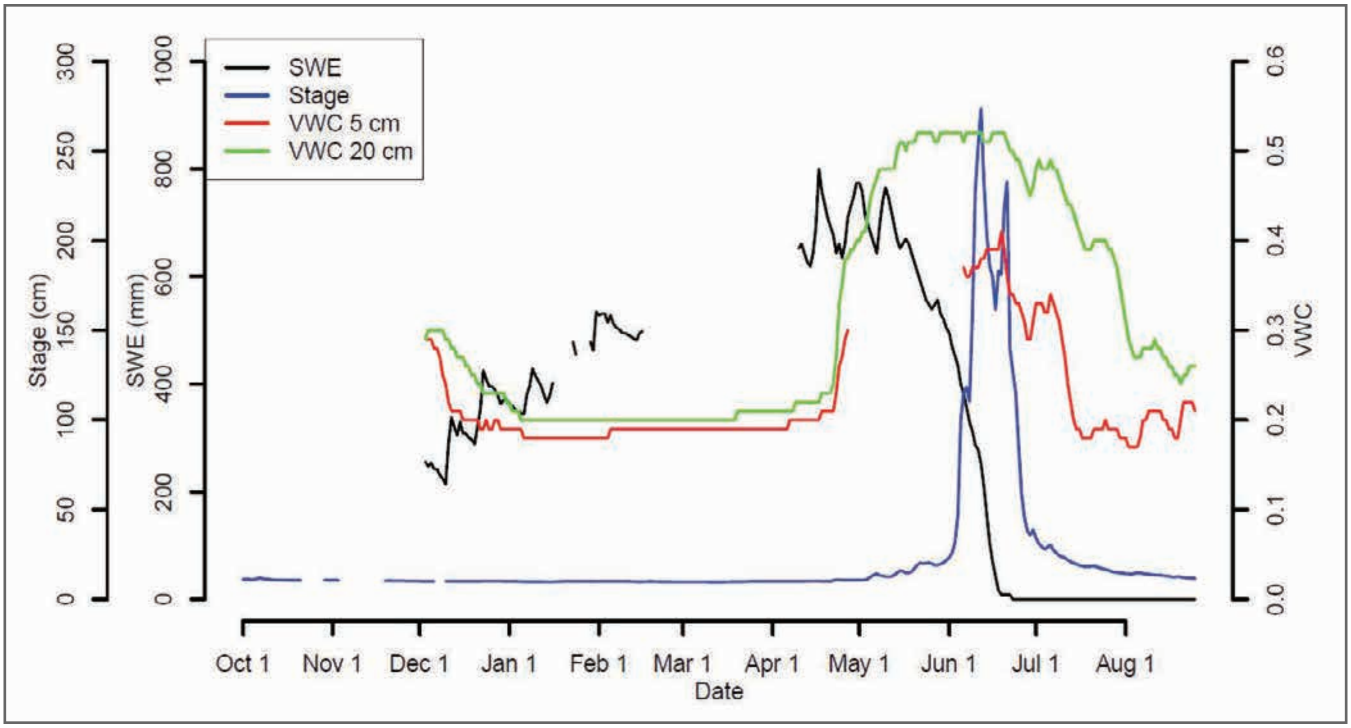


Figure 4. Snow water equivalent (SWE), stream stage, and soil volumetric water content (VWC) for the Michigan River watershed (Persistent).

Figure 5. Michigan River watershed (Persistent) near the outlet in May (left) and August (right).

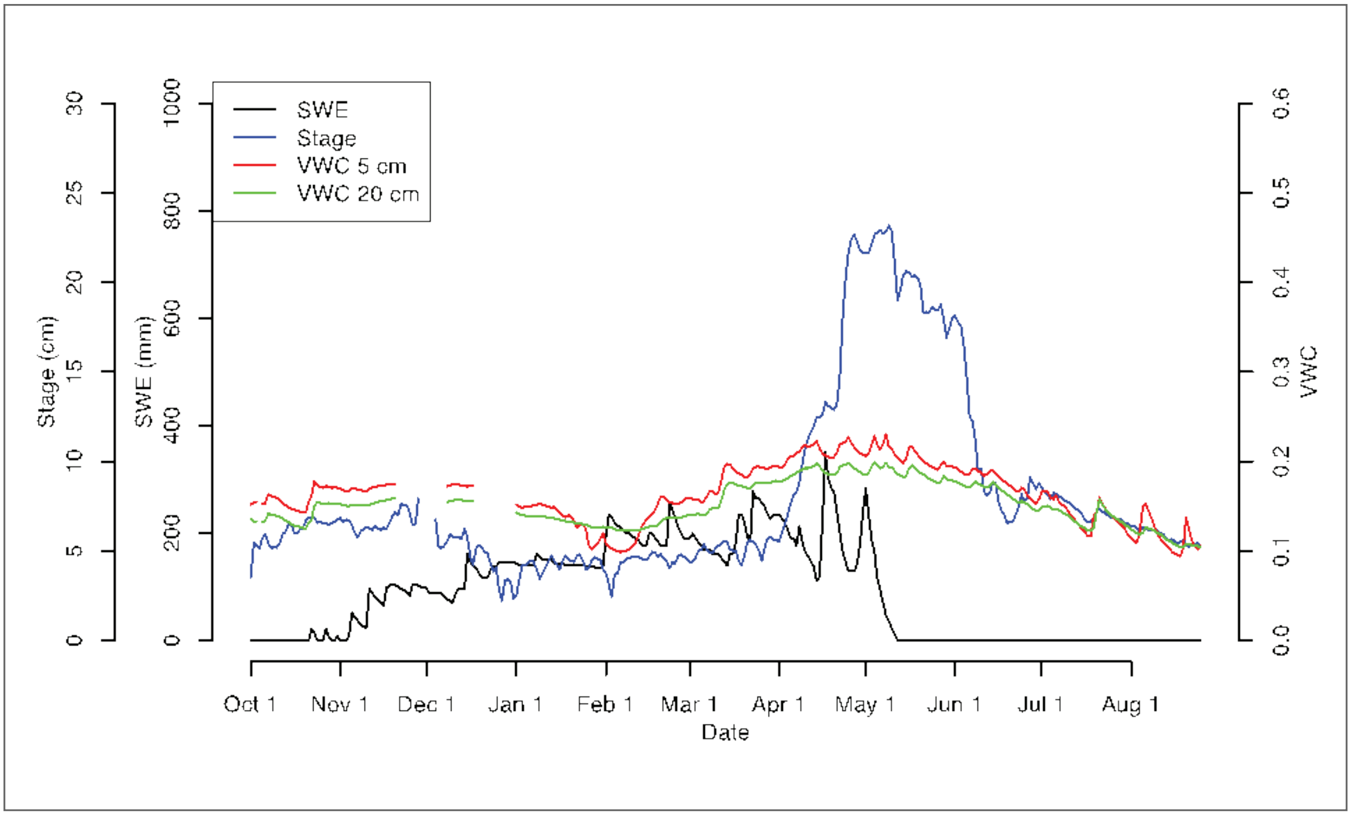


Figure 6. Snow water equivalent (SWE), stream stage, and soil volumetric water content (VWC) for the Lazy D watershed (Transitional).

sites monitored. Snowmelt generated saturation excess overland flow in the late spring during the rise and peak of the hydrograph. The hydrograph of Michigan River is dominated by the spring snowmelt signal without substantial increases in discharge in response to summer rainfall. Peak discharge at this site lags peak SWE by 65 days, with snow completely disappearing three days following peak discharge.

Transitional Snow Zone

The Lazy D watershed, similar to Michigan River, retained snow from the onset of accumulation to the date of snow disappearance, though the total accumulation of snow depth and SWE was less than half that observed at the persistent site. Only 25 days elapsed between peak SWE and snow disappearance. Soil moisture response at this site was considerably muted as compared to the persistent site. Stream stage at Lazy D also exhibited a clear snowmelt signal (Figure 6), but with the additional input of spring rain during snowmelt. The hydrograph at this site was less flashy than at the persistent site, possibly because wetland areas adjacent to the stream dampened the hydrograph in contrast to the more confined channels in the persistent and intermittent watersheds.

Intermittent Snow Zone

At the Mill Creek watershed snow fully melted several times mid-winter (Figure 7). In the last snow event, which happened to have the greatest observed SWE value, only four days elapsed between this peak and snow disappearance. Unlike the persistent and transitional sites, the stream responses to snow accumulation and melt was similar in magnitude to the response to summer rainfall. The effects of slope-aspect at this site were most apparent, with snow completely disappearing on south-facing slopes within hours or days after falling. Soil moisture responded rapidly to rain and snowmelt. Mid-winter snowmelt events at Mill Creek were large enough to generate streamflow, and stream stage peaked when the antecedent soil moisture was already high from snowmelt and rainfall inputs. Summer rainfall after June 15 no longer generated runoff in Mill Creek because of lower soil moisture. This was the only Front Range site to completely stop flowing (Figure 8).

Lessons Learned and the Path Ahead

Thus far we have been able to make broad assessments on differences in hydrologic response between snow zones and the West and East slopes of the Southern Rocky Mountains, with detailed comparisons of the timing and magnitude of hydrologic response to come. Our first field season taught us several lessons about monitoring watersheds ranging from snowmelt dominated systems with deep snowpacks to intermittently flowing streams

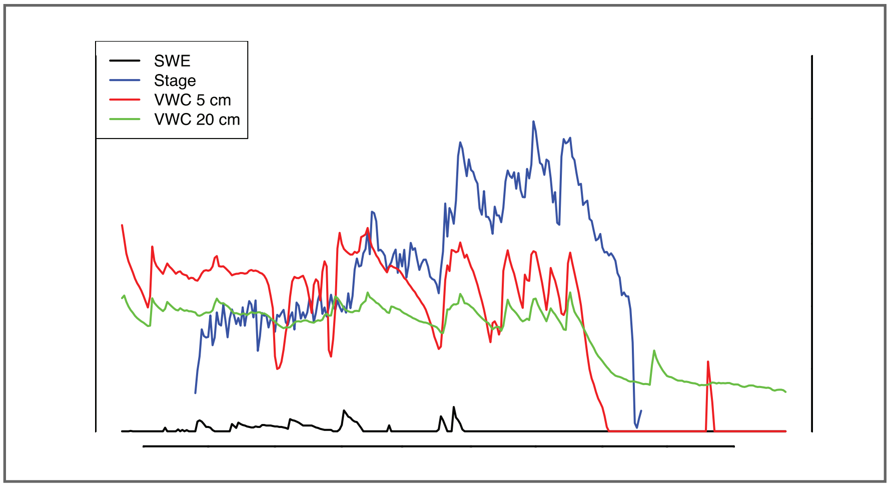


Figure 7. Snow water equivalent (SWE), stream stage, and soil volumetric water content (VWC) for the Mill Creek watershed.

Figure 8. Mill Creek watershed at the outlet in May (top) and August (bottom).

where simply observing rare flow events is difficult. In general, we see more mid-winter melt on the Grand Mesa as well as shorter duration of snowpack. The persistent site in the Front Range accumulates more snow, does not get much mid-winter melt, and has little to no mid-winter infiltration. In comparison, the persistent site on the Grand Mesa does have some mid-winter infiltration with soil temperatures >0. This difference in soil water input likely has consequences for streamflow response that we will continue to examine in future years. In areas with intermittent snow, the subsurface geology appears to be an important control on whether or not streams flow. Intermittent sites have similar snow intermittence and soil moisture responses in both the Front Range and Grand Mesa. However, while materials underlying Mill Creek include weathered igneous and metamorphic parent material that allows deep infiltration through fractures that supply intermittent flow, shale on the slopes of the Grand Mesa must not be allowing enough deep infiltration and/or have the fracture network to deliver flow to streams.

Conclusion

Closing the flow prediction knowledge gap is critically important as Colorado faces growing population and potential loss of snow. Water management in the state must balance water for a wide range of uses, such as irrigation, recreation, industrial, municipal, and environmental flows. Management of these water uses requires understanding water supply availability and its sensitivity to future change. With our ongoing watershed monitoring across a broad range of snow conditions in Colorado, we continue to learn about the factors that increase or decrease streamflow in the headwater streams that supply the state's major rivers. As the monitoring continues through future water years, these findings will aid future flow prediction for Colorado's river basins.

Evaluating Wood Jam Stab

Dan Scott, PhD Student, Geosciences, Colorado State University;
Dr. Ellen Wohl, Geosciences, Colorado State University

SYNOPSIS

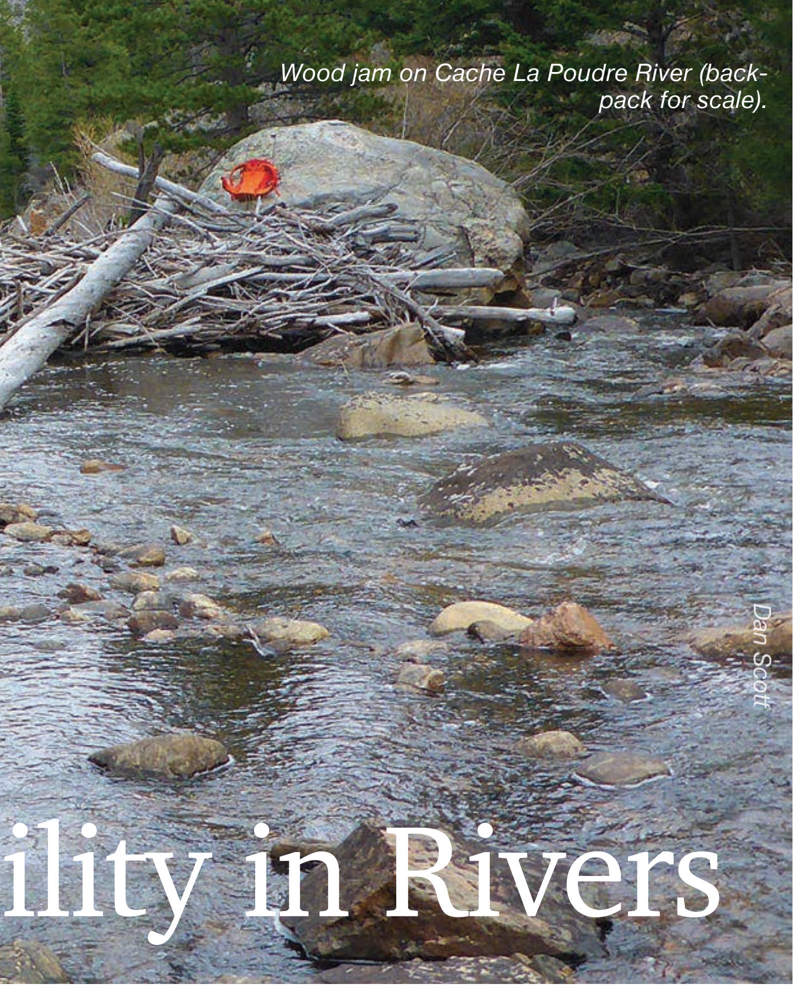
Wood in and along rivers and streams provides a riverine ecosystem with nutrients and habitat for other species within waterways of Colorado. By focusing on the risk of these timbers moving downstream into more heavily populated areas as a result of flooding in most instances, a systematic database and structural model was developed to aid forest managers and other local management.

Figure 1. Dan Scott and Ellen Wohl performing fieldwork on North St. Vrain Creek, Colorado.

Background

Management of instream and floodplain wood in Colorado and across the nation has been focused on widespread wood removal, with management oriented solely toward reducing risk. The Colorado Front Range exemplifies the current state of wood management. Rivers on the Colorado Front Range are generally wood-impoverished (Wohl et al., 2015) due to human removal of wood. Despite the abundance of wood mobilized and deposited into streams in the Colorado Front Range during the September 2013 flooding, most major rivers such as the Big Thompson and St. Vrain have been subsequently stripped of wood. This trend has been the national standard for more than a century, with most wood having been removed from rivers and floodplains, especially prior to the 20th century (Wohl, 2014). This has led to a widespread misconception that wood is unnatural in rivers and a lack of understanding regarding the benefits of wood (Chin et al., 2008). Namely, wood provides essential riverine habitat and nutrients to fish and insects, stabilizes otherwise highly erosive systems, and maintains nutrient and water delivery to riparian ecosystems, all helping to maintain the general ecological health of river corridors (Gurnell et al., 2005; Wohl, 2013).

Wohl et al. (2015) presents a management strategy for determining whether to remove wood in a river or on a floodplain. This strategy is designed to evaluate the benefits and risks of wood and provide a stability analysis for a single wood piece, with the end goal of improving the balance between



Wood jam on Cache La Poudre River (backpack for scale).

Dan Scott

maintaining the benefits of wood while minimizing the risks wood poses to infrastructure. However, these guidelines are limited in their applicability to entire wood jams, and lack a robust observational backing.

City, state, and national organizations have already begun to adapt the guidelines proposed by Wohl et al. (2015). However, many of these organizations have contacted Dr. Wohl about applying the guidelines to wood jams, which motivated the proposed research. These organizations include, but are not limited to the City of Fort Collins, USDA Forest Service Stream Systems Technology Center, Boulder County, Friends of the Poudre, and The Nature Conservancy. Dr. Wohl's communication with these organizations has demonstrated the immediate need for an expanded set of guidelines that will address all forms of wood in riverine environments.

> "Wood provides essential riverine habitat and nutrients to fish and insects, stabilizes otherwise highly erosive systems, and maintains nutrient and water delivery to riparian ecosystems, all helping to maintain the general ecological health of river corridors"

Our broad goal for this project is to develop an understanding of the hydrologic, morphologic, and biotic conditions that impact the stability of wood jams in rivers. Our specific objectives for this project are to: 1) create a dataset of wood jam characteristics and conditions under which wood jams are significantly changed or mobilized that will enable us to develop a model to predict wood jam stability across a wide range of river environments, 2) develop a model sufficiently robust as to enable its use by managers, technicians, consultants, and researchers to predict wood jam stability and make informed management conditions that balance ecological integrity and human uses of rivers, and 3) structure the model and associated tools to evolve using new, user-submitted data on a regular basis to reflect evolving understanding of wood jam dynamics.

Methods

Our general approach involved surveying individual wood jams across the Colorado Front Range as well as in the Cascade Range of Washington State to capture a wide variety of channel geometry, hydrologic regime, and tree species. We measured wood jam geometry, channel geometry, bed material size, and wood jam characteristics (e.g., whether the jam was anchored on a relatively immobile object, included rootwads or live wood, obstructed flow, etc.) across a sample of 38 jams (Figure 1). We placed time lapse cameras near a subset of 18 jams to observe them at 1-hour intervals throughout the high flow season. We then returned to each jam after high flow season (spring in the Colorado Front Range and autumn in the Cascades) to record whether the jam significantly changed (gained or lost substantial amounts of wood), remained substantially unchanged, or was transported downstream.

We plan to model wood jam stability using the variables we measure before peak flow. We will use a statistical decision tree model to predict whether a jam experienced significant change or transport due to high flow conditions. This model will maximize the amount of interpretation users can glean from its results, meaning that any probability assigned to a modeled jam will have a clear explanation for the reasoning behind that probability and an estimate of the uncertainty associated with it. For example, a jam may be predicted to be unstable due to its close proximity to the deepest portion of the channel and lack of anchoring material. However, if a user is attempting to model a jam that includes, for example, tree species that are very different from the dataset used in the model, the model will flag its prediction as being potentially unreliable due to the lack of data for that particular species. This allows for context-dependent predictions to inform management decisions regarding wood jams in rivers.

Our wood jam stability model will be hosted on a Colorado State University (CSU) website and will be freely accessible to the public. Because of the complexity inherent in wood jam dynamics, we will regularly update this model with new data from our own field work as well as from those who use the model. Users of the model can provide us with new data simply by recording whether the model correctly or incorrectly predicted the stability of jams they are monitoring. In this way, we hope to develop an evolving model that can bring to bear as much of our understanding regarding wood jam stability as possible to every management scenario.

Current Findings

Only three of our currently surveyed jams experienced significant change, probably due to relatively mild high flow seasons in both study regions. This has limited our ability to develop our statistical model at the present. However, we have gleaned important observations from our timelapse camera data. Diurnal flow fluctuations in snowmelt systems cause a repeated dilation and contraction of wood jams during peak flow, which we hypothesize has a cumulative effect in destabilizing jams over time, sometimes resulting in total breakup and transport of the wood jam. We have also noticed that the angle of key structural logs (i.e., those that support the bulk of the wood in the jam) relative to the horizontal controls the effect that an incremental rise in stage will have on the destabilization of the jam. A horizontal log will be buoyed and potentially floated downstream by only a small increase in stage, whereas a nearly vertical log requires a much larger stage increase to cause floating and transport, resulting in a more stable jam. We are currently integrating these findings into revising our field measurements.

Future Directions

We plan to expand our dataset to over 100 wood jams by the beginning of spring snowmelt in the Colorado Front Range. We will also deploy another 12 timelapse cameras. We are currently revising our field methods to minimize variability between different people taking measurements. This will allow for more reliable, widespread use of our field methods to increase the rate at which we collect data. Over the next two years, we plan to expand our field sites to include small ephemeral streams in the desert southwest, a larger multi-thread river in the Pacific Northwest (Hoh River, Washington), and a low gradient plains river (Laramie River, Wyoming). We hope to achieve a dataset of at least 200 jams through at least one peak flow season before making the model available to the public and soliciting data from model users. Thus, we hope to have the model fully operational in late 2018 or early 2019. Coupled with the model, we will be hosting a publicly accessible dataset of wood jam characteristics, including the persistence and location of surveyed wood jams. These web resources will be accompanied by a Forest Service General Technical Report, to be published in late 2017, that will place our wood jam stability analysis tools in a holistic context of wood management in rivers. We hope these resources will assist others in understanding, managing, and researching wood jams in the future.

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Wood Jam near the Big South Trail on the Cache La Poudre River (backpack for scale).

Evolution of Drought Management of South Platte Water Providers and Implications for their Capacity to Cope with Water Stress

Amber Childress-Runyon, PhD Student, Ecosystem Science and Sustainability, Colorado State University;
Dr. Dennis Ojima, Ecosystem Science and Sustainability, Colorado State University, Senior Scientist, Natural Resource Ecology Laboratory

SYNOPSIS

Although droughts are common in Colorado, climate projections predict they may become more frequent and severe in the coming decades, making management more difficult. To understand how water providers may adapt to future changes, this study evaluated the variance in the capacity of South Platte River Basin water providers to meet their demand obligations and attributes that affected their capacity to respond to those droughts.

(Top) PhD Student Amber Childress-Runyon and her advisor (Bottom) Dr. Dennis Ojima

Introduction

Droughts in the western U.S. are common and as any water user knows, the question is not if drought conditions will return, but when (Dai, 2013; Cook et al., 2015). Water management in Colorado has developed as a result of periods of water scarcity, based on lessons learned and refinements made to water policy and management strategies during and after droughts. Over time, these incremental adjustments have led to a more robust water system over time (Jones and Cech, 2009).

Water providers are organizations that often bear the responsibility of mitigating drought risk for water users, as they are the link between the environment and end users. Vulnerability created by droughts is mediated between actions taken by water providers. Most people in the U.S., particularly those residing within the western portions of the country, commonly receive their drinking water from these organizations, a percentage that is expected to grow in the coming decades (Hutson et al., 2004; Kenny et al., 2009; Engle, 2012).The primary objective is to distribute clean water to customers, which is achieved through a variety of strategies (e.g. maintaining large reserves, reservoirs, restrictions, education, pricing, etc.) that are made more difficult when conditions fluctuate far beyond normal. Engle (2012) notes that the increasing dependence of humans and ecosystems on water providers, combined with the potential impacts of climate variability and change, will make the delivery of high-quality water increasingly difficult in the future (Cromwell et al., 2007).

Climate change vulnerability reports (Statewide Water Supply Initiative, 2010; Western Water Assessment, 2011; Colorado Water Conservation Board, 2013, 2015; Gordon and Ojima, 2014) suggest that in water-scarce regions strategies historically used by water providers to manage water resources may become insufficient. This uncertainty about the future raises the need to understand how water providers have dealt with water stress in the past and to determine what strategies to utilize in the future as the environment continues to change.

Studies conducted by the State (Colorado Water Conservation Board, 2013) suggest that actions taken as a result of the 2002 drought increased the adaptive capacity of many water providers. However, because the results were aggregated by basin, the differences between providers' capacities and factors that contribute to increased adaptiveness – both important for developing actionable policy aimed at reducing vulnerability – were not investigated. Leaving the ability of these water providers to adapt to future environmental changes unknown. Therefore, the objective of this study was to evaluate the variance in the capacity of water providers in the

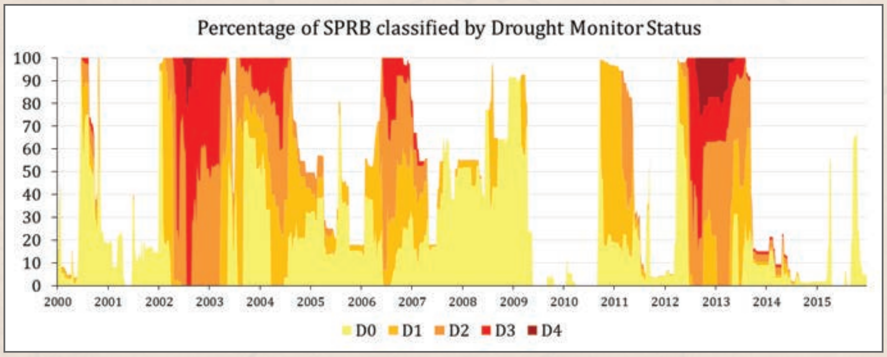

Figure 1. Drought Monitor status in the SPRB throughout the study period. http://droughtmonitor.unl.edu/

South Platte River Basin (SPRB) to meet their demand obligations, attributes, and institutions that affect their capacity to respond to droughts. This two part study evaluated the role that internal (organizational) and external (drought severity) factors play in affecting the capacity of water providers to meet water demands over time and strategies they use to mitigate drought effects. The first part is presented here, the second part builds off of this analysis to investigate institutional motivations or constraints for strategy selection and how that might impact capacity over time.

Methods

This study used an analogue approach, looking at past drought periods to understand what to expect in future droughts. Conveniently, there were two recent major droughts in the SPRB, in 2002 and 2012. The drought events were quite different temporally and in severity. The 2002 drought lasted longer than the 2012 drought, but the 2012 drought was more severe (Figure 1). Studying the impacts of both droughts from the perspective of water managers provides an opportunity to understand how incremental management and policy adjustments can evolve into long-term strategies on how to deal with water scarcity.

An event history calendar (EHC) was used to collect qualitative and quantitative data from managers in the SPRB. Engle (2013) proposed using EHC to gather temporal data on water management and adapted the tool which has commonly been used in anthropology to collect temporal data on individuals (Freedman et al., 1988; Axinn et al., 1999; Engle, 2012). This methodology uses a matrix of visual cues and an interactive interview process to make memory recall easier for participants. The EHC collects time-series data of water providers' management strategies and functioning through time (Figure 2).

The EHC collected two primary pieces of information from 2000-2015 including: 1.) strategies water provides used and variations in the strategies, and 2.) their relative capacity to meet water delivery requirements (referred to simply as capacity). Strategies listed in the EHC were chosen from a review of sources evaluating management in the basin and expert interviews (Kenney and Morrison, 2003; Kenney et al., 2004; Colorado Water Conservation Board, 2013). To measure capacity in the EHC, participants were asked to rank from 0 to 3 their ability to meet their water delivery requirements over the time period: where 3 represents no impairment, full ability; 2 indicating moderately impaired but still able to meet all commitments; 1 – seriously impaired with questionable ability to meet commitments, and 0 – unable to meet commitments.

Twenty-five water providers were interviewed for this study and were selected through stratified purposeful sampling. This type of sampling required dividing the 257 providers into five strata based on characteristics such as their primary water source, population, and sub-region. Senior-level water managers filled out the EHC, guided by the interviewer in a semi-structured interview. All management documents and web content for each provider were also reviewed and utilized to fill in gaps where managers were unsure of strategies used or exact timing. In addition, conservation plans were also helpful in the research analysis.

One of the many benefits of using the EHC was that it allowed for mixed methods research, requiring the collection of qualitative and quantitative data. This provided a more robust approach, resulting in an abundance of data used to analyze how providers managed their water systems, the functioning of their system over time, characteristics of their system, and motivations for changes (Engle, 2013). However, here only the variance in capacity among the water providers and an evaluation of internal characteristics that contributed to their 'adaptiveness' are presented. Future articles will contain further analysis.

Results

This study asked each water provider to provide a semiannual rank for their capacity to meet water delivery demands, which served as a proxy for their capacity to cope with conditions over time. Results from a Wilcoxon signed rank test indicated that capacity was reduced from normal levels during the 2002 drought, but not during the 2012 drought. In fact, capacity scores were higher in the second drought than the average of other non-drought periods, indicating that there was an increase in adaptive capacity. This was supported by interviews with water managers who said that lessons from the 2002 drought caused them to be more proactive during the 2012 drought, in addition to policy and structural changes made between the periods.

The severity of drought effects on water providers and the suite of drought-mitigation techniques available to them are largely determined by

W = Winter (Oct - Mar) S = Summer (Apr - Sep)

Group		Severe Drought	2000 W	2000 S	2001 W	2001 S	2002 W	2002 S	2003 W	2003 S	2004 W	2004 S	2005 W	2005 S	2006 W	2006 S	2007 W	2007 S	2008 W	2008 S	2009 W	2009 S	2010 W	2010 S	2011 W	2011 S	2012 W	2012 S	2013 W	2013 S	2014 W	2014 S	2015 W	2015 S	W
Management Information	P1	Drought Plan																																	
	P2	Conservation Plan																																	
	P3	Develop triggers for drought-related actions																																	
	P4	Coordination between water and land-use planning efforts																																	
	C1	Communicate - State																																	
	C2	Communicate - Local																			P								P						C
	C3	Formal education and public communication											P		W						R								R						O
	R1	Declare a drought emergency											R		A						E								E						
	R2	Establish water hauling programs											E	H	T						S								S						W
	R3	Restrict / prohibit new taps											S	U	E						I			D					I	D					A
	S1	Rehabilitate reservoirs to operate at design capacity											I	R	R						D			M					D	M					T
	S2	Develop new storage facilities											D	R							E			R					E	R					E
	S3	Use mechanism for storing conserved water											E	I	F						N			P					N	P					R
	S4	Use of reservoir distribution techniques					S						N	C	O						T								T						
	S5	Review water rights for modifications / flexibility during drought					E						T	A	R									2						2					P
	S6	Dry year leasing of water rights from agriculture					P							N							O			0					O	0					L
	S7	Water banks established for the sale, transfer, and exchange of water					T						B	E	2						B			1					B	1					A
	S8	Interruptible water supply agreements											U		1						A			0					A	3					N
	S9	Reuse					1						S		S						M								M						
	S10	Wet year leasing of water rights to agriculture					1						H		T						A								A						
	D1	Voluntary outdoor watering restrictions											R	K	C						E								R						
	D2	Mandatory outdoor watering restrictions											E	A	E						L			U					E	U					F
	D3	Enforcement of watering restrictions											-	T	N						E			P					-	P					I
	D4	Implement, upgrade water metering and water loss control systems											E	R	T						C			D					E	D					N
	D5	Water-efficient fixtures and appliances											L	I	U						T			A					L	A					A
	D6	Low water use landscapes and efficient irrigation											E	N	R						E			T					E	T					L
Impacts	D7	Rate structures to influence water use											C	A	Y						D			E					C	E					I
	M1	Monitor water supply components (e.g. snow pack, stream flow, etc.)											T		A														T						Z
	M2	Evaluate effectiveness post-drought and modify plans											E		C														E						E
	M3	Track public perception and effectiveness of drought measures											D		T														D						D
	A1	Water Delivery																																	

Figure 2. Example of EHC study participants filled out with interviewer. For each time period represented in columns (semi-annual from 2000-2015), they indicated if each strategy was used, rows. They then characterized their 'capacity' to meet water delivery requirements by ranking their system from 1-3 throughout the time period.

characteristics unique to each water provider (e.g. their source of water supply, seniority of rights, the type of community they serve, population growth rates, etc.). These internal factors shape both the motivation and ability to use management actions and their effectiveness. To evaluate how internal attributes contributed to capacity of water providers to meet their water demands over time and their choice of strategy, this study used hierarchical cluster analysis (HCA) to group the water providers based on organizational attributes. The Gower distance metric (Gower, 1971; Hennig and Liao, 2013) was used to calculate the dissimilarity between the water providers (which is appropriate for mixed-type datasets) and the providers were divided into four clusters.

Figure 3 illustrates the average number of strategies used by each of the clusters, which serves as a measure of their 'adaptiveness'. Groups 2 and 3 continued to adopt new strategies after the 2002 drought, while groups 1 and 4 saw an increase in the number of strategies used during the 2002 drought and adopted a small number of strategies in the subsequent years. However, their adoption of new strategies leveled off in the mid-2000s and did not increase again, even during the 2012 drought period. This indicates that Groups 2 and 3 are likely more adaptive and continually alter their water management strategies to be reflexive to changing conditions, while Groups 1 and 4 have more rigid responses.

Generalized estimating equations were included to evaluate strategies most likely used by different water providers during droughts of varying severity, as well as how capacity changed relative to provider groups and drought conditions. These results revealed that Groups 2 and 3 used a more diverse suite of supply-augmenting and demand-reduction strategies both during and between droughts. However Groups 1 and 4 primarily relied on supply increasing techniques between droughts and imposed mandatory restrictions during droughts.

Discussion

Looking to the past serves as a useful guide to understand how water systems will cope with future climate and population induced stresses. It is important to evaluate lessons learned and what enabled those lessons to transition into resilience. The increase of capacity for all water providers throughout the period of time presented in this study suggests that periodic droughts actually can increase the resilience of water managers, if they improve upon lessons learned. Because they were caught off guard and systems were impaired in 2002, water managers used the period after the drought to reorganize and develop new policies and/or update their systems. Then in 2012, when the signs of drought first appeared, water managers had established protocols in place. Some water providers were more adaptive to external pressures and continued to improve their management over time, while others were more rigid and only responded to abrupt changes, suggesting that the latter could be vulnerable to sudden or more severe droughts. While these results are only the first part of this study, they reveal that there is an association between internal and external factors and strategy choice and capacity. This analysis provides a better understanding of how water providers manage drought and their motivations for future adaptation. Further qualitative analysis will be conducted on this dataset to evaluate the role that institutions play as stimuli or barriers for adaptation and increasing adaptive capacity of water providers.

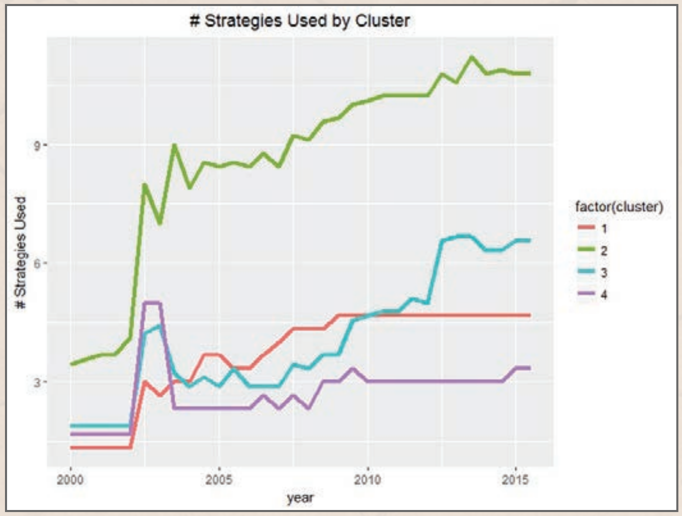

Figure 3. Number of strategies used by each provider cluster group. Groups that continued to adopt new strategies throughout the time period are more 'adaptive' while others are more reactive.

My Tenure as State Engineer

Some Reflections, Insights, and Foresights

Dick Wolfe, M.S., P.E., Colorado State Engineer and Director, 2007-2017, Colorado Division of Water Resources

My tenure with the State Engineer's Office began in July 1993 after seven successful years working as an engineering consultant with Spronk Water Engineers. I am thankful to countless people who have inspired and shaped who I am today, including foremost my family, for whom I would not even had the opportunity to serve if not for their unending support and love of my sometimes crazy passions.

People Make the Difference

The State Engineer's Office was created in 1881 and has evolved over 136 years to become recognized as a leading water agency in the Western United States and around the world. It has dedicated itself to preserving what is best and to embracing the future bravely and confidently.

Reflecting back on the past 24 years, I recalled an article that was published in Colorado Water by my predecessor, Hal Simpson, shortly after his retirement in May 2007. Not surprisingly, the first thing Hal addressed was the role of women in the workplace. Diversity of our employees has been a major focus of our vision for the DWR. At the center of every story is people, and our commitment to the citizens of Colorado is that our agency represents the diversity of culture in the community we serve. Hal remarked that we had one professional engineer in 1972 and one female water commissioner. Today, we are proud to boast that women make up 30% of our staff, which also reflects the approximate percentage of women in professional positions.

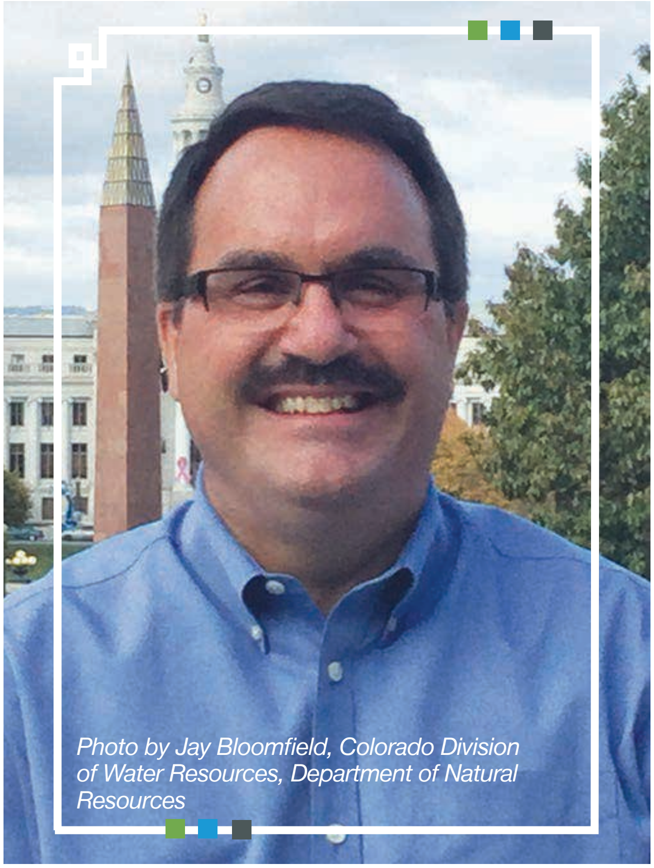

Photo by Jay Bloomfield, Colorado Division of Water Resources, Department of Natural Resources

We have continued to meet the challenges of our jobs despite cuts in our budget and staffing over the past 10 years. Specifically, the DWR has 19 fewer full-time employees working today than we did in 2007. With advances in technology, we have empowered our staff to develop innovative solutions. As public servants, we are committed to being an agency that is accountable, imaginative, innovative, and known for its integrity despite the many challenges we face. We take pride in our outstanding customer service by being accessible, responsive, and respectful in our customer relations.

Although most people know us for water administration DWR has an important safety program involving dams and water wells. Over the past 5 years in particular, our dam safety engineers have made a concerted effort to reach out to local entities, private dam owners, as well as state and federal agencies to hear their needs with respect to our program with the end goal of developing sound parameters for the safety of Colorado's dams and the people in the State. Further, collaboration with states and engineering groups on a national level has further raised the bar within Colorado to consistently make our program second to no other program in the nation. The response to the September 2013 flood was a testament to this collaboration and reflects the importance of our robust dam safety program.

Our current well inspection program was created in 2003 and although it does not have the funding level and staffing as originally envisioned, the current staff still provide critical inspections and enforcement of standards to ensure that wells are constructed to provide long-term safety to the public and the groundwater.

I would encourage our continued endeavors in both local and national levels to develop sound science to keep our citizens, wells, and waterways safe for all to enjoy. Our staff has acquired great investigative skills and has proven to be effective problem solvers always tempered with openness and sound judgment. We continually endeavor to have the courage to do the right thing, but never compromise what we know to be true and lawful, including our commitment to service and excellence within our community and stewardship of our natural resources.

Colorado's Water Administration System is Well-Suited for the 21st Century

It is undisputed that Colorado water law is complex and not easily understood. But it has served the State well overall and continues to evolve to meet the ever growing population demands and associated needs for the environment, recreation, and agriculture. I believe the Doctrine of Prior Appropriation will continue to serve us well in the future because it has the ability to respond to the many variables that affect hydrology, including the challenges of future climate variability. Although it does not solve the challenges of meeting future water needs, it does provide the foundation that decision makers can rely upon when making difficult decisions about future tradeoffs between our consumptive and non-consumptive needs.

Moreover, we must continue to educate the citizens of Colorado regarding the complex interrelationships of water demand and water supply because misunderstandings and misperceptions can lead to conflict. We all must ensure that the proper legal and institutional regulatory framework continues in order to properly protect and administer water. Users want and demand regulatory certainty.

Colorado will do an excellent job meeting its need to develop and manage a sustainable water supply, including healthy forests and watersheds for the future. Colorado has a lot of brilliant people working together in an effort to achieve this goal. We must institute plans today that are based on sound science that will allow us to plan as far ahead as possible. The existing planning horizons of 30-50 years reflect the limit of our ability to predict any further into the future due to limited data and our current understanding of the complex world we live in. Respectively, we must continue to be flexible to the evolving circumstances within this horizon given the inability to predict with absolute certainty.

> "I started this off with thanks to my family for allowing me to have this adventure that I have truly loved and I am going to end it there as well. But this thank you is to a greater and more extended family being everyone whose life has touched my life during this amazing run."

We must continue to recognize the important roles that recreation and the environment play throughout the state. Recreational in-channel diversions have created a significant economic boost in many areas of the state, but have also potentially limited future upstream development. In-stream flows have also played a vital part of the preservation and enhancement of the environment, and their full benefit may not be fully recognized for years to come when these rights become more actively administered.

Cooperative approaches are necessary to address some of our state's most contentious environmental issues. The use of in-stream flows in water resources has aided consumptive water users by ensuring that Colorado meets its obligations under the Endangered Species Act. Colorado is already implementing collaborative solutions through several Endangered Species Recovery Programs, wherein water and resources are being provided to maintain and improve streamflow for endangered fish.

Sustainability of our Resources and Systems

The DWR (including our Modeling/Decision Support System Group and the Water Information Team) works closely with the Colorado Water Conservation Board and other agencies to develop and protect Colorado's compact entitlements through data acquisition, decision support systems, as well as studies to support the complex and difficult issues related to water resource development, and potential future interstate conflicts. The DWR continues to apply advanced computer programming, updated data and information, modeling expertise in the development, utilization of hydrologic computer models, and decision support systems.

The conversion of manual data recording devices to electronic instruments has been one of the significant modifications that has allowed the DWR to respond to the increased administration demand with less human capital. Water users have increasing expectations and demands about the availability of real-time data for various gages and diversions that result in more electronic data collection and telemetry systems. In some cases, new stream gauges are being installed and, therefore, related work load increases.

Our hydrographic program has continued to grow over the years. Specifically, we have expanded the satellite monitoring system to over 600 gages today to assist in water administration and distribution, compact administration, flood and drought prediction, water storage and release, recreation and environment, along with wildlife, and water quality demands. Tactically, you cannot manage what you do not measure. Colorado is the only state in the West that has such a complete program and still continues to demonstrate its ability to operate and maintain its state-of-the-art program in the most cost-effective and efficient way possible.

The use of high-speed Internet and portable electronic devices by field staff has made it possible for water commissioners to use tools for reviewing flow conditions, setting calls, checking email, receiving and reviewing complex accounting spreadsheets, and using database management applications that include GIS and scanned images. The use of database management systems has allowed increased levels of real-time administration that are not expected to abate anytime soon. One significant ongoing need is the systemization of collecting this data and easily translating it into diversion records, administrative accounting information and data that can be used to demonstrate compliance with court decrees and administrative orders. Increasing innovations in data collection will provide more time for everyone involved to meet the increasing demands of future water administration.

Most importantly, we all must be stewards of our most precious resource and be collectively responsible for planning our future. We must realize that the choices we make today on how we live will directly affect how we will live in the future. Our world is complex and we continue to evolve in our understanding of all the forces at play. It is essential to develop system models that incorporate scientific, social, economic, environmental, and administrative interrelationships that will lead to better planning, and ultimately legal and institutional systems to support the management of a sustainable water supply.

Lastly, cooperation, flexibility, and honesty have shaped the river management system that we employ today to meet the challenges of effective and efficient management of the State's water resources. The enormous challenges facing us require the collective input of all stakeholders and a collaborative decision-making process that reaches common ground for developing a sustainable water future that meets our numerous and diverse needs.

"Lessons Learned"

Education and effective communication are vital to success. It is the foundation that builds trust among people. One of the keys to great communication is to be a good listener. We desperately need to talk and listen to the people we disagree with the most, if we are to build on the foundation of trust. We must promote open and honest communication wherever and whenever we can because it builds the trust, respect, and loyalty amongst ourselves and the diverse community that we serve.

In times of conflict and negotiations we must never assume the other parties have bad intentions, but rather assume their intentions are well-placed based on their perspectives. In doing so, we are able to reach solutions that work for all parties involved.

Litigation is not a substitute for sound science and facts. Cooperation and restraint from litigation will provide greater certainty and a more secure water supply for the entire state. Essentially, we must encourage greater and earlier coordination and collaboration amongst users and uses. Addressing issues in a conflict-rich environment rarely yields timely and effective solutions.

We must also develop laws based on sound science. This most certainly will be a difficult task in that sometimes the law being proposed is to serve a particular interest group or specific situation that may lead to an absurd result for the whole. Also, a law may reach the Legislature based on sound science and yet a particular interest group or groups may try to obfuscate the true science behind the proposal. Again, I would point back to the listening skills above to try and pierce through positions to discover the underlying interests of all of the parties to reach laws based on scientific reality.

The need continues for transparency of information and bases for our actions. Transparency creates accountability that leads to trust. During my tenure, the publication of white papers and administrative orders has been invaluable. Yes, some have caused a stir among the water users at times. However, the value of our agency vetting internally, as well as externally, the reasons we make the decisions results in more effective government and water administration for the public at large. Respectively, the public at large has a clearer idea of our position from the start.

Lastly, one other important lesson learned. Employ people who have a passion for their job. It pays off big time. A perfect example of this occurred during the flooding of September 2013. Our eastern slope was inundated by flooding that was at times epic in proportions. During this crisis, our water commissioners, hydrographers, dam safety engineers, and numerous other employees within the DWR spent endless hours and months proactively assisting from the first rain drop to the clean-up efforts that followed. People with a passion for their work can make all the difference in the world. I am comforted to know these employees have that same passion for the work they do today.

Conclusion

I started this off with thanks to my family for allowing me to have this adventure that I have truly loved and I am going to end it there as well. But this thank you is to a greater and more extended family being everyone whose life has touched my life during this amazing run. From my fellow employees, to the numerous professionals, to the farmers, and all water users throughout the state and bordering states—I thank you. I truly thank all of you for enriching my life and professional career and allowing me to serve you. Water has been and always will be a passion for me and I have been truly blessed to work in a greater community that also cares so deeply for our most precious resource—water!

Microbial Community Responses to Metals Contamination

Mechanisms of Metals Exposure and Bioaccumulation in a Stream Food Web

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Dr. William Clements, Fish, Wildlife, and Conservation Biology, Colorado State University;
Dr. Ed Hall, Ecosystem Science and Sustainability, Colorado State University

Stream flow measurements at the upper Arkansas River.

Sam Duggan

SYNOPSIS

Our goal was to better understand the effects of metals pollution on stream dietary resources and determine the mechanisms for how metals enter the aquatic food web. We examined how community composition, metals concentrations, and resource dietary quality from two primary diet types (biofilm and seston) affect aquatic insects at sites upstream and downstream of a metals source in the upper Arkansas River.

Introduction

Mining practices have generated an estimated 45 billion metric tons of waste that have impaired approximately 8,000 km of streams in the U.S. These effects are widespread in Colorado, where a recent survey suggested that about 25% of mountain streams showed some level of degradation due to metal exposure. With the recent accidental release of metals from historical mining into the Animas River in 2015, it is clear that impacts from historical mining will continue to be an important issue to the public.

Our research is focused on the upper Arkansas River (near Leadville, Colorado) that has been historically impacted from mining activity. The Arkansas River itself is the 6th longest in the United States and represents a major tributary to the Mississippi River. It also provides an important water source to many communities such as Pueblo, Colorado . Thus, researching the impacts of mining activity on this river system may have broad-level implications for other impaired streams of Colorado, and to downstream users in other States.

In 1983, the U.S. Environmental Protection Agency (EPA) added California Gulch, the main source of metals (e.g. Cd, Cu, and Zn) into the upper Arkansas River, to the National Priorities ('Superfund') List. Traditional monitoring of this area was performed using aquatic insect communities as 'bioindicators' of stream health. This form of bioassessment is founded on the principle that certain aquatic insect taxa are more sensitive to contaminants than others. Thus, the relative abundances of these different groups may be used as indication of stream health. Indeed, it was found that metals contamination caused a shift in stream benthic insect community composition, with more

"Mining practices have generated an estimated **45 billion metric tons** of waste that have impaired approximately 8,000 km of streams in the U.S."

'sensitive' taxa at upstream reference sites (no metals contamination) and more 'tolerant' taxa at contaminated sites downstream of California Gulch.

Much of the upper Arkansas River has since been remediated to remove most of metals sources (completed by 1999). However, despite significant improvements in water quality, the relative abundance of 'sensitive' taxa remain low at sites downstream of California Gulch (Figure 1).

The traditional approach for setting stream water quality guidelines has relied upon laboratory experiments and assumed direct aqueous exposure (e.g. exposure to external gills) to aquatic insects. However, dietary exposure is increasingly becoming recognized as an important route of toxicity in stream insects. Interestingly, the most sensitive stream insects are also commonly consumers of benthic microbial biofilms (a complex matrix of bacteria, algae, archaea, and fungi attached to substrate). In contrast, other groups such filter-feeders of stream seston (material suspended in the water columns) are typically more abundant in metals contaminated streams. The difference in dietary preference between sensitive and tolerant stream insects is consistent with the hypothesis that dietary metals exposure is important; however, the exact mechanism through which this affects the fitness of stream organisms has yet to be evaluated. Therefore, we sought to better understand how metal pollution affects stream resources to understand the exact mechanism for how metals enter the aquatic food web.

Research Questions

Specifically, we addressed the following research questions: (1) are metals concentrations greater within benthic biofilms than in seston at downstream ('impacted') sites?; (2) are there differences in upstream and downstream resource composition and dietary quality (i.e. nutrient content)?; and (3) what are the effects of exposure to metal-contaminated biofilm and seston on aquatic insect consumers?

We had two competing hypotheses through which differences in metals at the base of the food web may affect stream insect communities. Our first hypothesis was that insects consuming biofilms likely bioaccumulate relatively more metals through dietary exposure (i.e., greater direct exposure) than consumers of seston. Our second hypothesis was that aqueous metals concentrations may be low enough at downstream sites that are not directly toxic to the consumer, but high enough to alter biofilm community structure and resource quality (i.e., greater indirect effect in biofilms). We tested these hypotheses by examining biofilm community composition, metals concentrations, and resource dietary quality (e.g. nutrients content) from biofilm and seston at sites upstream and downstream of California Gulch.

Methods

(1) Are metals concentrations greater within benthic biofilms than in seston at downstream ('impacted') sites?

To determine if metals are the key determinants of microbial communities it was important to explicitly test if metals concentrations are higher at downstream locations (Figure 2) and test if metals are higher in benthic biofilms than seston. To address this question, ceramic tiles were deployed at one site upstream (reference) of the metals contamination source (California Gulch) and one site downstream (impacted). Tiles were retrieved approximately 5 weeks later following pronounced microbial biofilm colonization.

Biofilm on tiles were scraped with a sterile ceramic knife and placed immediately into cryogenic vials and flash frozen in liquid nitrogen. Seston was collected by suspending an 80 µm plankton net in the water column for 5 minutes. Each seston sample was transferred from the net into a cryogenic vial and flash frozen in liquid nitrogen. Upon return to the laboratory, all samples were immediately transferred in a -80°C cryofreezer. Samples were then freeze dried and analyzed for metals (Cd, Cu, and Zn) concentrations using Atomic Absorption Spectrometry.

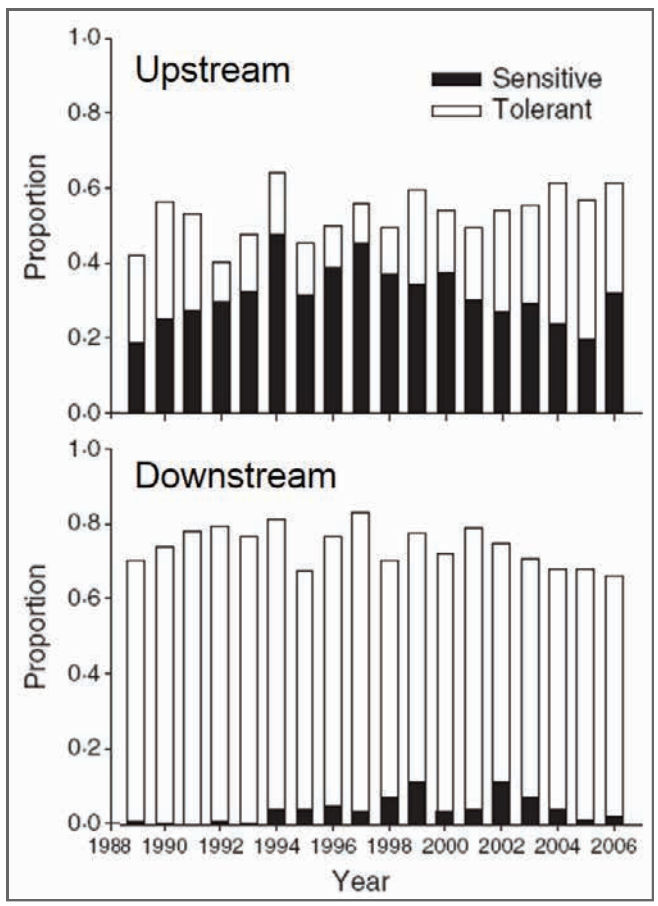

Figure 1. Relative proportions of 'sensitive' and 'tolerant' aquatic insects from the upper Arkansas River, 1998 – 2006.

(2) Are there differences in upstream and downstream resource composition and dietary quality (i.e. nutrient content)?

We sought to determine if metals exposures altered biofilm community structure. Removal of certain taxa could fundamentally change dietary quality available to aquatic insects. To determine biofilm community composition, we used an in situ handheld fluorometer (BenthoTorch®) on natural rock substrate at sites upstream (reference) and downstream of California Gulch ('impacted'). This instrument works by exciting cell pigments with varying wavelengths that ultimately is used to estimate abundance of green algae, diatoms, and cyanobacteria from a single measurement.

To address the effects of metals on nutrient content of microbial communities we measured C:N from natural rock substrate at sites upstream (reference) and downstream of California Gulch ('impacted'). Samples were freeze dried and submitted to the Cornell University Stable Isotope Laboratory (COIL) for C:N analysis.

(3) What are the effects of exposure to metal-contaminated biofilm and seston on aquatic insect consumers?

Finally, we measured metal concentrations and C:N of

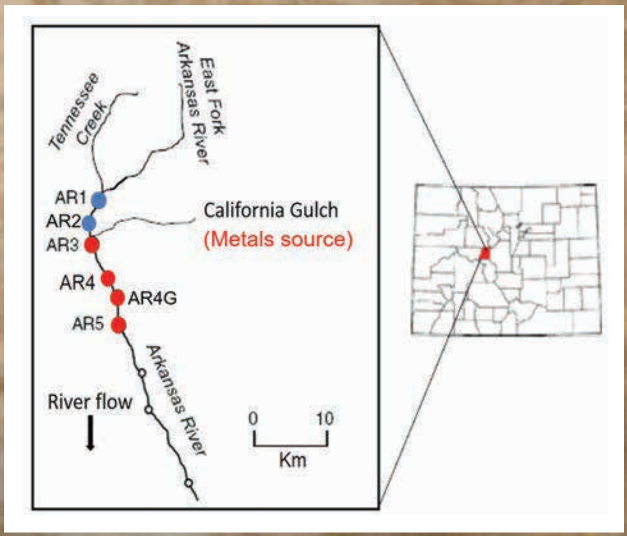

Figure 2. Map of study sites on the upper Arkansas River, Leadville, Colorado. All sites in blue represent upstream 'reference' sites, and those in red represent downstream 'impacted' sites.

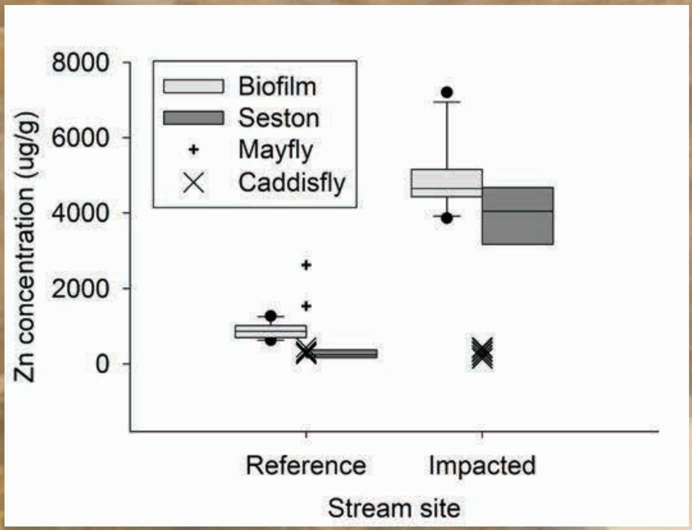

Figure 3. Metals concentrations from samples collected at sites upstream ('Reference') and downstream ('Impacted') of California Gulch on the upper Arkansas River.

Tiles deployed in river for benthic biofilm colonization.

Sam Duggan

upstream and downstream aquatic insects representing two different feeding guilds: (1) benthic biofilm grazing mayflies, and (2) seston filter-feeding caddisflies. Directly measuring metals and C:N from insects provided a direct measure how differences in dietary exposure affect higher trophic levels.

Results

Our analysis suggests that seston and biofilms downstream of California Gulch have much higher metals concentrations than at upstream reference sites (Figure 3). Additionally, we found that metals concentrations in biofilms were greater than in our seston samples. Metals analysis of a seston-feeding caddisflies revealed that concentrations remained unchanged between upstream and downstream sites (Figure 3). We found that mayflies at upstream reference sites had higher metals concentrations that found in the caddisflies. However, we did not have enough dried mayfly biomass at the downstream 'impacted' site for metals analysis. Thus, we were unable to determine if mayflies are also able to regulate metals bioaccumulation at downstream sites.

Despite higher metals concentrations in downstream biofilms, we found higher chlorophyll-a, suggesting that metals do not have a negative effect of algal biomass (Figure 4). However, the community composition was different between reference and impacted sites. The reference sites had greater abundance of diatoms and green algae, but the impacted site had greater abundance of cyanobacteria, with no green algae present (Figure 4).

Results from our C:N ratios suggest that metals may influence resource quality. Biofilm C:N ratios were lower in the reference sites, implying greater nitrogen or less carbon availability; however, seston C:N ratios were not different between sites (Figure 5). Interestingly, mayfly C:N ratios remained relatively unchanged between reference and impacted sites despite the observed changes in C:N ratios of their diet.

Discussion

Overall, our results show that the effects of metals on stream ecosystems are highly complex. The fact that metals accumulation in caddisflies did not change between reference and impacted sites suggests that these insects may have the capacity to regulate metals. Without currently having metals concentrations of mayflies downstream of California Gulch, it remains unclear whether those types of insects are also able to maintain consistent metals concentrations at impacted sites as well.

Metals also likely created a shift in algal biomass at impacted sites and it appears that theses shifts resulted in changes in resource quality. However, resource quality only changed between reference and impacted site biofilms, but not seston C:N. Therefore, metals, in combination with a shift in resource quality, may be more stressful to insect scrapers than filterers.

There is a limited amount of previous research on how stream resources change in relation to mining activity. However, our approach has expanded upon this work by determining how such changes in microbial resources affect higher levels of organization through examining putative pathways for bioaccumulation of metals and resulting shifts in dietary quality. Our research will contribute to water quality and stream assessments by filling a much needed knowledge gap of how stream resources facilitate or mitigate metals exposures.

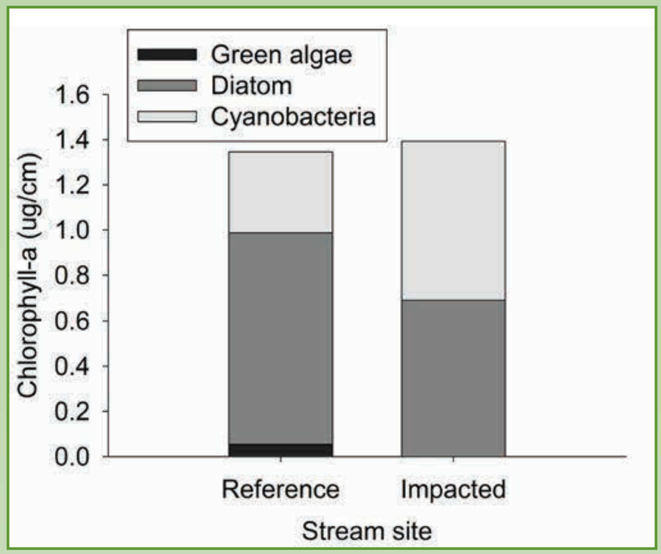

Figure 4. Biofilm chlorophyll-a from BenthoTorch measurements at sites upstream ('Reference') and downstream ('Impacted') of California Gulch on the upper Arkansas River.

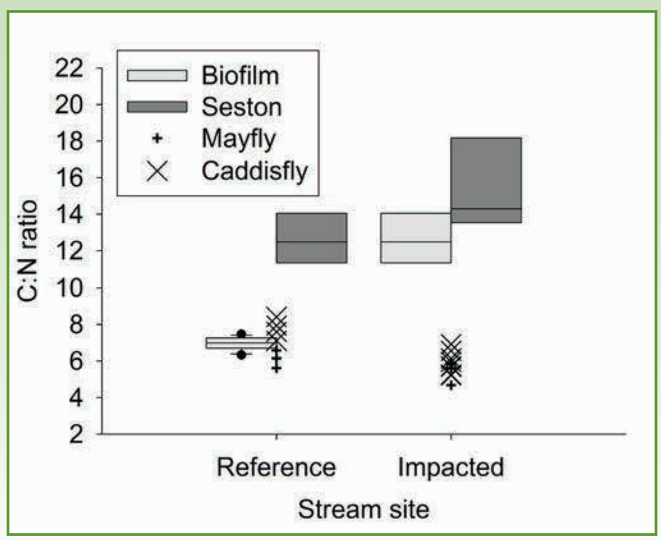

Figure 5. Percent carbon to nitrogen (C:N) ratios from samples collected at sites upstream ('Reference') and downstream ('Impacted') of California Gulch on the upper Arkansas River.

Changes in Water, Sediment, and Organic Carbon Storage in Active and Abandoned Beaver Meadows

DeAnna Laurel, PhD Candidate, Geosciences, Colorado State University; Dr. Ellen Wohl, Geosciences, Colorado State University

SYNOPSIS

Beaver prefer unconfined meadows with slow flowing streams which are ideal for building their dams. This study assessed active and abandoned beaver meadows and examined the changes in storage and attenuation of sediment, organic carbon, and water storage within Rocky Mountain National Park.

Ellen Wohl

PhD Candidate DeAnna Laurel installing instrumentation to record water height (stage) on Glacier Creek in Rocky Mountain National Park.

(Background image) Moraine Park Valley in Rocky Mountain National Park Photo by Frank Schulenburg

Introduction

In the Colorado Mountains, stream reaches are mostly steep and narrow, confined by valley walls. The exceptions are isolated unconfined, lower gradient meadows that are like beads along the "string" of the river. Compared to the confined river segments, the unconfined meadows have relatively less efficient downstream transport and greater storage and attenuation of fluxes of water, sediment, and organic carbon. During high streamflow, water carrying sediment and particulate organic matter spills over the main channel banks into the floodplain. As streamflow decreases though the summer, the floodplain water is stored or drains back into the main channel. Beaver (*Castor canadensis*) favor the unconfined meadows where lower stream gradient results in slower velocity flows that they can dam and there is room for a large riparian corridor.

Prior to European settlement, beaver were present in North America in every suitable habitat from northern Canada to southern Mexico. Fur trapping subsequently almost eradicated beaver from their historic habitats. In the last few decades, beaver populations in Colorado have been recovering, although they still face challenges such as grazing competition with elk and conflicts with human infrastructure that have removed them from mountain stream meadows. Beaver manipulate their environments to suit their needs by building dams that alter channel and valley bottom morphology. Beaver dams encourage more streamflow to spill over onto the floodplain and into secondary stream channels resulting in complex, multi-thread wet valley meadows. In contrast, meadows where beaver have been removed tend to have single-thread channels and less complex, drier floodplains. This study aims to quantify the alteration in storage and attenuation of three fluxes: water, sediment, and organic carbon, which result from the simplification of channel and floodplain geomorphology after beavers have left a meadow. The hypothesis is that increased complexity in the meadow environments as a result of beaver activity enhances the retention of fluxes by increasing overbank flows and deposition away from the main channel. Abandoned beaver meadows that lack complexity will have relatively less attenuation of water fluxes, and less storage of organic carbon than complex active meadows. This article will focus on the hydrology and some preliminary organic carbon results. Processing of the sediment and additional organic carbon (OC) samples is still underway.

Study Area

The study takes place in central and northern Colorado within and near Rocky Mountain National Park, Colorado. The rivers in the study have snowmelt-dominated hydrology with an annual peak streamflow (discharge) occurring sometime around late May or early June. The streamflow then gradually returns to baseflow over the course of the summer, with occasional small, short increases as the result of summer storms. The active (North St. Vrain, Glacier Creek and Hollowell Park) and abandoned (Cow Creek, Hidden Valley, Upper Beaver Meadows and Moraine Park) beaver meadows on each stream are relatively wide flat-bottomed valley features in otherwise steep, narrow mountain streams, in areas that experienced glaciation. The meadows are underlain by Precambrian crystalline bedrock and have riparian vegetation in the floodplain with forested valley slopes. The forested vegetation consists of trembling aspen, fir, spruce, and pine trees. In valley bottoms, the riparian vegetation is dominated by river birch and willow in the active meadows and by grasses and sedges in the abandoned meadows. Across the study meadows there is a range of beaver activity from the North St. Vrain, Wild Basin meadow that supports multiple beaver colonies to Moraine Park and Upper Beaver Meadows that have been abandoned for at least three decades.

Methods

Geomorphic complexity of each meadow was measured by conducting surveys in multiple transects across each meadow. Complexity is characterized by the number of distinct geomorphic units present and the evenness of distribution of those units in each meadow. To measure hydrologic attenuation, instruments were placed at the inflow and outflow of each study meadow for the duration of the summer field season. The instruments recorded the water height (stage) at 15-minute intervals from before the snowmelt peak until return to baseflow in late September or early October. A geomorphic survey of the channel cross-section geometry was conducted for each instrument site, along with repeat surveys of the flow velocity. The surveys were conducted by stretching a measuring tape across the channel and recording elevation and velocity at increments across the channel using a survey auto-level and a wading rod. From the channel cross-section surveys, the velocity, and the stage data, the channel discharge could be calculated and a mathematical relationship developed for each site to convert the 15-minute stage data into 15-min flow discharge data. Attenuation of streamflow in each meadow was then quantified by comparing the timing and duration of the peak flow and flow recession at the inflow and outflow of each meadow.

Organic carbon stocks were calculated for one abandoned and one active meadow that represent end members for the range of beaver activity across the study sites. Soil samples were collected using a standard soil corer. The organic carbon concentration in each sample was measured by the Colorado State University Soil, Water, and Plant Testing Lab. Bulk density of the soil samples was calculated using the oven-dry weight and the volume of sample collected. Soil organic carbon stocks were calculated from the percent organic carbon in the sample and the bulk density.

Results and Discussion

The results of the morphologic complexity surveys, hydrologic attenuation, and organic carbon dynamics create a more complicated picture than what was hypothesized. Active beaver meadows showed greater complexity via a greater diversity of geomorphic units and a more even division between the geomorphic units present than the abandoned meadows. Active meadows had an average of 7.6 geomorphic units and a more even distribution of surface area between the units, whereas abandoned meadows had an average of 6 geomorphic units, with only 1 or 2 dominant units (Figure 1). Complexity appears to be related not only to the presence or absence of beaver, but also to the level of beaver activity and the length of time since beaver abandoned the environment. North St. Vrain Wild Basin and Upper Beaver Meadows represent the end members of the six sites examined for morphologic complexity. North St. Vrain is a highly

DeAnna Laurel

Dr. Ellen Wohl conducting fieldwork on the North St. Vrain Creek in Wild Basin, Rocky Mountain National Park.

active multithread channel meadow that supports multiple beaver colonies and has the greatest number of geomorphic units (10) and the most even division of area between those units. Upper Beaver Meadows on the other hand has been abandoned for upwards of 3 decades, has a single channel and is dominated by only two geomorphic units. The other sites, whether active or abandoned, fall somewhere in-between. Cow Creek had only been abandoned for two years at the time of the survey and displays complexity similar to Mill Creek at Hollowell Park, which has limited beaver activity.

In a related project to this study, colleagues at CSU found that the highly active beaver meadow, Wild Basin on the North St. Vrain, attenuated streamflow by acting as a sink for water during the high flow periods and a source of water during low flow periods. The results from this study support the attenuation result found for Wild Basin on the North St. Vrain. Mill Creek at Hollowell Park was a sink for water while the streamflow was increasing toward snowmelt peak in early Spring, but became a source of water at peak flow and throughout the rest of the summer as streamflow decreased. Like North St. Vrain, it shows some attenuation of flow by delaying the downstream transport of water entering the meadow. Glacier Creek did not show any attenuation of streamflow even though it has current beaver activity. For the abandoned meadows, Cow Creek and Hidden Valley both show the same attenuation pattern as North St. Vrain – becoming a sink at high streamflow and a source at low streamflows. Although these meadows are abandoned and have lower overall morphologic complexity, they retain remnant beaver dam and pond features that may still be affecting the hydrology even though the beaver have left. Further analysis of this dataset will be required to tease out the details and intricacies of hydrologic flux dynamics in Colorado mountain beaver meadows.

The organic carbon analysis only includes two meadows – North St. Vrain, a highly active meadow and Moraine Park, a meadow like Upper Beaver Meadows that has been abandoned for more than three decades. The percent organic carbon (OC) in the soil samples is not statistically different between the active and abandoned meadows, although the active meadow does have much greater variability in OC concentration. Moraine Park has an average of 55.90 Mg C/ha and Wild Basin has 36.38 Mg C/ha. Moraine Park has greater soil OC stocks than the active meadow in contrast to the hypothesis, but the difference is not statistically significant. These preliminary results indicate that beaver activity may not play a role in soil OC storage in Colorado mountain meadows, although the analysis of the data for the remainder of the meadows is necessary before any firm conclusions are made.

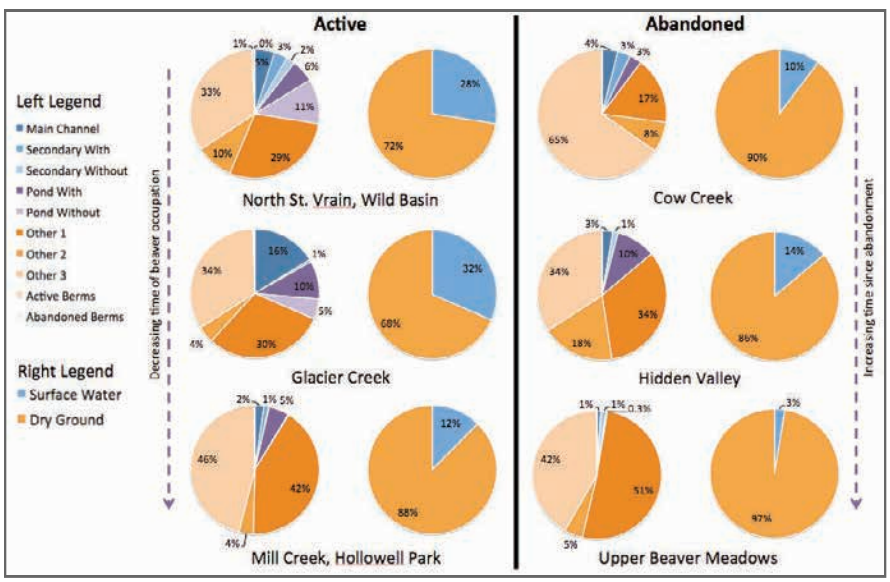

Figure 1. Geomorphic surveys to determine floodplain complexity of active and abandoned beaver meadows. Ten different geomorphic units were identified for the meadows including: the main stream channel, secondary stream channels, ponds with or without perennial surface connection to the main channel, active and abandoned beaver berms, and three categories of "other" distinguished by their elevation, wetness throughout the summer, and their vegetation. Greater complexity is indicated by a larger number of distinct geomorphic units present and increased evenness of distribution of those units in each meadow.

WATER CENTER
COLORADO STATE UNIVERSITY

We are pleased to announce the recipients of our 2017-2018 CSU Water Center Competitive Grants

The CSU Water Center has selected four Multi-Disciplinary Water Research Teams and three Water Faculty Fellows as recipients of Water Center funding for 2017-2018. Our request for proposals called for projects that would catalyze innovative water research, education, and engagement through interdisciplinary collaboration and creative scholarship among CSU faculty and students. The selection process was competitive and the breadth of topics covered by the submitted proposals is indicative of the successful water research community at CSU. Congratulations to these research teams and faculty members!

Water Research Teams

- *A systems modeling approach to quantify forest fuel treatment effects on wildfire severity and post-fire erosion*

  Tony Cheng, Benjamin Gannon, Kelly Jones, Stephanie Kampf, Lee MacDonald, Katherine Mattor, Peter Nelson, Yu Wei, and Brett Wolk

- *Developing a comprehensive understanding of metal impacts on stream ecosystems in Colorado*

  Will Clements, Ed Hall, Katy Warner, and Brian Wolff

- *Biotreatment of pharmaceuticals and personal care products during water treatment for reuse: Ensuring human safety at the food-water nexus*

  Susan De Long, Karen Rossmassler, Jessica Prenni, and Corey Broeckling

- *Quantifying the scope and impact of permanent agricultural dry-up due to rural to urban water transfers*

  Michael Falkowski, Dale Manning, Drew Bennett, Sarah Parmar, and Steven Filippelli

Water Faculty Fellows

- *From information to prices: What drives residential and commercial water demand?*

  Jesse Burkhardt, Department of Agricultural and Resource Economics

- *Integrating green infrastructure within land-use and water planning*

  Kelly Curl, Department of Horticulture and Landscape Architecture

- *Stream fish conservation in extreme habitats*

  Yoichiro Kanno, Department of Fish, Wildlife, and Conservation Biology

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Water Sampling and the Effects of Adsorption on Aqueous Heavy Metals

Haley Sir, BS Student, Environmental Science, Water Quality and Hydrologic Science, Metropolitan State University of Denver;
Dr. Randi Brazeau, Earth and Atmospheric Science, Metropolitan State University of Denver;
Dr. Sarah Schliemann, Earth and Atmospheric Science, Metropolitan State University of Denver

SYNOPSIS

When collecting water samples, it is important to consider the type of material used to gather and store samples, as well as the impact heavy metals may have on the results. This project focused on understanding how aqueous heavy metals impact sampling containers and mimicked water samples from the Las Animas River after the Gold King Mine Spill in Silverton, Colorado

Background

In environmental research, sampling techniques can strongly influence the results of a study. Therefore, it is in the researcher's best interest to reduce variability in order to provide the scientific community, as well as the public, with the most accurate data possible. This study specifically investigated the concentrations of aqueous heavy metals in sampling containers spiked with lead and cadmium. The study aimed to mimic water samples that would have been collected along the Las Animas River in August of 2015 after the Gold King Mine Spill in Silverton, Colorado.

Historically, Colorado mining has often been one of the main sources of income for small towns throughout the Rocky Mountains. However, many mines within Colorado have long since been abandoned and have become possible sources of environmental damage due to acid mine drainage. The Gold King Mine in Silverton, Colorado has been out of commission since 1923, but like other historic mines, it has posed an environmental threat due to tailings that release heavy metals into soil, sediment, and surrounding surface waters. Past studies have shown that dissolved metals in aqueous samples may not be as stable as we once thought (Sekaly et al., 1999). The effects of these types of heavy metals that may be released into waterways are varied and sources for these types of inorganic chemicals should be closely monitored. The Environmental Protection Agency (EPA) has set very strict standards on these types of contaminants for drinking in the United States. The metals of concern in this study (cadmium and lead) are on this regulated list at extremely low levels (Environmental Protection Agency, 2016). The Las Animas Spill in 2015 dumped concentrations of lead, arsenic, and cadmium far exceeding these levels into the waterway causing panic and possible harm to drinking water treatment facilities downstream for many miles (Environmental Protection Agency, 2015).

In cases like these, countless samples are taken, assessed, and often times stored for possible use in the future. Storage containers for environmental water samples range in size and shape, although most are made of plastic

Figure 1. Location of alpine river sampling for this study (The Arkansas River north of Buena Vista, Colorado).

Sarah Schliemann

Figure 2. Student Haley Sir running samples on the ICP-MS for analysis at Metropolitan State University of Denver.

or glass. High-density polyethylene (HDPE) is one of the most commonly used materials. Past research has concluded that during the collection, transport and storage of water samples, various constituents may be removed from the aqueous solution as they become adsorbed to the bottle (Spangenberg, 2012). Polymer used to make many synthetic materials such as plastics, has proven to be an excellent adsorbent and has been used in the past to remove heavy metals from wastewater by combining a recycled polymer substance with natural clay (Alsewailem and Aljlil, 2013). These studies support the hypothesis that plastics may play a role in metal adsorption and could very well be a significant factor in inaccurate data for water samples. As plastics become more widely used throughout the world, more caution is being brought to their chemical properties and their economic, social, and environmental impacts. Adsorption of aqueous metals by glass has been less studied than plastics, but its use also raises some concern. By limiting sampling conditions and focusing on a few particular variables, this study aimed to investigate the effect that sampling techniques may have on aqueous metal adsorption.

Methods

In this study, a total of twelve samples were observed including four controls. Water samples were taken from the Arkansas River upstream from the town of Buena Vista (Figure 1) and spiked with standards of cadmium and lead. Spiked concentrations were far below those reported in the Las Animas River spill due to detection limits of the equipment used. The uniform spiked sample was then divided into eight closed-lid sampling bottles of approximately the same shape and size, half glass and half plastic. From each plastic and glass sample group, half were stored at a refrigerated temperature of 35 degrees C and half were stored at room temperature. The four control samples included the two different sampling bottles (plastic and glass); two containing natural river water (one at 35 degrees C and one at room temperature) and two with distilled water spiked with the metal standards of concern (one at 35 degrees C and one at room temperature). Concentrations of cadmium and lead were measured every hour for four hours on the first day. On the second day, they were measured first thing in the morning (approximately 20 hours after the initial sample) and then a little later on (about 22 hours after the initial sampling) using an inductively coupled plasma mass spectrometer (ICP-MS) (Figure 2). Concentrations were then compared with initial readings to determine the change in cadmium and lead concentrations.

Results

A consistant downward trend in concentration can be seen in all of the samples (Figures 3-6). There did not seem to be an overwhleming difference between the glass and plastic sampling containers. Nor was there a significant difference in samples kept at the refrigerated temperature and those kept at room temperature. For all four samples, lead decreased slightly faster than cadmium. Lead had an average decrease of 21% while cadmium only decreased by an average of 13% for all four samples.

Discussion and Conclusions

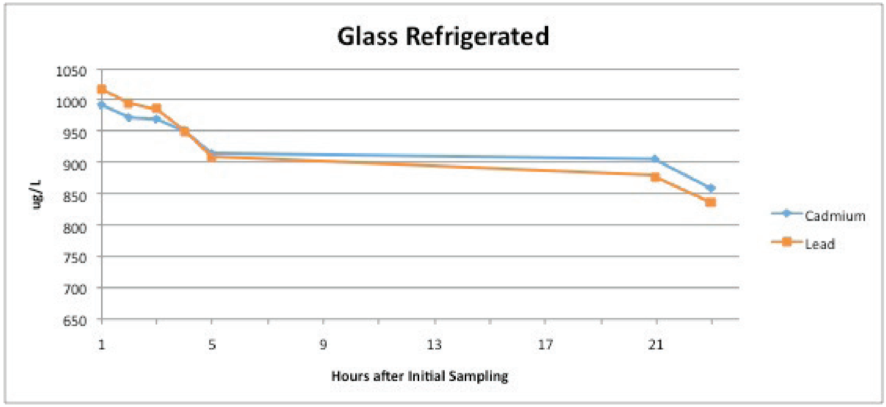
A steady decrease of both elements was observed throughout the 24 hour period, suggesting possible adsorption of these aqueous heavy metals to the sampling containers. However, there did not appear to be a significant difference due to bottle type (plastic vs glass) or temperature. In both the plastic samples, there was a small uptick in the lead concentration near the end of the sampling period. This may be due to desorption of the metals within the plastic containers after a period of time, however further research would need to be done to verify this. The results from this research suggest that there should be some consideration taken when analyzing water samples for heavy metal contamination. In particular, water samples should be analyzed as soon as possible after sampling to minimize adsorption. Samples stored for long periods of time, even in cold temperatures may produce erroneously low readings. We suggest that studies analyzing heavy metal concentrations in water should report the time elapsed between collection and analysis to account for possible adsorption.

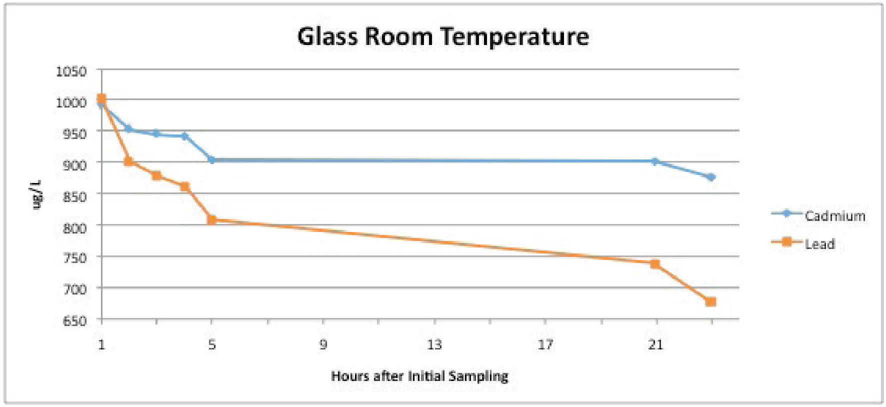
The results of this study also suggest that heavy metals may adsorb to plastics in other locations, in particular, plastic pipes in the premise plumbing of homes. Future research is needed to determine if this adsorption is occur-

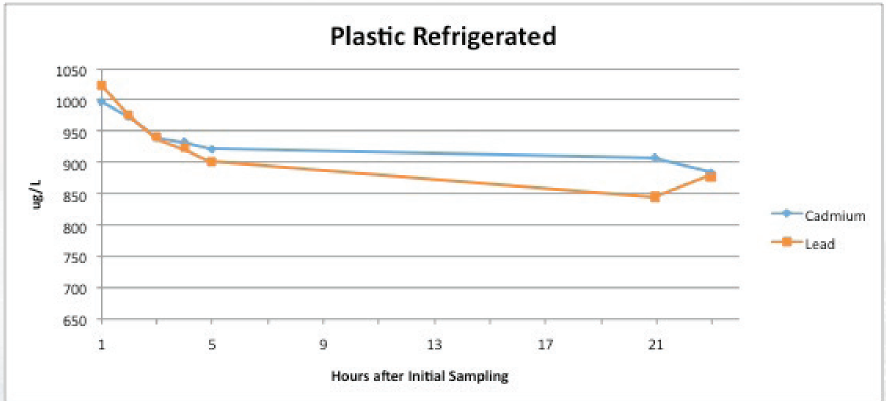
(Background Image) Labeling and first sampling of containers into ICP tubes.

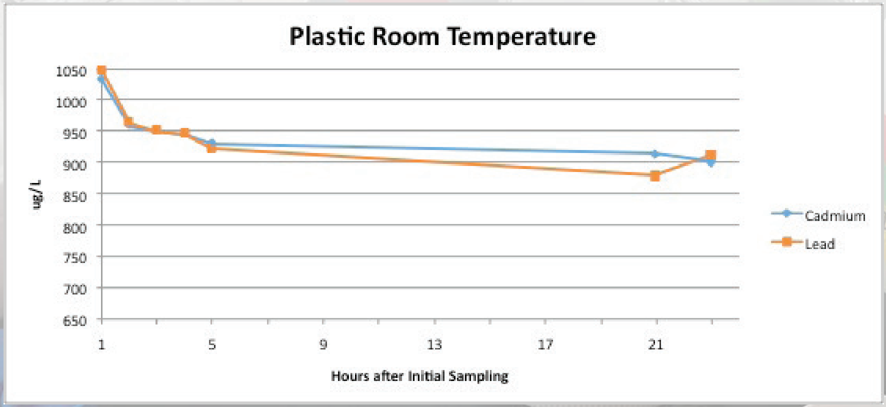
Haley Sir

Haley Sir









Figures 3-6. Cadmium and lead concentrations for each type of sampling container over a 24 hour period.

ring and, if it is, what measures should be taken. For example, adsorption and desorption of heavy metals may affect recommended flushing protocol in times of contamination. These types of recommendations are not fully understood and often vary between events and types of contaminants. Further understanding of how heavy metals interact with various materials may help to develop an understanding of how we may better address these types of situations that are often time-sensitive for the residents in an affected area.

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Effects of River Restoration on Surface Water-Groundwater Interactions, Upper Colorado River, Rocky Mountain National Park

Matt Sparacino, MS Student, Geosciences, Colorado State University;
Dr. Sara Rathburn, Geosciences, Colorado State University

Matt Sparacino and Sara Rathburn measure discharge during 2015 high flow on the Upper Colorado River, Rocky Mountain National Park.

Dave Dust

SYNOPSIS

The effects of a river restoration project on surface water-groundwater interactions between a high elevation, montane wetland, and the adjacent Colorado River were assessed for this research study. A 190 m section of the Colorado River in Rocky Mountain National Park was realigned into a historic channel through the center of the wetland. The channel realignment altered surface water flow paths and decreased surface water-groundwater exchange.

Introduction

Wetlands provide valuable ecosystem services by facilitating processes like water filtration, oxygen cycling, fine sediment storage, flood peak attenuation, nutrient cycling, and they support diverse ecological communities. These processes occur when water is temporarily stored within the floodplain, delivered through either overbank flooding or subsurface flow paths. During the past 200 years, increased human activity and land use changes have reduced total wetland area in the continental United States by more than half. High elevation wetlands, which are delicately sustained by during short growing seasons, are especially vulnerable to degradation. In response, river and wetland restoration has become increasingly popular in the United States.

In Rocky Mountain National Park (RMNP), a 2003 debris flow eroded 36,000 m^3 of sediment from the hillslope below Grand Ditch, an earthen water diversion structure. The debris flow scoured channels, deposited up to a meter of sediment at the head of Lulu City wetland ~2 km downstream and altered the course of the Colorado River through a west channel. In 2015, RMNP completed restoration work to divert and realign a portion of the Colorado River as it flows into Lulu City wetland (Realigned Reach; Figure 1). The primary goal of the restoration was to restore the wilderness character and natural self-sustaining functioning of the affected system. The main goal of the research was to assess the effects of the channel

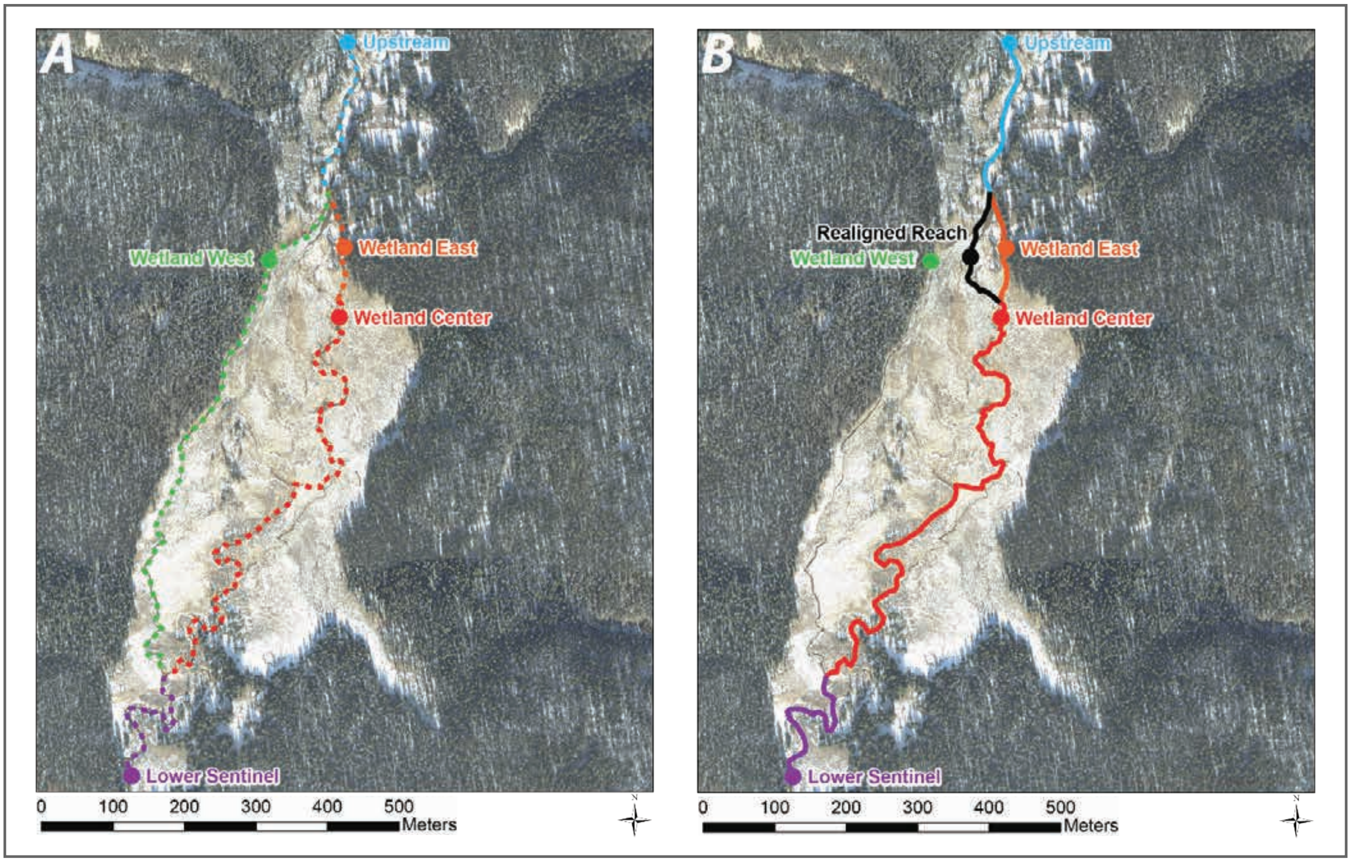

Figure 1. Measurement site locations and major stream flow paths through Lulu City wetland, Rocky Mountain National Park Colored circles indicate discharge and surface conductivity measurement locations. Colored streamlines indicate major flow paths through Lulu City wetland. Panel A: Pre-realignment (2015) flow paths. Panel B: post-realignment (2016) flow paths. Note the straight, western flow path (green dashed line) compared to the sinuous center flow path (red solid line).

restoration on a variety of channel and wetland hydrogeomorphic functions, focusing on two objectives including: 1) the surface flow redistribution and 2) surface water-groundwater exchange within Lulu City wetland.

Methods

A series of replicate measurements were collected throughout Lulu City wetland under similar environmental conditions in 2015 (pre-restoration) and 2016 (post-restoration) to assess the effects of the channel realignment. To address objective (1), hydrographs (flow discharge through time) were used to characterize changes in flow redistribution throughout Lulu City wetland. To address objective (2), a salt tracer injection test was paired with continuous surface conductivity measurements to quantify changes in surface water-groundwater interactions.

Hydrographs were calculated from discharge measurements collected weekly at six monitoring sites throughout the wetland (Figure 1). Average daily flow rates for the upstream and downstream (Lower Sentinel; Figure 1) sites were extracted from hydrographs and normalized by drainage area to produce comparable values. A daily discharge flux was calculated by subtracting the upstream daily flow rate from the downstream daily flow rate. This discharge flux provided an indication of how evapotranspiration and storage within the wetland changed as a result of the river restoration.

A salt solution, injected at the upstream site was used to elevate the conductivity of surface water above background concentrations, which allowed us to track the movement of water through the wetland. Continuous measurements of surface water conductivity at all downstream sites were used to calculate how much mass was stored within Lulu City wetland (Figure 1). Mass recovery through time, as represented by breakthrough curves, was used to evaluate the exchange behavior between surface water and groundwater.

Results and Discussion

Prior to channel restoration, two thirds of surface flow through Lulu City wetland was routed through a western channel underlain by permeable debris flow deposits (Figure 1). The remainder of flow was routed through a longer and more sinuous historic channel through the center of the wetland, underlain by less-permeable, fine-grained deposits. The channel restoration effectively rerouted all but the highest

Ed Ogle

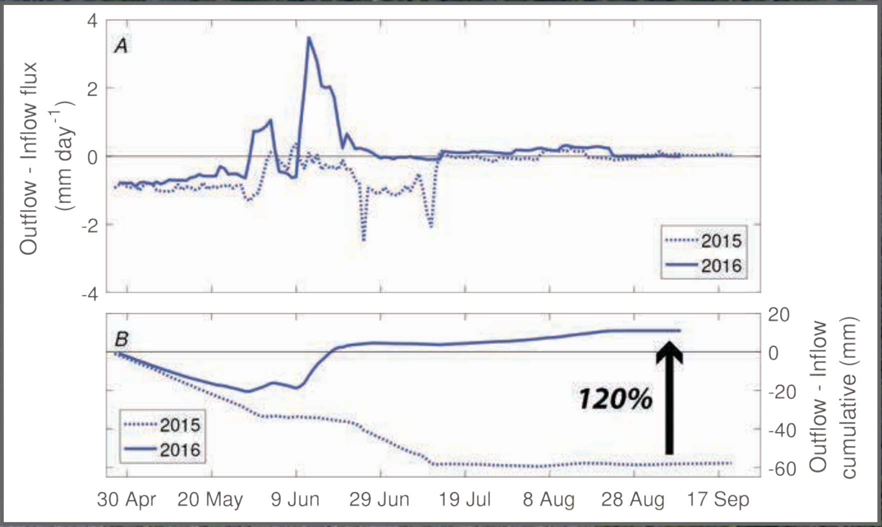

Figure 2. Discharge flux through Lulu City wetland.
Panel A: The daily discharge flux through the wetland was calculated for 2015 prior to restoration, and 2016 post restoration. The discharge flux provides an indication of wetland storage and evapotranspiration: negative values = more; positive values = less. Panel B: Cumulative discharge flux through the wetland increased by 120% between 2015 and 2016.

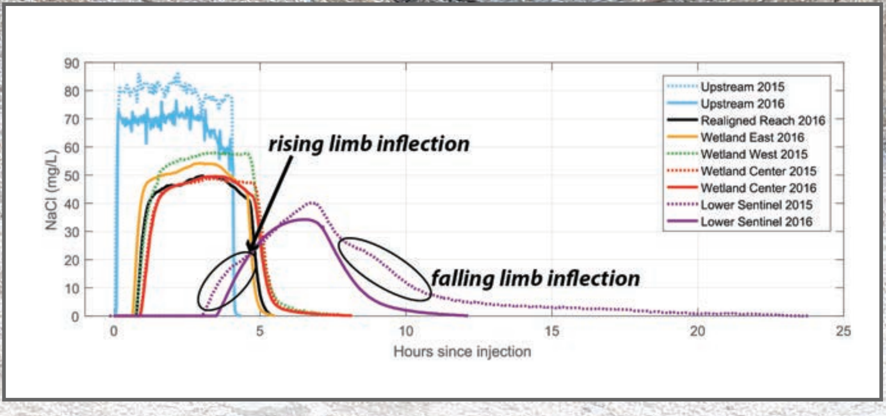

Figure 3. Surface conductivity breakthrough curves from salt tracer injection. Breakthrough curves from all study sites are listed in order of distance from the upstream site. Note Lower Sentinel rising and falling limb inflections present in 2015, but not 2016.

(Background Image) Grand Ditch. Rocky Mountain National Park, 2003

"After one year, this restoration project was effective at drying the west side of Lulu City wetland, as indicated by a **120%** decrease in discharge flux calculations"

flows through the center channel, resulting in a 48% decrease in flow through the west channel. The restoration also decreased the combined wetland flow paths by 650 m, which decreased the channel wetted perimeter (area in contact with flow) and open channel surface area by half.

The change in surface flow dynamics as a result of the restoration affected how and where water is retained within Lulu City wetland. Under the pre-restoration condition, the cumulative discharge flux indicated 58 mm of water was retained in storage or lost to evapotranspiration. Conversely, the discharge flux calculated over the same post-restoration time period indicated a gain of 11 mm water (Figure 2). Together these results indicate that less water was retained in the wetland through storage or lost to evapotranspiration as a result of channel restoration. Less storage means water was routed through the wetland more quickly, thereby limiting the beneficial ecosystem processes that require stored water.

The change in discharge flux through Lulu City wetland between 2015 and 2016 can be explained by channel changes that effectively routed all surface flow through one channel instead of two. Decreases in wetted channel perimeter and exposed water surface area lowered the total potential storage and evapotranspiration by 50%. The channel realignment also altered channel complexity through the wetland. Despite a longer flow path, the center channel facilitates less exchange between surface water and groundwater because of a comparatively fine-grained, impermeable bed. Prior to restoration, the coarse bed and steep slope of the then-active west channel facilitated stream water movement into longer subsurface flow paths, which may explain the water retention in Lulu City wetland in 2015.

Breakthrough curves from the wetland outlet indicate that along with a negative discharge flux (more water storage in the wetland), there was more surface water-groundwater exchange in 2015 than 2016 (Lower Sentinel; Figure 3). Inflections on both the rising and falling limbs of the 2015 wetland outlet breakthrough curve are distinctly absent from the same curve in 2016 - an omission that indicates differences in surface water-groundwater exchange dynamics between the two years. The rising limb inflection can be explained by the fact that in 2015 the west channel was the fastest flow path between the wetland inlet and outlet. The falling limb inflection indicates that a portion of tracer water was slowed during its travel to the downstream site prior to restoration, but not after. This can again be explained by the subsurface pathways that were accessed through the west channel and not the center channel.

Management Implications

The goal of the channel restoration in RMNP was to restore the wilderness character and hydrologic function of the affected Colorado River-Lulu City wetland system. The construction of a shorter, straighter, and less geomorphically-complex flow path that consolidated flow into the historic center channel with lower substrate permeability resulted in less surface water retained within the wetland. This loss of surface water-groundwater exchange pathways between the river and adjacent wetland is an important, and unintended, side-effect of a project that prioritized the restoration of form over function.

In this system, restoration guided by the belief that human-induced disturbance must always be reversed has limited the potential gains in wetland biodiversity supported by the hyporheic exchange pathways in the western channel. After one year, this restoration project was effective at drying the west side of Lulu City wetland, as indicated by a 120% decrease in discharge flux calculations. If this drying continues, the lowering of water tables will facilitate the encroachment of upland vegetation on the west side of the wetland and inhibit the growth of desired wetland vegetation. More intensive restoration is planned for Lulu City wetland to further enhance the hydrologic functioning of the wetland; however, constructed wetlands often do not provide the same level of ecosystem services as natural ones because of unintended disruption of key processes. Given the unique location of Lulu City wetland within a national park, this system may be an ideal setting in which to observe the natural river restoration process.

Matt Sparacino (right) and his advisor Sara Rathburn (left) measure discharge during 2015 high flow on the Upper Colorado River, Rocky Mountain National Park.

Rick Aster

Discussing Leadership at Water Tables 2017

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

Archivist Patty Rettig introduced the evening's theme "Refilling the Leadership Reservoir" by announcing the newest collection donation, the papers of former State Representative and Water Leader Diane Hoppe.

"Inspirational."

Use of this word to describe a dinner conversation indicates not only a special experience, but also a successful evening. This is just what Water Tables, a fundraising dinner for Colorado State University's Water Resources Archive, intends to provide.

The event, held January 26, 2017 in conjunction with the Colorado Water Congress annual convention at the Hyatt Regency Denver Tech Center, had as its theme "Refilling the Leadership Reservoir." Each of more than 20 tables was hosted by either an established or an emerging water professional selected for their leadership qualities. Hosts included Aspinall Award recipients, Water Leaders Program alumni, and other water experts from a variety of sectors.

The evening provided attendees the opportunity not only to network with water leaders, but also to engage in dinner conversations about leadership. As expected, each table had widely varying conversations. These ranged from the basics of educational preparation for water professions to more advanced topics like succession planning at water organizations.

The “inspiration” for some attendees came from listening to their table host’s past experiences, including successes and challenges. Table hosts shared sage advice for those navigating careers in Colorado’s water community. The advice included taking leadership classes, spending time on self-reflection to know your own strengths and areas for improvement, and staying open to input. The best leaders know themselves well and listen to others.

More than 20 companies and organizations sponsored the evening, with the platinum sponsor being the Colorado Water Conservation Board (CWCB). These sponsorships enabled 17 students—future water leaders—from Colorado State University, the University of Wyoming, and Metropolitan State University of Denver to participate.

The dinner raised $32,000 for the Water Resources Archive. These funds enable the Archive to employ student assistants who prepare collections for research use, to visit people with significant historical materials across the state, and to create outreach materials to raise awareness

Table 1 hosted by Nicole Seltzer, Science and Policy Manager at the River Network, had an engaging discussion about leadership transition.

Table host Travis Smith, Superintendent of the San Luis Valley Irrigation District, talked about challenges over the course of his career.

about archival services. The support of the water community allows all to discover and better appreciate the legacies created by water leaders of the past.

During the evening, archivist Patty Rettig announced the Archive's newest collection donation, the Papers of Diane Hoppe. This produced a round of applause for the well-known and accomplished water leader who passed away in February 2016. The papers documenting Hoppe's service both as a state representative and on many boards, including those of the CWCB and the Colorado Foundation for Water Education, were donated by her sons, who commented that "it was an honor" to be invited to have their mother's legacy preserved among those of other prominent water leaders at the Water Resources Archive.

The Water Resources Archive's next event, the Western Water Symposium and Barbecue, will be Monday, July 24. The day will feature thought-provoking speakers, networking opportunities, a barbecue lunch, and tours of the Archive. In combining looks at history and current events, undoubtedly more inspiration will arise.

For more information about the Water Resources Archive and its events, see the website (http://lib.colostate.edu/water/) or contact the author (970-491-1939; Patricia.Rettig@ColoState.edu) at any time.

Water Tables Committee Member David Stewart concluded the evening by thanking sponsors, hosts, and attendees.

Water Tables 2017 Sponsors

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Colorado Water Conservation Board

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"Citizen Science" at Work in Colorado

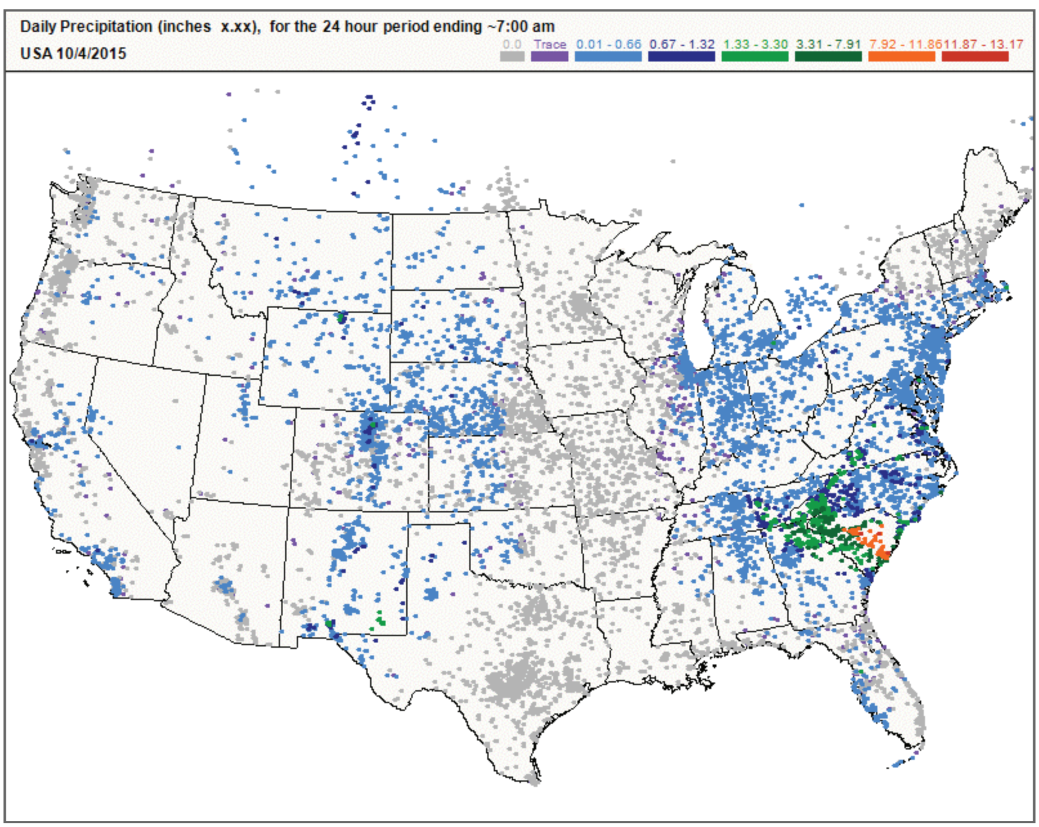
Noah Newman, Research Coordinator, CoCoRaHS Education Coordinator, Colorado Climate Center;
Nolan Doesken, Colorado State Climatologist, Colorado Climate Center

Introduction

Over time there have always been individuals fascinated about the world around them and commonly scientifically minded. Prior to the mid-1800s there were very few professional scientists. However, over time this has changed. As the 21st century progresses, there has been an increase in the number of individuals with professional degrees and more specifically increases in the number of scientists in a variety of fields including –medical professionals, physical scientists, chemists, biological engineers, environmental scientists, atmospheric scientists, and astronomers -- many of whom find professional jobs in the government and educational settings. There are also a plethora of individuals, both college educated and not, who are scientifically savvy, but may not commonly be known for their scientific curiosity and expertise simply based upon their profession. These individuals are located across different geographic landscapes and climates, with access to immense scientific knowledge at their fingertips. In addition, farmers are part of a community of unsung scientists with vast understandings of variable weather, phenological fluctuations, soil microphysics, microbiology, evolving insect populations, and chemistry.

NOAA

Volunteers observed temperature, precipitation, and sky conditions at a cooperative weather station in Granger, Utah, circa 1930.



Daily CoCoRaHS precipitation map from October 4, 2015. While most of the country reported measurements of less than ½ inch, floods battered South Carolina with some observers reporting over 12 inches of rain during the previous 24 hours.

"Citizen Science"

There is a term that describes the growing community of informal scientists around the world—“Citizen Science”. This refers to individuals around the world who have an interest in a field where their volunteer participation and collection of observations is advancing scientific research within their communities. Many “citizen scientists” may not be formally educated in a particular sub-set of science, commonly are not paid for their work, but their contribution to the collection of data is priceless.

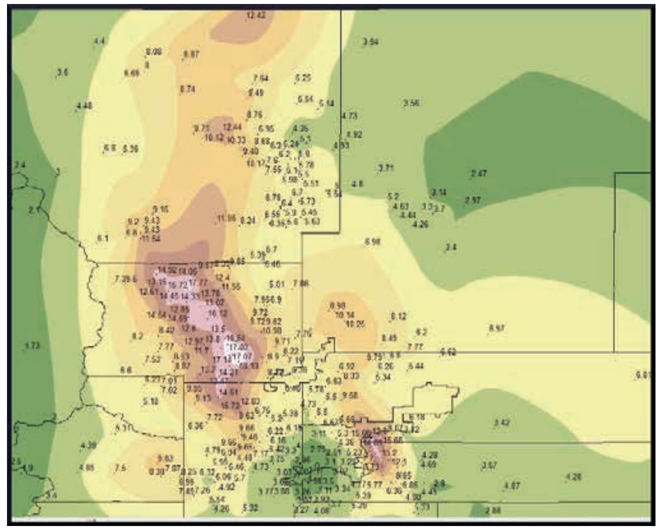
Over the last 20 years, the field of “citizen science” has seen tremendous growth which can be attributed to technological advancements and the importance of the Internet. Also, the sudden potential for tens of thousands of individuals to contribute meaningful and sometimes actionable data for the greater good becomes a reality for scientists who would never have been able to collect such vast amounts of data in the past. Now, matchmaking platforms exist where interested volunteers can select from thousands of projects depending on the area they live and what they are interested in doing (https://scistarter.com/). As technology progresses, some projects require volunteers to analyze data and photographs from their computers. In these instances, the projects would have never been accomplished without the help of committed volunteers. Some projects entice volunteers by making it into a game featuring points, badges, and leaderboards (http://www.npr.org/2014/05/05/309694759/computer-game-aides-scientist-mapping-eye-nerve-cells). In addition, many projects by “citizen scientists” have produced published research and advances to their fields (https://www.engadget.com/2016/09/19/gamers-beat-scientists-to-protein-discovery/). Also, if an individual has an idea for their own project, there are platforms for creating their own customized “citizen science” programs (http://www.citsci.org/). This was developed right here at Colorado State University.

The Crowd and the Cloud

A four-part series now featured on public television in the U.S. describes the history and advancements in the field of “citizen science”. Highlighting several projects around the world, former NASA Chief Scientist Waleed Abdalati hosts “The Crowd and the Cloud”, showing how the advancements in technology and increased access to mobile phones and the Internet have allowed “citizen scientists” to help make rapid advances in science. All four episodes will air on local PBS channels. Check your local listings or they can be viewed online at http://crowdandcloud.org/watch-the-episodes/episode-one.

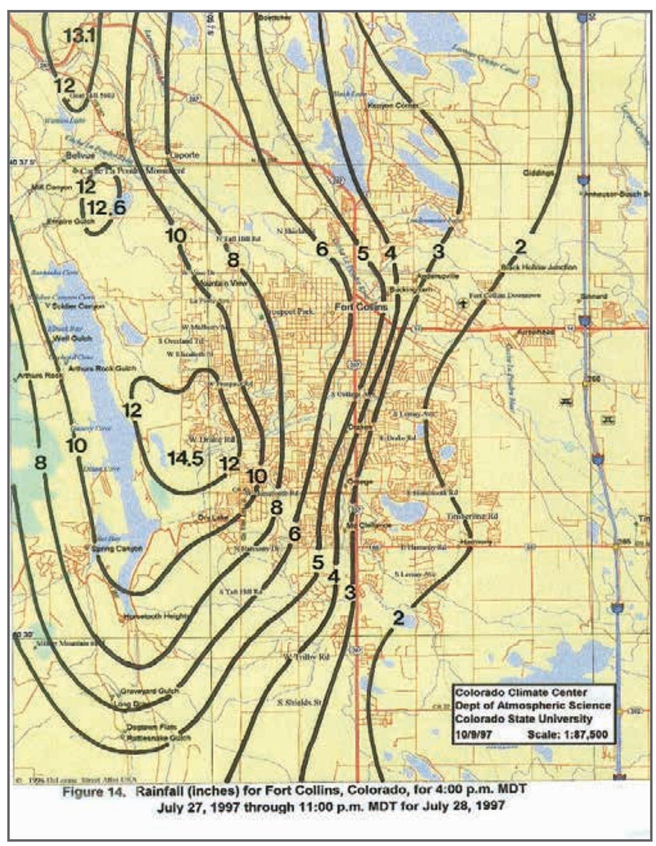
Weather and Climate Benefits from “Citizen Science”

Colorado and the Colorado Climate Center have benefited from “citizen science”. While a portion of our historic weather data that we use to assess patterns in the climate has come from professional meteorologists, the majority of the data stems from a set of vital volunteers -- especially over Colorado’s large rural and remote landscapes. Some weather stations have been maintained over 50 years by dedicated local volunteers. For example, the “Leroy” weather station in southern Logan County has been kept in the same family



Courtesy of the National Weather Service—Boulder

2013 storm rainfall totals were gathered from NWS COOP, CoCoRaHS, SNOTEL, RAWS, alert reports, and spotter reports. The map highlights Boulder and Aurora, Colorado as the heaviest hit spots, with Aurora totals between 10 and 15 inches and many areas in Boulder over 15 inches.



Rainfall (inches) for Fort Collins, Colorado, July 27-28, 1997.

since the late 1800s. The origins of the National Weather Service (NWS) Cooperative Weather Observer Network dates back to the mid-1880s and it still continues today. This humble program has provided an incredible wealth of data for tracking both recent and historic weather and climate across every county of Colorado and the entire U.S.

Would You or Someone You Know Like to Help?

Despite having thousands of volunteers, we are still in need of additional volunteers. Our goal is to have at least one volunteer per square mile throughout the urban and suburban parts of Colorado. This entails ideally having at least one volunteer every 36-50 square miles, especially in sparsely populated rural areas. To reach this goal, we ask for your help and please consider joining CoCoRaHS today! If you work for a business that needs precipitation data, consider sponsoring CoCoRaHS. Help us do a better job analyzing and mapping water resources.

NOAA

Over 11,000 volunteer citizens across the country take daily weather readings as part of the Cooperative Observer Network Program, helping to build and maintain the cornerstone of our nation's climatological record. Officials estimate that volunteer observers contribute over one million hours of service per year.

Aditi Bhaskar

Aditi Bhaskar, Assistant Professor, Civil and Environmental Engineering

I joined the faculty of the Department of Civil and Environmental Engineering at Colorado State University (CSU) in August 2016. My focus is on changes to hydrologic systems resulting from urban and suburban growth. In urban areas, water in engineered systems (drinking water and landscape irrigation, wastewater, and stormwater) directly interfaces with water in "natural" systems (rivers, groundwater, and evapotranspiration). This direct interaction between engineered and natural water underlines the importance of considering holistic water system changes resulting from urbanization.

I grew up in a Maryland suburb of Washington D.C. and received my Bachelor's degree in Geophysics from Brown University in Providence, Rhode Island. I went back to Maryland to receive my Ph.D. in Environmental Engineering from University of Maryland, Baltimore County. During graduate school, I was a trainee of the National Science Foundation Integrative Graduate Education and Research Traineeship (NSF-IGERT) in "Water in the Urban Environment". This traineeship emphasized the interdisciplinary nature of urban water challenges and solutions through exposure to students, projects, and courses from other disciplinary perspectives. After my Ph.D., I was awarded a NSF Earth Sciences Postdoctoral Fellowship, which took me to the U.S. Geological Survey (USGS) in Reston, Virginia, before I joined CSU.

My past work has been focused on hydrology in Baltimore and suburban Washington D.C. I have examined changes in the overall water budget, stream flow, base flow, groundwater-surface water interactions, subsurface storage, and water table fluctuations resulting from various processes of urbanization. These urban processes have included increasing imperviousness, managed infiltration of stormwater, water imports and exports, leaky water distribution and wastewater infrastructure, lawn irrigation, and changes to vegetation and evapotranspiration. The methods I have used to address these questions have ranged from integrated groundwater-surface water modeling to field data collection to analysis of remotely sensed datasets.

A recent project examined a watershed-scale implementation of green infrastructure, a type of stormwater management that uses distributed infiltration of stormwater. I found that both total flow and low flow in the stream rose during urbanization in our Clarksburg, Maryland study watershed, as vegetative cover decreased and as pre-development evapotranspiration became stormwater infiltration through green infrastructure.

In my transition to the Colorado Front Range, I am now turning my attention to challenges in this area associated with urban expansion and effects on water. I aim to consider effects on downstream flow regime, low flows, water availability, water use, water quality, and water budgets as urban areas in the Front Range grow, especially in agricultural to urban conversions.

I teach courses at both undergraduate and graduate levels in Civil and Environmental Engineering. In the fall, I teach an upper-level undergraduate course that focuses on nonpoint source pollution. This course examines urban runoff, agriculture, and mining influences on water quality as well as structural and non-structural management practices for control of nonpoint source pollution. A graduate class I will teach next spring will focus on urban water systems including stormwater modeling and management. I look forward to developing partnerships to address water issues in my new home of Colorado.

Aditi Bhaskar
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Civil and Environmental Engineering
Colorado State University
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Water Calendar

June

11-14 Annual Conference & Exposition: Uniting the World of Water; Pennsylvania, PA
Join the American Water Works Association to learn more about the world of water.
awwa.org/conferences-education/conferences/annual-conference.aspx

12-14 Nutrient Symposium 2017; Fort Lauderdale, FL
As the wastewater industry encounters significant changes, researchers work with practitioners and operators to form innovative solutions.
wef.org/Nutrients/

13-15 Universities Council on Water Resources/ National Institutes for Water Resources Conference; Fort Collins, CO
This joint-annual conference offers the opportunity for participants to learn how water is constantly changing the environment.
ucowr.org/conferences/2017-ucowr-conference

14-16 Water History; Grand Rapids, MI
This conference will examine the history of water, including rivers, rain, oceans, and lakes.
iwha.net/conference/date-and-location

27-29 One Water Summit; New Orleans, LA
Participate in a national summit regarding the sustainability of water in the future.
uswateralliance.org/summit/one-water-summit-2017

July

23-27 IWA International Conference on Water Reclamation and Reuse; Long Beach, CA
This event supports the advancement and development of water reuse around the world.
iwareuse2017.org/

August

23-25 Colorado Water Congress Summer Conference; Vail, CO
This high-energy conference is packed with great topical content and a great opportunity for those who wish to stay informed about water issues in Colorado.
cowatercongress.org/summer-conference.html

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

Trout Lake
Telluride, CO

Alex Berger

Water Research Awards 2/10/17 — 7/1/17

Bailey, Ryan T., USDA-NIFA National Institute of Food and Agriculture, Improved Modeling Framework for Assessing Phosphorus and Nitrogen Transport in Tile-Drained Watersheds, $497,500

Hoag, Dana Loyd Keske, Washington State University, High Efficiency Sprinkler Irrigation in the Lower Arkansas Valley, Colorado: Balancing Economic Risks of Adoption with Pollution Risks from Not Adopting, $48,398

Manning, Dale Thomas, Purdue University, Borlaug Fellowship—Aaron Hrozencik: Evaluating a Water Conservation Text Messaging Service in Moulouya River Basin, $24,081

Rathburn, Sara L., City of Longmont, Post-Flood Sediment and Wood Flux into Ralph Price Reservoir, North St. Vrain Creek, CO, $47,136

USGS Recent Publications

The U.S. Geological Survey Monthly Water Balance Model Futures Portal, 2017, U.S. Geological Survey Fact Sheet 2017–3002, 6, A.R. Bock

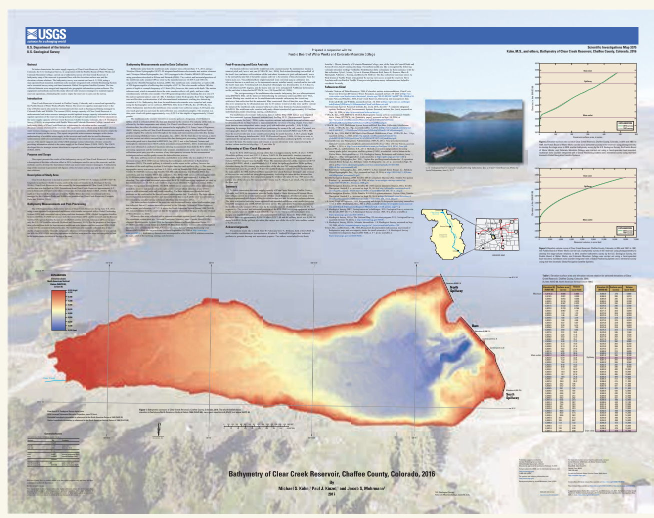
Bathymetry of Clear Creek Reservoir, Chaffee County, Colorado, 2016, 2017, U.S. Geological Survey Scientific Investigations Map 3375, 1 sheet, M.S., Kohn, P.J. Kinzel, and J.S. Mohrmann

Gridded bathymetry data of Clear Creek Reservoir, Chaffee County, Colorado, 2016, 2017 U.S. Geological Survey data release, M.S. Kohn

Effects of internal phosphorus loadings and food-web structure on the recovery of a deep lake from eutrophication, 2017 Journal of Great Lakes Research, v. 43, issue 2, p. 255-264, F. Lepori, and J.J. Roberts

Nonnative trout invasions combined with climate change threaten persistence of isolated Cutthroat Trout populations in the southern Rocky Mountains, 2017, North American Journal of Fisheries Management, v. 37, issue 2, p. 314-325, J.J. Roberts, K.D. Fausch, M.B. Hooten, and D.P. Peterson

A software tool to assess uncertainty in transient-storage model parameters using Monte Carlo simulations, 2016, Freshwater Science, v. 36, 195-217, A.S. Ward, C.A. Kelleher, S.J.K. Mason, T. Wagener, N. McIntyre, B. McGlynn, R.L. Runkel, R.A. Payn



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U.S. Fish and Wildlife Service Headquarters

Great Spring Creek, Great Sand Dunes National Park and Reserve