Colorado Water

January 2022

COLORADO WATER CENTER

RESEARCH REPORTS

COLORADO STATE UNIVERSITY

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On the cover—The White River photographed near Meeker, Colorado. See page 35 to read about research being conducted in the watershed by Jessica Sanow and Dr. Steven Fassnacht. Photo © adobe.stock.com.

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

References can be found in the online version of this newsletter at watercenter.colostate.edu/water-news

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Director's LETTER

Jennifer Gimbel, JD

Welcome to the Colorado Water Center's annual newsletter highlighting fifteen current research and investigations into issues important to the sustainability of water around the world. The Water Research Awards section highlights over 125 CSU research projects around water are noted and over $12 million of research grants. The list inspires faculty and students, post-graduate, graduate, and undergraduate, to continue their work and explore the implementation of the results for the benefit of a sustainable water supply for people, agriculture, recreation and the environment. This newsletter provides a glimpse into a few of those projects funded through the Colorado Water Center.

Last fall saw horrific wildfires here in Northern Colorado. The effect of those wildfires on water supply is well documented: water quality degradation, flood events, debris flows and much more. Still, how to re-establish the destroyed ecosystem is important to understand. One research project looks at ecosystem control points for post-fire transport of sediment and other constituents into the Rocky Mountain headwaters. The South Platte River is the focus of a couple of projects researching its riparian ecosystem and streamflow depletion due to groundwater pumping. An agricultural research project suggests a cost-effective tile-drainage system to manage water quality impacts. The Yampa River and White River watersheds are featured in studies on floodplain management and the effects of snow depth on snow surface roughness. Research in the Saint Vrain and Big Thompson watersheds discusses ecosystem sustainability. Please sit back, put your feet up and enjoy reading about some of the latest research.

Jennifer Gimbel, JD

Interim Director, and Senior Water Policy Scholar, Colorado Water Center

The Water Research Awards section of this newsletter highlights over 125 CSU research projects around water and over $ 12 million of research grants.

Post-fire ecosystem recovery research (top) is highlighted on page 10 of this issue. Photo courtesy of the U.S. Forest Service/USDA. A fire (below) burns near Twin Lakes, Colorado. Photo Tony Webster /Wikimedia Commons.

Toward Understanding the Global Impacts of Human Activities on Floodplain Integrity

Dr. Ryan Morrison, Assistant Professor, Civil and Environmental Engineering, Colorado State University, **Dr. Adnan Rajib**, Assistant Professor, Environmental Engineering, Texas A&M University, **Dr. Antonio Annis**, Research Assistant, Water Resources Research and Documentation Center, University of Foreigners of Perugia, **Dr. Fernando Nardi**, Associate Professor, Hydrology, University of Foreigners of Perugia, Director, Water Resources Research and Documentation Center, **Dr. Heather E. Golden**, Physical Scientist, U.S. Environmental Protection Agency, **Dr. Qiusheng Wu**, Assistant Professor, Geography, University of Tennessee, **Dr. Charles R. Lane**, Research Ecologist, U.S. Environmental Protection Agency, and **Kira Simonson**, Master's Student, Civil and Environmental Engineering, Colorado State University

Floodplains are Imperiled

Riverine floodplains are vital and productive ecosystems that provide essential biological, geomorphic, and hydrologic functions. Services provided by floodplain—including regulation of disturbances (e.g., flood attenuation), water supply, and waste treatment—are valued at approximately US $\$1.5 \times 10^{12}$ per year globally (in 2007 US$). Yet floodplains are continually threatened by human development and encroachment, including loss of floodplain-river connectivity due to channelization and levee construction, which exacerbates habitat loss and hydrologic alteration.

Human modifications to floodplains include changes in land use from activities such as urbanization, agriculture, industry, and mining. For instance, approximately 80-90% of floodplains across Europe have been intensively cultivated, and 90% of floodplains in North America are non-functional due to cultivation. New developments in floodplains expose an increased population in the U.S. to flooding, and even a 1% chance of flooding can cause losses exceeding $78 billion per year in the U.S.

Flood-risk management efforts of the previous century have focused on minimizing flood impacts on humans through large and expensive infrastructure projects at the expense of floodplain ecosystem health and resilience. However, floodplain buyouts and conservation programs can produce co-benefits for economies and floodplain ecosystems. Still, they require a comprehensive understanding of the history of floodplain changes along the full river continuum to ensure sustainable and effective floodplain and flood-risk management.

Figure 1. Antonio Annis (Univeristà per Stranieri di Perugia) and Dr. Ryan Morrison in Fort Collins, CO. Ryan has been working with researchers in Italy to understand changes in floodplain ecosystems since 2015. Photo by Ryan Morrison.

Despite the human-induced changes in floodplains over the past century, comprehensive data of long-term land-use change within floodplains of large river basins are limited. No studies have attempted to identify floodplain regions at large scales and integrated long-term (>30 year) data to examine changes in floodplain land use across a large river basin. Data of long-term and large-scale floodplain land use are required to effectively quantify floodplain functions and development trajectories and for a holistic perspective on the future of floodplain management and restoration and concomitantly flood-risk mitigation.

Old and New Project Goals

When I was awarded this Water Fellow grant, I intended to host an international workshop at the Water Resource Research and Documentation Centre (WARREDOC; warredoc-unistrapg.org/en/) in Perugia, Italy. The workshop would leverage the strong collaborations developed with researchers at the Univeristà per Stranieri di Perugia (Figure 1) to gather a global dataset that would help me evaluate the degradation of floodplains worldwide. However, the COVID-19 pandemic derailed these plans.

Therefore, I shifted my Water Fellow research goals to focus on 1) assessing floodplain changes in the U. S. (rather than globally) and 2) participate in a new effort to evaluate long-term datasets of floodplain land use with the help of international researchers. These goals were still important for the overall intent of my Water Fellow award—understanding the extent of human influence on floodplain functionality so that we can better manage and preserve floodplain ecosystems. These goals were achievable through coordination and collaboration via Zoom with Dr. Fernando Nardi and Dr. Antonio Annis from WARREDOC. Other collaborators included Dr. Adnan Rajib (Texas A&M University; lead author on the new study), Dr. Heather Golden (U.S. EPA), Dr. Charles Lane (U.S. EPA), Qianjin Zheng (Texas A&M University), Dr. Quisheng Wu (University of Tennessee), and Dr. Jay Christensen (U.S. EPA).

The Missouri River, a tributary of the Mississippi River, pictured in South Dakota. Photo ©Patrick Ziegler/stock.adobe.com.

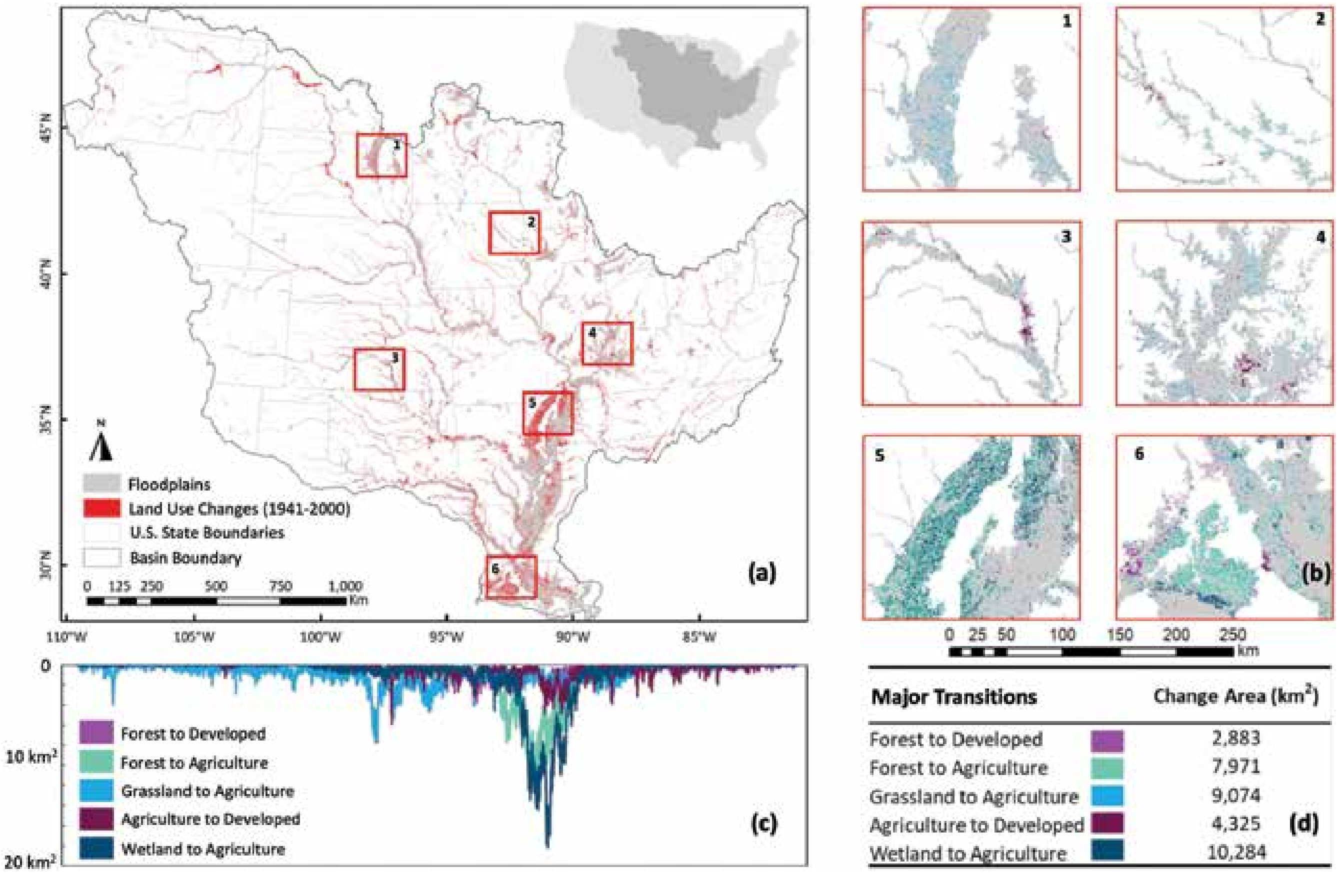

Figure 2. Land-use change in the Mississippi River Basin (MRB) floodplains between 1941 and 2000. (a) The "change" in this map is defined as the non-uniqueness of individual land use grid cells between the two end years. (b) The maps 1-6 correspond to six objectively chosen domains across different geophysical settings and stream orders in South Dakota (1), Iowa (2), Kansas (3), Indiana (4), Arkansas (5), and Louisiana (6). Plot (c) graphically shows how the five major potentially irreversible land transitions vary along the latitude at every 250-m horizontal resolution. Plot (d) summarizes the areal extent (km²) of change between 1941 and 2000. Figure by Adnan Rajib.

Mississippi River Basin Floodplain Land Use

What emerged from this collaboration is the first long-term dataset illustrating the drastic changes in floodplain composition throughout the Mississippi River Basin (MRB) during the past 60 years.

The MRB covers 41% of the U.S. and, with a drainage area of over 3,288,000 km², is the fourth largest river basin in the world. As such, floodplains in the MRB have supported important ecosystem services for much of the U.S. However, the MRB is also one of the most engineered systems globally due to the vast numbers of levees, dams, and dikes constructed in the basin. Runoff with excessive nutrient concentrations caused by the combination of agriculture and urban development in the MRB is responsible for the expanding "dead zone" in the Gulf of Mexico.

The Missouri River (above), photographed in South Dakota, is the longest river in the U.S. and a tributary of the Mississippi River. Runoff with excessive nutrient concentrations in the 3,288,000 km² drainage area of Mississippi River Basin is responsible for the expanding "dead zone" in the Gulf of Mexico. Photo ©Patrick Ziegler/stock.adobe.com.

Using remote sensing data, land cover data, and a new 250 mresolution global floodplain dataset (GFPLAIN; github.com/fnardi/GFPLAIN), the collaborative team, led by Dr. Rajib, evaluated how floodplain land use (e.g., forest, wetlands, agriculture, development, etc.) has changed in the MRB between 1941 to 2000. The floodplain area in the GFPLAIN dataset represents the flood-prone regions implicitly identified through analyses of digital elevation models (likely less than the 500-year flood event but greater than the 100-year flood event). The team used the National Land Cover Databased and 30 years of LANDSAT imagery to classify land types in the MRB into the following categories: open water, developed area, barren land, forest, grassland, agriculture, and wetland. Finally, using a combination of transition matrix analysis and statistical approaches, we detected changes in land cover within the floodplains and developed "nature of change" matrices for every remote-sensing pixel. As expected, analyzing this vast amount of historical data requires powerful computational systems, for which we used a custom code in Google Earth Engine.

Our results highlight the spatial and temporal extent of land use changes within floodplains of the MRB, specifically the expansion of agricultural and developed land since 1940 (Figures 2 and 3). More than 10,000 km² of wetland habitat and 8,000 km² of forested land have been lost during the same time period due to agricultural growth (Figures 2 and 3). These irreversible transitions in floodplain composition reduce storage and conveyance of natural flow, amplify flood risks posed by climate change, and hinder ecosystems and human well-being.

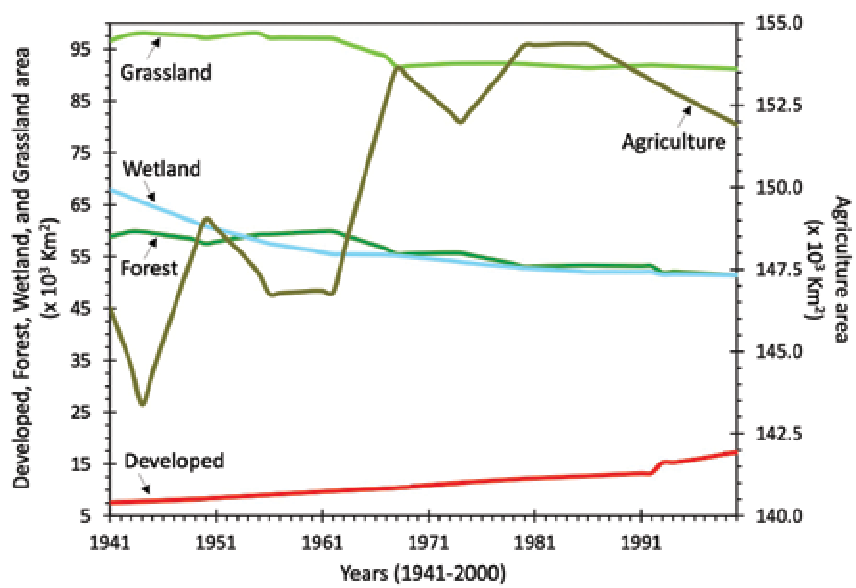

Figure 3. Time-series graphs showing 60 years (1941-2000) of continuous changes in different land-use classes. Figure by Adnan Rajib.

Data Availability for Floodplain Management

The 60 years of floodplain changes we illustrate in our data may be useful for guiding floodplain management in the MRB. A recent strategic plan of the Upper Mississippi River Restoration partnership, representing 0.5 million km² of the MRB, envisions "a healthier and more resilient Upper Mississippi River ecosystem that sustains the river's multiple-use," and can use our datasets to understand where floodplains have been most impacted by human development. Furthermore, as the first long-term dataset on floodplain changes in the U.S., our methods can be used to study other river basins in both the U.S. and globally.

Finally, we have made our data freely available through HydroShare, a public repository for water-related datasets. The data can be found here: doi.org/10.4211/hs.41a3a9a9d8e54cc68f131b9a9c6c8c54. Also, the changes illustrated in Figure 2 can be further visualized at this interactive map interface: gishub.org/mrb-floodplain.

Along with the data that comprises our results, we also provide an online tutorial with visualizations, facilitating classroom code applications and an instructional video demonstrating code application and database reproduction.

Integrating Low-Technology Process-Based Restoration Techniques to a Degraded Perennial Stream System: A Community-Driven Research Model

Blake Osborn, Water Resource Specialist, Colorado Water Center and **Dr. Luke Javernick**, Executive Director, River Science

Background

Colorado's streams and rivers are often central figures in our state's economy, history, and identity. These natural waters have inspired a new branch of legal doctrine, are stretched to meet the demands of our economies, support thriving ecosystems, and provide inspiration to us all, regardless of perspective. Our diverse state (economically, ecologically, climactically, etc.) helps shape our streams and rivers into place-based features that often support multiple uses or multiple benefits. However, one thing all our unique streams, or even segments of the same stream, have in common is that each one is managed for different outcomes.

There are many factors, including locations and intended uses that help determine these different management strategies. For example, some streams contain rare or important riparian species and are managed for conservation values. Yet other streams are vital engines for land uses that provide food, fiber, or other goods. Some streams are important for recreational and scenic values. Fortunately, it is increasingly common to find collaborative management plans or activities that recognize the importance of achieving multiple desired outcomes.

Today, many community organizations, private landowners, and government agencies are finding value in restoring riverine systems that historically have been managed for other uses. Low-techology and process-based (LT-PBR) stream restoration treatments are emerging as a viable stream restoration method to restore natural functions to stream systems that have historically been managed for uses other than ecosystem integrity. Examples of these LT-PBR methods include engineered log jams, post-assisted log structures, beaver dam analogs and many different "Zeedyk structures." This restoration philosophy is becoming more popular at a time when "over-engineering" streams are losing favor. There are several reasons for LT-PBR treatments gaining in popularity, including: 1) their relatively simple design and implementation, 2) their effectiveness at restoring natural stream functions, and 3) acceptance among both practitioners and academics. Although much of the hydraulic and fluvial impacts of LT-PBR methods are well documented (SITE), the hydrologic impacts of these treatments are relatively unknown. This project engaged the local community to fund and implement LT-PBR treatments to better understand the complex hydrologic and ecological impacts.

Project Rationale

This project is centered on LT-PBR methods and their impacts on the local hydrologic systems. However, we expanded beyond the singular goal of assessing LT-PBR methods. The project team developed three main objectives for this project, including: 1) educate and train students and water professionals in natural river processes and restoration techniques, 2) improve hydrogeomorphic conditions of a roughly two-mile degraded stream system of Oak Creek, and 3) provide information to state water managers on the impacts of process-based restoration on stream system hydrology.

Outreach and Engagement

Many resources on LT-PBR exist (CITE), which help conservation practitioners and researchers identify potential benefits from implementing LT-PBR treatments. However, more training is needed to properly identify, construct, and maintain LT-PBR structures in the field. This project intended to engage two specific audiences, current and next-generation water professionals.

Improve Conditions

Oak Creek is a typical foothills watershed. The stream begins in higher elevation, steeper terrain and descends to meet the rolling plains in lower elevation, shallower topography before it converges with the Arkansas River. The watershed has increasing development pressure and changes in land and water uses over the past 10-25 years, and hydrologic changes likely stemming from prolonged drought and other environmental factors. The creek is considered ephemeral and highly incised throughout many areas of the foothills/plains transition. The opportunity exists to expand the primary floodplain and reconnect the surface/groundwater recharge dynamics.

Drilling shallow alluvial groundwater wells. Photo by Blake Osborn.

Georeferenced orthomosaic and digital surface m-sodel. Photo by Blake Osborn.

Provide Information

This study will provide needed information for local and state water administrators on how LT-PBR systems may affect local hydrology. The information will be presented as a process model for implementing and maintaining LT-PBR structures and data and other products relevant to water administration.

Methods

Community Outreach and Engagement

This project relied on several local partnerships to develop, train, and fund this Phase 1 work. First, we developed and implemented a new honor's level high school course at Canon City High School. The class, called River Science, used this project as the field laboratory. Unfortunately, COVID-19 protocols and periodic school closures limited our ability to implement field treatments. However, students did make two trips into the field and learned about LT-PBR methods while working remotely. Likewise, we expected to host a field day for water and conservation professionals in April 2021, but this activity was canceled because of COVID-19 protocols.

Implement LT-PBR Treatments

This project can only proceed at the speed and scale of expected hydrologic changes. Some conditions may change instantaneously after treatment implementation (sediment aggradation), while some may take years (aquifer recharge). For this reason, this study is divided into three phases. The current activities were part of Phase 1 and allowed the project team to collect baseline field data, including survey data to document geomorphic and topographic conditions. Baseline geomorphic and topographic data were collected using Structure from Motion techniques and a DJI Mavic drone. Images were processed using Pix4D software. Orthoimages and a Digital Surface Model were used in delineating existing geomorphic conditions and identifying LT-PBR treatment areas. We also installed six piezometric monitoring wells perpendicular to the stream to monitor groundwater levels.

Results and Impact

Seventy-one locations were identified for LT-PBR structures based on geomorphic analysis of the digital surface model. The most appropriate LT-PBR methods for this stream reach include mid-channel, bank attached, and channel spanning Post-Assisted Log Structures (PALS) as well as Beaver Dam Analogues (BDAs). It is expected that these structures will be built in 2021/22. To date, piezometer wells have not yielded any data. We expect groundwater levels will not rise until LT-PBR treatments are implemented. The treatments will be partially installed and monitored by students in the River Science course at Canon City High School.

Blake Osborn teaches students about geomorphic processes using a physical floodplain model. Photo by Carrie Trimble.

The most significant Phase 1 outcome is the development of the partnerships to create and implement this project. Despite setbacks from the COVID-19 pandemic, the project moved forward with the assistance of many local partners. First, the students and administration at Canon City High School provided technical and financial assistance. Several local businesses and individuals supported this project as a teaching tool for training students practical with workforce skills. This project was also supported by two local non-profits and the gracious private landowner that we work with to test methods and teach students. All this momentum has built a surging awareness within the local community of the importance of healthy rivers and streams, local training and workforce development, and complex issues around stream restoration and impacts on other water uses.

Conclusions

Much work remains to answer the questions of how LT-PBR methods may impact reach scale ground and surface water dynamics at our study site. However, Phase 1 of this project has been successful in developing a unique process-model that integrates applied research and workforce training. The high school class, River Science, will continue, and the class curriculum is set to expand to other schools across the state.

Future Research

Funding has been secured through the Colorado Water Conservation Board for Phase 2. This next phase of the project will be led by the non-profit organization River Science. Future research plans include continued monitoring of surface and groundwater interactions/movement after installation of LT-PBR treatments and analysis of water rights under different flow conditions.

Students learn about geomorphic and biological assessments and data collection along Oak Creek. Photo by Carrie Trimble.

Acknowledgments

Financial and technical support from the Colorado Water Center is greatly acknowledged. Funding also came from local Fremont County businesses and individuals. This work would not have been successful without the support of Canon City High School, specifically Bill Summers and Carrie Trimble, as well as support from two local non-profits, the San Isabel Land Protection Trust and River Science. Finally, the partnership with Lynn and Judie VanNorman made this project possible.

Colorado State University Mountain Campus photographed in 2005. Photo by Runner1928/Wikimedia Commons.

Building a Long-Term Watershed Research Site at the Colorado State University Mountain Campus

Kira Puntenney-Desmond, Research Associate, Ecosystem Science and Sustainability, Colorado State University, **Dr. Sara Rathburn**, Associate Professor, Geosciences, Colorado State University, **Dr. Michael Ronayne**, Associate Professor, Geosciences, Colorado State University, **Jens Christoph Suhr**, Masters Student, Geosciences, Colorado State University, **Dr. Stephanie Kampf**, Professor, Ecosystem Science and Sustainability, Colorado State University, **Dr. Steven Fassnacht**, Professor, Ecosystem Science and Sustainability, Colorado State University, and **Dr. Daniel McGrath**, Assistant Professor, Geosciences, Colorado State University

Introduction

The Colorado State University (CSU) Mountain Campus (formerly known as Pingree Park) was once a hub for research, with >45 Masters and Doctoral theses written about the area between 1962-1971. Situated at approximately 2,740 m between Comanche Peak Wilderness in the Roosevelt National Forest and Rocky Mountain National Park, the campus is well-positioned for interdisciplinary research focused on hydrology, geology, snow, and climate. The South Fork Cache la Poudre River (South Fork), a vital tributary to the Cache la Poudre River, flows through the valley where the campus is located. While the CSU Mountain Campus has long been an area of inquiry and educational exploration, streamflow and weather monitoring within the South Fork Watershed has been limited over the past few decades. With support from the Colorado Water Center, Office of the Vice President for Research, and the Warner College of Natural Resources, at CSU the campus is being re-instrumented to support a new era of research. In 2020, an interdisciplinary team of CSU researchers strategically expanded the growing network of hydrologic and meteorological instrumentation. Here we summarize the monitoring network and highlight research conducted during the 2020 field season that advances understanding of the valley hydrology through surface water and groundwater well monitoring, surficial geologic mapping, sediment coring, and geophysical surveys.

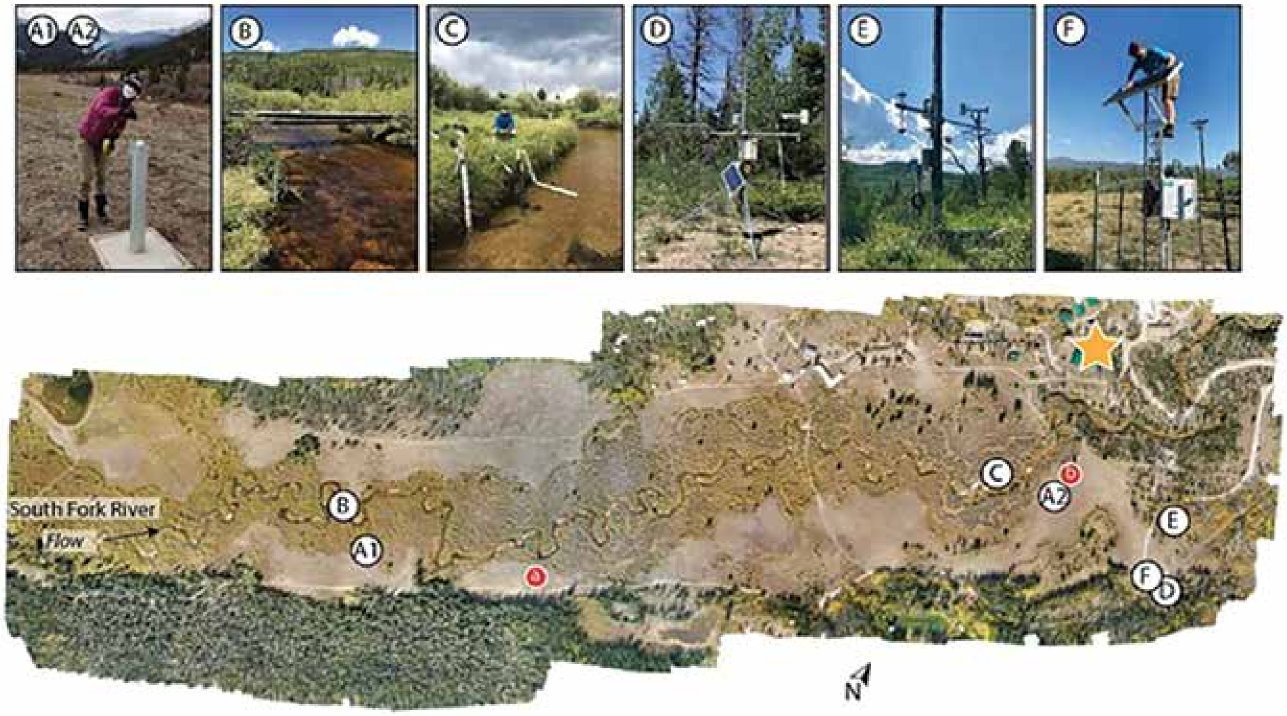

Figure 1. Established monitoring locations at the CSU Mountain Campus: A1. and A2. Deep groundwater wells (not telemetered, pictured: Valerie Doebley, MS Hydrogeology student); B. Upstream surface gage (not telemetered); C. Downstream surface gage (telemetered, pictured: Lucas Zeller, MS Geosciences student); D. Forest Weather Station (telemetered), E. Main Weather Station (telemetered); F. Seismic station (telemetered, pictured Hank Cole, MS Geosciences graduate). Telemetry base station (Research Building) marked with a star. General location of Figure 4 GPR transects marked with red circles.

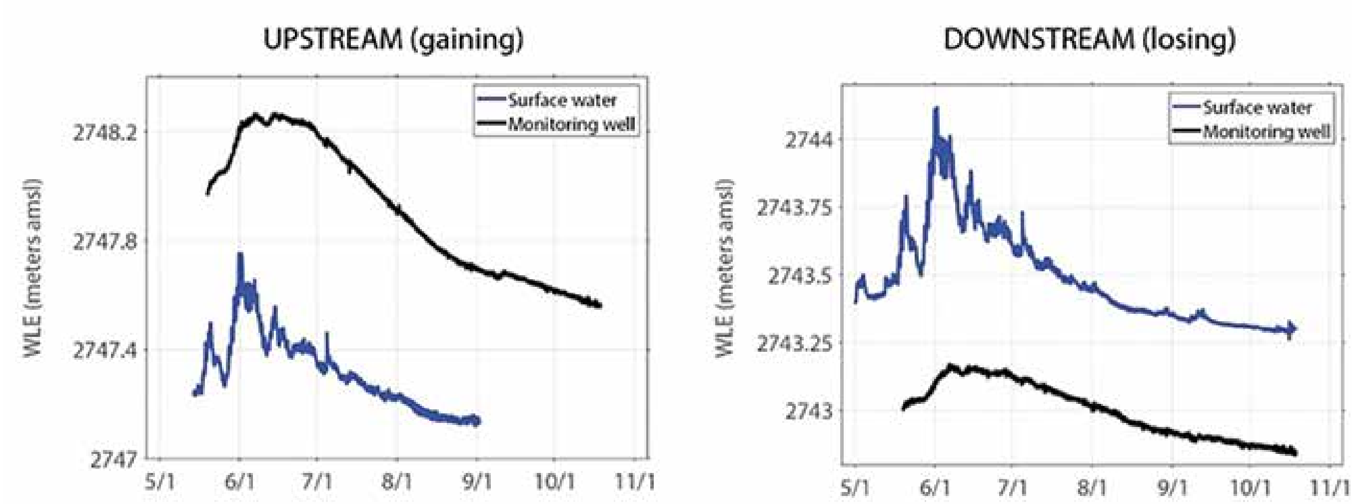

Figure 2. Water level elevation (WLE) was measured during 2020 at stream gages and co-located deep monitoring wells (locations shown in Figure 1) (M. Ronayne, unpublished data).

The Instrumentation Network

The vision for CSU Mountain Campus instrumentation was to initiate a long-term record of hydrological and meteorological data to serve as baseline data for future research and inquiry. A telemetered weather and river monitoring network was initially installed in 2018. Since then, the network has expanded to include two telemetered weather stations (main and forested locations), groundwater monitoring wells, two surface water gages (one telemetered, one seasonally logged), a precipitation gauge, a seismic station (in partnership with the Colorado Geological Survey), and a webcam (Figure 1).

Weather monitoring includes air temperature, relative humidity, wind speed, wind direction, radiation, snow depth, rainfall, soil moisture, soil temperature, and barometric pressure at two locations, one in the open and one in a nearby forested location. Stream monitoring includes river stage and discharge, turbidity, and a suite of other water quality parameters (stream temperature, dissolved oxygen, pH, and conductivity). Groundwater wells are located near each stream monitoring site, with two shallow wells (~1 m deep) near the stream and one deep well (10+ m depth) on the adjacent terrace. Near real-time telemetered data as well as webcam footage of current conditions at the CSU Mountain Campus are viewable at datavis.warnercnr.colostate.edu. In addition to the instrumented monitoring network, other relevant datasets are being archived, including a high-resolution orthoimage of the valley (Figure 1) produced from drone imagery (flown in 2019), temperature, and relative humidity sensors to measure cold air drainage along a hillslope elevation gradient.

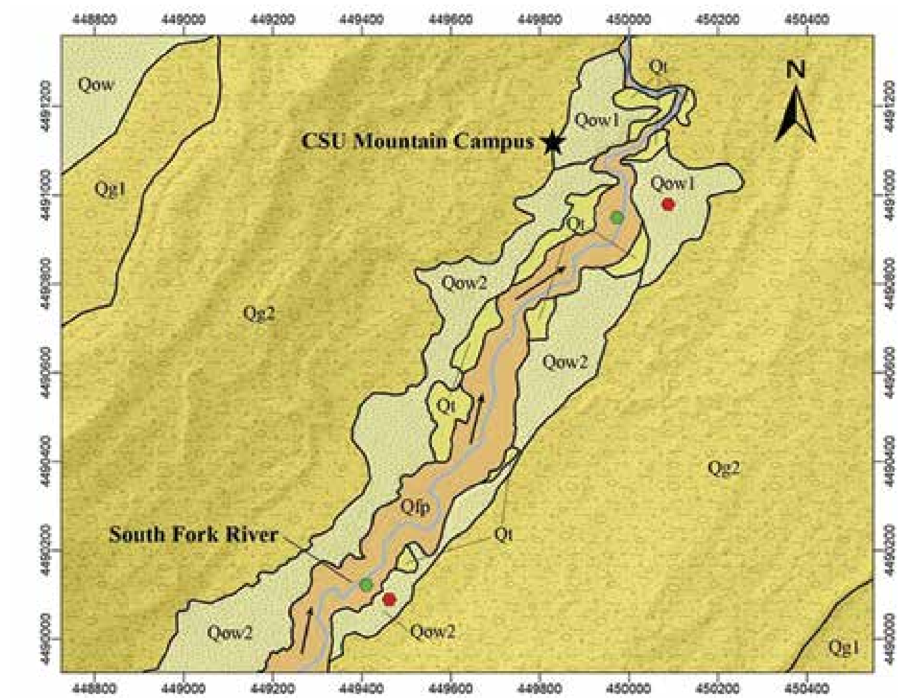

Figure 3. Geologic map of the South Fork River Valley at the CSU Mountain Campus. Units include glacial till (Qg1, Qg2), outwash terraces (Qow, Qow1, Qow2), fluvial terraces (Qt), and the active floodplain (Qfp). Locations tick marks are in WGS UTM zone 13N. The star indicates the main campus location, stream monitoring sites are marked as green hexagons, and deep groundwater wells are marked with red hexagons. Flow is from bottom left to top right, as indicated by arrows (modified from Suhr et al., 2021, Report for USGS EDMAP Award)

Hydrology of the South Fork River Valley

An important objective of long-term hydrological monitoring is to gain a better understanding of streamflow timing and water source areas throughout the year. Within the valley, the South Fork River interacts with a local groundwater system, where water flows through permeable glacial outwash as well as modern river sediments. River deposited sediments are at least 10 m deep, based on observations made during well drilling in 2019. Surface stream gages and adjacent deep groundwater well monitoring revealed that the South Fork River transitions from gaining (i.e., the groundwater level is higher than stream water level) to losing (i.e., the groundwater level is lower than stream water level) as it flows down the valley (Figure 2). A hydrogeological model that incorporates the physiography and mapped surficial geology is currently being developed to explore

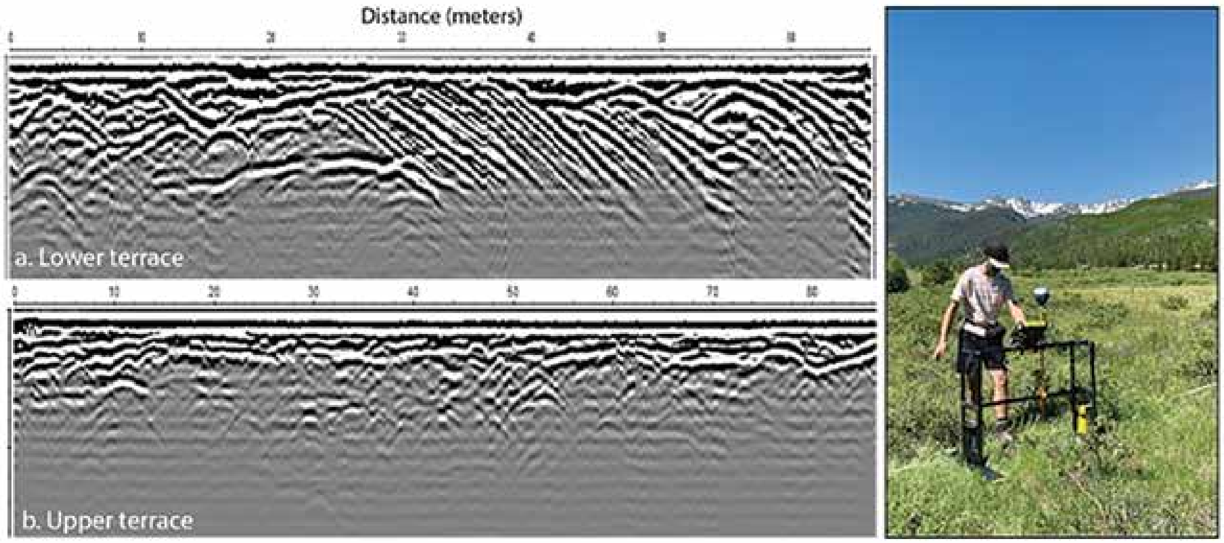

Figure 4. Ground penetrating radar (GPR) radargrams were collected on a lower terrace (a) and an upper terrace (b) within the South Fork Valley at the CSU Mountain Campus. The general location of transects are indicated by red circles on the Figure 1 map. Picture: Christoph Suhr, MS Geosciences student, operating the GPR) (modified from Rathburn and Suhr, 2020, Report for Natural Resources Research Award).

groundwater and river water interactions.

In addition to logging water levels, this project included sampling for stable isotopes (^{2}H/^{1}H, ^{18}O/^{16}O), which occur naturally as part of the water molecule and can be used as hydrologic tracers. Analysis of the isotope data is ongoing; however, initial results clearly illustrate different isotopic signatures for groundwater and surface water. The isotopic composition of stream water varies throughout the year and likely reflects an increase in local groundwater contributions during the late summer and fall.

Surficial Geology, Sediment Coring, and Geophysical Surveys of the South Fork River Valley

Groundwater and surface water processes along the South Fork River are influenced by the characteristics and distribution of glacial and post-glacial river sediments deposited in the valley. In the summer and fall of 2020, portions of an existing U.S. Geological (USGS) geologic map were remapped at higher spatial resolution. Sediment cores were collected for radiocarbon analysis to determine sediment ages, and ground-penetrating radar (GPR) and seismic refraction surveys were completed to examine the stratigraphy and thickness of valley bottom sediments.

These analyses revealed key insights into the glacial and post-glacial history of the South Fork River Valley. The surficial geologic mapping identified two unique glacial till deposits (Qg1 and Qg2) formed by at least two episodes of glaciation (Figure 3); till mapped as Qg1 is older and more weathered, while till mapped as Qg2 was deposited more recently and displays prominent glacial landforms. Radiocarbon analyses of sediments collected within the younger (Qg2) till indicate that the most recent glacial advance to reach the location of the Mountain Campus must have retreated before 16,800 years ago. This age relationship suggests that Qg2 glacial deposits were formed during the Pinedale glacial period, occurring approximately 30,000-12,000 years ago.

Following Pinedale deglaciation, over 10 m of glacial outwash was deposited within the South Fork Valley. Subsequent reworking of outwash sediments by the river formed two high terraces (Qow1 and Qow2; Figure 3). The topographically highest terrace (Qow1) represents the valley surface after deposition of post-glacial outwash, forming the sediment into which the deep downstream well is completed. The Qow2 terrace represents the valley bottom after 1 to 2 m of river incision into the Qow1 surface and consists of sediment into which the upstream deep well is completed. Sediment cores from lower, more recent river terraces (Qt) produce dates of 1,330 and 2,080 years old, while sediments collected on the modern floodplain (Qfp) date to approximately 520 years. Initial interpretation of the GPR data reveal distinct dipping reflections and horizontal reflection patterns, consistent with point bar migration and overbank deposition, respectively (Figure 4). Ongoing analyses will investigate the surface and groundwater interactions in the context of valley sediment and depositional environment. In addition, the varying reflection patterns from the GPR surveys will be analyzed in more detail to understand alluvial processes forming the South Fork River Valley landforms.

Looking to the Future

The year 2020 presented many challenges as a COVID-19 pandemic, and the Cameron Peak Wildfire led to limited access to the CSU Mountain Campus for research and full campus closure to all normal educational activities. However, the work completed has established a solid foundation for research opportunities to continue to grow at the CSU Mountain Campus. Telemetered data are currently viewable to the public and downloadable by request. We are continuing to expand resources for data download and documentation to facilitate future educational benefit, including use in K-12 and university courses at the CSU Mountain Campus and beyond. The instrumentation network also provides an opportunity to leverage further research prospects, as has already happened in the wake of the Cameron Peak Wilfire, where ongoing monitoring at the CSU Mountain Campus is now part of a larger funded effort to study the impact of the wildfire on snowpack, streamflow, sediment transport, and water quality throughout the Cache la Poudre River Basin.

Financial Support:

This project was supported by funds from the Colorado Water Center Water Research Team Grant, previous and current funding from the Colorado State University Warner College of Natural Resources Mountain Campus Research Support (created by Dr. James R. Meiman), and USGS EDMAP National Mapping Initiative, Award No. G20AC00136, FY2020.

Beaver ponds within the study area in North Park, Colorado. Photo by Mike Wilkins.

Beaver-Generated Wetlands as Ecosystem Control Points for Post-Fire Transport of Sediment, Carbon, Nutrients, and Toxic Metals into Rocky Mountain Headwaters

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Background

Wildfire is a key disturbance that structures forest ecosystems across the western U.S., which has impacted 6.3 percent of the forested area over the past three decades. Moreover, the severity of wildfires in conifer forests of western North America has increased dramatically in recent decades and is predicted to continue increasing in the future as our climate changes. Indeed, last year (2020) saw the largest forest wildfire season in this region in recorded history, with over 6 million acres burned across the American West. A critical event following a wildfire is the export of nutrients – particularly carbon and nitrogen—from terrestrial burned hillslopes to aquatic ecosystems, where they can significantly impact downstream water quality and drinking water treatability. For example, nutrient export can lead to increased eutrophication of downstream waters and increased potential to generate harmful disinfection byproducts during drinking water treatment. Therefore,

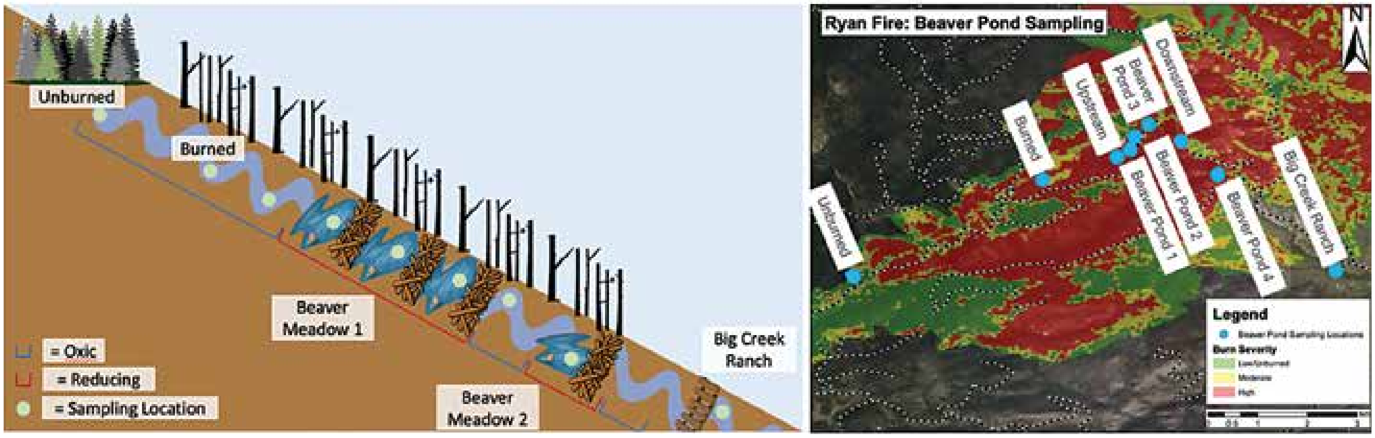

Figure 1. Water sampling locations along a transect through unburned and burned regions following the 2018 Ryan fire. Graphic by Holly Roth.

understanding the fate and transport of these nutrients from burned watersheds is of the utmost importance.

Through the construction of channel-spanning dams and smaller shunts, beavers actively divert large fractions of river flow onto the adjacent floodplains, including during times of lower river stage when the flow is typically contained by riverbanks. These diversions can have substantial impacts on biogeochemical processes, including storage of organic carbon, cycling of reactive nitrogen, and export of metals. Indeed, it is thought that prior to human hunting activities that almost wiped out beaver populations across North America, the majority of upland catchments contained extensive beaver generated floodplains and wetlands that supported abundant biodiversity, retained carbon, silt, and water, and stimulated aquifer recharge. Despite this near extinction of beaver over prior centuries, these species have returned to many western watersheds, including many of those recently impacted by wildfire.

Project Rational

For this project, we aimed to determine how beaver wetlands influence the movement of carbon and nitrogen within burned watersheds. These wetlands have distinct chemical conditions relative to both adjacent floodplain and hillslope soils and free-flowing stream sections and thus likely catalyze unique biogeochemical processes within the watershed. Given the return of the beaver to many western U.S. watersheds and the predicted future increases in wildfire activity, these engineered features are likely to play increasingly important roles in influencing the quality of water exported from burned landscapes.

Methods

To understand post-fire biogeochemistry, we employed an interdisciplinary approach that coupled high-resolution chemical analyses of aqueous nutrients with profiling of the microorganisms that inhabit beaver wetlands and can drive transformations of nutrient species. The work was performed within an area along the Colorado-Wyoming border that burned during the 2018 Ryan wildfire and that hosted a series of interconnected free-flowing stream sections interspersed with multiple beaver wetlands (Figure 1). Time-resolved water samples were collected monthly throughout the summer of 2019 and 2020 from multiple locations along this transect (Figure 2), with particular focus on up-gradient sections of the stream that weren't impacted by the Ryan wildfire and the beaver wetlands within the burned area. Furthermore, sediment samples from within the beaver wetlands were collected. We employed a mass-spectrometry approach to characterize the dissolved nutrients leaching from burned landscapes into the stream, using analytical resources at the National High Magnetic Field Laboratory at Florida State University. We also extracted DNA from collected sediment samples and performed DNA sequencing to analyze the composition and function of the microbial community.

Figure 2. Graduate students Holly Roth (top) and Amelia Nelson (above) collecting water samples from beaver wetlands. Photos by Mike Wilkins and Holly Roth.

Results and Impact

Our spatial and temporal sampling scheme revealed that both dissolved organic carbon and dissolved total nitrogen accumulated within the beaver wetlands (Figure 3). In particular, high-resolution mass spectrometry analyses of nutrients within the water column indicated that compounds generated during a wildfire that contain nitrogen were enriched and retained in beaver wetlands

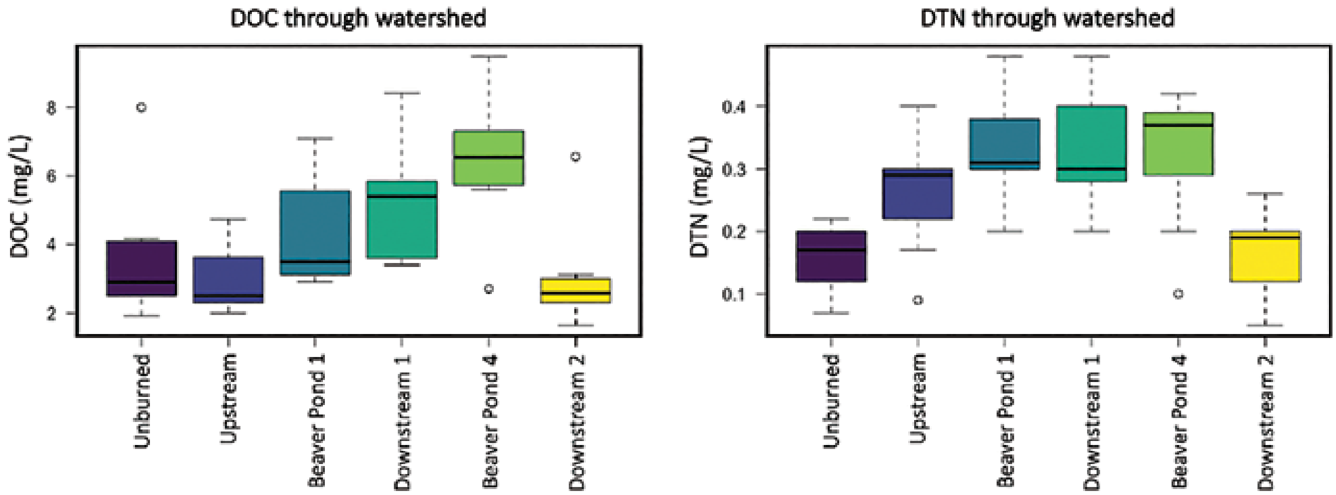

Figure 3. Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) through the Ryan Fire-impacted watershed. Each box and whisker plot consists of five samples and each is from June-October 2019. Graphic by Holly Roth.

(Figure 4). The microbial community within the beaver wetland sediments was distinct from communities found in free-flowing river sediments and adjacent burned soils. Importantly, these communities could tolerate the oxygen-free conditions encountered in the carbon-rich sediments but did not encode the genetic machinery necessary to degrade many of the aromatic hydrocarbons accumulated in these features. However, many of the microbes inhabiting beaver pond sediments were able to degrade other compounds generated by wildfire – for example, dead microbial biomass ('necromass') that was likely produced when soils within the watershed were burned. Moreover, the wetland microbes were also able to convert iron and manganese into aqueous species, suggesting that beaver wetlands may potentially contribute to elevated downstream fluxes of some metals.

Together, these results indicate that beaver wetlands do indeed play a key role in retaining C and N compounds that are initially generated by wildfire and that are susceptible to transport from burned hillslopes. As such, these features likely play oversized roles in biogeochemical cycling within burned regions.

Conclusions

This work revealed that beaver wetlands are able to retain carbon and nitrogen compounds generated during a wildfire. By limiting the downstream transport of these molecules, additional problems typically encountered following wildfire (e.g., the formation of carcinogenic disinfection by-products at water treatment plants) may be alleviated. These wetlands also hosted unique microbial populations within the watershed that were distinct from those present in adjacent burned soils or river sediments. While many of these microbes could potentially degrade some of the fire-generated compounds retained within the wetlands (i.e., dead biomass), they also have the potential to mobilize metals (e.g., iron, manganese); the implications of potential metal transformations are a key area for future research.

Future Research

The work described here suggests that beaver wetlands within burned catchments may play an important role in limiting the downstream transport of nutrients, potentially limiting the extent to which water quality is impacted. Acknowledging that this study was performed within one catchment, future work will aim to expand these observations to additional beaver wetlands, potentially within areas burned during the historic 2020 Colorado wildfire season. For example, there are many beaver wetland complexes present within the area burned by the Cameron Peak wildfire that are likely intercepting nutrients that have leached from ash. Finally, beaver dam or wetland analogues are receiving increasing attention across the U.S. as a mechanism of controlling water flow and quality; these results suggest that such features could be a valuable tool in post-fire management in burned watersheds.

Acknowledgements

This work was supported by the Colorado Water Center and by the National High Magnetic Field Lab (NHMFL), Ion Cyclotron Resonance User Facility, National Science Foundation Division of Materials Research and Division of Chemistry #DMR-1644779.

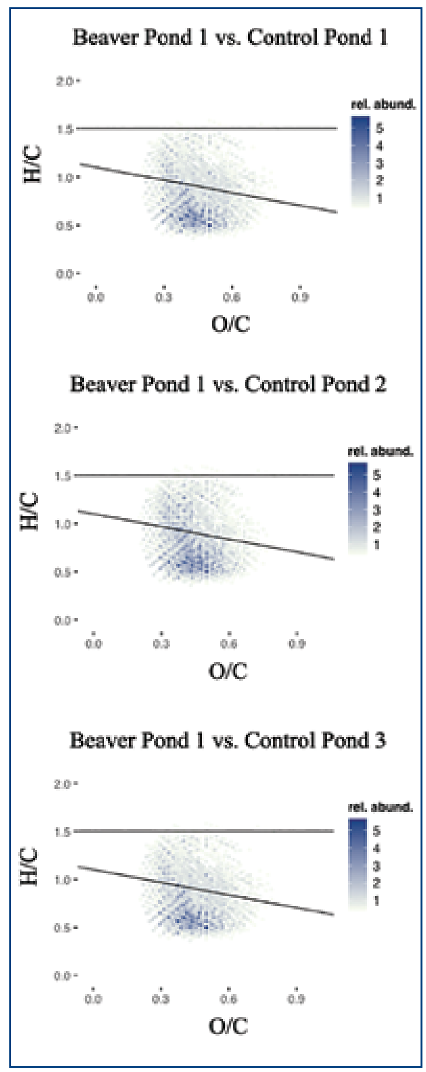

Figure 4. Series of van Krevelen Diagrams depicting the enrichment of unique aromatic organic compounds in beaver ponds. Graphic by Holly Roth.

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Streamflow Depletion on the South Platte River Due to Groundwater Pumping:

Analysis Via Field Work and Groundwater Modeling

Luke Flores, Masters Student, Civil and Environmental Engineering, Colorado State University and
Dr. Ryan Bailey, Associate Professor, Civil and Environmental Engineering, Colorado State University

Background

The interactions between a stream and underlying alluvium play a vital role in various physical, chemical, and biological processes, including, but not limited to, streambed erosion and channel morphology, contaminant and nutrient transport, and regulating water temperatures for healthy wildlife habitat. Being able to quantify these interactions is also paramount for water resource managers and policy makers in states such as Colorado, where surface water rights and groundwater are jointly administered. Of practical importance is predicting surface water-groundwater exchanges that have been influenced by groundwater pumping wells. It has long been established that alluvial groundwater pumping near a stream disturbs the existing water table and produces a cone of depression around the well. If this cone reaches the stream, then the well can begin to either induce streamflow depletion, increase the existing streamflow depletion, or decrease the amount of groundwater discharging to the stream. This process can be tempered by low conductivity sediment along the streambed that resists the flow of water leaving the stream.

In light of this, a stream-aquifer study was conducted along the South Platte River (SPR) near Denver, Colorado, just downstream of Chatfield Reservoir. This reach of the SPR was chosen due to four alluvial pumping wells immediately adjacent, approximately 120-260 meters away.

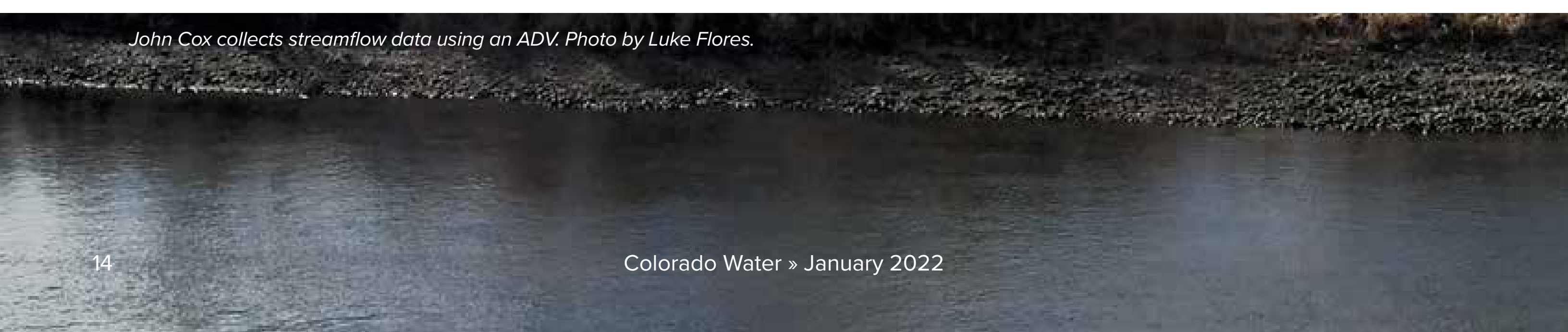
The purpose of this study was twofold. First, we wished to monitor and observe the system with a network of groundwater wells and in-stream streamflow gauges to determine the nature of the system. *Do the data suggest the pumping wells are impacting streamflow? If so, how severely? In which ways does this impact manifest itself?* Second, we wished to better quantify these interactions on a small field scale such as this site. *What models are best at estimating pumping-induced streamflow depletion? What are the existing model's shortcomings in predicting these losses, and how can they be improved? What processes or physics are currently not being captured in existing models?*

Figure 1. 1a (Left): Location of the study site and relative proximity to Chatfield Reservoir and City of Denver; 1b (Right): Map of South Platte River reach where streamflow and groundwater levels were monitored, showing five monitoring well locations, four pumping wells, two streamflow gauging sites, and location where river stage was monitored. Map by Luke Flores.

Data Collection

Groundwater monitoring wells were drilled at three different locations within the study region. The data from these wells assisted in understanding how the pumping wells influenced the water table and the estimation of aquifer parameters. Location A (see map) had three nested wells at various depths, which provided valuable insight into stream-aquifer interactions.

The plot in Figure 3 shows the water elevation of both the groundwater and the stream. First, it is clear that stream levels are greater than the groundwater levels, implying that the stream is losing water to the aquifer. Second, when the pumping wells turn on, the groundwater levels sharply decrease (suggesting even more streamflow loss will occur) but then begin to stabilize after four days of pumping. Finally, ubiquitous in all of this are the small daily variations, or oscillations, in stream stage which are due to changes in incoming upstream flow. Interestingly, these changes manifest themselves in the groundwater almost instantaneously; any change in the stream is seen in the groundwater.



John Cox collects streamflow data using an ADV. Photo by Luke Flores.

Figure 2. Drilling of observation well A in South Suburban Park, Littleton, Colorado, USA (see map). The proximity of the well to the river provided valuable insight into the stream-aquifer interactions. Photo by Luke Flores.

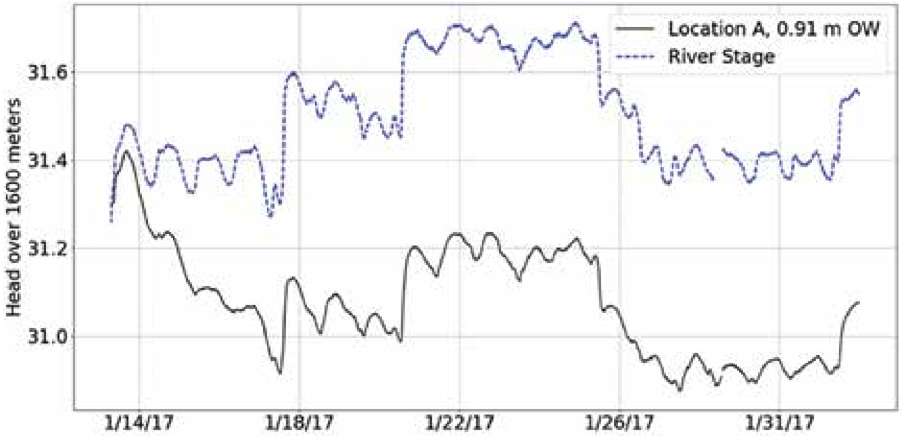


Figure 3. River stage compared to 0.91 observation well at Location A. Plot by Luke Flores.

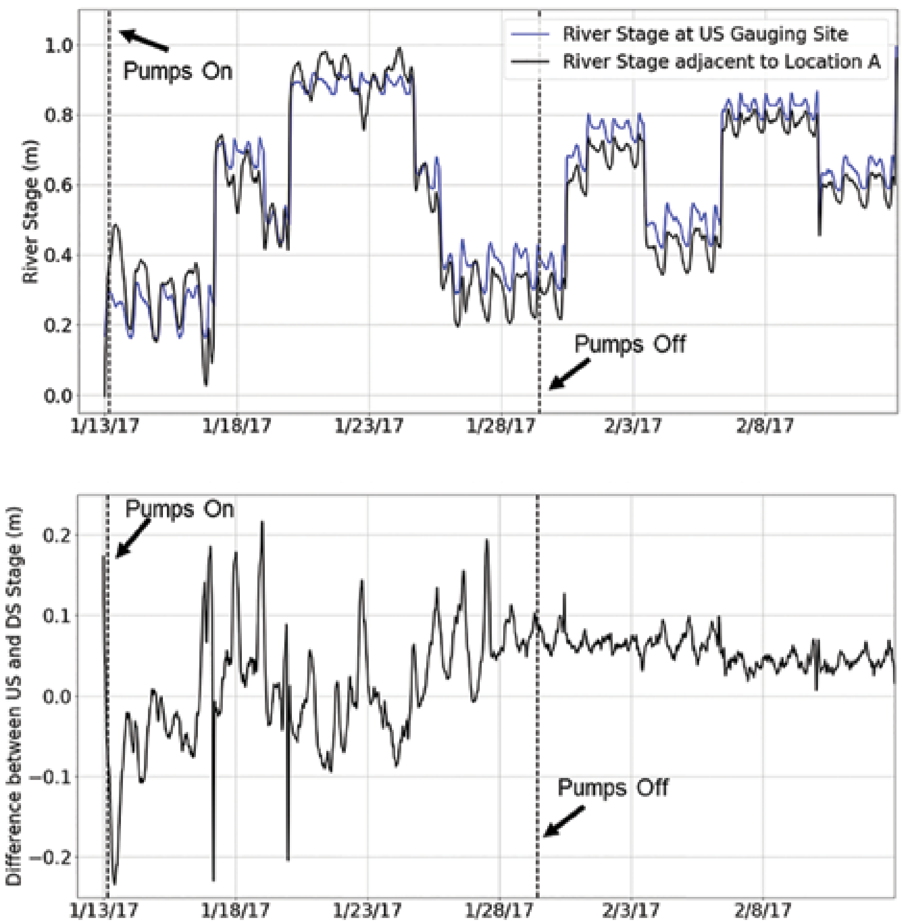
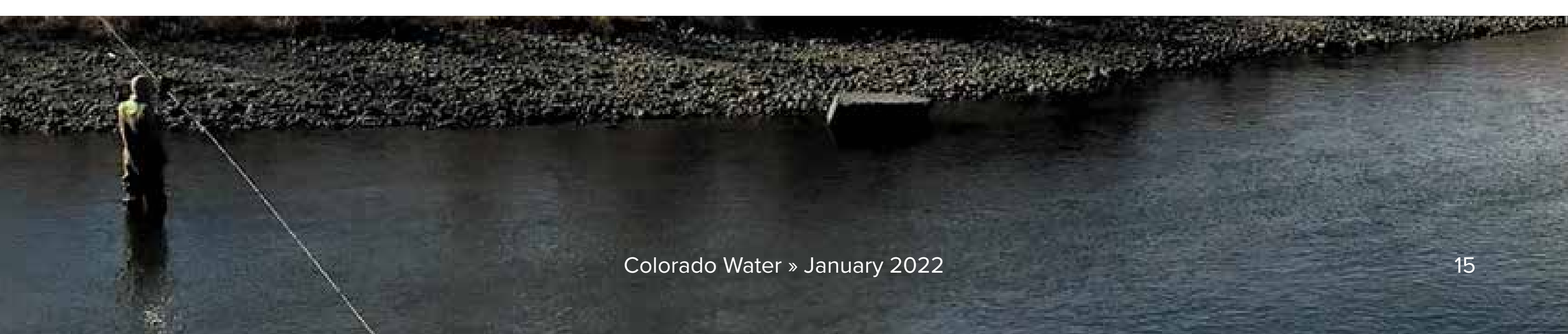


Figure 4. (Top) Comparison of upstream and downstream stage hydrographs. (Bottom) Difference between upstream and downstream hydrographs. Plot by Luke Flores.

This suggests a strong hydraulic connection between the stream and aquifer or that water flows freely between the two.

However, this begs the question: *If changes in the stream manifest in the groundwater, should not changes in the groundwater also manifest in the stream?* This is true and can be seen by observing stream levels upstream and downstream of the pumping wells. Far enough upstream, we can safely assume that the pumping wells are not influencing the stream so that downstream stream levels (which are influenced by pumping) can be compared to upstream levels serving as a baseline. This is seen in Figure 4 where stream levels are shown together upstream (in blue) and downstream (in black).

As the pumps turn, the upstream levels remain consistent, as is expected. However, the downstream levels slowly decrease due to the pumping wells. The trend stabilizes after approximately four days. Over the entire pumping period, we see the difference between upstream and downstream stream levels increase and gradually decline as the pumping wells turn off. This is further evidence of a stream and aquifer with a strong hydraulic connection and therefore a stream susceptible to groundwater pumping.



Modeling

Up until now, we have only looked at secondary processes and variables to analyze stream-aquifer interactions along this reach. However, we ultimately wish to be able to directly model and account for direct streamflow loss. To test the models, we also measured downstream streamflow directly with an acoustic Doppler velocimeter (ADV) to compare with incoming upstream streamflow. We then attempted to fit the data with two well-known and accepted analytical streamflow models (Glover and Hunt models). Analytical models are cheap and easy to apply but solve idealized problems with assumptions often not met in the field. With this in mind, Figure 5 highlights measured streamflow losses compared with the predicted streamflow losses from the Glover and Hunt models.

Qualitatively, the models perform relatively poorly. Both models appear to capture the general increase in streamflow loss as the pumping begins but with variability. Moreover, neither model captures streamflow losses accurately after the pumping ceases. *Why is that?* To answer this question, we need to turn to more sophisticated models. Among the many assumptions and idealizations that the analytical solutions make, perhaps the most constricting is the assumption of an infinitesimally narrow river, i.e., a line. A river reach of the SPR downstream of a large dam and wastewater treatment release point is especially prone to not fitting this assumption as the river width is constantly changing. This facet of the reach proved to be very consequential in determining streamflow losses. Intuitively a wider stream has the potential for more streamflow loss as the stream has a larger area to lose flow. This issue is compounded when there is a rapid increase in streamflow loss (as is often the case here due to changes in dam releases) and new areas of inundation become part of the stream. These newly inundated areas are generally not saturated and act like a sponge, leading to very large streamflow losses. In short, there are losses contributing to the total streamflow loss along the reach that are independent of pumping.

This explains why the analytical solutions struggled to fit the data after the pumps turned off: the cessation of pumping coincided with an increase in incoming streamflow, leading to a wider stream, which induced streamflow loss through unsaturated soil. We turned to the numerical model MODFLOW, developed by the U.S. Geological Survey (USGS), to reconcile this dilemma. To account for a dynamically changing stream, a new MODFLOW stream module was written, which we called MODFLOW-DSF. The module solves more physically-based equations for determining stream depth, velocity, and width than existing stream modules. Figure 6 showcases streamflow loss along a small portion of the reach for two different flow rates. It is clear that not only does larger streamflow result in a wider stream, but also where a stream loses its flow varies greatly. This is seen by the dark red bands along the outer banks of the stream, which represent streamflow loss through unsaturated soil with significantly greater loss rates.

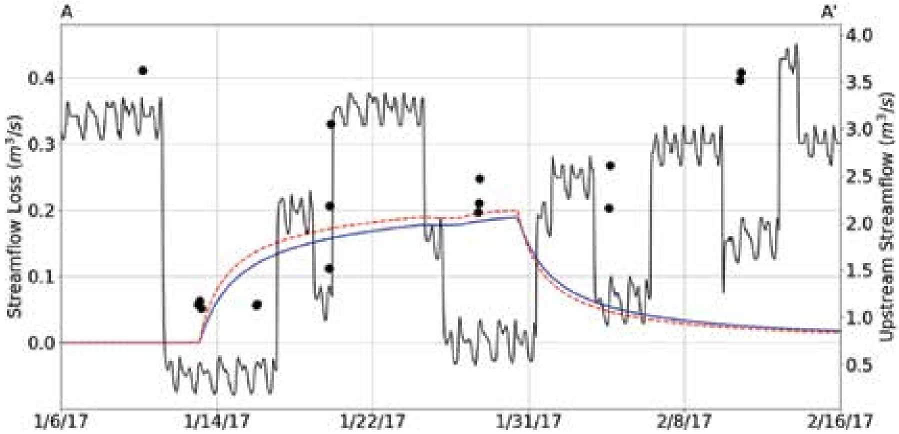


Figure 5. Streamflow loss (left axis) predicted by Hunt (in blue) and Glover (in red) solutions. Collected data is shown as black dots. Analytical solutions struggle to fit data when upstream streamflow becomes large (right axis). Plot by Luke Flores.

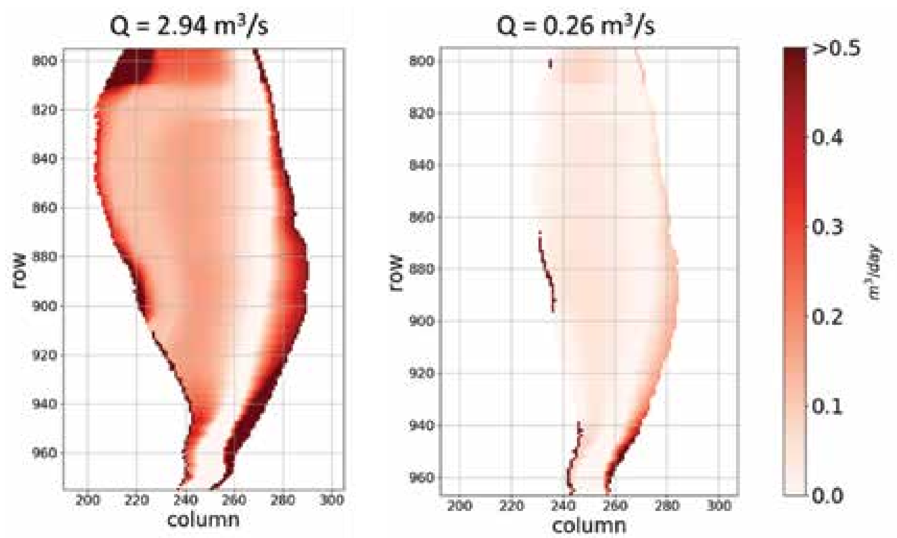


Figure 6. Area of inundation for a large flow (Q = 2.94 m3/s) and a small flow (Q = 0.26 m3/s). For the large flow, the stream width is almost 20 meters wider than for the small flow. Large streamflow losses along the banks of the river result. Plot by Luke Flores.

Conclusion

Ultimately the interactions between streams and underlying alluviums are inherently intricate. While each system must be analyzed independently,, this reach of the South Platte River exhibited behaviors indicative of a highly interactive stream with its alluvium. Groundwater wells show that in close proximity to the stream, water levels between the two systems were nearly linearly related. Subsequently, pumping wells were able to reduce both stream stage and streamflow. At the same time, factors beyond pumping will always contribute to streamflow loss. For the reach of this study, a highly variable upstream streamflow contributed a highly variable stream width which led to bank storage and resulting unsaturated zone flow. However, consequential stream-aquifer studies, for both humans, animals and biota, often do not include such processes. It is our hope that this work serves to further encourage comprehensive stream-aquifer studies that do not exclusively rely on existing methods and are willing to use unique methodologies and models for their specific site.

Investigating Bi-Directional Water Exchanges Across Intact and Degraded Floodplains

Alexander C. Brooks, Doctoral Student and **Dr. Timothy P. Covino**, Assistant Professor, Watershed Science, Colorado State University

Connectivity between rivers and their floodplains has been identified as a key provider of beneficial ecosystem services. Human activities have caused widespread floodplain disconnection and generated a need for restoration efforts that improve floodplain connectivity and function. This connectivity is often quantified as the bi-directional exchange of water between a river and its adjacent riparian corridor. This study seeks to improve quantification of the spatial and temporal variability of these exchanges across both intact and degraded floodplains. Exchanges will be measured through continuous stream and groundwater monitoring and salt tracer tests that quantify both gross and net water exchanges at sub-reach scales. Hydro-geomorphic, geospatial and ecologic variables controlling these exchanges will be investigated in order to develop predictive metrics of connectivity that can be utilized at larger scales than allowed for by tracer injections. These efforts aim to both support concurrent work investigating cumulative regional impacts of river-floodplain connectivity and provide tools that assist in the development and assessment of river-floodplain restoration efforts.

Over a century of human driven disconnection between Colorado rivers and their floodplains has likely exacerbated statewide water resource risks including increased flooding, impaired water quality, the extirpation of beaver, in-channel placer mining, the construction of roads, railroads and buildings in valley bottoms, and the altering of flow regimes through diversions and dams (Wohl, 2006). Collectively, these have caused a loss of floodplain function as rivers have incised and floodplain inundation has been reduced. Functional floodplains provide crucial and valuable ecosystem services including regulating hydrologic disturbances, improving water quality and moderating water supply (Tockner & Stanfod, 2002; Costanza et al., 1998). This creates the need to deepen our understanding of the hydrologic function of natural floodplains to help assess the regional and cumulative implications of degraded and disconnected floodplains. Recent statewide interest in increasing resiliency by restoring river-floodplain connectivity is hindered by a lack of understanding of the temporal and spatial variability of natural river-floodplain behavior.

As our understanding of the value of floodplain connectivity has improved, water resource managers have increasingly incorporated it as an objective in restoration projects (Wohl et al., 2015). In Colorado, after the 2013 Front Range floods, $63.2 million dollars were supplied for watershed recovery projects that explicitly sought to accommodate natural river-floodplains processes including river-floodplain exchanges (Colorado Emergency Watershed Protection Program). Development and assessment of these types of projects requires an

Big Thompson Canyon photographed from the air during the September 2013 floods. Following this flood event, $63.2 million dollars were supplied for watershed recovery projects that explicitly sought to accommodate natural river-floodplains processes, including river-floodplain exchanges. Photo by Jon Soucy/U.S. Army.

understanding of the complex controls that impact river-floodplain exchanges. Accordingly, there is a need for better quantification of connectivity in intact and degraded floodplains to inform the development of scalable predictive metrics useful in restoration and management.

Results

In mountainous headwaters, connected floodplains in lower gradient unconfined valleys are known to provide a host of beneficial ecological and hydrologic services. River-connected wetlands promote biogeochemical processing and increase ecological resilience (Hauer et al., 2016). In addition, these wetlands mediate hydrologic regimes through the attenuation of peak flows (Wegener et al., 2017), maintaining local water tables and sustaining late-season flows (Schneider et al., 2017). These services are all assumed to be dependent on the level of floodplain connectivity, which can be defined by the bi-directional exchange of water between a river and its adjacent riparian corridor. The degree of river-floodplain connectivity is a function of complex interactions between a river's geomorphology, hydrology, ecology, and the degree of anthropogenic alteration. Connectivity can be highly heterogeneous at small spatial scales and varies widely between different rivers. It is also influenced both by predictable cyclically and seasonal patterns and by abrupt disturbances created by events like floods and beaver dam dynamics.

Common approaches used to assess floodplain function either quantify connectivity using reach-scale water balance (net difference in discharge between reach inflow and outflow)(Wegener et al., 2017); field based or aerial imagery assessments of surface water, ponds or control structures like beaver dams (Weber et al., 2017); and/or measurements of water-table pressure gradients (Naiman et al., 1994; Westbrook et al., 2006) . More recent techniques can assess connectivity at scales smaller than the valley-floodplain complex and calculate total gross lateral water exchanges (Payn et al., 2009; Majerova et al., 2015; Covino et al., 2011; Covino & McGLynn, 2007).. This research seeks to expand upon two critical areas: (1) *Quantifying spatial and temporal variability of hydrologic exchange at sub-reach (<200m) scales* encompassing systems ranging from [i] connected and disconnected stream-floodplains and having [ii] natural and human-altered flow regimes. (2) *Deepening understanding of hydro-geomorphic and ecological controls on these exchanges* to improve the development of scalable, predictive metrics for applications in monitoring and restoration efforts.

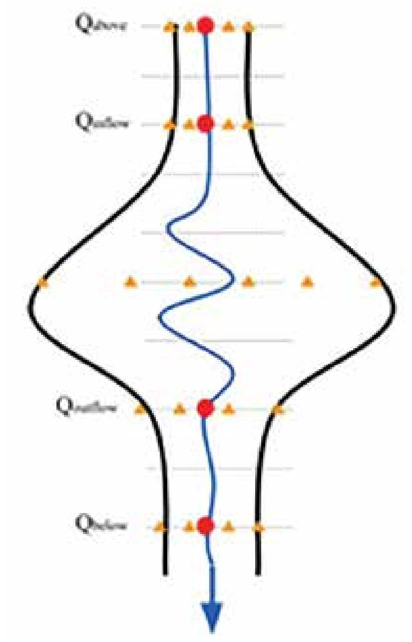


Figure 1: Field Design Schematic displaying gauging stations (red dots), groundwater wells (orange triangles), and tracer injection points (dotted lines).

Scope and Objectives of Doctoral Research and Future Research

This research study is a portion of doctoral research overall that investigates whether hydrologic connectivity in mountain valleys has cumulative impacts that matter at scales relevant to water resources managers. I am investigating this impact across scales from the sub-reach scale (this project) to basin and regional scales (concurring National Science Foundation (NSF)-funded work). Understanding this connectivity at the sub-reach scale can both improve our understanding at a process level and elucidate patterns that will inform my ability to scale this research.

My objectives include the following:

» Objective 1: Explore sub-reach patterns of bi-directional flows across gradients of valley confinement, connectivity, and altered flow regimes.

» Objective 2: Identify scalable predictive metrics that can be utilized to predict bi-directional exchange.

In addressing my first objective, I will establish gauging stations at two stream networks within the Fraser Experiment Forest that will monitor hydrologic exchanges across a mountain to valley transition. Stations will bracket an upstream confined section, the unconfined section, and another downstream confined section. Channel water balances will be calculated across the growing season (~April to October). At one of the sites, Denver Water diversions withdraw water for much of the year from just upstream and downstream of two unconfined reaches. At this site, additional gauging stations will bracket the diversion to assess the altered flow regime's impact on channel water balance and hydrologic connectivity. Four salt tracer injection campaigns will be conducted at each site across four differing flow states (rising limb snowmelt, snowmelt peak, mid-summer recession and late summer/early fall recession . Each campaign will measure gross (gains and losses) and net water exchange at ten sub-reaches spanning from upstream to downstream of the unconfined valley bottom. Discharge will concurrently be measured at each injection site using an Acoustic Doppler Profiler, enabling the calculation of gross exchange (method from Payn et al., 2009). Nested groundwater-piezometer wells will be installed along riparian banks at the four discharge monitoring sites and at the hillslope-floodplain interface. Wells will be continuously measured for level. During tracer tests, wells will be monitored for conductivity to measure lateral movement of stream flow to groundwater.

Measuring gross lateral exchange via the methodology outlined in this study can be a time and resource intensive process. Water resources managers and restoration practitioners often lack the resources to complete this type of study at necessary scales. In addressing this second objective, I will investigate whether predictive metrics can be developed that can rely on data that are simpler to collect and/or can be assessed at larger scales. To accomplish this, I will conduct geospatial analyses utilizing available Digital Elevation Models and previously flown LIDAR to test relationships between connectivity and geospatial metrics including: streambed slope, stream sinuosity and meander form; contributing area to unconfined valley area ratios; riparian vegetation height; surface water to floodplain area; and topographic wetness index. Additionally, I will quantify hydrologic metrics such as: stream flashiness; the peak to baseline flow ratio; pressure potentials between stream water and groundwater; and saturated hydrologic conductivity in soils (using bail tests in groundwater wells). Lastly, I will collect and test relationships with field based geomorphic variables including channel unit, grain size distributions and stream power.

Quantitative Assessment of Floodplain Functionality in Colorado Using an Index of Integrity

Dr. Ryan R. Morrison, Assistant Professor and **Marissa N. Karpack**, Master's Student,
Civil and Environmental Engineering, Colorado State University

Floodplain Functions

Floodplains are unique and vital ecosystems. They support unparalleled levels of biodiversity (Tockner and Stanford, 2002; Ward et al., 1999), are among the most productive landscape types (Tockner and Stanford, 2002), and are second only to estuaries in terms of global value of ecosystem services (Costanza et al., 1997). The characteristic intermittent wetting and drying of floodplains allows them to serve a multitude of purposes to support a healthy ecosystem. The most vital floodplain functions include flood reduction, groundwater storage, sediment regulation, organics and solutes regulation and habitat provision.

Despite the variety of important functions they perform, floodplains are among the most threatened ecosystems and are disappearing at a faster rate than other landscapes due to human alteration (Tockner and Stanford, 2002). A useful first step in improving or protecting floodplains using management and restoration efforts includes assessing overall floodplain health or integrity.

Integrity of Environmental Systems

The concept of integrity in an environmental context was first discussed by Leopold in his landmark 1949 essay that introduced his Golden Rule of Ecology that, "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong otherwise." (Leopold, 1949). In the following decades, various works explored and clarified the definitions of ecological and biological integrity and their use in environmental management (Angermeier and Karr, 1994; Karr, 1996, 1992; Karr and Dudley, 1981).

The definition of integrity proposed by Flotemersch et al. (2016) can be applied to ecological units besides watersheds, such as floodplains. At present, studies of integrity in floodplains are predominantly focused on ecological integrity in the floodplains rather than assessing integrity of the floodplains themselves (Chovanec et al., 2003; Chovanec and Waringer, 2001; Funk et al., 2017; Petts, 1996).

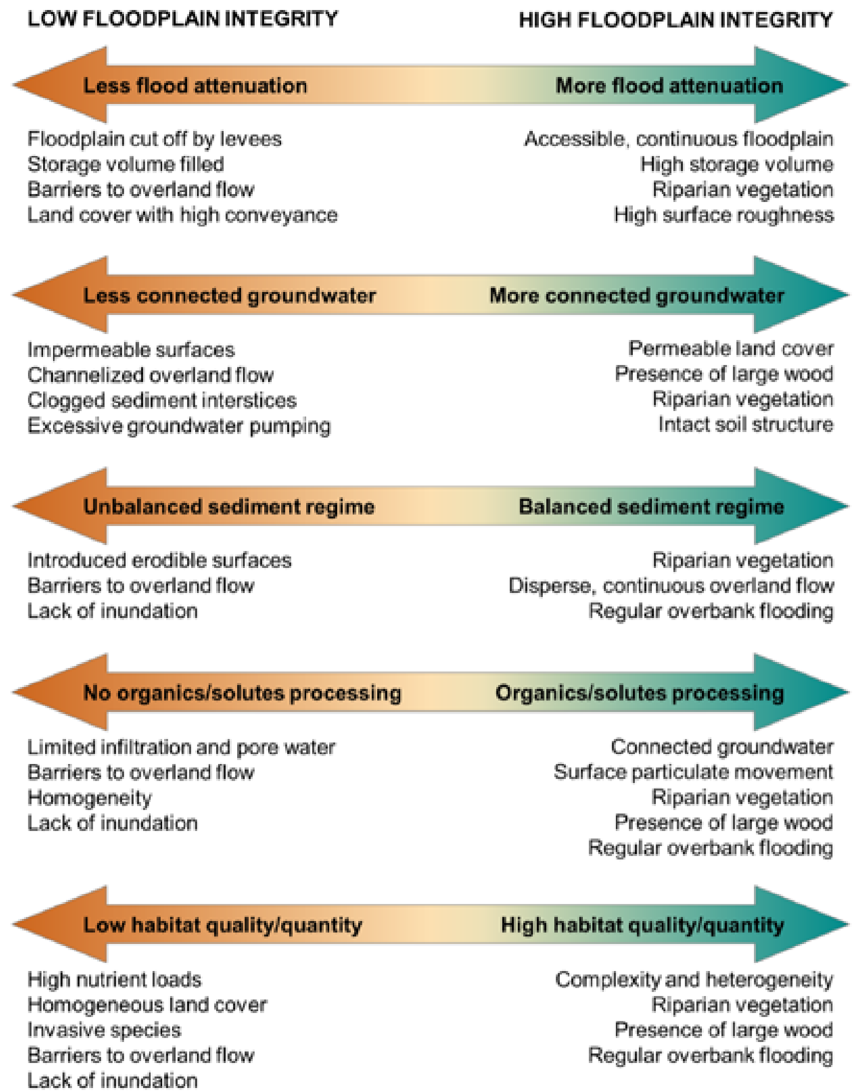


Figure 1: Conceptual diagram of floodplain functional integrity and the variables that change each function.

Quantifying Floodplain Integrity

Although a consistent definition of floodplain integrity is a necessary first step, the usefulness of the concept of floodplain integrity from a management perspective is in being able to measure it. Konrad (2015) provides an example of a method for assessing floodplain integrity at a broad spatial scale using GIS analysis of spatial data.

Congruent to this focus on quantifiable evaluations, Flotemersch et al. (2016) and Thornbrugh et al. (2018) develop and then employ a methodology to quantitatively assess watershed integrity, which we use as the basis for this methodology to quantify floodplain integrity presented in this paper. Thornbrugh et al. (2018) implemented this methodology to assess watershed integrity for the continental U.S. using broadly available datasets. The result was an Index of Watershed Integrity (IWI) and Index of Catchment Integrity (ICI) ranging from zero to one (lowest to highest integrity) for all catchments and watersheds associated with the National Hydrography Dataset Version 2 stream segments.

This study builds off the advances made in both the qualitative assessment of floodplains in the Puget Sound region of Konrad (2015) and the quantitative assessment of watershed integrity in Thornbrugh et al. (2018) by developing a novel methodology to quantitatively assess floodplain integrity and applying the methodology to floodplains in the state of Colorado.

Index of Floodplain Integrity

For the purpose of this study, floodplain integrity is defined as the ability of a floodplain to support essential geomorphic, hydrologic, and ecological functions that maintain biodiversity and ecosystem services provided to society. Similar to Thornbrugh et al. (2018), we aim to address the limitations of inefficient small-scale field studies and the lack of a truly unaltered reference environment by using available datasets to assess the level of alteration to floodplains. Because of the tight link between floodplain inundation and floodplain function, we chose to explicitly include human alterations to river hydrology, which were absent from Thornbrugh et al. (2018), as a stressor variable in the assessment of floodplain integrity.

The objectives of this research are to: 1) develop a methodology to assess floodplain integrity using geospatial datasets available for large spatial scales; and 2) use the methodology to evaluate spatial patterns of floodplain integrity in the state of Colorado. Through quantifying the abundance of anthropogenic alterations to floodplains in the state of Colorado, this research produces and analyzes an index of floodplain integrity (IFI) for each of the five floodplain functions and an aggregated overall IFI.

Methods

To assess floodplain integrity, we first identified datasets that represent the anthropogenic stressors to floodplain functions. Next, we calculated the prevalence of these stressors in discretized floodplain units. From the relative densities of these stressors in the floodplain, we calculated an IFI for each of the five floodplain functions. Then, we combined these functional IFI values to make an overall IFI metric. The functional and overall IFI values range from zero to one, representing floodplains where functionality is most to least altered, respectively. This process is represented graphically in Figure 2 and each step is described in detail in the following sections.

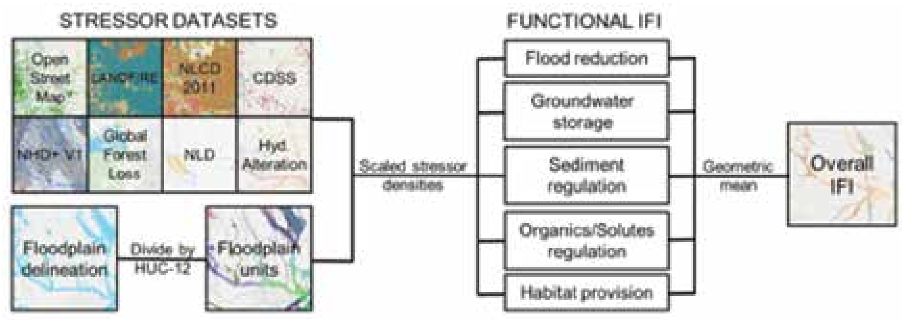


Figure 2. Overview of IFI methodology.

Identifying Links Between Floodplain Functions and Human Stressors

To quantify the effects of humans on floodplains, we first identified specific anthropogenic alterations that reduce floodplain functionality focusing on stressors related to flood reduction, groundwater, sediment regulation, habitat, organic and solutes regulation.

Identification of Stressor Datasets

Once we determined the relevant stressors for each floodplain function, we identified datasets that could be used to measure the amount of each stressor across Colorado floodplains. We selected datasets based on the following criteria: 1) information contained in the dataset was available for the entire state; 2) the datasets were the same or finer spatial scale than the floodplain delineation; and 3) the datasets were publicly available or soon to be publicly available. Our intention in focusing on publicly available datasets was to create a methodology that could easily be replicated and updated without needing to contact individuals or organizations for access to data.

Results

The methodology developed to compute IFI was successfully applied to the state of Colorado. With functional and overall IFI mapped for Colorado's floodplains, it is possible to visualize the anthropogenic effect on floodplain integrity across the state. At present, this work is the first to quantify the integrity of specific floodplain functions instead of measuring floodplain health solely by ecological integrity. Because the IFI is numeric, it is possible to use the IFI values computed here for a broad range of analyses. The examples of IFI by physiographic region, stream order, and city versus rural represent analyses that can be performed, but any other spatial division or pattern could be investigated without recalculating IFI.

Conclusions

This study presents a novel methodology to assess the integrity of floodplains and their functions over broad spatial scales and then demonstrates the methodology in the state of Colorado. The IFI methodology is based upon identifying and quantifying anthropogenic stressors that inhibit critical floodplain functions.. For Colorado, overall floodplain integrity decreased with stream order above third order streams. Overall integrity was also lower for floodplain that intersected urban areas. Finally, regional difference in IFI were identified, with the Interior Plains having higher integrity than the Intermontane Plateaus or Rocky Mountain System. The IFI methodology as presented in this study provides an important first step towards quantifying changes to floodplain integrity and the results of this study can provide a useful management tool for agencies that perform floodplain restoration projects. Understanding the extent of human influence on floodplain functionality is a crucial step towards preserving floodplains and their associated benefits.

Acknowledgements

This work was supported by the Colorado Water Center and with funding from the US Geological Survey, grant award 2018CO348B. We also would like to acknowledge Ryan McManamay at Oak Ridge National Labs and Christopher Sampson at the University of Bristol for providing necessary data for this study.

History of the South Platte River Riparian Ecosystem and Channel Change

Joshua Rogerson, Undergraduate Student and **Dr. Jessica Salo**, Associate Professor, Geography, GIS, and Sustainability, University of Northern Colorado, and **Dr. Gabrielle Katz**, Associate Professor, Earth and Atmospheric Sciences, Metropolitan State University of Denver

Introduction

The South Platte River system is a key natural resource in Colorado, providing water to the Denver Metropolitan area and the other Front Range cities, as well as to downstream municipal and agricultural water users. In addition to direct human needs, the South Platte floodplain supports riparian forests and wetlands that provide valuable ecosystem services, such as wildlife habitat, water quality enhancement, flood mitigation, and recreation opportunities (Strange et al., 1999). As a testament to the ecological value of the South Platte River riparian ecosystem, Colorado Parks and Wildlife operates more than 20 State Wildlife Areas on the South Platte River and key tributaries east of the foothills.

Riparian ecosystems are naturally dynamic, experiencing ecological disturbances typical of uplands as well as those associated with the river flow regime (Rood et al., 2007). River hydrology and geomorphic processes (e.g., erosion, sedimentation, and inundation) have a dominant role in shaping riparian vegetation patterns over time (Johnson, 1994). However, little research has been conducted on the historical changes of the South Platte River riparian ecosystem, which can be used to understand current conditions and predict future changes in the ecosystem.

The South Platte riparian corridor is a mosaic of forests, shrubs, and herbaceous vegetation. Human development is present, mainly agricultural activity and related water management, and in the form of urban and residential development surrounding towns. The dominant woody vegetation found in South Plate River riparian ecosystems is expansive cottonwood forest. Cottonwoods are generally considered to be near-obligate or obligate phreatophytes, species

Top of page—The South Platte research team conducts field work amongst riparian vegetation found at the study area east of Greeley, CO. Photo by Thomas "Woody" Myers

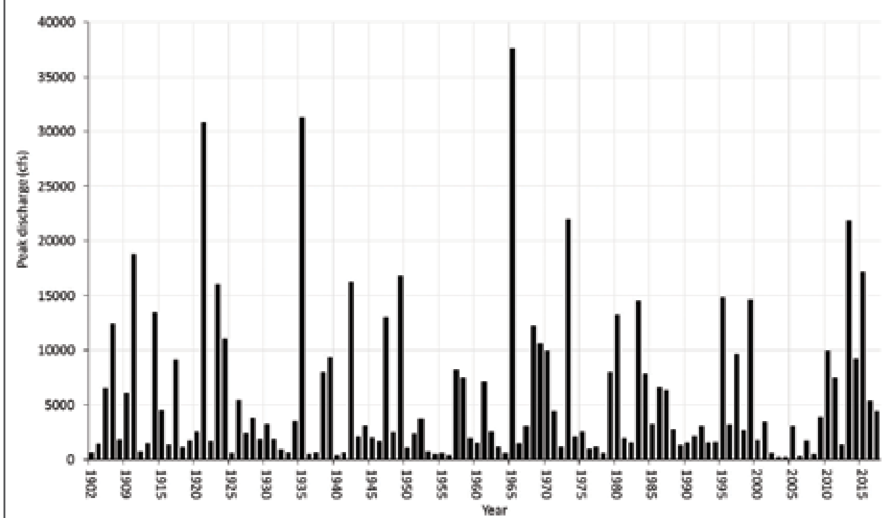


Figure 1. Annual peak discharge for South Platte River at Julesburg (USGS gage 6764000). 1902 – 2017. Graphic courtesy of USGS.

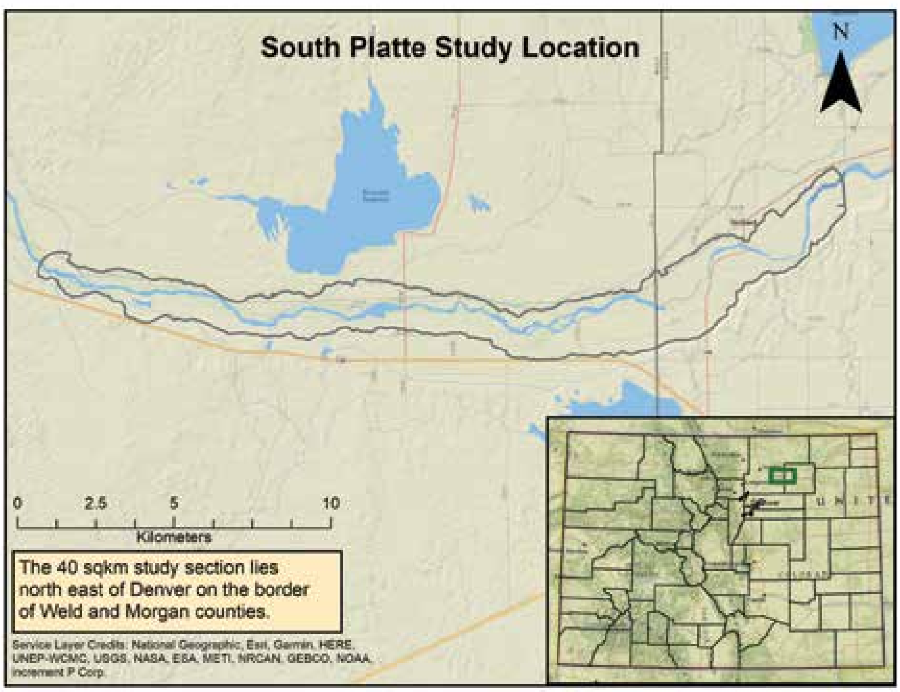


Figure 2. Location of the forty square kilometer study area along the South Platte River on the boundary of Weld and Morgan counties. Map by Joshua Rogerson.

that utilize groundwater sources for their water needs (Rood et al., 2003). The long-term persistence of a riparian cottonwood forest on the South Platte River depends on river processes and hydrologic conditions that allow for both seedling establishment and long-term survival.

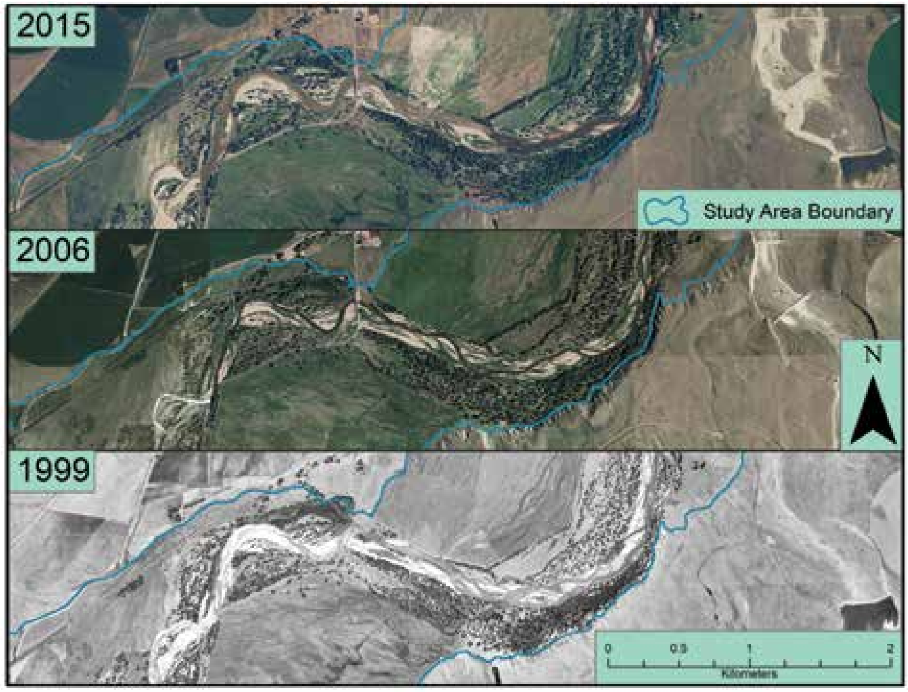


Figure 3. USDA Farm Service imagery of the same stretch of river from 1999, 2006, and 2015 from left to right. Graphic by Joshua Rogerson.

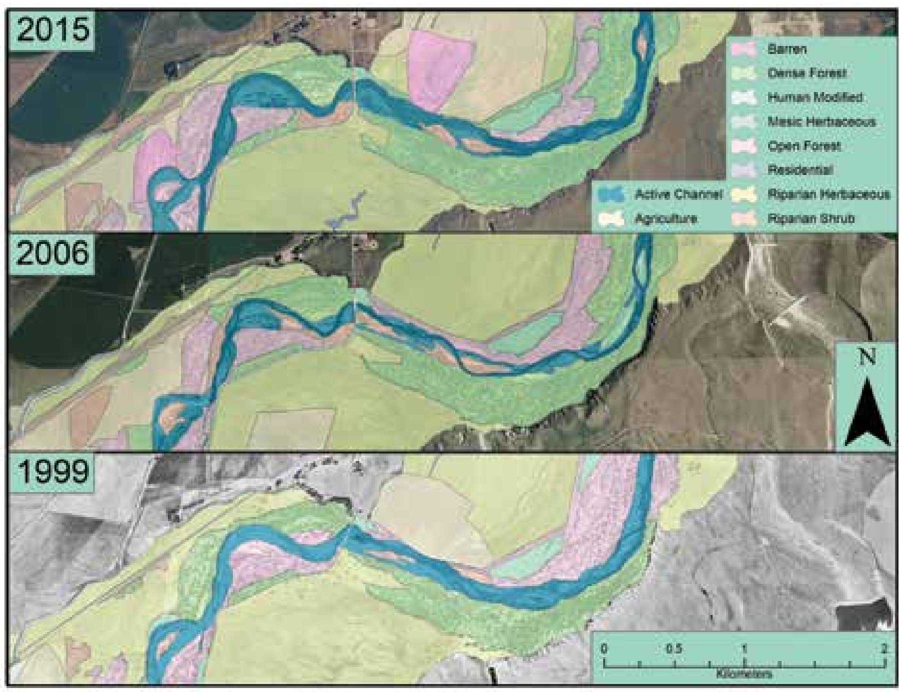


Figure 4. Delineated land cover polygons created from historic imagery and used to monitor riparian vegetation change. Graphic by Joshua Rogerson.

Starting in the 1840s, streamflow within the South Platte River system has been highly modified to meet human needs through considerable water inputs from trans-basin diversions, diversion points, and return flows from irrigation groundwater (Strange et al. 1999, Waskom, 2013). Prior to water development, South Platte River streamflow was dominated by mountain snowmelt, with high flows typically occurring in May and June and low flows occurring in late summer. There was substantial inter-annual variability in flow, resulting from climate fluctuations, resulting in a dynamic river system. A key effect of water management has been the stabilization of South Platte River streamflow (i.e., reduced seasonal flow variation) and augmentation of the alluvial aquifer by seepage from the vast network of recharge ponds irrigation ditches, canals and reservoirs (Waskom, 2013). The river still experiences yearly fluctuations (Figure 1), which impact the channel and surrounding vegetation. However, it is unknown how changes in streamflow from water management and natural variations (e.g., floods) currently impact channel location and riparian ecosystems. The objective of this research was to develop a method to understand historical trends in South Platte River channel migration and how those changes impact the land cover in riparian ecosystems.

Research Methods

Study Area

The study area is a 40 km section of the South Platte River, including the full extent of the riparian zone, approximately twenty-seven kilometers southeast of Greeley, Colorado (see Figure 2). It was randomly selected as one of three locations to test methods of historic cover type analysis. It includes the active channel, the surrounding riparian ecosystems, and human-made developments, which are representative of the river basin.

Data Collection

To investigate temporal change along the South Platte River, we classified and quantified the riparian land cover using geographic information systems (GIS) software and aerial images. Digital aerial imagery was acquired from the U.S. Department of Agriculture (USDA) Farm Service at roughly ten-year increments (i.e., 1999, 2006, and 2015, as seen in Figure 3 and Figure 4).

Using GIS and following stringent protocols, researchers used the aerial imagery to interpret and map land cover into ten categories: active channel (the wetted width and adjacent barren ground, including all sand bars and un-vegetated areas below the river banks), off-channel open water (irrigation ditches and reservoirs), mesic herbaceous (found adjacent to the active channel), herbaceous, shrub (vegetation > 6 m tall), open forest (25 – 50% forest canopy), dense forest (> 50% forest canopy), agriculture (irrigated fields, feed lots, and pastures), developed (urban, commercial, residential, industrial), and naturally barren land. Fieldwork was conducted as a part of a quality control program used to improve accuracy and familiarize researchers with

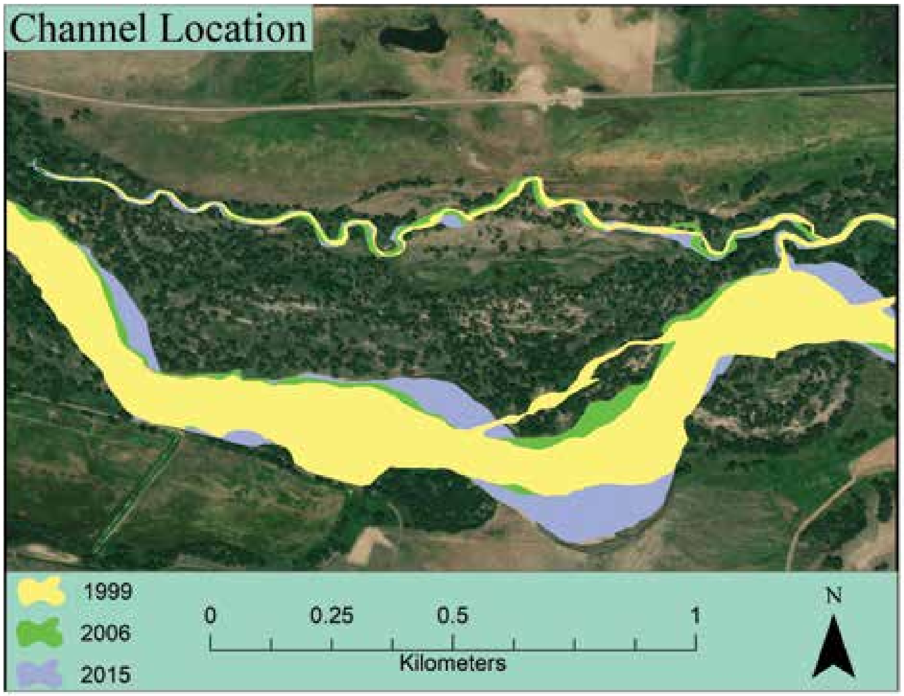


Figure 5. Active channel location from 1999 to 2015. Graphic by Joshua Rogerson

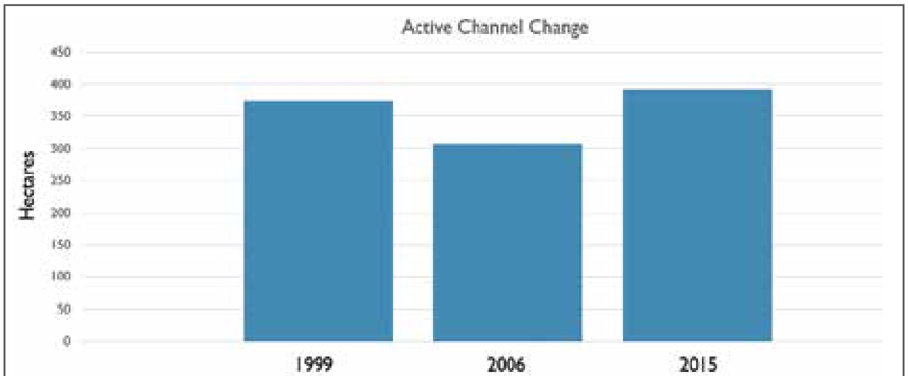


Figure 6. Active channel area fluctuation within the study area from 1998 to 2015.

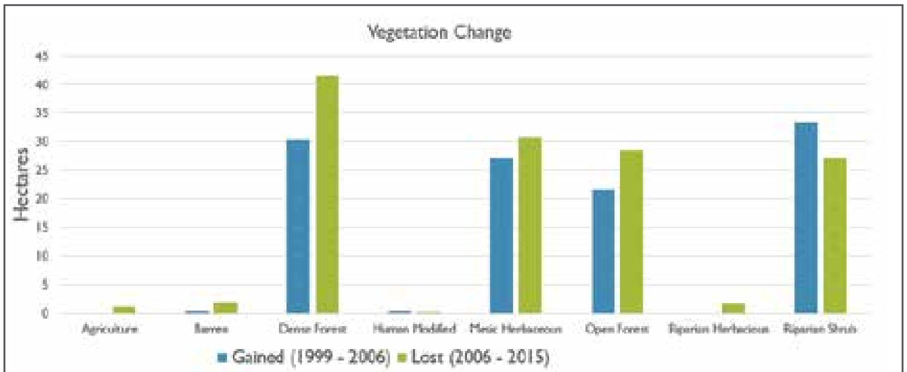


Figure 7. Selected land cover change from 1999 to 2006 and 2006 to 2015.

the study area.

Analysis

To compare and analyze active channel movement and its impact on surrounding vegetation, we intersected the active channel from a single year with the land cover data from the adjacent time period (e.g., 1999 to 2006). We summarized the overall area of each of the land cover types and calculated percent change for each pair of adjacent years. From this analysis, we determined if and what changes occurred in the riparian vegetation.

Results

As the active channel expands and contracts in response to changes in flow (Figure 5 and Figure 6), there are associated changes in the riparian vegetation. There was a period of active channel constriction from 1999 to 2006, with a 17.9 % decrease in active channel area during this time period which corresponded to drought conditions within the watershed. The constriction of the active channel from 1999 to 2006 allowed for the development of vegetation, including open and dense forests, mesic riparian herbaceous cover, and riparian shrubs.

The data analysis from 2006 to 2015, a period with multiple high flow events, revealed a 27.3% increase in the active channel area. During this time period, active channel expansion corresponded to large decreases in the area of specific land cover types: dense forest, mesic riparian herbaceous, open forest, and riparian herbaceous (Figure 7). The period of active channel contraction, during drought conditions, from 1999 to 2006 was accompanied by an expansion of most land cover types (Figure 7). However, from 1999 to 2015, there was a net decrease in a dense and open forest of 11.2 and 6.8 hectares, respectively, corresponding to an increase in the active channel area of 18 hectares. This inverse relationship could be indicative of a long-term decrease in riparian forests along the South Platte River. However, changes at the decadal scale are important to note and monitor, as longer durations of time fail to capture the dynamics of the South Platte riparian ecosystem.

Notably, more riparian shrub area was gained from 1999 to 2006 than was removed from 2006 to 2015 (Figure 7), resulting in a net increase in the area of this cover type. However, this growth could be due to seedling development of tree species instead of shrubs, as the method of delineation from aerial imagery does not allow for the differentiation between saplings and shrubs.

Conclusions

This pilot research indicates that the South Platte River corridor is a dynamic system and that variation in active channel area and position impact riparian vegetation. We documented changes in riparian vegetation that appear to be correlated with varying stream flows. However, it is unknown if this variation is substantial enough to cultivate new cottonwood forests. Further research is needed to help understand long-term land cover trends along the South Platte River and should gather data using more historical imagery to further understand the historical patterns of this ecosystem.

Participatory Mapping of Ecosystem Service Values in the Big Thompson Watershed

Luke Chamberlain, Master's Student and **Dr. Kelly Jones**, Associate Professor, Human Dimensions of Natural Resources, Colorado State University

Project Background

Ecosystem management can often benefit from increased representativeness through a concerted effort to incorporate values held by those who benefit from ecosystems. The ecosystem services concept offers researchers and managers a framework by which held values can be understood both spatially and non-spatially. Ecosystem services came into popularity with the Millennium Ecosystem Assessment (MA), where they defined them simply as "the benefits people obtain from ecosystems". Ecosystem services create tradeoffs in decision-making. For example, a forest provides services like habitat, biodiversity enhancement, carbon storage, and climate regulation. A forest also represents the potential for other services if it is, for example, harvested for timber, cleared to make way for agriculture, or enhanced to provide recreational opportunities. Understanding ecosystem service values allows decision-makers to understand tradeoffs that are present. They are then better equipped to predict which groups may benefit most from certain management decisions. Mapping ecosystem services is a tool in a manager's toolbelt that allows the spatial dynamics of these trade-offs to be visualized.

In Colorado, people benefit from a variety of services that the ecosystems provide. The mountain views, recreation, access to clean air and fresh water are near the top of the list. As more people move to the Front Range, an increased demand for ecosystem services is accompanied by an increased threat to those services from development, overuse, and wildfires. More people, values, and threats combined create a complicated, dynamic web of interactions between ecosystems, benefits, and beneficiaries.

Therefore, we set out to better understand the ecosystem service perceptions and preferences of the beneficiaries of one of Colorado's important watersheds—The Big Thompson. Our goal was to apply the ecosystem services framework to understand spatial and non-spatial patterns that drive demand for various ecosystem services in the Big Thompson. Then, we aimed to use the spatial patterns of ecosystem services and wildfire hazards to identify zones of concern in the watershed where values may be most at risk.

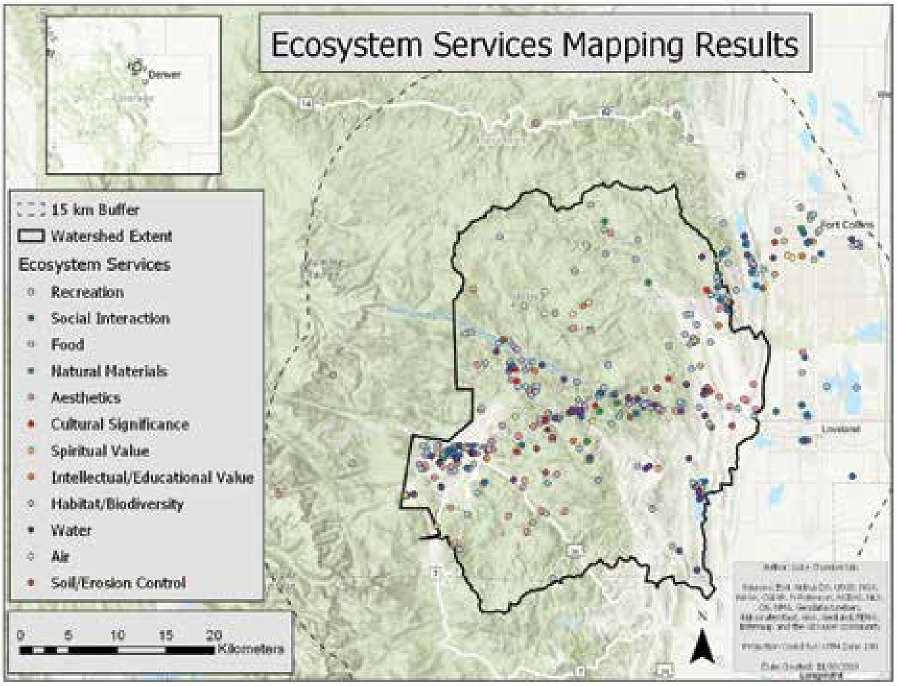


Figure 1. A map of the Big Thompson Watershed boundary as presented in the online mapping survey.

Methods

We elected for a participatory mapping approach to describe ecosystem service values in the Big Thompson Watershed. Our goal was to achieve a representative sample through a random household survey of beneficiaries of the watershed. People within the watershed boundary and people living in municipalities that receive water from the Big Thompson River were targeted. An online mapping survey interface was developed through maptionnaire.com and flyers advertising people to participate were sent out to a random sample of 2,000 households. The full survey is available at app.maptionnaire.com/en/6481/. This was supplemented by door to door handouts in randomly selected neighborhoods within the study area. Data collection was open through the online survey for a period of three months, from August to November 2019.

In the survey, participants were asked to map the location of their home and the locations of ecosystem services that they value. They were given a list of thirteen services to choose from (recreation, social interaction, food, natural materials, aesthetics, cultural significance, spiritual value, intellectual/educational value, intrinsic value, habitat/biodiversity, water, air, and soil/erosion control). Beyond the mapping portion, the survey also consisted of a value allocation exercise where participants were asked to assign a hypothetical dollar value out of a possible $100 for the protection of each of the thirteen ecosystem services in question. We used both the spatial and non-spatial aspects of a participant's ecosystem service values to create their "demand score" for each ecosystem service.

Table 1. Summary of mapped ES points, allocated value, and ES demand within the watershed boundary.

ES	# Mapped Points	Mean $ Allocated	StdDev $ Allocated	Mean Demand	StdDev Demand
Water	35	24.37	19.55	35.05	33.72
Biodiversity/Habitat	42	16.00	16.25	26.67	35.18
Recreation	105	10.08	9.93	26.58	32.89
Air	17	11.02	12.28	15.31	23.34
Aesthetics	78	6.81	7.87	15.08	21.17
Soil/Erosion Control	20	6.79	6.74	9.08	10.81
Food	12	6.65	8.75	8.44	12.94
Non-use	24	5.13	10.87	7.67	20.84
Cultural Significance	16	3.77	5.10	5.20	8.24
Natural Material	8	2.62	4.76	3.15	5.85
Intellectual/Education	14	2.35	3.94	2.99	5.06
Spiritual	13	2.18	5.55	2.92	7.01
Social Interaction	31	1.31	2.60	2.18	4.96
Total	415				
Total (15km Buffer Area)	396				
Total (Study Area)	321				

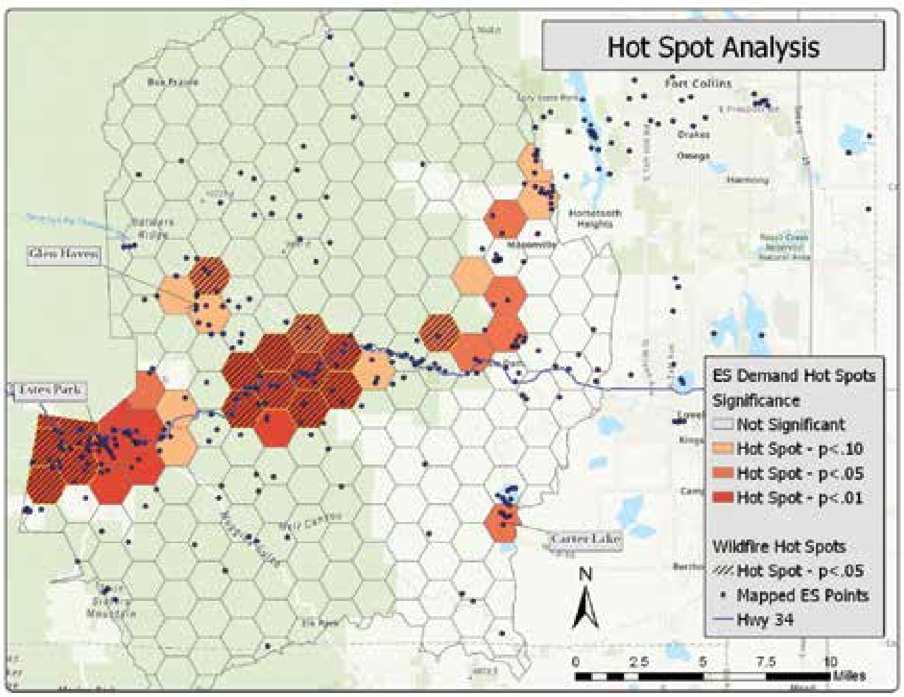


Figure 2. "A map displaying zones of overlap between ecosystem service perceptions (ES Demand) and wildfire hazard hotspots.

In our analyses, we identified spatial hot spots of ecosystem service value—areas where mapped points were clustered and assigned values for those services were high. We overlaid these hotspots with hotspots of wildfire risk to identify zones where ecosystem service values were most threatened by wildfires. We sought to draw correlations between ecosystem service demand and features on the landscape (e.g., presence of water, elevation, land ownership, land use, development, and accessibility). We also attempted to determine whether socioeconomic factors (education, income, occupation, state residency, land ownership, and familiarity with the area) affected a household's ecosystem service perceptions and preferences.

Results

In total, 98 respondents mapped 415 points (5.93 points per respondent). Water, biodiversity, recreation, and aesthetics were the most mapped services and, along with air, were the five most valued in the dollar allocation exercise. Table 1 displays the rankings of which services were most important to participants.

The presence of water was a strong predictor for demand value on the landscape (p=.007). Accessibility was the strongest predictor, with proximity to roads (p=.008), buildings (p=.006) and developed areas (p=.014) all being significantly correlated with ecosystem service demand. Elevation (p=.038) and forest land cover, interestingly, were both negatively correlated (p=.002).

There were fewer clear relationships between ecosystem service values and socioeconomic characteristics. However, some differentiation occurred in respondents with higher levels of income and education having a higher preference for recreation services. However, most socioeconomic relationships were insignificant.

See the maps below for the spatial distribution of all mapped points as well as the density distribution of the four most commonly mapped services (recreation, aesthetics, habitat/biodiversity, and water). Finally, the third map displays the locations of ecosystem service value and wildfire hazard hotspots.

Discussion

Future studies that wish to utilize similar methods could build on and improve upon our work by reaching a broader suite of stakeholders. Our study was limited in its over representation of voices that skewed toward higher income and higher education attainment. A greater effort to include the voices of those typically underrepresented in natural resources decision-making (i.e., the poor and working-class) would be a powerful addition to any future PPGIS studies in the area. Additionally, our decision to focus solely on individual perceptions of ES benefits excludes community and group benefits, an important aspect of ES demand that requires further exploration.

Our results highlight the power of participatory mapping as a device to increase the democratization of natural resources governance on a regional or small scale. These methods could be scaled down further to a more local level and could be used to target specific stakeholders, services, or threats. We hope that this will spark interest in more participatory research in the Front Range, and that we can use these spatial tools to increase the connection between science, the environment, and those that can benefit most from having their voices heard.

Quantifying Groundwater Recharge Below Losing Stream Reaches in the Denver Basin

Kristen Cognac, Doctoral Student and **Dr. Michael Ronayne**, Associate Professor, Geosciences, Colorado State University

Introduction

The predominant mechanism for recharge within basin aquifers that border mountain fronts, such as the Denver Basin is focused seepage along stream channels. Moreover, Seepage fluxes reflect the rate of exchange between surface and groundwater and are defined as the volume of water flowing through a unit cross-sectional area of streambed per unit time. Downward (negative) seepage fluxes indicate surface water recharge to groundwater, and upward (positive) seepage fluxes indicate groundwater discharge to surface water. Total recharge along a stream reach may be estimated by multiplying the seepage flux by the surface area of the streambed. As such, estimates of seepage are useful for understanding the rates at which aquifers are replenished.

In Colorado, most streams exhibit natural variations in stage and temperature related to geographic, climate, and anthropogenic factors. As a result, seepage fluxes can be highly variable through time and space and are notoriously difficult to quantify. Newer methods that use heat as a tracer to quantify streambed fluxes have become popular for their ease of use and cost-effectiveness. However, these methods have not been rigorously tested in mountain-front streams with large variations in water temperature.

This project aimed to quantify seepage fluxes below two losing stream reaches in Colorado through flow and heat transport modeling in order to:

1. Better understand the magnitude and variation in seepage recharge along mountain-front streams in Colorado.
2. Determine whether heat-based methods can be used to estimate seepage fluxes on streams that exhibit variable stage and temperature.

Study Sites and Streambed Piezometers

An existing network of nested piezometers located along with East Plum and Cherry Creeks in Douglas County, Colorado, provided an initial monitoring framework for this study (Figure 1). Each nest location includes a minimum of two piezometers with slotted intervals installed at different depths beneath the streambed. This project enabled a targeted expansion of the piezometer network to include an additional deeper piezometer and more detailed instrumentation at sites highlighted in Figure 1. Each piezometer was instrumented with temperature and pressure sensors programmed to log data at 10-minute intervals. A barometric pressure logger was centrally located to aid in the conversion of pressure data to hydraulic head.

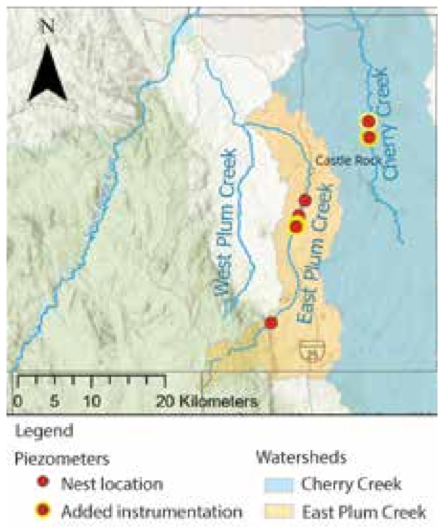


Figure 1. Piezometer nest locations along East Plum and Cherry Creeks in Douglas County, Colorado. Locations with added instrumentation (this project) are highlighted.

Figure 2. Undergraduate research assistant Matt Tyrell collecting data from piezometer nests along Cherry and East Plum creeks.

Site visits were carried out every three months to download data, perform maintenance tasks, and conduct field testing. Field testing involved performing seventeen falling head permeameter tests for estimation of streambed hydraulic conductivity and collecting eighteen streambed sediment samples for subsequent lab analysis to constrain thermal and hydraulic parameters for modeling (Figure 2).

Estimating Seepage Fluxes

Seepage fluxes were estimated using numerical flow and heat transport modeling, as well as Darcy based methods for comparison. Numerical modeling was performed using the U.S. Geological Survey model VS2DH, which simulates water flow and heat transport through sediments beneath the stream. For each nest location, upper and lower model boundary conditions were assigned using the measured temperature and head data from shallow and deep piezometers, respectively. Intermediate-depth piezometer data were used to calibrate hydraulic and thermal parameters to achieve the best-fit between model and field data. Thermal and hydraulic parameters were constrained using estimates from field tests and reported values from the literature. For Darcy-based seepage, fluxes were estimated as the vertical hydraulic gradient, calculated from hydraulic head data, multiplied by the best fitting, hydraulic conductivity from field tests and modeling.

Results

Seepage flux estimates ranged from -0.01 to -4.2 m/d across the four sites, with general flux results summarized in Table 1 and plotted in Figure 3. Downward seepage fluxes were documented throughout the study period in all four piezometer nests except location CC-A, which exhibited upward seepage for a brief period in August 2020. Daily, seasonal, and event-based seepage variations occurred at all four measurement locations. Variability included year-round daily fluctuations in seepage, which correlate with daily temperature signals and are likely related to cycles of evapotranspiration and stream stage. Seasonal trends document the greatest seepage losses between July and January and minimum seepage losses between March and May. Locations with the greatest mean downward seepage also showed greater seasonal variations. Event-based variability included sudden, non-trending and non-cyclical changes in seepage that lasted for days to weeks related to sudden stream stage changes (possibly by rapid snowmelt) or nearby beaver dams observed during site visits.

Numerical heat and flow modeling was successfully used to quantify streambed fluxes along four highly variable losing stream reaches. Models accurately reproduced observed hydraulic heads, temperatures, fluxes, and general seepage patterns compared to field data and Darcy flux estimates, as highlighted in the example model results in Figure 4. Numerical modeling enabled better constraints on hydraulic parameters that are necessary for estimating seepage fluxes as compared to Darcy methods. Sensitivity testing confirmed that while heat-based models were able to reproduce seepage variations, time-varying hydraulic-head inputs were essential for accurately matching field data.

Research Impact and Next Steps

Colorado streams show highly variable seepage fluxes over daily, seasonal, and sporadic time scales. Quantifying the magnitude, timing, and variability of seepage fluxes is essential for making accurate estimates of groundwater recharge. This study showed that heat-based modeling approaches may be useful for improving seepage estimates below losing streams in Colorado. Numerical models can also provide additional insights into the controls and dynamics of observed seepage variations, which is the focus of our forthcoming paper that incorporates related methods and datasets.

Acknowledgments

Support from the Colorado Water Center for this project is greatly appreciated. Additional funding for the instrumentation and monitoring was provided by Castle Rock Water.

Table 1. Summary of seepage fluxes at four active measurement locations during the study period.

Location	Seepage Flux (m/d)			
	Min.	Max.	Mean	Max. Daily Change
CC-A	-0.50	0.08	-0.10	0.2
CC-B	-4.2	-0.80	-2.1	0.7
PC-B	-3.3	-0.70	-1.3	0.7
PC-C	-3.5	-0.12	-1.0	0.6

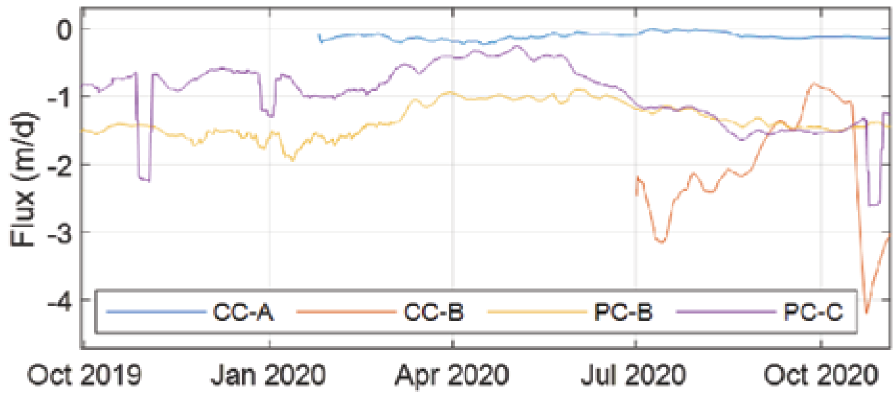


Figure 3. Fluxes at four modeled sites during the study period. Plotted fluxes are smoothed to highlight general trends. Locations CC-A and CC-B were installed during the study period, and CC-B was affected by a downstream beaver dam in October, 2020

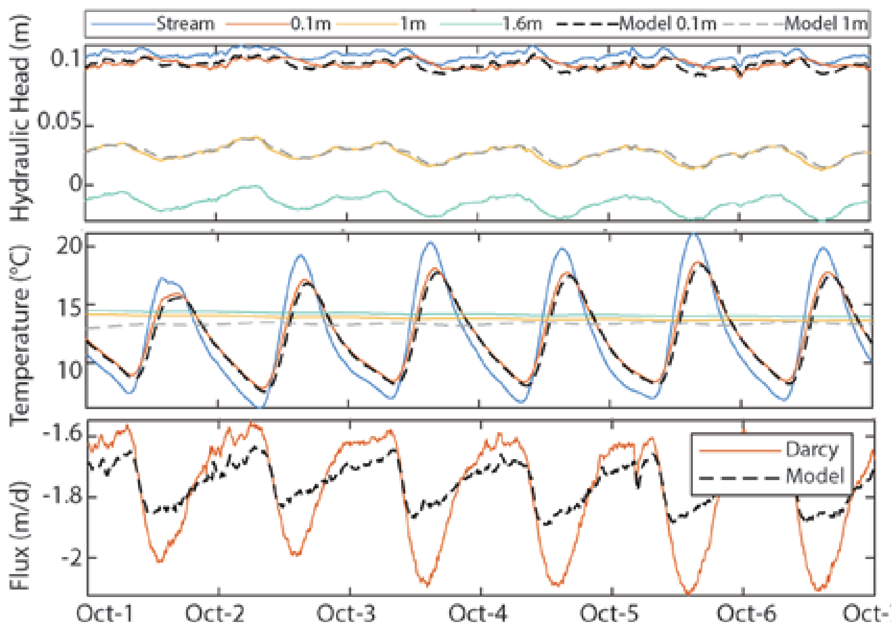


Figure 4 – Example model results from location PC-B which includes four piezometers slotted, from shallow to deep, within the stream, and at 0.1m, 1m, and 1.6m below the stream. Simulated hydraulic heads and temperatures are compared to observed values (at intermediate measurement depths) in the upper two plots. Model results closely track the field data. The bottom plot shows estimated seepage fluxes from Darcy and VS2DH (heat-transport modeling) methods. Despite notable differences in diel variations, general trends and the overall magnitude of fluxes are captured very well.

Floodplain Forest Establishment and Legacy Sediment Within the Yampa River Basin, Northern Colorado

John Kemper, Doctoral Student, Geosciences, Colorado State University, **Richard Thaxton**, Doctoral Student, Laboratory of Tree-Ring Research, University of Arizona, **Dr. Sara Rathburn**, Associate Professor, Geosciences, Colorado State University, and **Dr. Jonathan Friedman**, Research Hydrologist, U.S. Geological Survey

Introduction

Floodplain forests are among the most productive, diverse, and dynamic ecosystems in dry landscapes (Naiman et al., 2010). In a natural state, these forests exhibit high biodiversity and productivity and have important recreational and aesthetic value. However, floodplains are among the most altered environments worldwide (Tockner and Stanford, 2002). Colorado is no exception: dam-associated flow diversions, sediment entrapment, and peak flow alterations have led to the decline of forests in many locations (Schook et al., 2016). Maintenance of these ecosystems for a future fraught with potential changes in hydrology, land use, and land cover requires improving our understanding of water, sediment, and vegetation dynamics at scales capable of capturing the linkages between geomorphic, hydrologic, and ecological processes (Steward et al. 2004; Carbonneau et al., 2012).

Throughout the Yampa River system of northwestern Colorado, Fremont cottonwoods (*Populus fremontii*) are the most abundant native tree species found in riparian floodplain forests (Scott and Friedman, 2018). These cottonwood forests are disturbance-driven ecosystems dependent on sediment-laden floods that result in channel migration that creates new floodplain surfaces (Scott et al., 1996). Three key tributaries of the Yampa River show evidence of extreme erosion that created deep, vertical-walled, flat-bottomed channels known as arroyos, which occurred sometime in the late 19th to early 20th century. Given the dependence of cottonwood forest on channel change for the establishment and that considerable increases in sediment load—such as those that occurred due to extreme erosion across the Colorado River Basin (Gellis et al., 1991)—have been shown to drive channel morphological change (Nelson and Dube, 2016), we use this opportune assemblage of watershed characteristics to investigate the hypothesis that downstream cottonwood floodplain forests are a direct result of extreme erosion in the headwaters that deposited a large volume of legacy sediment along the Yampa from the late 19th to early 20th century. This research seeks to expand understanding of the controls on floodplain cottonwood establishment and highlight the value of sediment as a critical ecological resource to be managed jointly with the flow in order to ensure the maintenance of vital riparian ecosystems.

Top of page—John Kemper (left) and Dr. Sara Rathburn inspect a cottonwood core, Dinosaur National Monument

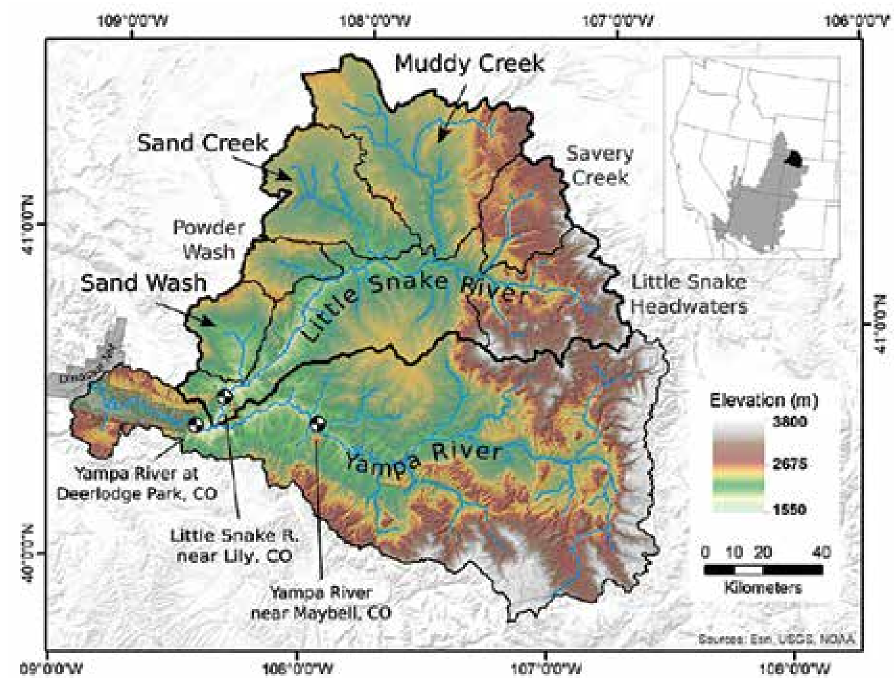


Figure 1. The Yampa River Basin and major tributaries

Study Site

The Yampa River is the last largely unregulated major tributary in the Colorado River system. In the semi-arid climate of northwestern Colorado, the Yampa River is an essential water source for agriculture, power generation, and municipalities as it flows westward from the Rocky Mountains across broad lowlands (Roehm, 2004). In addition to a vital water supply, the Yampa River floodplain forest, composed largely of cottonwood trees, creates diverse ecosystems that provide essential ecological and human benefits disproportionate to forest size. For its final 70 km, the Yampa River flows through Dinosaur National Monument, an area of major conservation and recreation importance where extensive floodplain cottonwood gallery forest occurs, particularly in Deerlodge Park where this research is focused (Merritt and Cooper, 2000). The primary tributary to the Yampa is the Little Snake River, and 60% of the total sediment load of the Yampa is derived from the lower Little Snake tributaries of Muddy Creek, Sand Creek, and Sand Wash. Past substantial erosive floods have occurred within these basins (Topping et al., 2018), and evidence of historic arroyo incision is widespread.

Methods

In order to date the observed past arroyo incision, historical documents and photographs were compiled. General Land Office (GLO) survey notes were obtained for the initial GLO survey, and subsequent resurvey in Muddy Creek, Sand Creek, and Sand Wash. Survey notes contain qualitative descriptions and rough quantitative measurements of channel dimensions, ranging from simple notation and observation to measurements of the channel width and depth. In addition to survey notes, GLO maps were obtained for each township and range section in the tributary watersheds. Initial and resurvey GLO notes and maps date to 1882 and 1906 in Sand Wash, respectively, to 1883 and 1915 in Sand Creek, and to 1881 and 1916 in Muddy Creek. Aerial photographs for each tributary basin were obtained from the U.S. National Archives and U.S. Geological (USGS) Earth explorer. Earliest photographs date to 1938 for all three basins. Comparison between initial and resurvey notes and the 1938 photographs enabled arroyo incisions to be bracketed to certain periods of time.

To determine the area-age dates of the floodplain forest, we constructed polygons of the current forest using 2017 aerial imagery and generated 50 random points within the constructed forest polygons. In the field, we then used an increment borer to collect a core from the tree nearest the randomly generated points in order to obtain samples that represented 2% of the forest. Because cottonwoods are preferentially established on new, bare floodplain surfaces (Scott et al., 1996), this method also allowed the estimation of the age of the surfaces on which the trees were established. Using this assumption, along with historical aerial photographic analysis and interpretation of current tree size from modern NAIP imagery, we constructed a map of floodplain age within Deerlodge Park.

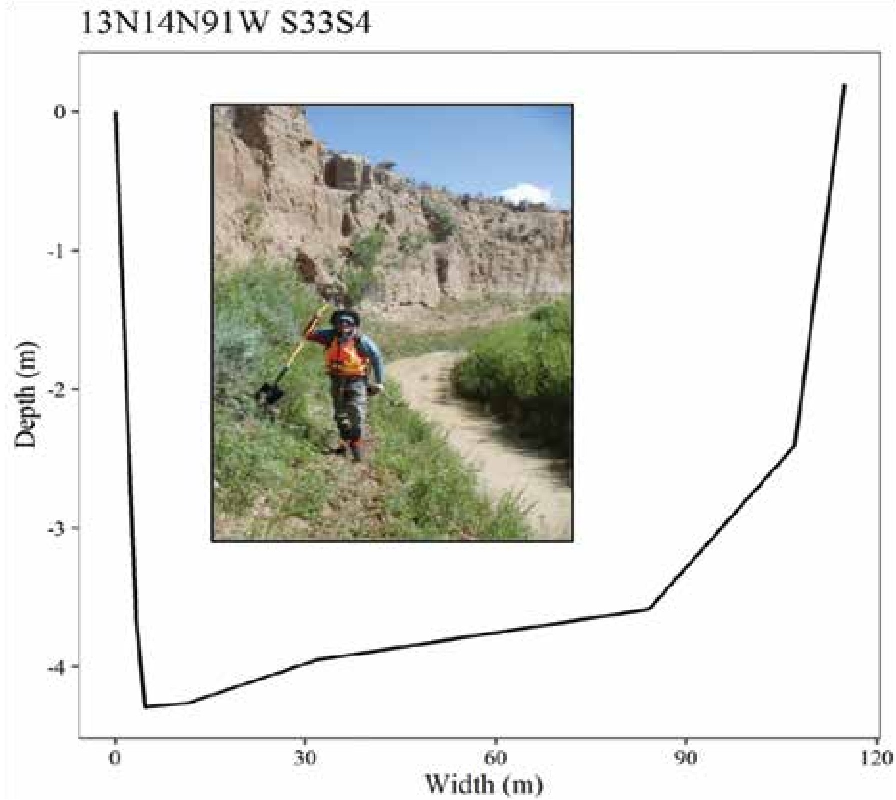


Figure 2. Present-day cross section and photo of Muddy Creek where it is crossed by the section line indicated in the upper left. 1915 GLO survey notes depict the creek as historically 20 ft wide at 2 ft deep.

John Kemper cores a cottonwood tree, Deerlodge Park, Dinosaur National Monument.

Results

Dating Arroyo Incision in the Tributaries

In Sand Wash, the most proximal tributary to Deerlodge Park (Figure 1), a comparison of the initial 1882 survey map and 1906 resurvey map suggests that arroyo incision likely occurred in the intervening years between surveys. The channel in the original survey map is represented by a thin line, and references in the survey notes refer to it as a "gulch," whereas in the 1906 resurvey map, the wash is depicted as a wide, stippled channel. We interpret these differences as evidence that a significant arroyo incision occurred sometime between 1882 and 1906 in Sand Wash.

In Muddy Creek, neither the 1881 initial survey notes nor the 1915 resurvey notes contain any mention of the substantial incision now present at nearly all locations where section lines cross the creek (e.g., Figure 2). In all cases, the surveyor's measurements suggest that the creek was shallow and of varying width. In addition, water rights for irrigation ditches dated to 1925 suggest that the creek was not yet heavily incised in these locations at that time; it is unlikely that gravity-fed ditches would have been used to irrigate out of a creek that was incised nearly 4 meters below the surrounding land surface. Finally, aerial photographs from 1938 show a channel that appears wide and deep at nearly all section lines. Taken together, we believe this is evidence that arroyo incision occurred between 1915-1940 in Muddy Creek, with the most active period of erosion falling between 1925 and 1940.

Deerlodge Cottonwood Forest and Floodplain Age

Ages calculated via dendrochronological analysis of tree cores from 50 spatially randomized cottonwoods were binned into twenty-year periods (Figure 3a). In total, about 22% of the surviving forest in Deerlodge was established prior to 1890. Immediately following this period of slow but steady establishment, ~44% of the forest was established between 1890-1930. About 7% of the forest was established from 1930-1950, and then very little establishment occurred until the period between 1990-2010 when the remaining 23% of the forest was established.

Given that the cottonwoods establish on newly constructed floodplain surfaces, we then used cottonwood ages to date disparate floodplain surfaces, which were identified via a Digital Elevation Model created from LiDAR (Figure 3b and 4). The most striking result of this analysis is that floodplain construction occurred in two pulses: a large pulse that built roughly 70% of the current Deerlodge floodplain during the period between 1870-1930 and a smaller pulse that constructed about 11% of the current floodplain from 1990-2010. Construction of the remaining floodplain area was dispersed throughout time.

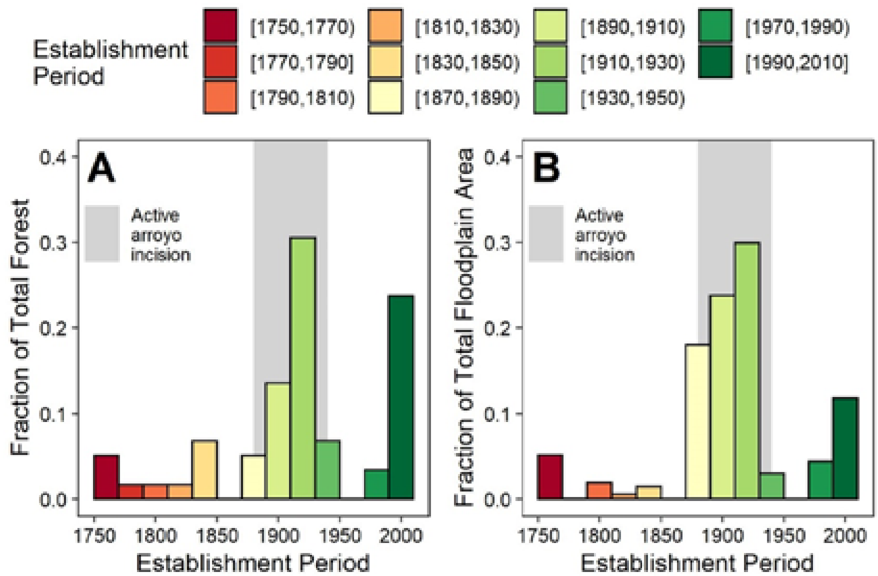


Figure 3. A) Proportion of the current Deerlodge forest by establishment period and B) Proportion of the current floodplain in Deerlodge Park by establishment period.

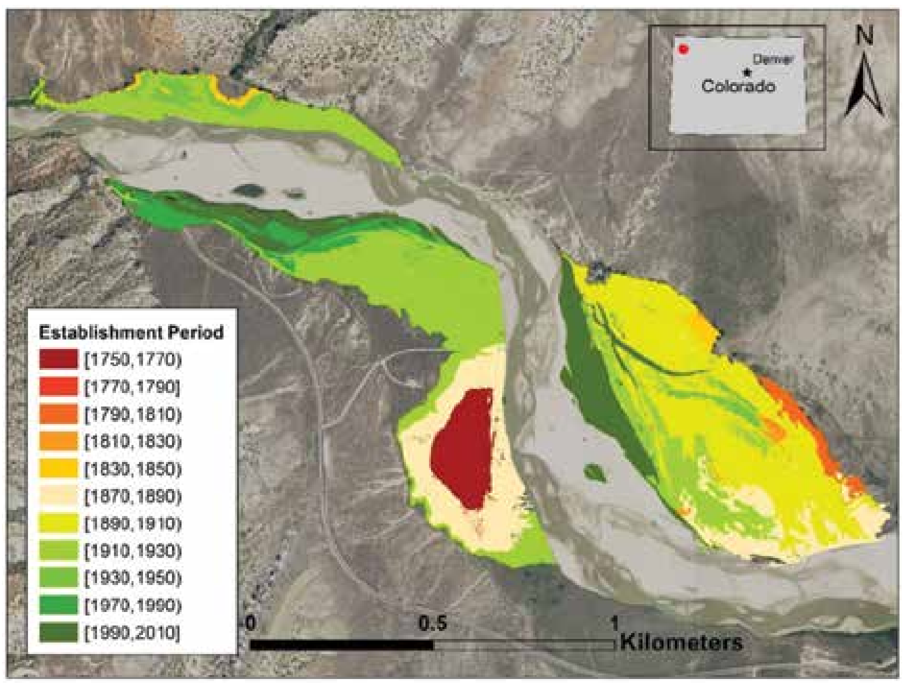


Figure 4. Map of the Deerlodge floodplain by establishment period.

Discussion and Conclusion

Inspection of historical documents and aerial photographs suggests that Sand Wash and Muddy Creek, two key tributaries of the Yampa River, underwent significant historical erosion via arroyo incision in the late 19th to early 20th century. We thus propose that there was a period from roughly 1880-1940 where one or both tributary watersheds were actively incising, which in turn suggests floods on the Little Snake and Yampa Rivers during this time were charged with sediment from active erosion in the tributaries.

Area-age distributions of the floodplain forest within Deerlodge Park (Figure 3a) indicate that much of the forest was established within the time frame of heightened sediment loads due to active arroyo incision in the tributaries. Floodplain area and maps of floodplain age (Figures 3b and 4) corroborate this finding and suggest that approximately 79% of the floodplain and associated cottonwood gallery was built as a result of active extreme erosion in the tributaries.

We propose that the demonstrable link between headwater erosion and distal downstream ecological processes (e.g., forest establishment) validates the idea that upstream watershed dynamics play a key role in governing ecological processes such as riparian forest establishment and growth. From these results, two important management implications arise: 1) cottonwood forests along the Yampa River will likely decline regardless of the maintenance of the current flows, and 2) management of upstream sediment loads and flows are fundamental to the long-term health of Yampa River forests. Overall, the results of this study suggest that holistic, basin-scale management of watershed resources—land, sediment, and water—are essential for floodplain forest and ecosystem health.

Fine Scale Data Collection for Future Snowmelt Modeling Near Silverton, Colorado

Alison Kingston, Doctoral Student, Geosciences, Colorado State University, **Dr. Steven Fassnacht**, Professor, Watershed Science, Colorado State University, and **Jeff Derr**y, Executive Director, Center for Snow and Avalanche Studies

Figure 1. A selfie after field work by Ashlee Clarke (left) with Alison Kingston (right).

Figure 2. Site map of the study area a) in the U.S., b) within Colorado, c) in the Senator Beck Basin (SBB) near Red Mountain Pass (RMP) SNOTEL, showing the Swamp Angel Study Plot (SASP) snow-meteorological station, and d) the location of the five temperature and relative sensors.

Introduction

The purpose of this study was to acquire and understand the impact of fine resolution inputs on snowmelt in Southern Colorado, specifically Senator Beck Basin. This report is going to focus on the data that were successfully collected in the field (Figure 1) for purposes of downscaling meteorological model data to drive a finer-resolution snow model. Modeling of snowmelt is key to providing useful new information for water resources management, especially in southern Colorado that has been in drought for much of the past two decades. This fieldwork collected temperature (T) and relative humidity (RH) data along a transect in Senator Beck Basin (Figure 2), near Silverton, Colorado using iButton sensors (Figure 3).

Methodology

While twelve temperature-only iButton sensors were installed across the study site, this analysis investigated T and RH spatial variation, thus data were only used from five T and RH iButton sensors (Figure 2). All sensors were installed in October 2018. In southern Colorado, the 2018-2019 winter had the deepest snowpack in two decades (Figure 4). The initial focus was the entire 2018-2019 winter, but due to logistics and sensor memory limitations, data were only available from late February 2019 through August 2019 (Figures 4 and 5). However, since some of the sensors were buried by snow for a portion of the study period (sensor E21 in Figure 5), the analysis was focused on the snowmelt period from mid-May to the end of July. The beginning of snowmelt was estimated using snow water equivalent (SWE) data from the nearby Red Mountain Pass (RMP) SNOTEL station (Figure 4).

Relative humidity data were converted to dewpoint temperature data for the

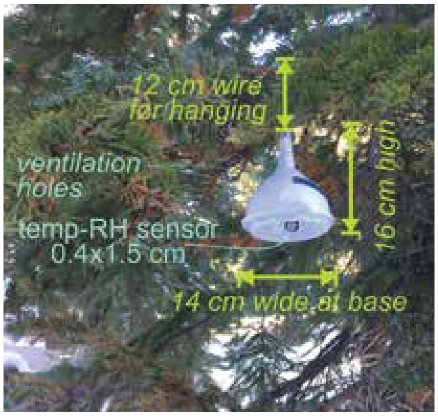


Figure 3. An iButton sensors housed within a double funnel, placed on the north side of an evergreen tree (Fassnacht et al., 2019; Collados-Lara et al., 2020). Photo by Steven R. Fassnacht.

analysis. To assess the spatial variability of air temperature (T_a) and dewpoint temperature (T_d), a linear regression was applied to the hourly temperature data versus the elevation of the sensors (Collados-Lara et al., 2020). The slope and correlation coefficient were computed for this temperature-elevation gradient. These were assessed as a mean for each hour over the focus period and as a mean for each day over the focus period.

Results

On average, dewpoint temperature-elevation gradients (TEG) were more consistent over the day than air TEG (Figure 6a). Dewpoint TEG varied from -12.1 C/km at 8 am to -2.2 C/km at 1pm, while air TEG varied from 13.6 C/km at 6am to -43.6 C/km at 10 am (Figure 6a). The strength of the correlation for dewpoint TEG was stronger at night, but for air TEG the correlation was similar, except at 7 am (dawn) and 8 pm (dusk) (Figure 6a).

The mean daily dewpoint TEG was initially positive then became consistently negative after June 1^{st} (Figure 6b). For air TEG, it was initially a large negative and then became smaller; after July 4^{th}, it began to fluctuate between mean positive and negative values (Figure 6c). The regression correlation was strongest when TEG was largest, both positive and negative (Figure 6d). While not shown here, temperature-elevation gradients varied more for individual hours (Collados-Lara et al., 2020).

Discussion and Further Research

Many downscaling assessments use the environmental lapse rate (ELR) of -6.5 C/km. The data show fine-scale temperature-elevation gradients can be quickly different than the environmental lapse rate, and at times can be positive. This occurs on calm nights due to cold air drainage (Collados-Lara et al., 2020). The variation in dewpoint temperature-elevation gradients was more consistent than those computed for air temperature since moisture content in the air varies much less over a day than the air temperature. The early melt period positive dewpoint temperature-elevation gradients (Figure 6b) were likely due to varying snow depths below the sensors.

The variation in temperature and relative humidity, shown here as dewpoint temperature, as we move up in elevation along a transect can be substantial, even in a relatively small study area. Additionally, there are interesting patterns over the day and over the melt period in the data (Figure 6). These results highlight the importance of considering fine-scale

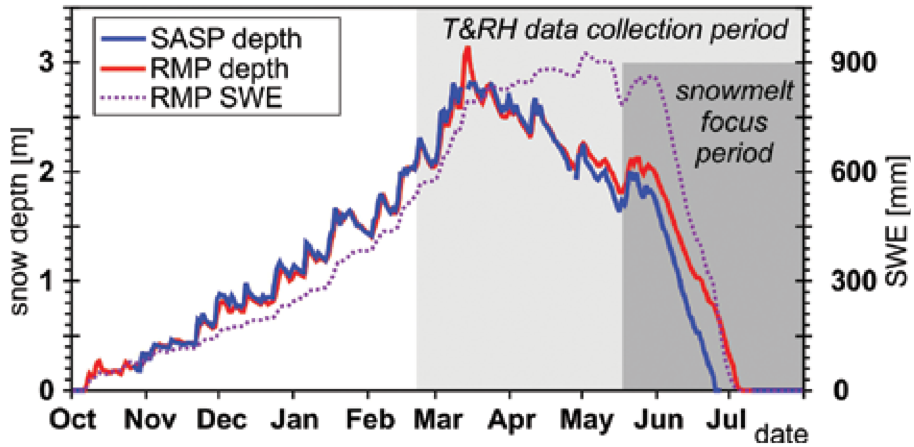


Figure 4. Snow depth at Swamp Angel Study Plot (SASP) at SBB for 2019, plus snow water equivalent (SWE) and snow depth recorded at the nearby Red Mountain Pass (RMP) SNOTEL. RMP SWE are for 2019 and the median from 1998 to 2019.

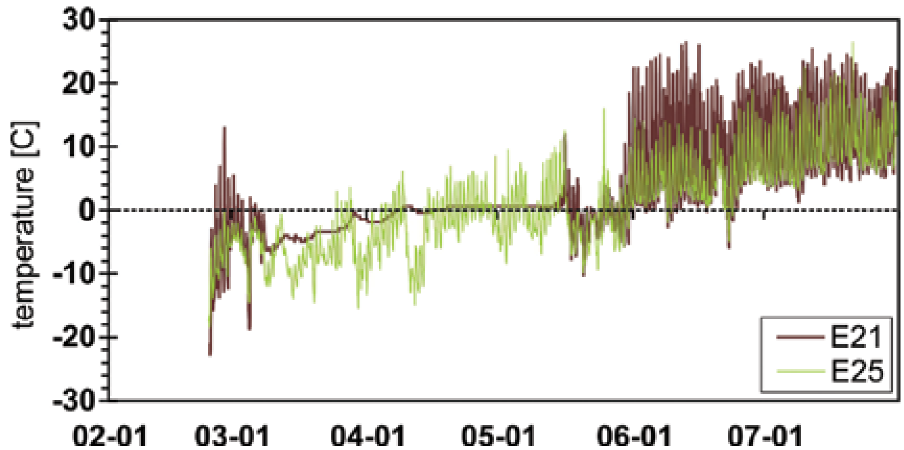


Figure 5. Hourly air temperature over the study period for E21 and E25. Sensor E21 was installed at an elevation of 3365 meters and sensor E25 was installed at an elevation of 3412 meters.

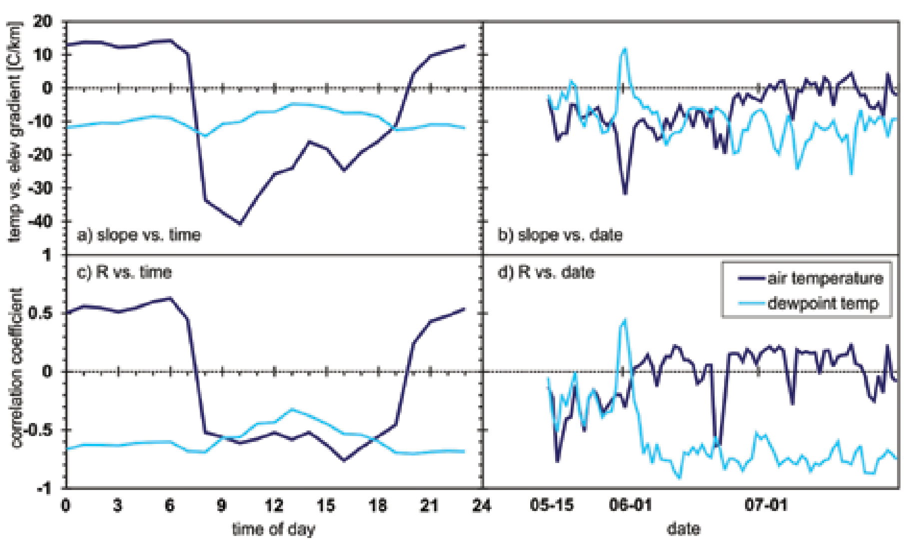


Figure 6. Mean temperature-elevation gradient or slope for a) time of day, and b) date, and correlation coefficient for the corresponding c) time of day, and d) date, over the study melt season.

variability in the meteorological driving data for snowmelt modeling. This can have implications for understanding melt processes and differential melt rates and can help better inform water managers about snowmelt input into headwater river systems. Future research will use these results to downscale meteorological data from the Weather Research and Forecast (WRF) model to use as input the data into SnowModel to better inform melt characteristics and runoff patterns.

Diel Signals in Hydrologic and Chemical Signals Along the North Saint Vrain

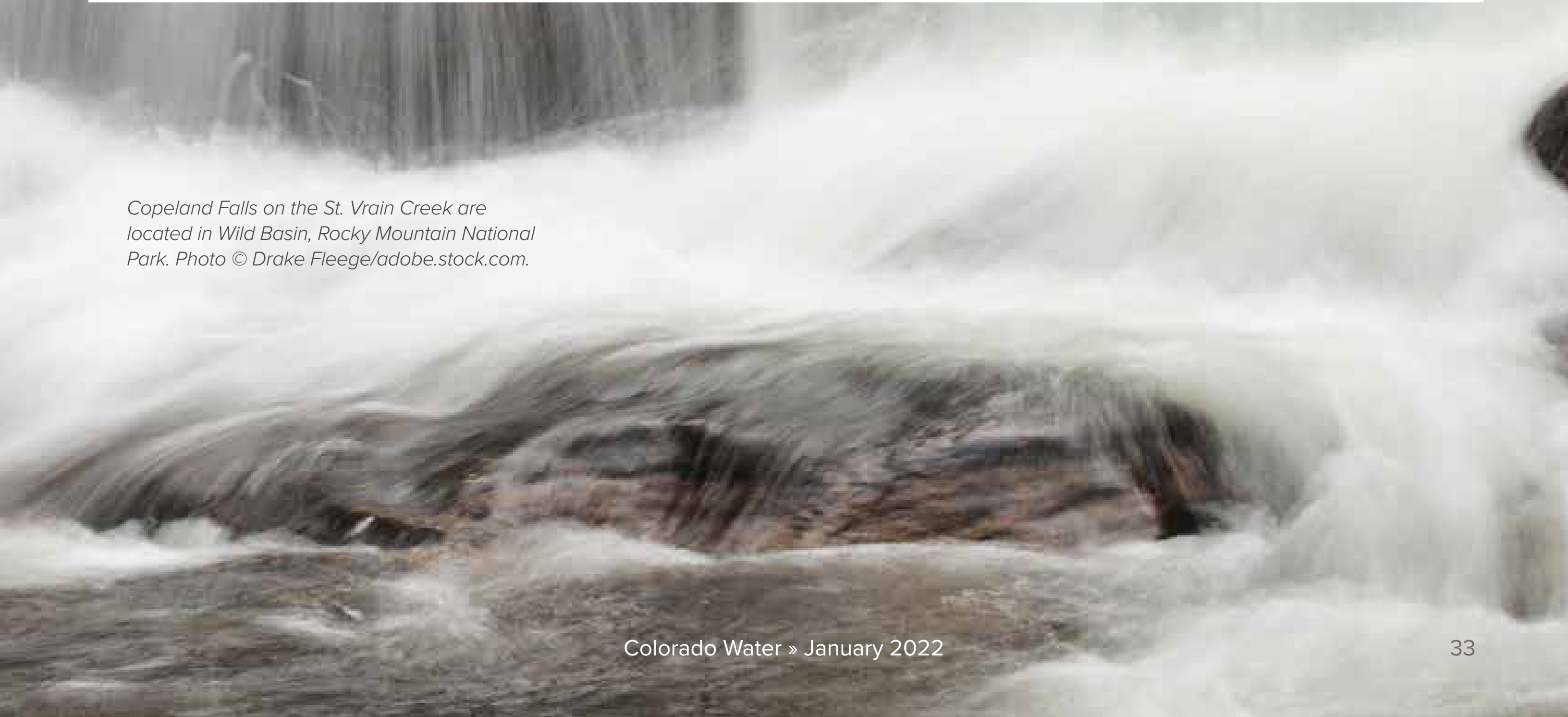
Danielle Palm, Undergraduate Student, Ecosystem Science and Sustainability, Colorado State University
and **Dr. Timothy P. Covino**, Assistant Professor, Watershed Science, Colorado State University

Human activities rely on consistent supplies of water, but often these activities also pollute and disturb naturally functioning waterways. River-floodplain systems provide important ecosystem services that can increase river network resiliency to these disturbances. However, deeper knowledge of their functioning is necessary for creating management and restoration projects that correspond to a river's natural processes. Research on water quality and river ecosystems often involves sampling at weekly or monthly intervals, but the frequency of this monitoring overlooks physiochemical changes in the system that occur at shorter time intervals, which can impact how the entire system functions. This study seeks to record and analyze the fine temporal scale physical and chemical changes occurring over one diel cycle in order to expand on our understanding of river-floodplain function. The research will be conducted through sampling of water and collection of real-time data from different areas of a river-floodplain system. Lab analysis of these samples will quantify the amplitude of changes and timing of river- floodplain physiochemical properties over one day and give insight on chemical and biological interactions and their dependency on daily temperature and light cycles. These efforts aim to validate and complement concurrent work investigating river-floodplain connectivity and to provide a quick assessment monitoring tool for scientific and resource management use.

Colorado is dependent upon water supply from the Rocky Mountains for socioeconomic stability and prosperity. A long history of human activity has created water quality concerns across the state that threaten public and ecological health. On the Front Range, increased nutrient deposition from agricultural practices and fossil fuel emissions threatens river health and public water supplies (Wohl, 2006).

Mitigating this problem requires an improved understanding of individual river processes and ecosystem services. Understanding processes at diel temporal scales can provide crucial insights into water quality management. For example, water quality monitoring programs typically examine yearly or monthly patterns but ignore daily variation (Nimick et al., 2003; Gammons et al., 2007). This approach fails to capture the hydrologic and ecological processes that create diel patterns within river-floodplain systems (Nimick et al., 2003). This diel variation has implications for water quality monitoring and management strategies derived from that monitoring. Ignoring sampling timing has been shown to increase error in the calculation of fluxes and even can lead to incorrect conclusions about drivers of water quality problems (Gammons et al., 2007). Discerning the processes that create diel water quality patterns will enhance our ability to manage water quality across the region.

Diel signals can also provide insight into the function of specific landforms, such as floodplains, within the river network. Functional floodplains provide crucial ecosystem services we rely upon, such as regulating hydrologic disturbances and potentially retaining nutrients (Tockner & Stanford, 2002). However, while healthy river-floodplain systems express dynamic hydrologic connectivity between the river and floodplain that enhances ecosystem resiliency, and water quality, 90% of North American river-floodplain systems have lost this dynamism and have been categorized as functionally extinct (Tockner & Stanford, 2002). Moreover, we currently



Copeland Falls on the St. Vrain Creek are located in Wild Basin, Rocky Mountain National Park. Photo © Drake Fleege/adobe.stock.com.

lack a complete understanding of the variation in river-floodplain function and their role within river-networks. Diel signals can help in developing new insights and tools to assess river-floodplain function and can help water resource managers incorporate natural processes as an objective in restoration projects (Wohl et al., 2015).

Past studies of diel variations in rivers have provided insight on biogeochemical processes, which play crucial roles in river functioning, water quality, and provisioning of ecosystem services (Nimick et al., 2011). The magnitude of diel signals can also change over seasons and can be used to infer river health (Webb et al., 2008). Diel signals are driven by both hydrologic and metabolic processes (Acuna et al., 2008) and are apparent in dissolved oxygen (DO) (Odum, 1956), mineral, nutrient, and gas concentrations (Drysdale et al., 2003). In this study, we focus on changes in these metabolic signals and incorporate further analysis of river quality with electrical conductivity, dissolved organic carbon (DOC), turbidity, temperature, and water level. Conducting analysis of diel signals in a variety of physical (hydrologic) and chemical (biogeochemical) properties will increase our understanding of river-floodplain system function. Using diel signals, we can quantify metabolism (Odum, 1956) and ambient nutrient uptake (Heffernan & Cohen, 2010), providing metrics to quantify ecosystem services provided by river-floodplain systems. Ongoing work within these floodplains has identified gaps in our understanding due to low-frequency sampling (Brooks, 2018). Analyzing river-floodplain signals on a high-frequency, 24-hour period can fill these gaps and provide uncertainty estimates for fluxes calculated using lower-frequency sampling.

With the success of this high-frequency sampling, we can develop a form of rapid assessment tool for other river-floodplain systems to analyze water quality signals and fluxes. This research looks to provide insight into two critical areas: (1) determining seasonal and spatial changes in diel signals through a river-floodplain system and (2) providing uncertainty estimates and validation for past and future riverine research results.

This research is being conducted as part of my National Science Foundation (NSF) research undergraduate experience project. The work is supported by doctoral student Alexander C. Brooks and Dr. Tim Covino as part of a larger project studying the importance of mountain river-floodplains on water quality and ecosystem function. I am analyzing seasonal variation in diel physical and chemical signals within a river-floodplain system. Understanding these dynamics will improve the quantification of water quality fluxes and aid in developing new insights into river-floodplain ecosystem services. The following objectives and analysis are included:

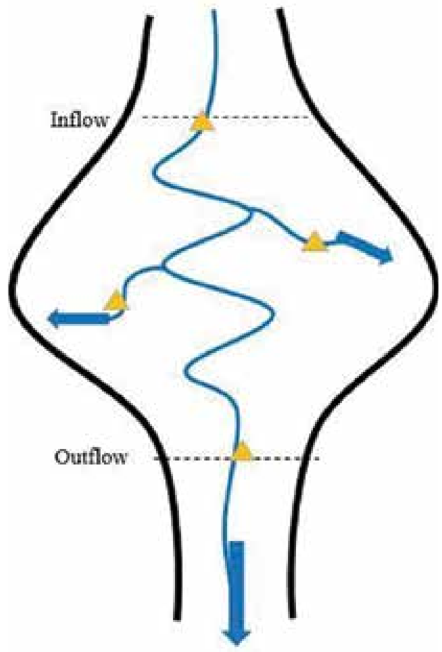


Figure 1. Field Design Schematic displaying sampling sites (yellow triangles) and areas of inflow and outflow.

Objective 1: Quantify seasonal and spatial changes in physical and chemical diel signals in a river floodplain system.

I will first establish four sampling sites along a river-floodplain system on the North Saint Vrain River in Rocky Mountain National Park. Sites will be established along the inflow and outflow of the main channel and two side channels within the complex. Once per season (April, July, September, and January), sampling will be conducted during a period of 24 consecutive hours. During the sampling period, the following hi-frequency sensors will be deployed to record at fifteen- minute intervals: electrical conductivity, fluorescent dissolved organic material, dissolved oxygen, turbidity, water temperature, and water level. Grab sampling will also be conducted every two hours by hand or through an ISCO auto- sampler. They will then be filtered and lab analyzed for nutrient and ion concentrations. Physical and chemical variables will then be analyzed for the amplitude of daily fluctuations and the timing of daily maximums and minimums. Metabolism will be modeled using the single station diurnal DO change method (Odum, 1956). Ambient diel nutrient uptake rate will be calculated as the slope of the line between daybreak and dusk (Heffernan et al., 2010). Patterns in diel signals will be compared for each site along the river to determine how hydrologic connectivity within the river-floodplain system impacts diel processes. The calculations will also be compared across seasons to quantify how diel signals respond to changing seasonal conditions.

Objective 2: Conduct sensitivity analysis of how modeled nutrient fluxes are influenced by the frequency of sampling timing.

Sensitivity analyses will be conducted by first modeling the daily flux of each measured solute at the inflow and outflow sites for each of the four sampling periods using Equation 1.

$$(1)\quad \mathrm{Flux}_{\mathrm{daily}} = \sum_{k=0}^{n} Q * C * t$$

Where Q is modeled discharge data (15-minute intervals), C is concentration, t is the timestep of data collection (15 minutes), and n is the number of samples taken during the day. Flux will be calculated separately, first using the minimum concentration measured, then the maximum concentration, and finally using the full suite of diel measurements. For variables measured by 2- hour grab sampling, inverse distance interpolation will be used to create 15-minute concentration data. Percent differences in modeled daily flux will be calculated between all three approaches, and sensitivity will be compared across all measured variables and between different seasons. I will then extend this analysis to seasonal fluxes using three years of inflow/outflow chemistry sampling that occurred weekly to bi-weekly from May to October. We will calculate fluxes using the original data. We will then integrate diel signals measured during this study and build a model that predicts daily diel changes based on time of day and seasonality. We will then remodel the seasonal fluxes using our sub-daily modeled concentrations and compare the results to the first approach. Differences in the calculated seasonal and net change between these two models will indicate the sensitivity across seasons in sampling frequency on water quality monitoring results.

Temporal and Spatial Effects of Snow Depth on Snow Surface Roughness Throughout the White River Watershed

Jessica Sanow, Doctoral Student and **Dr. Steven Fassnacht**, Professor, Watershed Science, Colorado State University

Introduction

Snow is a critical component of the hydrologic cycle, and meltwater provides drinking water for over 60 million people in the western U.S. (Bales et al., 2006). Accurate measurements of the snowpack and resulting snowmelt are crucial for water management, especially within a changing climate and an overall decrease in the snowpack (Mote et al., 2017).

Throughout the winter season, the snowpack changes substantially due to underlying terrain (Figure 1), depth, accumulation, and melt, leading to a heterogeneous snowpack in which a single point measurement (e.g., a SNOTEL station) is not representative of an entire watershed (Fassnacht et al., 2009a). Snow surface roughness (z_0) is the primary boundary between the air and surface throughout the winter and is a key parameter in estimating snowpack characteristics (Fassnacht et al., 2009b). Underlying topography, vegetation, and other surface features can be categorized as roughness features that affect the z_0 of an area. Once the snow depth begins to increase, the z_0 values begin to change (Figure 1). By understanding the relation between snow surface roughness (z_0) and the snow depth (d_s) throughout the entire winter season, estimations of snowpack characteristics can be improved (Luce and Tarboton, 2004).

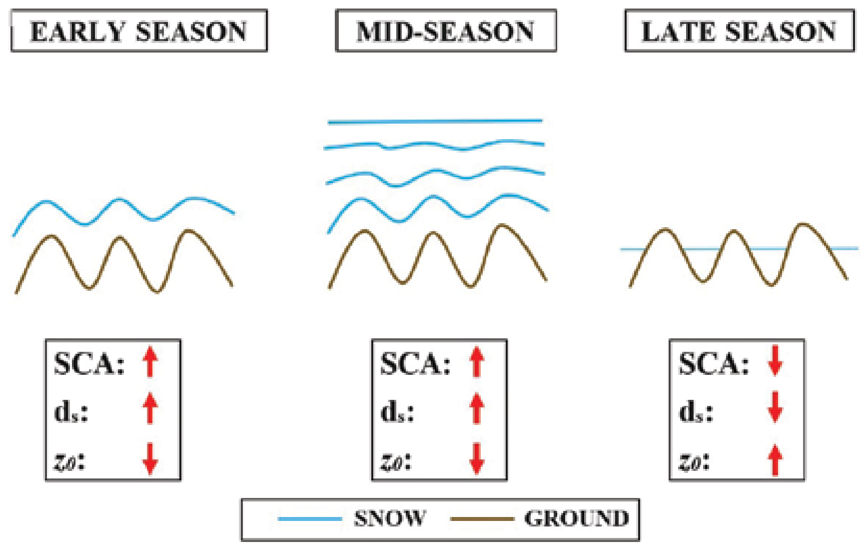


Figure 1. Example of changes within the snowpack throughout a winter season based on underlying terrain. This illustrates the hysteresis relation between snow-covered area (SCA), snow depth (ds), and surface roughness (z0).

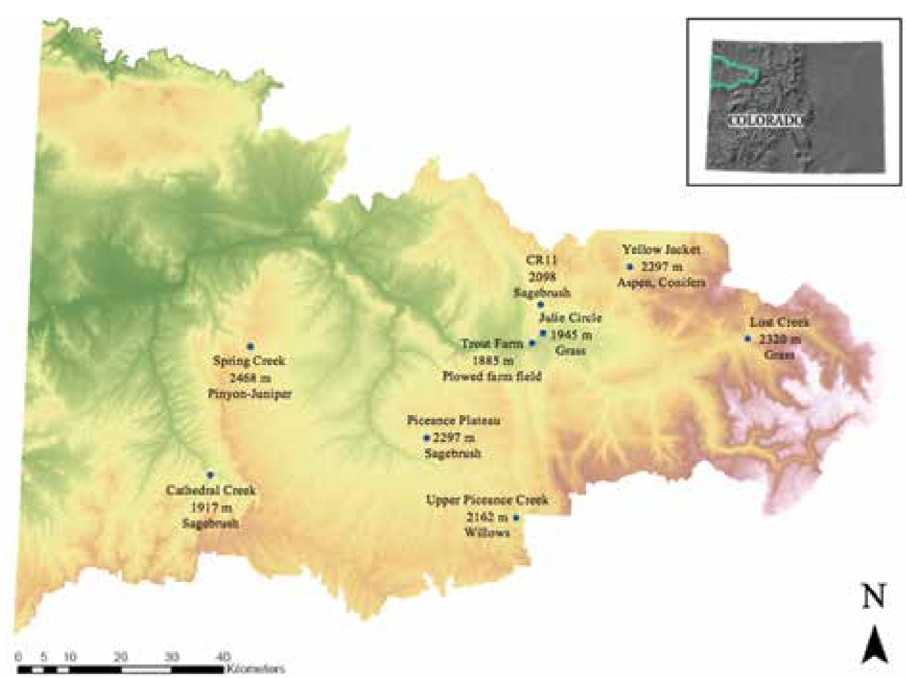


Figure 2. Locations of snow monitoring stations shown on a DEM around the Bureau of Land Management—White River Field Office, near Meeker, Colorado.

Study Sites

To account for the differences in the underlying terrain and thus possible variation in surface roughness throughout a watershed, nine snow sites were chosen throughout the White River Watershed (Figure 2). These sites varied based on elevation, location, underlying topography, and land cover type.

Methods

Terrestrial-based LIDAR scans using the FARO Focus3D X 130 model (faro.com/products/) were taken on daily to bi-monthly intervals at each of the sites, depending on distance and weather conditions. This LIDAR tool generates a point cloud scan of a given area with an error of +/- 2 millimeters and a resolution of approximately 7.5 millimeters. Three scans were taken at each site (Figure 3) to account for hidden elements within each scan. Photographs, air temperature, and snow depth at each snow stake were also recorded at every site visit (Figure 4).

The LIDAR scans were cropped and merged in the open source program Cloud Compare (danielgm.net/cc/). An example of a point cloud from the LIDAR scan is shown in Figure 5c. An Area of Interest (AOI) was cropped out similar to the example shown in Figure 3. This AOI was interpolated to a 0.01-meter resolution using the kriging method in the Golden Software Surfer (goldensoftware.com/products/surfer). This creates a gridded AOI, which was de-trended in the x-y plane to remove the bias in the slope of the field (Fassnacht et al., 2014) or the angle of the LIDAR. Using a MATLAB code (mathworks.com/products/matlab.html), individual roughness elements were identified, and for each element, the silhouette lot area and obstacle height were determined. These were used to estimate z_0 based on geometry.

Results

Results indicate that the various topographic and vegetation heights influenced the z_0 of the study sites, and those roughness features were further influenced by the addition of a spatially and temporally heterogeneous snowpack. Yellow Jacket, for instance, had an initial z_0 of 150 centimeters with no snow (Figure 5a). At the peak snow depth of 78 centimeters (2/26/2020), the z_0 had decreased to 20 centimeters (Figure 5b). The point cloud shown in Figure 5c shows the initial scan with no snow overlain by the 78-centimeter deep snowpack, illustrating the net change in the surface roughness.

Each of the other eight sites had similar results, indicating that as the snow depth changes, the z_0 is also changing throughout the winter season. Snow depth throughout the entire White River Watershed also varied depending on the elevation, aspect, etc., as expected. The results followed the overall pattern shown in Figure 1 with higher z_0 values initially when no snow was present to gradually decreasing as the snow depth increased and eliminated the smaller scale topographic features (forbes, grasses, small rocks). As the snow depth increased, the larger topographic

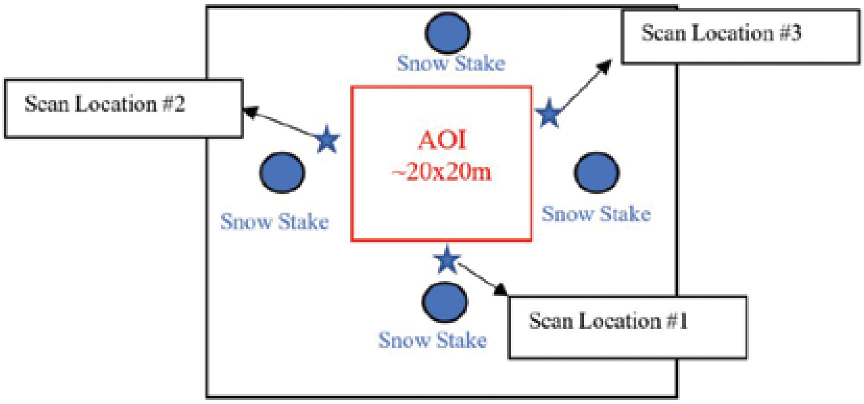


Figure 3. Diagram of the scans locations in reference to snow stakes. Scans will be performed continuously at each location and moved clockwise to the next scan location. The red box depicts the Area of Interest (AOI) with an estimate size of 20x20 meters, however, this size is dependent on each location.

Figure 4. Collecting meteorological data at the Trout Farm field site.

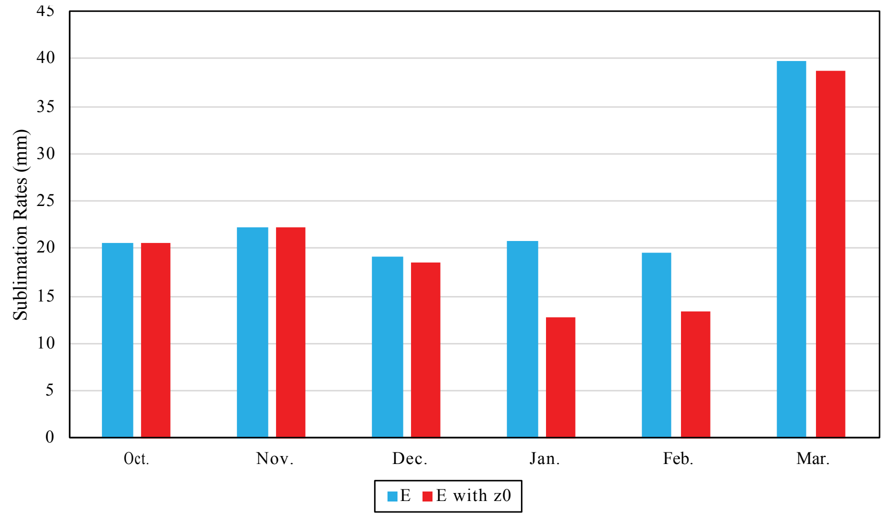


Figure 6. Monthly totals of sublimation rates over the 2019-2020 winter season at the Trout Farm snow study site. The blue columns represent the calculated sublimation using a static z0 value of 3.5 x 10-2 meters (this value was the calculated initial roughness at the site). The red column uses a dynamic z0 based on terrestrial LIDAR scans taken throughout the winter season at the site.

features (small shrubs/plants and larger rocks) began to be enveloped in the snowpack creating a smoother surface and decreasing the value of z_o. Once the maximum snowpack depth was reached and melt began, the z_o value increased again due to the larger shrubs and rocks beginning to be appear out of the snowpack. The spatial and temporal z_o were clearly defined throughout the winter as dynamic variables.

Discussion

Few studies have examined the temporal and spatial changes of the snowpack surface roughness at various sites across a watershed as the snowpack evolves. Roughness is a primary factor for understanding the micro and macro scale features and internal processes of a snowpack (Brock et al., 2006). Wind, topography, and vegetation cause snow depth variability from 1-meter to 100-meter scales (Deems et al., 2006), which can lead to very inaccurate results if using a static value for z_o.

The findings of this research have implications for improving modeling the effects of the cryosphere on the hydrologic cycle. The addition of a site-specific and temporally variable z_o could considerably improve water balance calculations. For instance, when estimating sublimation rates, a dynamic z_o can alter the estimations (Figure 6). This small calculation was done using the data from the Trout Farm site. Sublimations rates were calculated using the initial z_o value (3.5×10^{-2} meters) as a static parameter (shown in Figure 6 as the red columns) and again using a dynamic z_o value that were measured and calculated throughout the entire winter season (shown in Figure 6 as the blue columns). The total amount of static z_o sublimation was 140 millimeters, and the dynamic z_o sublimation was 120 millimeters or modeling that 17% more water was being stored in the snowpack.

Ongoing efforts are exploring the effect of scaling these results from a single site to a watershed scale and possibly to a mountain range scale. Since LIDAR is becoming more readily available, the addition of a dynamic z_o is useable within small and large-scale hydrologic and meteorological models. This can aid in accounting for spatial and temporal variability. The improvement of all variables within these models will advance results and increase understanding of cryosphere-atmospheric interactions.

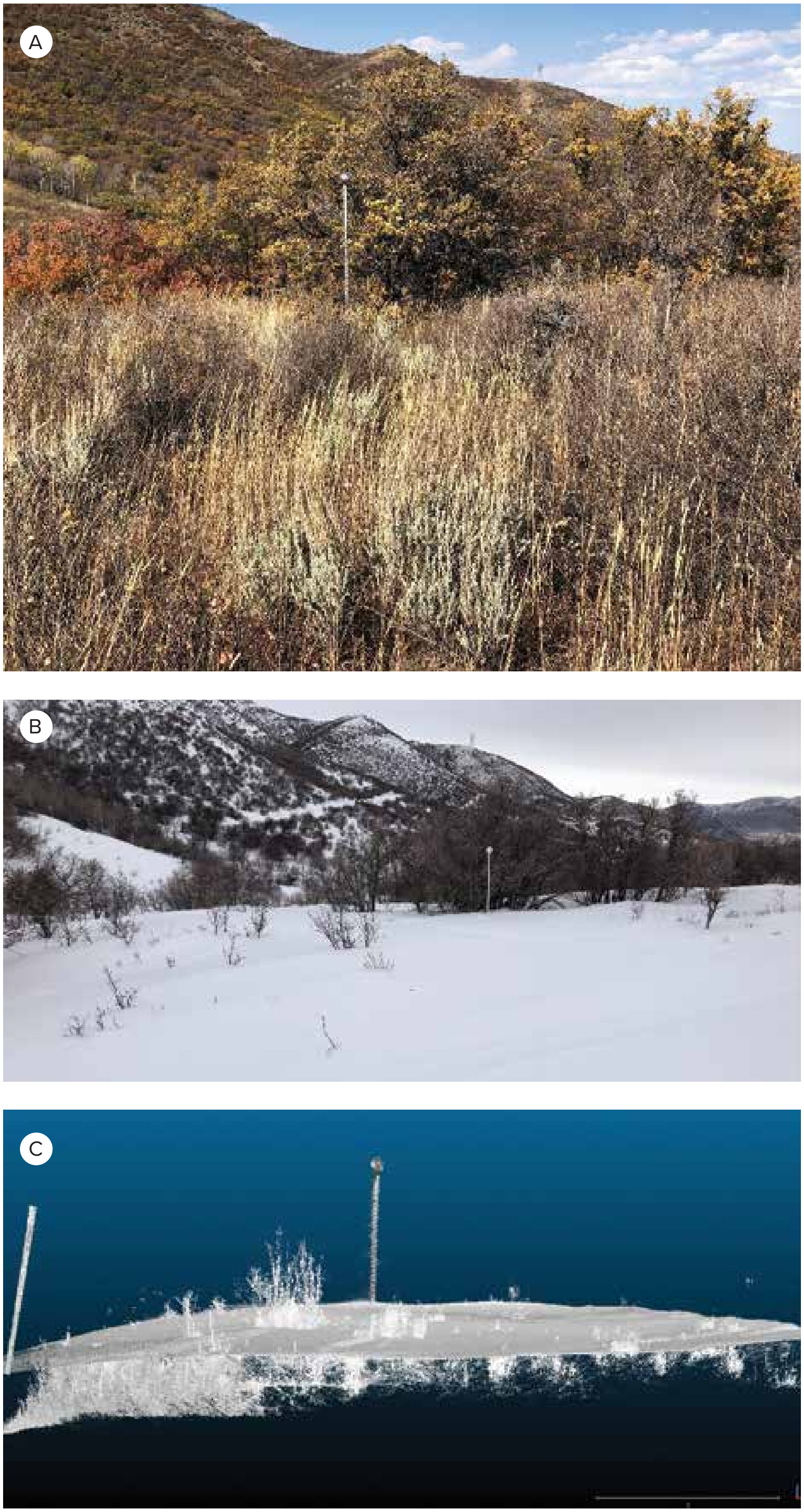


Figure 5. Yellow Jacket Pass, A) photo of the initial site set up, the t-post shown is to the north; B) photo during peak snow depth of 78 cm, this was taken from a slightly different angle than A, however the t-post is the same one in both photos; C) a screen shot of the point clouds from the snow free scan and the scan taken on 2-26-2020 showing the vegetation and snow pack depth, the t-post is the same as the within the other photos.

Cost-Effective Water Quality Management with Tile-Drainage System

Di Sheng, Doctoral Student and **Dr. Jordan Suter**, Associate Professor, Agricultural and Resource Economics, Colorado State University

Introduction

Agriculture serves as a major polluter of non-point source nutrients, and agricultural conservation is a popular approach to improve water quality. Successful agricultural conservation planning to protect water quality must include sufficient watershed and pollution source information (Osmond et al., 2012). Therefore hydro-economic frameworks are widely used to provide policy insights related to water quality improvement. This research aims to assess the policy implications of agricultural tile-drainage systems in water quality management.

Agricultural tile-drainage systems (TDSs), pervasively installed in the midwest portion of the U.S., primarily aim to transport excess water from the soil, which also transport nutrients dissolved in water from fertilizer and livestock production into waterways. Studies reveal that TDSs increase the speed of nutrient transportation from agricultural land to nearby waterways and likely increase the nutrient density of a waterbody. It is therefore critical to include information on the spatial location of TDSs into conservation policy design.

Our study incorporates spatial information of TDSs and adopts a hydro-economic framework to address the economic impact and policy implications of TDSs on water quality improvements. The results indicate that (1) incorporating TDSs into the PES design can significantly reduce the total cost of achieving a given nutrient reduction target; (2) the underlying distributions of conservation cost and nutrient reduction variables affect how much benefit TDSs information generate; (3) when the geographical scope of the problem expands, water quality trading among areas can also serve as a cost-effective water quality management tool.

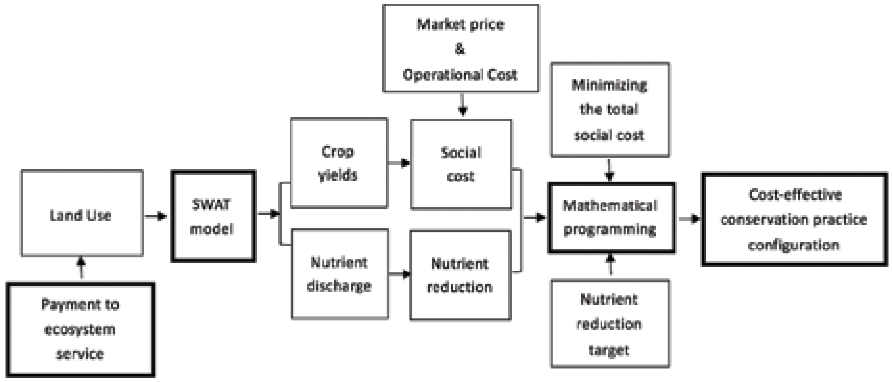


Figure 1. Framework Flow Chart.

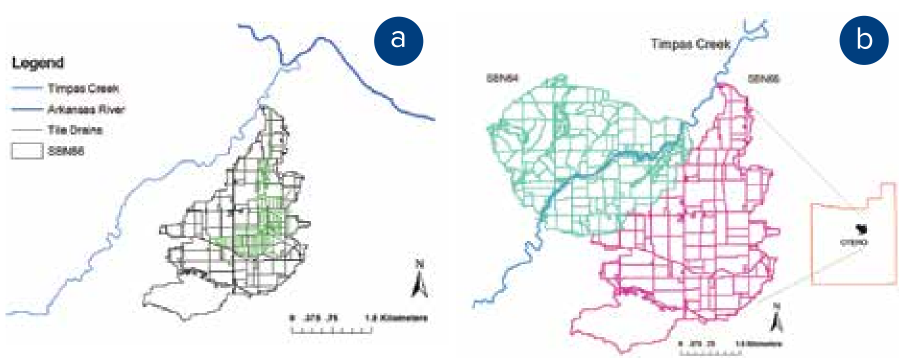


Figure 2. Study area—(a) Tile-drainage System in Sub-basin 66. (b) Sub-basin 64 and sub-basin 66.

Methods

In this study, we assume a PES program aiming to improve water quality (reduce nitrate loading). Landowners choose to enroll in the program and adopt a conservation practice (turn cropland into pasture land) if the payment is no less than the opportunity cost of conservation (net benefit of production). An optimization model is developed to identify the optimal payment rate ($/hectare) for agricultural conservation that minimizes the total social cost of achieving a given nitrate reduction target (Figure 1). Without TDSs information, all parcels face a uniform payment rate. When TDSs information is incorporated into the policy design, a higher payment rate is offered to tiled-parcels. We further develop simulations to assess the benefit of introducing TDSs information into PES under various parameterizations.

In addition, to assess the benefit of introducing water quality trading between neighboring sub-basins, we compare the optimal enrollment configuration of achieving reduction targets by each sub-basin individually and jointly achieving the reduction target by two sub-basins when paying each parcel with its opportunity cost of conservation.

A Soil and Water Assessment Tool (SWAT) model is utilized to provide optimization coefficients. In our SWAT model, a watershed is delineated into several smaller sub-watersheds based on elevation and stream locations. Sub-watersheds are further delineated into Hydrological Response Units (HRU) according to agricultural field boundaries (Wei and Bailey, 2018). HRUs possess homogeneous land use, land management and soil attributes. Our SWAT model is calibrated with observational nutrient loading data from 2015.

Study Area

There is a group of tiled parcels in the sub-basin 66 (Figure 2a) of the Lower Arkansas River basin in southeastern Colorado. There are 160 HRUs in the sub-basin, and we include 101 HRUs that planted corn, alfalfa, winter wheat or sorghum in 2015 and had positive crop yield in the optimization. 33 HRUs, with a total area of 496.04 hectares, are tiled HRUs. The remaining 68 non-tiled HRUs in total take up an area of 551.22 hectares. An HRU with N hectares is treated as N identical parcels. For the water quality trading analysis, we introduce the sub-basin 64 (Figure 2b) as a trading partner with sub-basin 66. There are 92 HRUs in the sub-basin 64 included in the optimization.

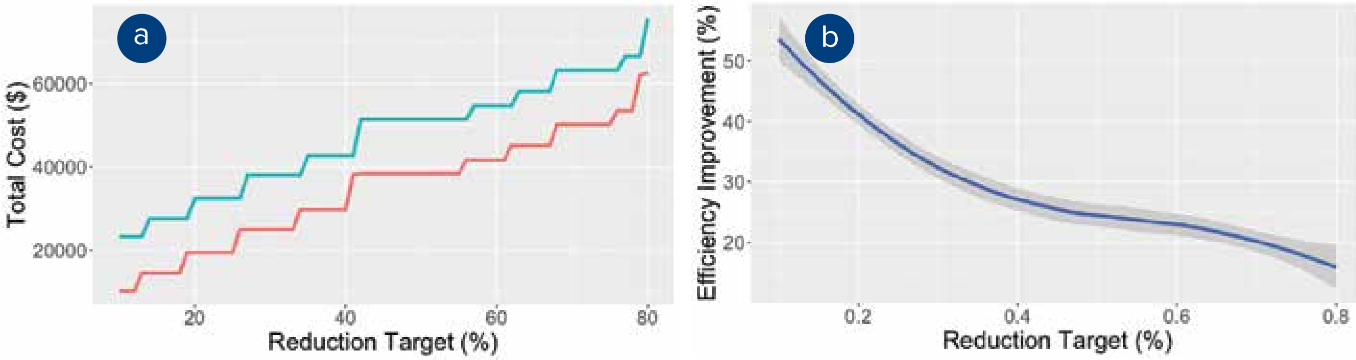


Figure 3: Outcome Comparison: PES with and without TDSs Information—(a) Total Cost Comparison. (b) Tiled-parcel Enrollment Rate Comparison
Note: Red line and blue line in panel (a) denote PES design with and without TDSs information, respectively

Results and Discussions

Figure 3a indicates that incorporating the TDSs information into the PES design can significantly reduce the cost of nitrate loading reduction. Figure 3b presents a loess-smoothed cost efficiency improvement curve of different nutrient reduction targets. Incorporating TDSs have decent efficiency improvement with moderate targets.

Further simulations are generated with different assumptions for distributions of conservation cost and nitrate loading reduction. Figure 4 summarizes the results from further simulations and shows that (1) when tiled parcels have the same or higher mean cost than non-tiled parcels, incorporating TDSs information in PES design always increases the cost efficiency of a PES. In other words, the total cost of achieving a given nitrate reduction target is lower in this case; (2) when tiled parcels have a lower mean cost, a higher payment rate for a tiled parcel is most beneficial with a moderate reduction target.

Figure 5a shows that water quality trading can serve as an alternative cost-effective water quality management tool. Optimal enrollment configuration with and without water quality trading is provided in Figure 5b. Comparison between with water quality trading scenarios and without it reveals that sub-basin 64 is more cost-effective in nitrate reduction on average than sub-basin 66.

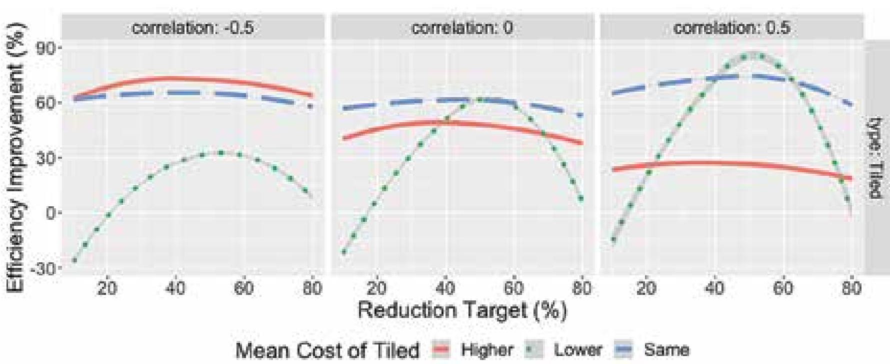


Figure 4: Cost Efficiency Improvement under Various Scenarios.
Note: "correlation" denotes the correlation between conservation cost and nitrate reduction variables, which varies from -0.5 to 0.5; "Mean Cost of Tiled" denotes the relationship between the mean conservation cost of tiled and non-tiled parcels. "Higher" means that tiled parcels are with a higher mean conservation cost compared with non-tiled parcels.

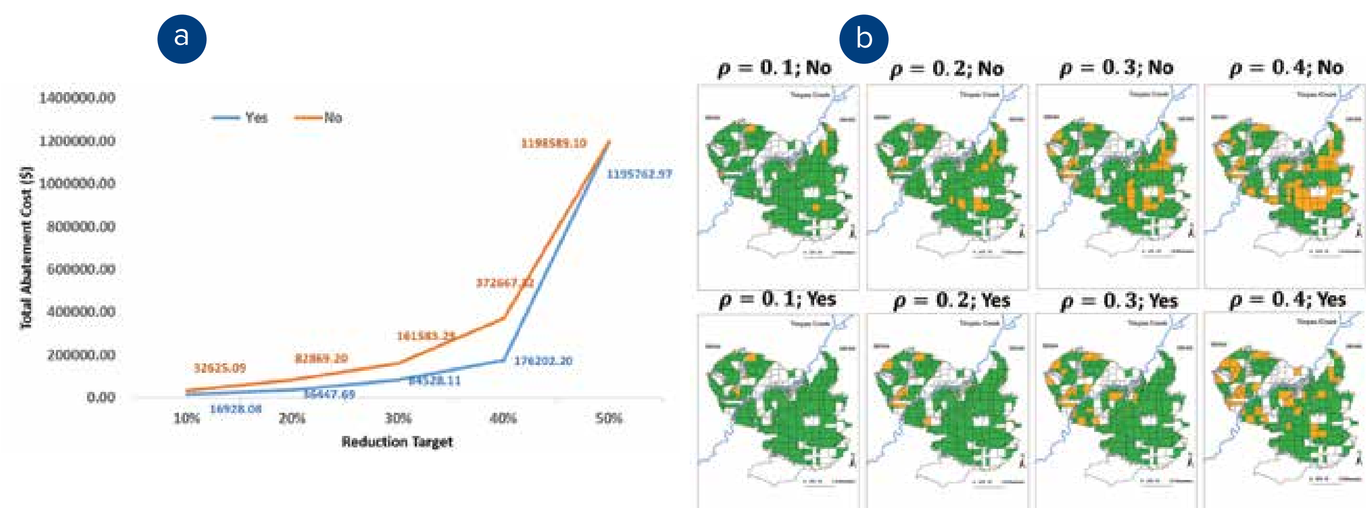


Figure 5: Outcome Comparison with and without Water Quality Trading— (a) Total Cost Comparison. (b) Enrollment Configuration Comparison.
Note: Orange parcels are selected to enroll the conservation. Coefficient denotes the nitrate reduction target, which ranges from 0 to 1. "Yes" denotes water quality trading is allowed.

Water Research Awards 10/18/2021-12/13/2021

Andales, Allan A., Colorado Water Conservation Board, Determination of Consumptive Water Use of Winter Wheat in the Arkansas Valley (Lysimeter Year 5), $50,178

Anderson, Jennie Adale, Department of Defense, U.S. Army Corps of Engineers, Fort Worth, CESU-CP: Natural Resources Support, Barry M. Goldwater and Luke Air Force Base, $144,238

Arabi, Mazdak, U.S. Department of Agriculture, U.S. Forest Service-Forest Research, Geospatial Flood Prediction Tool for Infrastructure Resilience, $80,000

Arabi, Mazdak, U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Colorado, Hydrological Modeling to Assess Vulnerability of Water Supply in the Contiguous U.S., $30,000

Arabi, Mazdak, U.S. Department of Agriculture, Agricultural Research Service, Process Modeling, Machine Learning and Computational Tools for Watershed Modeling from Fire to Field, $122,000

Bagley, Calvin F., Department of Defense, U.S. Army Corps of Engineers, Alaska, Management, Species, Cook Inlet Beluga Whale, Training Noise Impacts, Joint Base Elmendorf-Richardson, Alaska, $67,396

Bagley, Calvin F., Department of Defense, U.S. Army Corps of Engineers, Alaska, Management Species, Cook Inlet Beluga Whale/Ice Conditions, Management, Species, Harbor Porpoise, Management, Species Beluga Acoustical Monitoring JBER Alaska, $244,637

Bailey, Larissa, Department of the Interior, U.S. Geological Survey, CESU-RM: Effects of Climate on Host-Pathogen Distribution Dynamics for High-Elevation Amphibian Systems (USGS), $27,005

Bell, Christopher, Indiana University, Mirabegron and Cold Water Tolerance, $168,328

Bell, Michael Monroe, National Science Foundation, CIF: A Sea-Going and Land Deployable Polarimetric (SEA-POL) Radar for the Science Community, $247,588

Bell Michael Monroe, National Science Foundation, Collaborative Research: Dynamics, Thermodynamics, and Microphysics of Extreme Rainfall Observed During PRECIP, $190,528

Bestgen, Kevin R., Department of the Interior, Bureau of Reclamation, BOR New 5 year Agreement: KR143008 Project 128 Green River Pike Minnow Est., $70,180

Bestgen, Kevin R., Department of the Interior, Bureau of Reclamation, BOR New 5 Year Agreement: KR143009 Project 140 Native Fish Response, $68,278

Bestgen, Kevin R., Department of the Interior, Bureau of Reclamation, BOR New 5 Year Agreement: KR143006 Project 22f Larva Fish Monitoring, $130,889

Bestgen, Kevin R., Department of the Interior, Bureau of Land Management, BOR New 5 Year Agreement: Kr143010 Project FR-115 Lodore Whirlpool Monitoring, $110,912

Beveridge, Daniel T., U.S. Department of Agriculture, U.S. Forest Service-Forest Research, 2021 CAFA Deer Creek Coordinated Fuels Project, $300,000

Bringi, Viswanathan N., National Aeronautics and Space Administration, Light Rainfall Drop Size Distribution Shape and Variability: Improving the DPR-GMI Combined Algorithm, $123,346

Chen, Haonan, Department of Commerce, National Oceanic and Atmospheric Administration, Hydrometeorological and Water Resources Research, $8,334

Chen, Haonan, Department of Commerce, National Oceanic and Atmospheric Administration, Leveraging Artificial Intelligence for Enhanced Orographic Precipitation Retrievals and Super Resolution Data Fusion, $91,312

Chen, Haonan, Santa Clara Valley Water District, Remote sensing and Machine Learning for Hydrometeorology Applications, $49,412

Chirokova, Galina Yurievna, Department of Commerce, National Oceanic and Atmospheric Administration, CIRA Support to the Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS), $10,680

Chiu, Jui-Yuan, Department of Energy, Constraining Microphysical Processes of Warm Rain Formation Using Advanced Spectral Separations, An Ensemble Framework and Machine Learning Techniques, $128,505

Connell, Bernadette H., Department of Commerce, National Oceanic and Atmospheric Administration, SHyMet CIRA Support to GOES-R Training: The Satellite Hydro-Meteorology (SHyMet) Education and Outreach Program and GOES-R Commitment to the WMO CGMS Intl Vlab and GOES-R FDTD Satellite Training Liaison, $145,631

Connell, Bernadette H., Department of Commerce, National Oceanic and Atmospheric Administration, GOES-R VLAB-CIRA Support to GOES-R Training: The Satellite Hydro-Meteorology (SHyMet) Education and Outreach Program and GOES-R Commitment to the WMO CGMS Intl Vlab and GOES-R FDTD Satellite Training Liaison, $48,544

Connell, Bernadette H., Department of Commerce, National Oceanic and Atmospheric Administration, GOES-R FDTE Sat Training Liaison-CIRA Support to GOES-R Training: The Satellite Hydro-Meteorology (SHyMet) Education and Outreach Program and GOES-R Commitment to the WMO CGMS Intl Vlab and GOES-R FDTD, $169,903

Connell, Bernadette H., Department of Commerce, National Oceanic and Atmospheric Administration, GOES-R FDTE Sat Training Liaison-CIRA Support to GOES-R Training: The Satellite Hydro-Meteorology (SHyMet) Education and Outreach Program and GOES-R Commitment to the WMO CGMS Intl Vlab and GOES-R FDTD, $24,272

Cooper, David Jonathan, Northern Colorado Water Conservancy District, Northern Colorado Water Conservancy District, Scoping of Ecosystem Restoration Opportunities in the Kawuneeche Valley, $68,050

Cooper, David Jonathan, Colorado Department of Transportation, Summit Lake Watershed Study, $4,999

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Cooper, David Jonathan, Colorado Department of Transportation, Summit Lake Wetland Study, $10,000

Cotrufo, Maria Francesca, U.S. Department of Agriculture, Agricultural Research Service, Soil C Cycling in Irrigated Agroecosystems, $30,000

Creamean, Jessie, Department of Energy, Closing the Gap on Understudied Aerosol-Climate Processes in the Rapidly Changing Central Arctic, $261,962

Demott, Charlotte A., Department of Energy, Collaborative Research: Understanding Air-Sea Feedbacks to the MJO Through Process Evaluation of Observations and E3SM Experiments, $154,912

Demott, Paul J., National Science Foundation, Collaborative Studies: Secondary Production of Ice in Cumulus Experiment (SPICULE), $66,771

Demott, Paul J., Department of Energy, Understanding the Natural Sources of Aerosols and Their Impacts on Cloud Formation and Climate Across Hemispheres, $229,015

Edwards, Richard M., U.S. Department of Agriculture, U.S. Forest Service, Forest Research, White River National Forest Fuels Projects Good Neighbor Agreement, $339,000

Edwards, Richard M., U.S. Department of Agriculture, U.S. Forest Service, Forest Research, White River National Forest Fuels Planning Good Neighbor Agreement, $33,219

Fassnacht, Steven, Department of the Interior, National Park Service, CESU-RM: Supporting States Clean Water Act Integrated Reporting, $184,300

Fassnacht, Steven, Department of the Interior, National Park Service, CESU-RM: Notice Review-Water Rights Branch, $5,000

Forsythe, John M., Department of Commerce, National Oceanic and Atmospheric Administration, Merged Water Vapor CIRA Support to Proving Ground Risk Reduction, $143,833

Gao, Wei, University of Maryland, Improving Agricultural Water Use and Nutrient Management to Sustain Food and Energy Crops Production in the Corn Belt, $100,000

Gillligan, Laurie A., Environmental Protection Agency, Targeted Inventory and Assessment of Groundwater Dependent Wetlands in the Colorado Plains, $208,286

Glantz, Michelle M., University of Arizona, Rainfall Variability, Extreme Events, and the Response of Farmers in the Central American Dry Corridor, $15,477

Goemans, Christopher G., University of Nevada, Evaluating Alternative Water Institution Performance in Snow-Dominated Basins: Are Food Productions Systems at Risk From Changing Snow Water Availability?, $114,307

Hawkins, John A., Department of the Interior, Bureau of Reclamation, BOR New 5 Year Agreement: KR143007 Project 125NNF Management Yampa River, $336,527

Hurrell, James W., National Science Foundation, Collaborative Research: Quantifying the Role of the Ocean Circulation in Climate Variability, $959,588

Jacobson, Peter A., Department of Defense, Army, Corps of Engineers, Fort Worth, CESU-CP: Field Support for Waters of the U.S. and Other Surface Water Program Improvement Review Pursuant to the Sikes Act on Air Force Installations, $472,671

Jacobson, Peter A., Department of Defense, U.S. Army Corps of Engineers, Alaska, Water and Wastewater Program Support, Pearl Harbor, Hawaii, $268,488

Jacobson, Peter A., Department of Defense, U.S. Army Corps of Engineers, Alasksa, Environmental Support-UIC Inventory and Wastewater Joint Base Pearl Harbor-Hickam, Oahu, Hawaii, $154,811

Kampf, Stephanie, K., U.S. Department of Agriculture, U.S. Forest Service, Stream Trackers: Monitoring Intermittent Streams in National Forest, $20,750

Kanno, Yoichiro, U.S. Department of Agriculture, U.S. Forest Service, Forest Research, Field Investigations for Greenback Cutthroat Trout Recovery, $20,000

Kendall, William L., Colorado Division of Parks and Wildlife, Evaluation of Cripple Creek (Mule Deer Herd D16) and Wet Mountain (Mule Deer D34) Demographics (Auction and Raffle Funded M.S. Project), $38,212

Kendall, William L., Department of the Interior, U.S. Geological Survey, CESU-CP: Integrated Ecosystem Modeling for Fish in the Grand Canyon, $40,000

Knapp, Alan Keith, Alliance for Sustainable Energy-NREL, InSPIRE 2.0: Water Management Opportunities for Solar and Agriculture Co-Location, $30,000

Lemly, Joanna, Environmental Protection Agency, Colorado Intensification of the National Wetland Condition Assessment, $251,053

Lemly, Joanna, Department of the Interior, National Park Service, CESU-RM: Synthesizing Long Term Ecological Monitoring of Rocky Mountain Wetlands to Prioritize and Inform Restoration and Mitigation, Florissant Fossil Beds National Monument Case Study, $38,250

Lemly, Joanna, Colorado Department of Public Health and Environment, Colorado National Wetland Condition Assessment (CO NWCA), $64,600

Levinger, Nancy E., National Science Foundation, Collaborative Research: Unraveling Interactions that Drive Water-Osmolyte Interactions in Confinement and Impact Self-Assembly, $41,959

Liston, Glen E., University of Colorado, Sunlight Under Sea Ice: A Multisensor and Modeling Synthesis for Ecosystems in a Changing Arctic, $15,899

Liston, Glen E., Columbia University, Quantifying Socioecological Consequences of Changing Sow and Icescapes: A Data-Model Fusion Approach, $82,575

Marshall, Sarah M., Walton Family Foundation, Colorado River Basin Wetland and Beaver Dam Mapping, $64,476

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McGrath, Daniel, University of Nevada, Glacial Lake Outburst Flood Hazard Assessment and Forecast System (GLOF-HAFS): A Tool for Science-Based Decision Making in High Mountain Asia, $99,409

Marshall, Sarah M., Environmental Protection Agency, Wetland Restoration Prioritization for Resilient Colorado Headwaters, $210,922

McKay, John K., Department of Energy, Advanced Research Projects Agency-Energy, Root Genetics in the Field to Understand Drought Adaptation and Carbon Sequestration, $175,000

McGrath, Daniel, Department of the Interior, National Park Service, CESU-RM: Quantifying Ice Thickness and Volume of Middle Teton Glacier Using Ground Penetrating Radar (GPR) Surveys, $23,995

McGrath, Daniel, National Aeronautics and Space Administration, Participant Support: Evaluating NASA SnowEx L-Band InSAR for the Future of Snow Remote Sensing, $45,000

McGrath, Daniel, Department of the Interior, U.S. Geological Survey, CESU-RM: Resolving Spatial and Temporal Variability of Snow Accumulation in Mountain and Glacier Environments, $65,837

Miller, Steven D., Department of Commerce, National Oceanic and Atmospheric Administration, CIRA/DESDIS Support of the GOES-R AWG Cloud Team, $60,000

Morrison, Ryan Richard, Department of the Interior, U.S. Geological Survey, The Influence of Changing Climatic Conditions on Streamflow and Temperature in Headwater Systems in the North-Central Colorado Rocky Mountains, $48,000

Myrick, Christopher A., Wyoming Game and Fish Department, Swimming and Jumping Abilities of Wyoming Great Plains Fishes, $89,942

Noh, Yoo-Jeong, Department of Commerce, National Oceanic and Atmospheric Administration, CIRA/NESDIS Support for the Generation of Cloud Base Height and Cloud Cover Layers Products from EPS-SG METimage Data, $31,990

Ocheltree, Troy W., U.S. Department of Agriculture, U.S. Forest Service, Forest Research, Drought Recovery in the Northern Great Plains: Understanding Seasonal Precipitation Legacy Effects on Grazing and Forage Production, $55,000

Paustian, Keith H., U.S. Department of Agriculture, Natural Resources Conservation Service, Enhancing Functionality and Use of COMET Greenhouse Gas Assessment and Water Quality Tools, $500,000

Poff, Nathan LeRoy, Department of the Interior, U.S. Geological Survey, CESU-RM: Long-Term Monitoring of Riparian Vegetation Response to Biological Control of Tamarix Along the Lower Virgin River, $49,768

Quinn, Jason Charles, Colorado School of Mines, High-Throughput Directed Evolution of Marine Microalgae and Phototrophic Consortia for Improved Biomass Yields, $5,000

Rasmussen, Kristen Lani, National Science Foundation, Collaborative Research: Topographic Influences on Extreme Warm-Season Precipitation, $72,537

Rasmussen, Kristen Lani, National Science Foundation, Collaborative Research, Topographic Influences on Extreme Warm-Season Precipitation, $115,044

Rasmussen, Kristen Lani, Department of Energy, Investigation of Clouds, Aerosols, Vertical Motion, and Cold Pools During the Full Convective Lifecycle Using Observations and Model Simulations from the CACTI Field Campaign, $173,266

Sanford, William E., Department of the Interior, National Park Service, CESU-RM: NPS Groundwater Data Management, $50,000

Schneekloth, Joel. Monsanto, SD Systems Nitrogen by Density by Water VRI Testing, $13,860

Schulte, Darin K., Department of the Interior, U.S. Geological Survey, CESU-RM: Developing and Integrating Remote Sensing-Based Land Surface Penology (SP) Libraries with Agro-Hydrologic Modeling for Water Use and Availability Assessment on a Cloud Computing Platform, $80,000

Schumacher, Russ Stanley, Department of Commerce, National Oceanic and Atmospheric Administration, Building Drought Early Warning Capacity in Colorado Through Soil Moisture Model Assessment and Increasing Condition Monitoring in Forests, $147,181

Selby, Diana C., U.S. Department of Agriculture, U.S. Forest Service, Pike San Isabel-USPP Watershed Coordinator, $100,000

Selby, Diana C., Colorado Springs Utilities, CSA (5354011) Pike Watershed Protection Fuels Project GNA, $277,500

Selby, Diana C., U.S. Department of Agriculture, U.S. Forest Service, Forest Research, Pike Watershed Protection Fuels Project GNA, $380,526

Siemers, Jeremy, U.S. Department of Agriculture, U.S. Forest Service, Forest Research, Rare Plant and Wildlife Surveys on the White River National Forest, $31,062

Stewart, Jane E., U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Colorado, Drought Responses of Walnut Inoculated with Geosmithia Morbida, $30,000

Sueltenfuss, Jeremy, Department of the Interior, National Park Service, CESU-RM: Florissant Fossil Beds Wetland Restoration, $25,083

Toll, Weston, U.S. Department of Agriculture, U.S. Forest Service, 21CPG Water Quality Assessment Tool, $23,201

Van Den Heever, Susan, Department of Energy, Examining the Impacts of Microphysical-Dynamical Feedbacks on Convective Clouds in Different Aerosol Environments Using Enhanced Observational and Modeling Strategies, $225,078

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Van Den Heever, Susan, National Aeronautics and Space Administration, 16-CAMP2EX-16-0020 Aerosol Impacts on the Microphysical and Dynamical Processes of Tropical Convection and Cold Pools and Their Environmental Modulation, $89,208

Venkatachalam, Chandrasekaran, Department of Energy, Constraining Micophysical Processes of Warm Rain Formation Using Advanced Spectral Separations, An Ensemble Framework and Machine Learning Techniques, $57,215

Venkatachalam, Chandrasekaran, Department of Commerce, National Oceanic and Atmospheric Administration, Hydrometeorological and Water Resources Research, $175,000

Wardle, Erik M., Colorado Department of Agriculture, Training and Education for Agricultural Chemicals and Groundwater Protection-FY22, $475,000

Wilusz, Carol J., Larimer County, COVID-19: Wastewater Testing for Larimer County, $62,272

Wilusz, Carol J., Colorado Department of Public Health and Environment, COVID-19: Wastewater Testing for the State of Colorado, $1,000,000

Windom, Bret Colin, Gas Machinery Research Council, High Pressure Vapor Liquid Equilibrium Measurements of Gas and Water Mixtures Using Nuclear Magnetic Resonance Spectroscopy Phase II: C2-C4 Hydrocarbons and Water Mixtures, $70,000

Winkelman, Dana, Colorado Division of Parks and Wildlife, TO 2002 Field Examination of Wastewater Treatment Effluent Thermal Regimes and Effects on Reproduction of Johnny Darter Etheostoma Nigrum, $56,611

Winkelman, Dana, Colorado Division of Parks and Wildlife, Quantitative Assessment of Pelagic Fishes in Colorado Reservoirs, $66,000

Wohl, Ellen E., Colorado Open Lands, Carbon Sequestration Potential in Colorado Restored Floodplains, $12,200

Faculty HIGHLIGHT

Dr. Robin Rothfeder

Assistant Professor, Forest and Rangeland Stewardship, Colorado State University

Dr. Robin Rothfeder is an Assistant Professor of Natural Resource Policy in the Forest and Rangeland Stewardship Department at Colorado State University (CSU). Rothfeder has a diverse interdisciplinary background, including undergraduate degrees in Environmental Science and Environmental Economics from the University of California-Berkeley, a Master's degree in Environmental Humanities and a Doctorate in Ecological Planning from the University of Utah.

Dr. Robin Rothfeder

Rothfeder's classes use social-ecological challenges and opportunities as the focal point for engaged, interactive learning experiences. His teaching at CSU includes Natural Resource History and Policy, Environmental Impact Analysis, Integrated Ecosystem Management, and other courses focused on community sustainability and natural resource planning and management. His research covers two broad topics: (a) collaboration in social-ecological systems and (b) water resource planning, policy, and management, focusing on the arid western U.S. In both areas, he takes an interdisciplinary and mixed methods approach aimed at meeting real-world community needs.

In regards to water resource research, Rothfeder has conducted inferential statistical analysis to model water demand in arid Western cities, with a focus on understanding fine-grained (household scale) trends in outdoor landscape watering. One interesting finding has been that larger/wealthier homes with larger lawns use disproportionately more water than other households (i.e., a house with twice as much lawn as the average home might use 5-10 times more water outdoors). This is likely due to socioeconomic pressures at play between neighbors in certain types of neighborhoods. Moreover, Rothfeder has used system dynamics modeling to test the theory of 'induced demand' in water supply infrastructure. As an analogy, transportation planners have recently shown that widening roads or building new ones can have an amplifying effect on traffic, actually worsening congestion rather than solving it. His research has shown evidence of this same type of amplifying effect in water resource planning, where future water demand accelerates in response to new supply, potentially exacerbating water shortages rather than alleviating them.

Outside of academia, Rothfeder loves spending time with his family and their many pets. He is a certified yoga instructor and an avid outdoor enthusiast with a particular love for kayaking, rock climbing, sailing, scuba diving, and skiing.

Dr. Robin Rothfeder
Assistant Professor,
Forest and Rangeland
Stewardship,
Colorado State University
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USGS Recent Publications

Data Releases

Analysis of escherichia coli, total recoverable iron, and dissolved selenium concentrations and loads for selected 303 (d) listed segments in the Grand Valley of western Colorado, 1980-2018 (version 3.0); 2021, U.S. Geological Survey data release; R.G. Gidley, L.D., Miller, N.K. Day
doi.org/10.5066/P9P6WI44

https://Assessment of a conservative mixing model for the evaluation of constituent behavior below river confluences, Elqui River Basin, Chile; 2021, River Research and Applications (37)7, 967-978; C. Rossi, J. Oyarzún, P. Pastén, R.L. Runkel, J. Núñez, D. Duhalde, H. Maturana, E. Rojas, J.L. Arumí, D. Castillo, and R. Oyarzún
onlinelibrary.wiley.com/doi/10.1002/rra.3823_

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Water Calendar

March

2 **30th Annual Colorado Agriculture Forum**
Denver, CO
This event will be an opportunity to network and learn from leaders across Colorado's agriculture and business committees. The theme this year is "Agriculture, Out Wisest Pursuit".
coloradoagforum.com/

April

25-27 **American Geophysical Union Hydrology Days**
Fort Collins, CO
This conference provides the opportunity for students, faculty, and practitioners to engage in a wide range of water-related interdisciplinary research topics. This is a great opportunity to hear about cutting-edge research and engage with a diverse array of professionals and students.
hydrologydays.colostate.edu

View additional water events at watercenter.colostate.edu/events/

Corn that was planted without tillage—"no-till"—grows in a field previously planted to a cover crop of cereal rye. Photo ©bmargaret/stock.adobe.com

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Investigating Bi-Directional Water Exchanges Across Intact and Degraded Floodplains

Alexander C. Brooks, Doctoral Student and **Dr. Timothy P. Covino**, Assistant Professor, Watershed Science, Colorado State University

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Streamflow Depletion on the South Platte River Due to Groundwater Pumping: Analysis Via Field Work and Groundwater Modeling

Luke Flores, Masters Student, Civil and Environmental Engineering, Colorado State University

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Fine Scale Data Collection for Future Snowmelt Modeling Near Silverton, Colorado

Alison Kingston, Doctoral Student, Geosciences, Colorado State University, **Dr. Steven Fassnacht**, Professor, Watershed Science, Colorado State University, **Jeff Derr**y, Executive Director, Center for Snow and Avalanche Studies

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History of South Platte River Riparian Ecosystem and Channel Change

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Temporal and Spatial Effects of Snow Depth on Snow Surface Roughness Throughout the White River Watershed

Jessica Sanow, Doctoral Student and **Dr. Steven Fassnacht**, Professor, Watershed Science, Colorado State University

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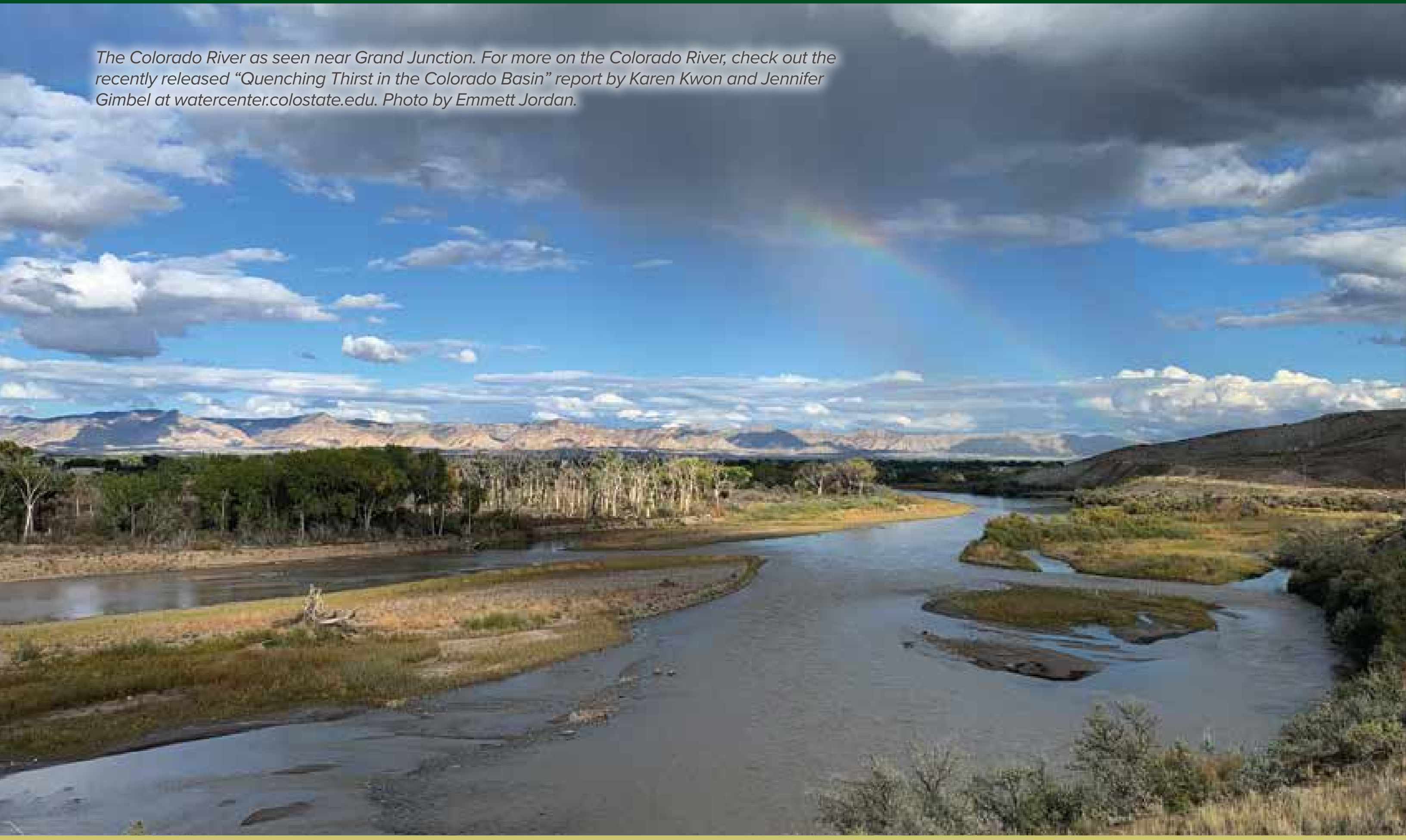

The Colorado River as seen near Grand Junction. For more on the Colorado River, check out the recently released "Quenching Thirst in the Colorado Basin" report by Karen Kwon and Jennifer Gimbel at watercenter.colostate.edu. Photo by Emmett Jordan.