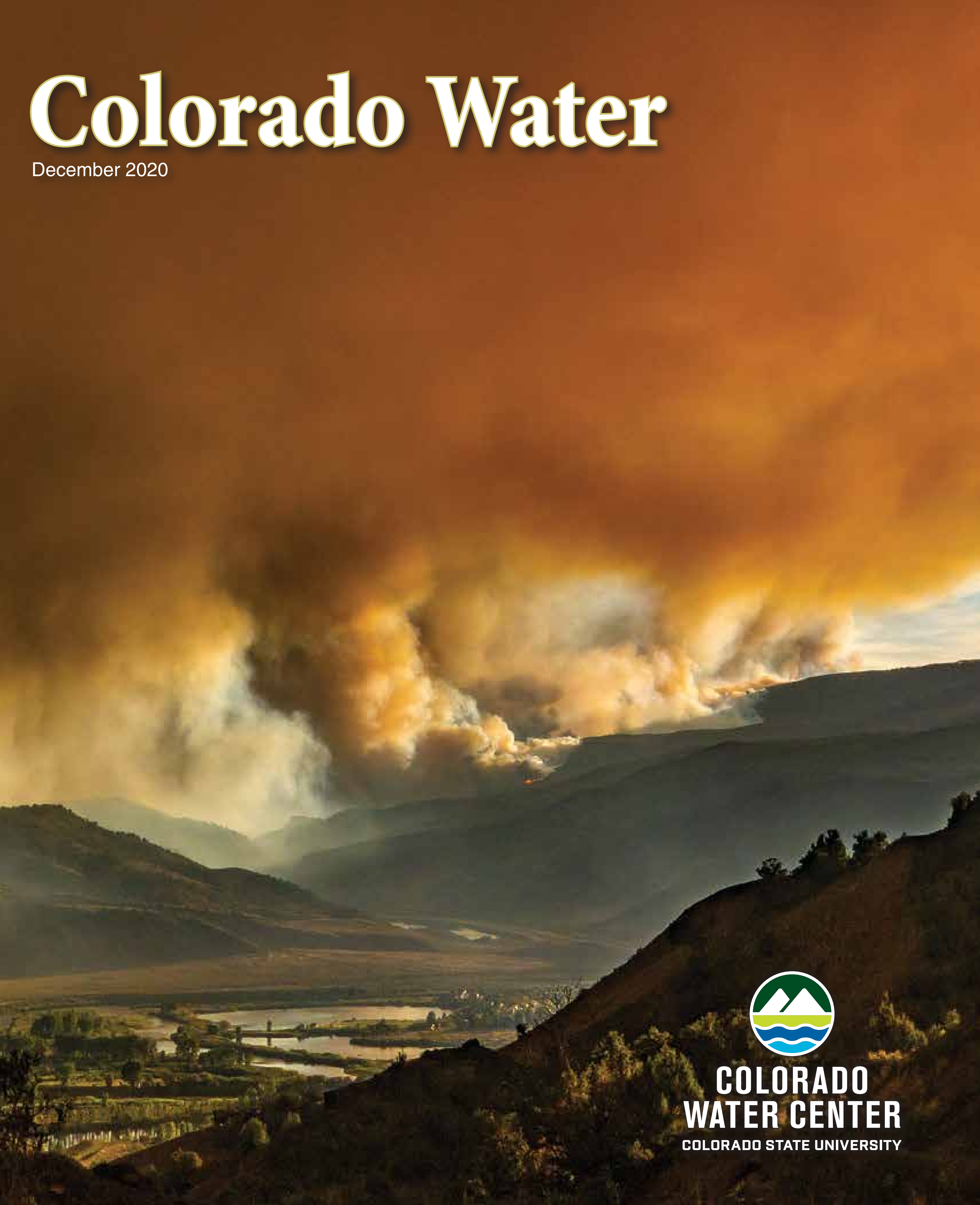
Colorado Water

December 2020



COLORADO WATER CENTER
COLORADO STATE UNIVERSITY

2019-2020 Project Reports

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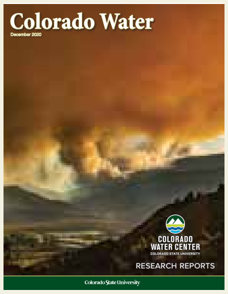

On the cover—Smoke and flames from the 2020 Grizzly Creek fire as seen looking into Glenwood Canyon. See page 22 for research on post fire land health assesments.
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References can be found in the online version of this newsletter at http://watercenter.colostate.edu/water-news

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

COLORADO **WATER**

Volume 37, Issue 3

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COLORADO WATER CENTER
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Director's LETTER

As I leave my position as Director of the Colorado Water Center at Colorado State University on December 31, I would like to take this opportunity to thank my colleagues and coworkers and reflect a bit on my time at CSU over the last 34 years. I was fortunate to have had several outstanding mentors at CSU—Lee Sommers, Lloyd Walker, Dwayne Westfall, Dan Smith, Evan Vlachos, Robert Ward, Lou Swanson, and others who taught me much and to whom I owe much. I have enjoyed working with many fine colleagues, both at CSU and external to the University, who made the work fun, challenging, and worthwhile—too many to name, but you know who you are and I thank you. I have also had the pleasure of working with hundreds of students over the past three decades, who made the experience rich.

When I came to the Colorado Water Resources Research Institute in 2000, I found it a solid operation, capably run by Robert Ward and his predecessors, Neil Grigg and Norm Evans. All three of these gentlemen worked tirelessly throughout their careers for the greater good of the water mission at CSU, with a clear eye on the needs of the public and our external partners. Passion for both the water resource and the stakeholders managing the resource caught my imagination and it was a pleasure to build on.

For the past 15 years it has been my privilege to guide the Colorado Water Institute/Center during three CSU administrations, several down budget cycles, severe droughts, destructive floods, and several other historic water events and changes in Colorado. I was honored to serve on the Boards of a number of water organizations. The cumulative learning from leadership positions, research projects, community engagement opportunities, and difficult people and problems is hard to put into words that do justice to the overall experience. This past year has changed us, as the coronavirus pandemic kept us from our work places, masked us, and made us fearful to be close to each other. Forest fires, the down economy, being isolated at home, and social unrest across our country affected us deeply. A number of us at CSU have chosen to retire this year, each for our own reasons, but we leave much work undone. Our water supplies remain vulnerable, resource conflicts persist, students need training and guidance, and we still must learn how to prosper in the arid West without sacrificing the environment.

My career at CSU began in 1986, working on a USAID funded biotech project on crop improvement for drought, salinity, and acidic soils. In my work I traveled internationally in Asia, Africa, Europe, and South and Central America, learning much about agriculture and water resources in other lands. In 1991, I became the CSU Extension Water Quality Specialist, working to implement Colorado SB90-126, the Agricultural Chemicals and Groundwater Protection Act, developing statewide agricultural best management practices. A highlight of that time was when I found myself embroiled in a battle between two billionaires over hog waste, resulting in a statewide ballot initiative and one of the billionaires calling for the University President to fire me. I survived, and subsequently became the CSU Extension Water Resource Specialist and Associate Director of the Colorado Water Resources Research Institute in 2000, in time to engage in the historic 2002 drought and fires, which CSU played a major role in addressing. Robert Ward retired in December of 2005, leaving me with the keys to the shop as the South Platte Basin well crisis reached a boiling point. That saga culminated for me personally when the Legislature passed Colorado HB12-1278, requiring the Colorado Water Institute to study the problem of high water tables in the South Platte River Basin (resulting from the well shutdown) and provide recommendations to the Legislature to ameliorate the situation. Nothing in my previous experience had prepared me to conduct research in the midst of such a highly polarized and raw emotional conflict with so much at stake economically. We were conducting the HB-1278 studies during the 2012 drought and fires, and the historic 2013 flood, at the same time that I was President of Colorado Water Congress and President of the National Institutes of Water Resources, and the only academic representative on the six-state Bureau of Reclamation Colorado River Basin Next Steps Study. It was the most difficult period of my career but in some ways the most rewarding. One lasting change I was able to guide at CSU was unifying the Colorado Water Resources Research Institute, the CSU Water Center, and the CSU Extension Water Program under the umbrella of the Colorado Water Center in 2018. My work at CSU was capped off by the opportunity to serve briefly as the interim Vice President of Engagement after Lou Swanson retired in 2019. Now the 2020 pandemic, drought, and fires have put the final exclamation point on my time at the University.

> Looking back, it is the hard and challenging times that are most memorable and that accelerate personal and professional growth. How we individually and collectively weather difficult times says much about our character. Systemic change happens in one of two circumstances —crisis or leadership.

So what does one learn that can be put into a few brief words from three decades of engagement on Colorado's endless water resource challenges from the perspective of higher education? Looking back, it is the hard and challenging times that are most memorable and that accelerate personal and professional growth. How we individually and collectively weather difficult times says much about our character. Systemic change happens in one of two circumstances—crisis or leadership. I've seen a number of crises, and have witnessed the best of humanity emerge in crisis, but a few parting observations on leadership seem most useful here.

In my career I have had the opportunity to study and learn from many fine leaders, and some failed leaders. I've learned that experience or job title alone do not ensure wisdom or imbue the qualities of leadership. Indeed, there is no script for leadership. It is a mindset, a call to serve something larger than oneself that requires us to listen, learn, self-correct, and have the courage to make difficult choices. Effective leaders amplify and organize ideas that are already in existence into a form that can be accepted. Leadership sets the vision or direction, aligns resources to that direction, and builds commitment within the team to achieve the vision. While many suppose leadership positions are desirable, true leaders forego self-indulgences such as cynicism, negativity, loose words, and irresponsibility. Personal integrity is the key quality of trusted leaders. People of integrity do not have the option of cutting ethical corners and thus must work harder, be more self-vigilant and patient, and become more strategic in pursuing their goals. Today's leaders need to ask: Are we thinking broadly enough? Have we defined the right problem to solve? Do we have the right people at the table to avoid blind spots? Are all the interests fairly represented in the process/solutions? Are there groups that we need to rethink how to engage to achieve lasting success? Consensus should always be sought, but in the end, true leaders own the decision, take responsibility for the outcome, and give away any credit.

The retirement of many senior faculty and staff at CSU this year, coupled with new administration at the University, creates opportunities for others to lean into leadership roles —either formally or as thought leaders among peers. At the Water Center, I want to personally thank Jennifer Gimbel and Julie Kallenberger for stepping up into leadership roles as I depart. I ask you to support them as you have me.

What good fortune! I have had the privilege to serve at a major Land-Grant University, in the magnificent State of Colorado, on the critical topic of water, with many fine people. I am grateful to have had such a career. Thank you.

Reagan Waskom

Director, Colorado Water Center

Patterns and Mitigation of Street Flooding in Denver, Colorado

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Stephanie Kampf, Department of Ecosystem Science and Sustainability, Colorado State University
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SYNOPSIS

The pattern of street flooding complaints in Denver, Colorado was compared with modeled flooding. In a case study of the Harvard Gulch watershed, a stormwater model showed that street flooding depth and extent is mitigated by green stormwater infrastructure, but more observations on street flooding are needed to compare with models.

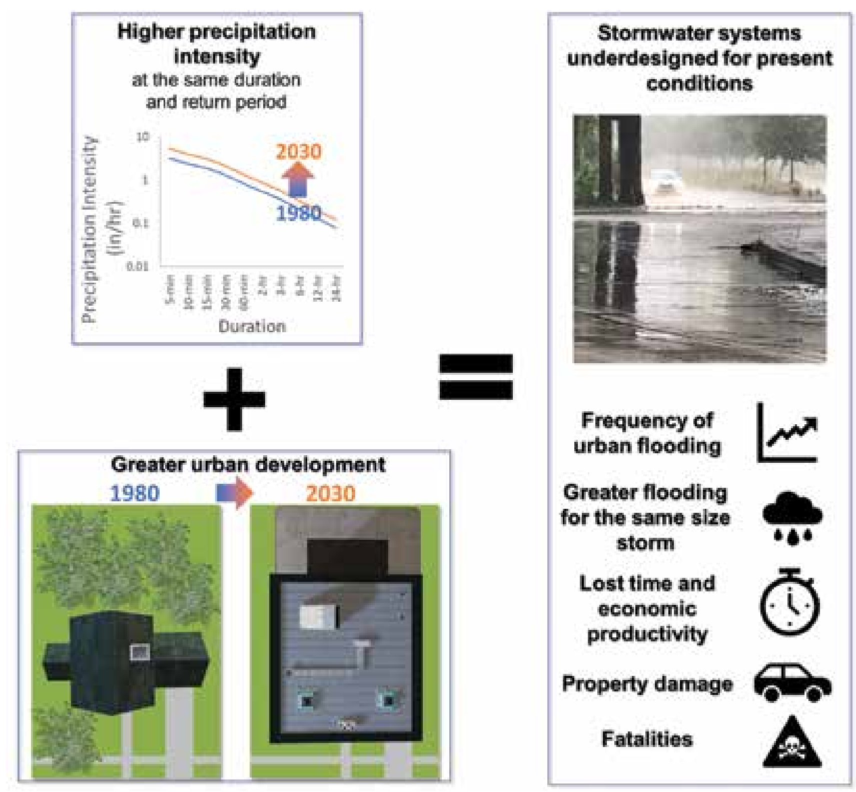

Figure 1. Causes for rising urban flooding over time. Illustration: Aditi Bhaskar, Colorado State University.

Background

Urban flooding is a growing cause of economic loss and social disruption in communities across the U.S. (Galloway et al., 2018; National Academies of Sciences, 2019). Two types of urban flooding occur in Colorado:

1. fluvial flooding caused when streams overtop their banks
2. pluvial flooding when precipitation intensity exceeds the capacity of natural and engineered drainage systems and flooding inundates streets and structures

Flooded streets lead to lost economic productivity, emergency vehicle delays, and even fatalities in Colorado (Pregnolato et al., 2016; Suarez et al., 2005; Veldhuis, 2011) (Figure 1). Using the best available data on urban flooding from the Federal Emergency Management Agency (FEMA), losses in major cities can average $200 million per year (National Academies of Sciences 2019), but this far undercounts true losses. FEMA estimates do not include pluvial street flooding, and FEMA data only includes flooding of insured property in designated 100-year floodplains. Urban flooding outside of the floodplain is often not covered by insurance, and is also concentrated in low-income areas with the least resources to recover (Galloway et al., 2018; National Academies of Sciences, 2019).

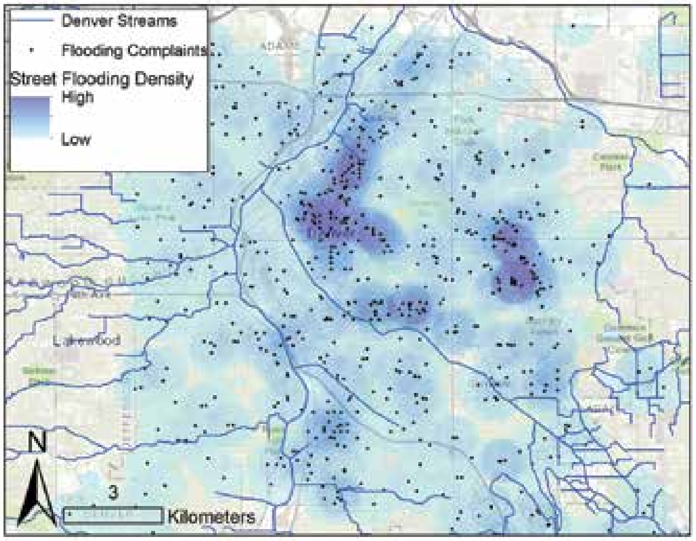

Figure 2. Street flooding complaints and density from municipal service requests to Department of Public Works, City and County of Denver, obtained by request in 2019. Image Credit: Aditi Bhaskar, Colorado State University.

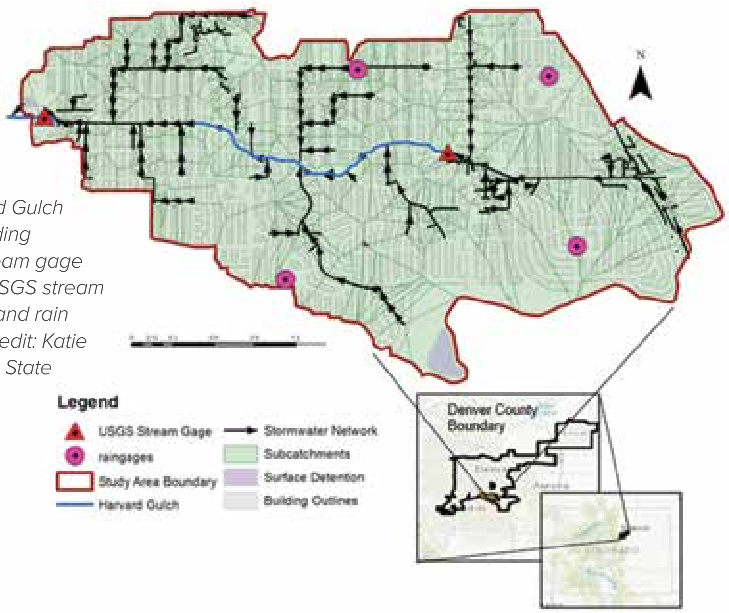

Figure 3. Harvard Gulch study area including outfall USGS stream gage 06711575 (left), USGS stream gage 06711570, and rain gages. Image Credit: Katie Knight, Colorado State University.

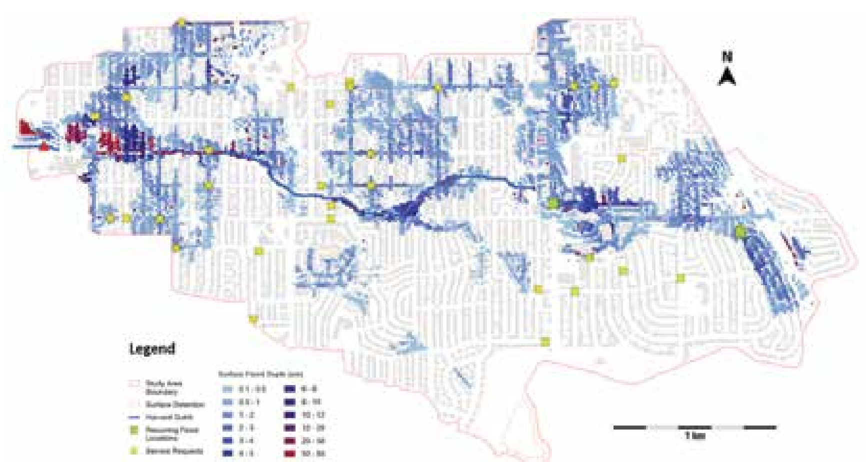

Figure 4. Overall flood extent and distribution of depths for the Pre GSI scenario during the peak flood extent at 18:30 MDT on June 24, 2015, with flood-related resident reports (service requests) from August 10, 2009 to November 25, 2019 made to the City and County of Denver Department of Public Works and DPW-identified recurring flood locations. Image Credit: Katie Knight, Colorado State University

Modeling of the Benefits of Green Stormwater Infrastructure for Street Flooding in Harvard Gulch

There were 1,067 municipal service requests reporting street flooding from 2000-2019 in Denver, Colorado (Figure 2), with uneven distribution across the city. One possible strategy to mitigate street flooding is the implementation of green stormwater infrastructure (GSI), such as bioretention cells that reduce the amount of water entering the subsurface stormwater network. We investigated how GSI affects street flooding depth and extent in Harvard Gulch, an 8.26 km2 watershed located in Denver, Colorado (Figure 3). To model the interactions between overland flow and the subsurface stormwater network, a dual drainage model with major and minor system domains was developed in PCSWMM, which is software for water management modeling (CHI Water). The model was used to simulate the response to a storm from 15:45 MDT to 23:45 MDT on June 24, 2015 during which a total rainfall of 20.07 mm fell. The model was calibrated using the downstream USGS stream gage.

Four GSI scenarios were created by targeting 1%, 2.5%, 3.5% and 5% of the directly connected impervious area (DCIA) of each modeled subcatchment for conversion to GSI. The percent of impervious area treated by GSI was distributed evenly across all impervious area. GSI units were represented by a bioretention cell representing a streetside stormwater planter (City and County of Denver, 2016).

Results

The resident-reported recurring flood locations and flooding reports to the Denver Department of Public Works were generally co-located with areas where flooding is modeled (Figure 4). There are areas at the downstream (western) edge of the study area with depths approaching or exceeding 1m (3.28 ft) with no occurrence of co-located resident reports. However, there were general reports from this storm, describing "heavy flow in the streets when pipe capacity was exceeded … Residents noted 2.5 to 3 feet of water in their backyards, alleys, and streets" (Matrix Design Group, 2016), but these reports were not spatially located.

The extent of street flooding was smaller through the storm in GSI scenarios compared to the baseline (Pre GSI) scenario (Figure 5). The extent of street flooding also decreased with more DCIA converted to GSI (Figure 5). The mean street flood depth peaked earlier than the peak street flood extent (Figures 5 and 6). Generally, greater DCIA conversion to GSI led to less mean street depth (Figure 6). However, when the total street flood extent reduction across the storm event was normalized by percent of DCIA converted to GSI in each scenario (i.e., the efficiency of street flood extent reduction), the most efficient scenario was the 2.5% GSI scenario (Figure 7a). In contrast, largest reduction in mean street flood depth per percentage of DCIA converted to GSI occurred for the 1% scenario, and the efficiency decreased as the percentage of DCIA converted increased (Figure 7b).

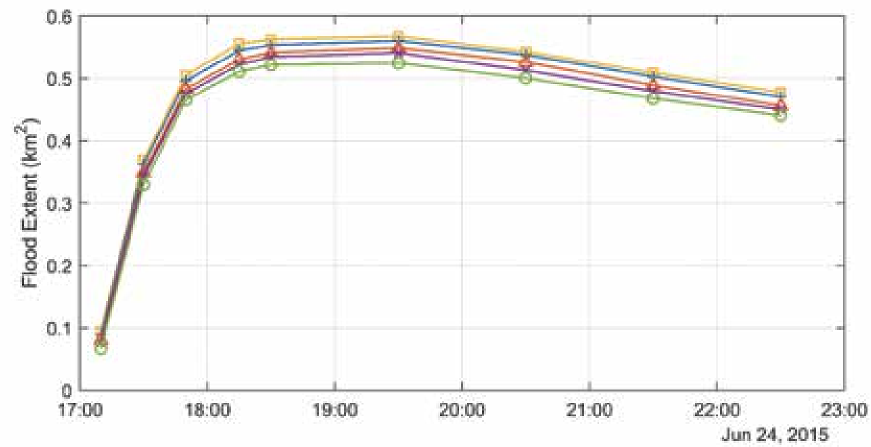

Figure 5. Street flood extent (km2) at select times in the simulation period. Image Credit: Katie Knight, Colorado State University.

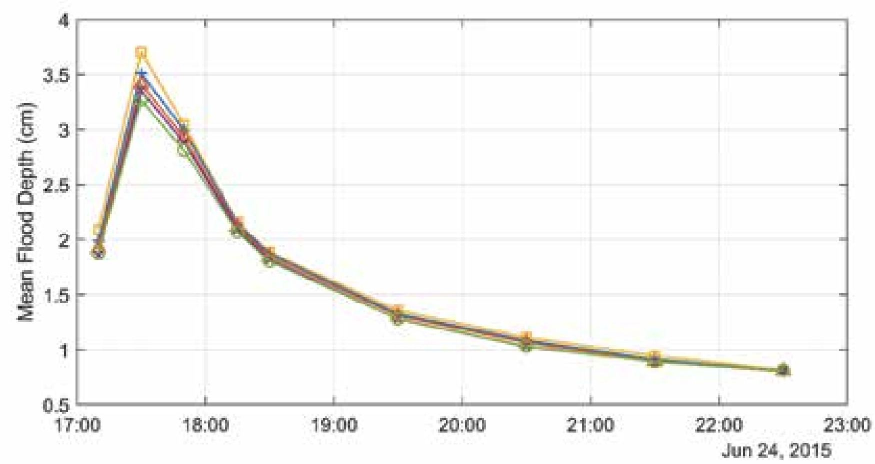

Figure 7. Mean street flood depth (cm) at select times in the simulation period. Image Credit: Katie Knight, Colorado State University.

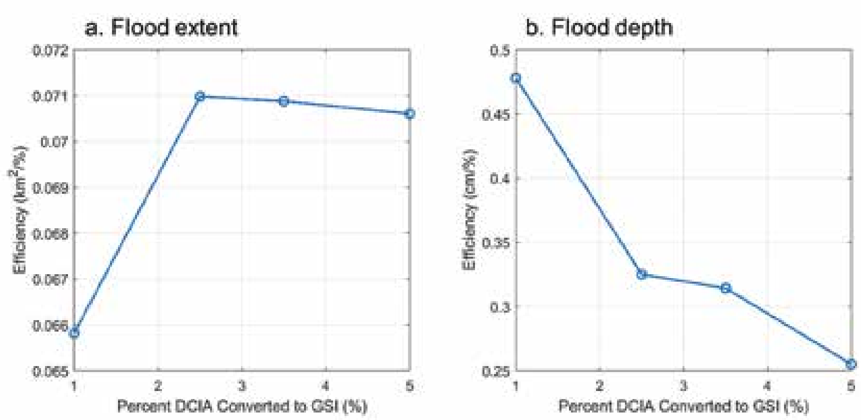

Figure 6. a. Total street flood extent reduction over the duration of the simulation (km2) normalized by the percentage of DCIA converted to GSI vs. percent DCIA converted to GSI, b. Total mean street flood depth reduction over the duration of the simulation (cm) normalized by percentage of DCIA converted to GSI vs. percent DCIA converted to GSI. Image Credit: Katie Knight, Colorado State University.

Conclusions

Even 1% of DCIA converted to GSI led to a smaller extent and mean depth of street flooding. Conversion of increasing percentages of DCIA to GSI (2.5%, 3.5%, and 5%) further reduced the flood spatial extent and flood mean depth (Figures 5 and 6), although with diminishing returns (Figure 7). Although models are capable of simulating street flooding, we do not have corresponding observations of spatially distributed data on the depth and timing of street flooding to compare to model results.

Resident reports to the Denver Department of Public Works were used to qualitatively compare locations, but more widespread observations are needed to advance prediction and mitigation of street flooding. Flood Tracker (floodtracker.org) is a crowdsourced science app that was created by CSU researchers to meet this need. Users can submit locations of street flooding, with optional information on flooding depth (below or above curb), flooding extent (number of lanes affected), and photos.

Acknowledgments

This work was supported by the Colorado Water Center and the Mountain-Plains Consortium.

Characterizing Gene Flow of Non-native Brook Trout to Aid Colorado's Largest Native Cutthroat Trout Restoration Project

Audrey Harris and Yoichiro Kanno, Department of Fish, Wildlife, and Conservation Biology, Colorado State University

▼ SYNOPSIS

Multiple organizations are undertaking a large-scale restoration project for Colorado's state fish, the greenback cutthroat trout, in the upper Cache la Poudre River. Our study uses microsatellite genetic markers to understand gene flow and spatial population structure of non-native brook trout, a root cause of native trout declines in Colorado. Our results will guide brook trout removal and greenback cutthroat trout reintroduction efforts in the project area.

The Poudre Headwaters Project

Trout have high cultural, ecological, and economic importance around the world, and native trout conservation is an increasingly popular concept. The state of Colorado once harbored six distinct lineages, or subspecies, of native cutthroat trout, each occupying a substantial portion of a major river basin. Unfortunately, this biodiversity has been diminished due to human impacts, and cutthroat trout are often relegated to isolated headwater streams. In addition, demand for recreational fishing has led to widespread trout stocking, which began in Colorado more than 100 years ago. Through this process, non-native trout have been introduced to many waters, and the competition with non-native trout is a key reason for the decline of native cutthroat trout populations.

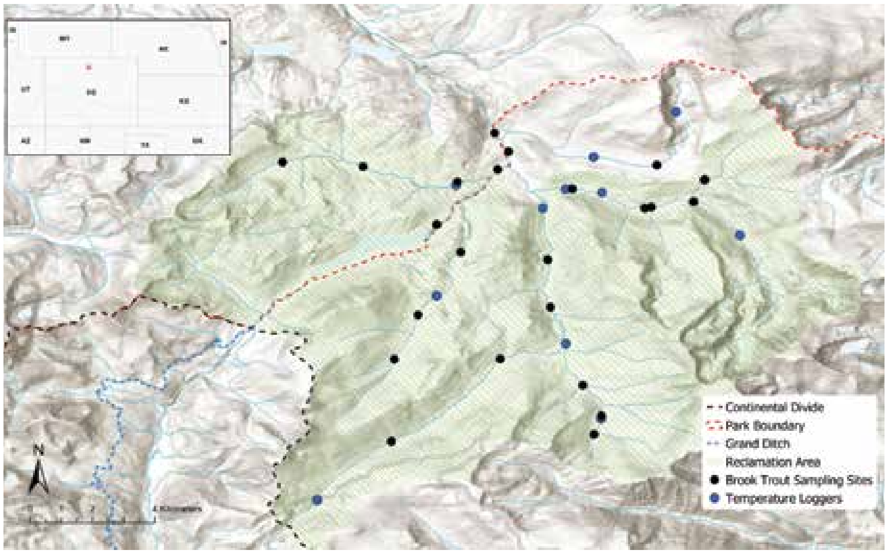

Figure 1. Brook trout study area located in the upper Cache la Poudre River. Image credit: Audrey Harris.

Greenback cutthroat trout (*Oncorhynchus clarkii stomias;* GBCT), the state fish of Colorado, were once declared extinct and are currently listed as threatened under the Endangered Species Act. In 2012, a study using genetics of wild populations and museum specimens found that only a single population of GBCT persisted, stocked outside their native range in the Arkansas River basin (Metcalf et al. 2012). Recovery efforts have intensified since then, with several projects underway to reintroduce GBCT to streams in their native range, the South Platte River basin. Currently, U.S. Forest Service, National Park Service, U.S. Fish and Wildlife Service, Colorado Parks and Wildlife, and Trout Unlimited are working collaboratively to restore GBCT to 37 miles of a continuous stream network in the headwaters of the Cache la Poudre River near Long Draw Reservoir (Figure 1). The Poudre Headwaters Project is the largest native trout restoration effort in Colorado to date and will result in a fivefold increase of GBCT habitat in their entire native range. The recla-

Figure 2. Corral Creek, one of the study sites in the upper Poudre River Basin. Photo by Yoichiro Kanno.

mation area is highly protected—it lies within Arapaho and Roosevelt National Forests and Rocky Mountain National Park. However, the reclamation area is currently dominated by non-native brook trout (*Salvelinus fontinalis*).

Modern approaches for native cutthroat trout conservation center on isolating populations in headwater streams by removing non-native fish and constructing permanent barriers at the downstream boundary of the reclamation area. However, because the Poudre Headwaters Project reclamation area is so large, biologists plan to install a series of additional temporary barriers that will allow them to remove non-native brook trout sequentially by stream. After all brook trout have been removed, GBCT will be reintroduced with an anticipation that they will occupy and move throughout the stream network. This large-scale restoration effort will take place over the next 15 years and provide a safe haven for Colorado's state fish.

Project Rationale

We aim to provide crucial scientific support for the Poudre Headwaters Project by evaluating brook trout spatial population structure in the reclamation area. Genetic data inform the spatial extent of trout movement, and when combined with environmental data, can help us understand which environmental variables (e.g., temperature) may facilitate or impede movement.

Analyzing brook trout spatial population structure will support the Poudre Headwaters Project in two distinct ways. First, understanding how individuals move between streams in the reclamation area will provide key scientific guidance for brook trout removal efforts. Second, identifying barriers and environmental drivers of spatial structure will likely inform GBCT reintroduction efforts in the coming years. Understanding how the riverscape influences connectivity and population persistence will allow biologists to release fish in key stretches of habitat that ensure the highest probability of reintroduction success. In this sense, our project uses a non-native trout as a surrogate for understanding spatial ecology of a native trout.

Methods

In the summer of 2019, we collected 1,391 brook trout tissue samples from 20 sites on nine different streams in the reclamation area (Figure 2). We used backpack electrofishing units to capture fish (Figure 3) and collected tissues non-lethally for genetic analysis (Figure 4). We also installed in-stream temperature loggers throughout the reclamation area to measure spatial thermal patterns. Tissue samples are analyzed for 12 microsatellite genetic markers. A subsample of 796 individuals was selected for genetic analysis, which began in fall 2019 but has been delayed due to COVID-19. Once genetic analysis is complete, the spatial population structure will be evaluated.

Results and Conclusions

Preliminary analyses of genotype data show that brook trout are spatially structured in the reclamation area, meaning that each stream often harbors a unique group of individuals that exhibit some gene flow with nearby populations. Essentially, we can cluster individuals by stream based on genetic signatures, but we also see evidence of trout movement between streams. This has important implications for brook trout removal—for instance, if we see that certain streams are source populations to provide immigrants to other streams, biologists may choose to prioritize the source populations for removal.

In the future, we will use a riverscape genetics framework to understand how

Preliminary analyses of genotype data show that brook trout are spatially structured in the reclamation area, meaning that each stream often harbors a unique group of individuals that exhibit some gene flow with nearby populations.

environmental variables influence brook trout gene flow and movement. Understanding the influence of various environmental factors on trout movement in the reclamation area will be integral to ensure GBCT reintroduction success. Our preliminary analyses using a non-native trout demonstrate that trout occupy and move within a large headwater stream network, a promising sign for re-establishing a robust GBCT population in the upper Poudre River.

Figure 3. Research team collecting brook trout by using backpack electrofishing units and dip nets. Photo by Kate Hansen.

Figure 3. Audrey Harris (middle) processes brook trout and collects fin clips for genetic analysis, along with Dr. Kurt Fausch (left). Photo by Yoichiro Kanno.

Next Steps and Future Research

Our work with brook trout spatial population structure has led to another important research question regarding the Poudre Headwaters Project. We aim to use genetic markers to study movement of cutthroat trout through the Grand Ditch located across the Continental Divide, a transbasin water diversion structure located at the upstream boundary of the reclamation area (Figure 1).

Transbasin water diversions connect previously isolated watersheds and may result in unintended hybridization of aquatic organisms. Because isolation from non-native trout is an integral part of successful restoration projects and a different sub-species of cutthroat occupies the opposite side of the Continental Divide, understanding how transbasin diversions influence fish movement has significant implications for GBCT reintroduction in the study area. This work is particularly relevant in Colorado, where there are more than 44 transbasin diversions and a large emphasis on native trout restoration.

Impacts and Partnerships

Balancing water supply and conservation is critically important in Colorado, where there is a significant and growing demand for water with implications for biodiversity and ecosystem protection. As anthropogenic impacts— non-native species introduction, water management, and climate change—continue to confine trout populations to headwater stream networks, understanding environmental drivers of population persistence and spatial structure in a riverscape is critical to conserving and restoring native trout.

The Poudre Headwaters Project is the largest native cutthroat trout reclamation project in Colorado's history and will help preserve an important legacy of cutthroat trout biodiversity. Throughout this project, we have forged strong relationships with the Rocky Mountain Flycasters Chapter of Trout Unlimited, U.S. Forest Service, National Parks Service, U.S. Fish and Wildlife Service, and U.S. Geological Survey. This research has been supported by a Water Faculty Fellow grant from the Colorado Water Center, as well as the National Fish and Wildlife Foundation, U.S. Forest Service, and Trout Unlimited.

Peering into the Future

The Evolution of Seasonal Snow in the Colorado Rocky Mountains

Snow scientist studies the characteristics of snow crystals after digging a snow pit. Photo by Daniel McGrath.

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Graham A. Sexstone and Daniel McGrath, Department of Geosciences, Colorado State University
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▼ SYNOPSIS

A coupled high-resolution regional climate model and detailed snowpack model are used to investigate how predicted changes in climate will impact the snow hydrology of the Colorado Rocky Mountains. Warmer temperatures in the fall and spring lead to a shorter snow season, less total snow water equivalent, and decreased solid precipitation in the region.

Introduction

The life cycle of snow links Earth's climate system with atmospheric, hydrologic, and ecological processes that provide critical resources to humans and wildlife around the world. Streamflow in the western U.S. is largely derived from seasonal mountain snow that accumulates during the winter and spring, and melts during the spring and summer each year.

Mountain snowpacks are experiencing climate-induced changes that include: earlier snowmelt, declining snow-covered area, and decreases in the fraction of precipitation falling as snow. These changes pose a major risk to future water availability in the western U.S., yet there is currently uncertainty about future snow dynamics given the complex interactions between snow and the atmosphere, land cover, and terrain.

Recent advances in the field of atmospheric science have resulted in high-resolution regional climate models (horizontal grid resolution of 4 km) that provide unprecedented information on the future impacts of climate change. These new models can resolve complex topography and mesoscale (intermediate scale) atmospheric processes, including orographic precipitation.

However, despite the rapidly growing body of research on high-resolu-

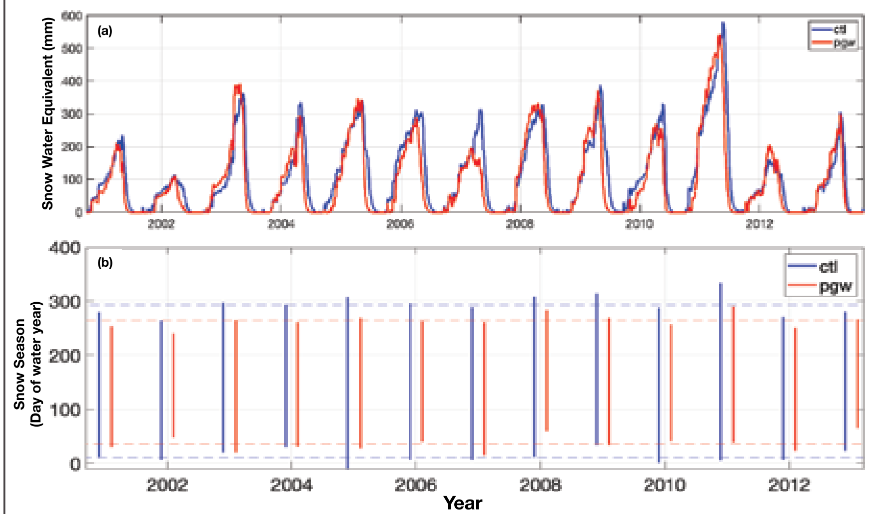

Figure 1. (a) Changes in snow water equivalent in the SnowModel simulations from 2001-2013 over the northern Colorado Rocky Mountains. (b) Representation of the snow season relative to the day of the water year (starting 1 October each year) in the SnowModel simulations.

tion regional climate models, these models have not previously been coupled to snow hydrology models to more accurately represent snow physics processes in a future climate. There is a need for fine-scale process-based model simulations from coupled snow-atmosphere-land cover models to rigorously evaluate how snow processes will respond to projected climate change, and specifically how water availability (both total volume and timing) will be altered by changes to snow dynamics.

Thus, our research targets this gap, by coupling a high-resolution regional climate model to a detailed snowpack model to investigate how predicted changes in climate will modify the snow hydrology of the Colorado Rocky Mountains.

The specific objectives of this research are to evaluate:

- » how future climate forcings will influence each simulated component of the water balance
- » the distribution of snow and variability in snowpack properties
- » future anticipated changes in forest structure and their influences on snow water resources

Methodology

For the last 35 years, Glen Liston, a research scientist at the Cooperative Institute for Research in the Atmosphere, has developed a suite of snow-distribution and snow-evolution modeling tools called SnowModel, with broad applications across earth system science. SnowModel is a spatially-distributed snow-evolution modeling system designed for application in all landscapes, climates, and conditions where snow occurs. SnowModel and associated tools are arguably the most widely used and most published snow modeling tools in the world. SnowModel can be thought of as a detailed process suite that takes our understanding of snow physics and converts basic meteorology such as air temperature, humidity, precipitation, wind, and radiation, into the evolution of complex snow variables such as depth and density. The results are spatially and temporally continuous snow-property distributions that match both our physical understanding of snow processes and the available field and remote sensing observations.

To represent detailed snow physics processes in a current and future climate, our research uses the Weather Research and Forecasting Model (WRF), a novel high-resolution convection-permitting and orography-resolving regional climate simulations over the contiguous U.S. (CONUS). WRF provides the input of atmospheric conditions to drive SnowModel in a current and future climate scenario. These 4-km simulations were recently completed at the National Center for Atmospheric Research. A key advance of these simulations is the use of convection- and orography-resolving grid spacing (4 km), obviating the need for a convective parameterization.

Two continuous 13-year (2000-2013) WRF model simulations were completed: (1) current climate simulation using ERA-Interim reanalysis as the forcing dataset every 6 hours (CTRL method), and (2) future climate simulation us-

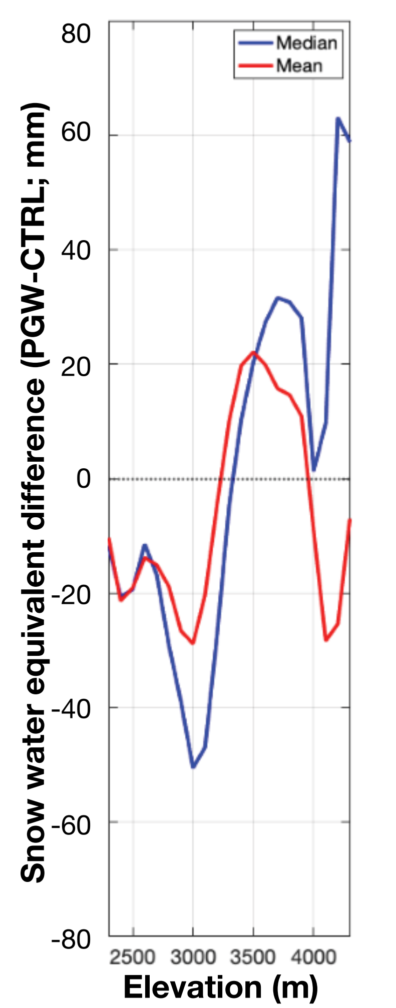

Figure 2. Differences in snow water equivalent (PGW-CTRL) represented by elevation over the northern Colorado Rocky Mountains.

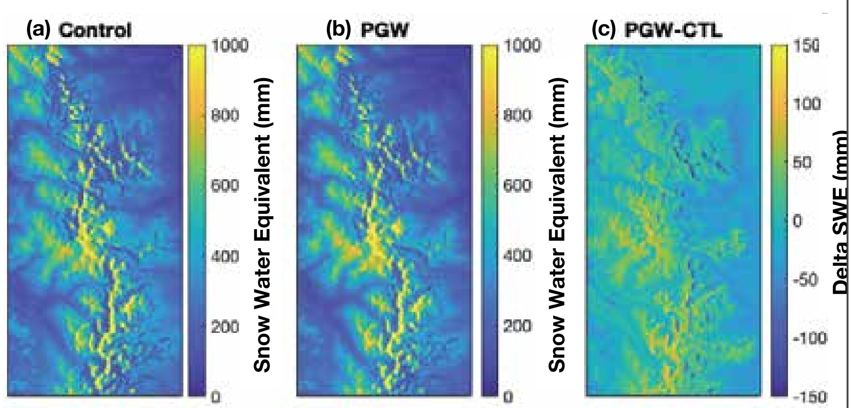

Figure 3. Snow water equivalent maps over the study domain for the (a) CTRL, (b) PGW, and (c) PGW-CTRL difference.

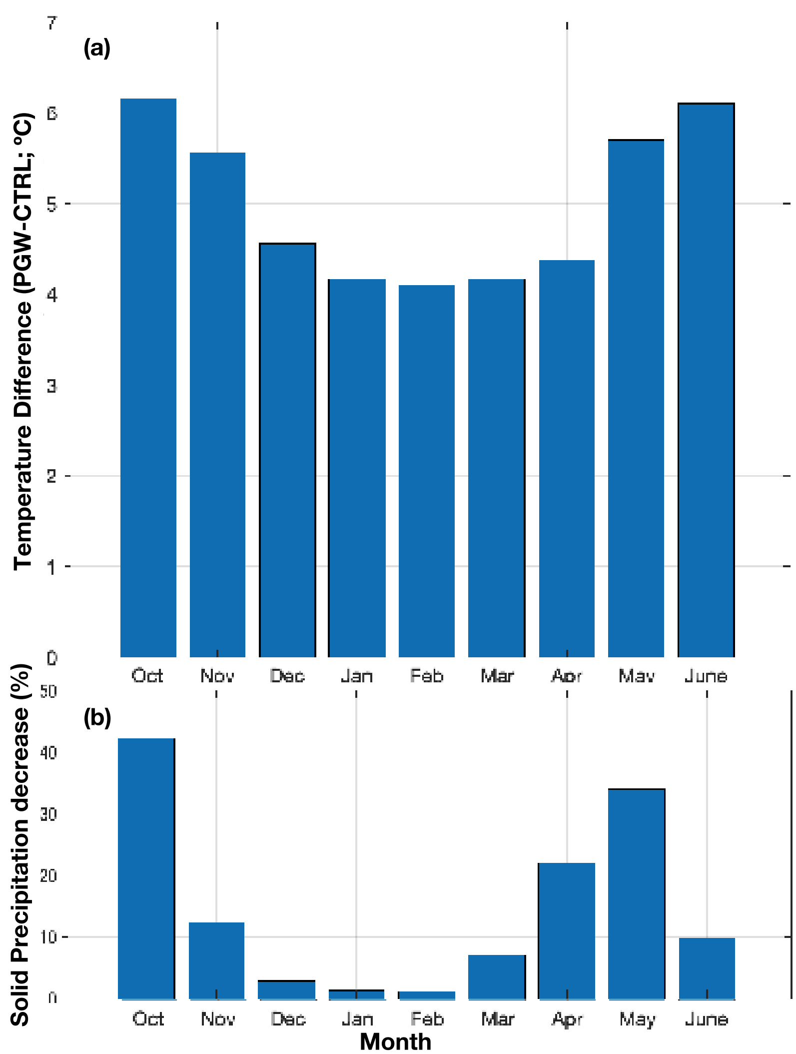

Figure 4. (a) Monthly average temperature differences (PGW-CTRL) for the 13 year coupled simulations. (b) Monthly average solid precipitation decreases (%).

ing the pseudo-global warming (PGW) method that uses the ERA-Interim reanalysis for the same period as (1), but adds a climate delta from 100 years in the future for the most extreme Representative Concentration Pathway (RCP) 8.5 scenario. Specific variables that are perturbed in the future climate simulation are: horizontal wind, geopotential, temperature, specific humidity, sea surface temperature, soil temperature, sea level pressure, and sea ice.

To achieve the project objectives, we downscaled the WRF CONUS simulations to a domain centered on the northern Colorado Rocky Mountains for input conditions to SnowModel. SnowModel was run at 100-m resolution over this region over two intervals: a historic (2000-2013) and future (2080-2093) period. For each year in the simulations, the start of the snow season is defined as the initial rise in snow water equivalent (SWE) and the end is when all of the SWE was melted. This procedure was repeated for both the CTRL and PGW simulations for each water year.

Results

Future changes in SWE over the northern Colorado Rocky Mountains indicate a shorter snowpack duration with less overall SWE in all 13 years of the simulation (Figure 1a). In general, the snow season starts later and ends earlier in a future climate (Figure 1b). Analysis of the length of the snow season shows that the future snowpack may be approximately 50 days shorter in each of the simulation years.

Analysis of the mean and median change in SWE by elevation in the region shows that SWE decreases below approximately 3,300-3,400 m and increases above these elevations (Figure 2). However, the mean SWE shows a decrease at the highest elevations above 4,000 m. Spatial maps of mean SWE in the CTRL and PGW simulations and their difference (PGW-CTRL) show that the locations with the greatest increase in SWE in a future climate are

Skiers take in the view of the Colorado Rocky Mountains. Photo by Erin Dougherty.

on the western slopes of the Rocky Mountains, with notable decreases in the lee (Figure 3). Decreases in SWE are particularly noticeable in the immediate lee of the high topography, likely explaining the decrease in mean SWE from Figure 2. These results suggest a shift in the orographic precipitation patterns or wind redistribution in a future climate along the highest mountain peaks and could have significant implications for water resources in the Colorado Front Range.

In a future climate, warmer atmospheric temperatures will likely play an important role in the snowpack evolution in the northern Colorado Rocky Mountains. Figure 4a shows the temperature anomalies (PGW-CTRL) averaged by month in all years of the simulations. In general, the fall and spring seasons are predicted to experience the greatest increase in temperatures (approximately 4.5-6 °C). This warming is likely the reason for the shortening snowpack duration seen in Figure 1. In addition, decreases in the percentage of solid precipitation are greatest in the fall and spring seasons, as a result of these temperature changes (Figure 4b). In summary, as a result of warming temperatures, which are most pronounced in the fall and spring, the snow season is shorter, in part due to reductions in the percentage of precipitation falling as snow. This result has important implications for water resource management in Colorado in a future climate, and should be carefully considered.

Discussion

Water in the West is a critical issue facing our society, and our team developed a novel interdisciplinary coupled atmosphere-snowpack modeling system to examine water resources and snowpack changes in a future climate. Snowpack dynamics simulated at 100m over the Colorado Rocky Mountains in a future climate show that the snow season will be shorter by approximately 50 days, and will have less SWE at lower elevations. The greatest increases in SWE are west of the continental divide, with decreases in the lee. Future atmospheric temperatures are expected to warm more in the fall and spring seasons, leading to a shortened snow season and decreased solid precipitation. The implications of these changes are significant and widely relevant to water managers, agricultural stakeholders, and outdoor sports enthusiasts in Colorado.

Future Research

Our interdisciplinary Water Research Team will continue to work together to understand changes in snowpack conditions in the Colorado Rocky Mountains. We plan to study the link between orographic precipitation characteristics and snowpack variability, snow processes within the snowpack over different vegetation types, and a more detailed SnowModel simulation over smaller basins at 10m resolution.

Acknowledgments: This research was funded by the Colorado Water Center at Colorado State University.

Numerical Modeling of Evolving Recharge-discharge Sources in a Multi-aquifer System

Michael Ronayne and Kristen Cognac, Department of Geosciences, Colorado State University

▼ SYNOPSIS

Effective management of groundwater resources requires an accurate characterization of aquifer recharge and discharge. These water-budget components may change through time in response to long-term groundwater pumping. Using variably-saturated flow models, this project explored the geologic and hydrologic factors that control recharge-discharge dynamics in aquifer systems stressed by pumping. The Denver Basin in Colorado provided a representative case study.

Introduction

Long-term groundwater pumping may lead to aquifer storage depletion and altered water budgets. Sources and rates of recharge and discharge for an aquifer are not fixed in time. Often, the amounts of inflow (recharge) and outflow (discharge) are influenced by pumping-induced variations in hydraulic head. Understanding these changes in recharge and discharge is critical for effective management of groundwater resources. In multi-aquifer systems, the water budgets for individual units may be linked across large vertical intervals, and deeper aquifers may be hydrologically connected to near-surface aquifers and streams. This project explored new methods to evaluate evolving recharge-discharge sources in heterogeneous aquifer systems, with specific focus on the Denver Basin in Colorado.

Recent studies of the Denver Basin Aquifer System (DBAS) have revealed substantial declines in water levels caused by groundwater pumping over the last several decades (Figure 1). These water-level declines have the potential to change aquifer water budgets. In particular, the exchange of groundwater between alluvial and bedrock aquifers is dependent on hydraulic heads within each aquifer. Using the DBAS as a case study, this research explored quantitative methods to evaluate how aquifer recharge and discharge respond to long-term pumping.

Specific questions addressed in this research include the following:

1. How does geologic heterogeneity (e.g., the locations of channelized sandstones) impact the alluvial-bedrock groundwater exchange?
2. What hydrogeologic conditions give rise to unsaturated zones between the alluvium and bedrock?
3. When do the aquifers become "disconnected," such that further declines in the bedrock water table no longer affect seepage losses from the overlying alluvium?

Representing the Aquifer Structure

Accurate groundwater flow models require a realistic representation of the aquifer architecture. In the DBAS, channelized sandstones occur within a less permeable mudstone and shale matrix (Figure 1). The sandstones are coarser-grained, and thus form the primary aquifer material. Quantifying the abundance, relative positions, and connectivity of the sandstones is critical for developing accurate models of groundwater flow.

For this project, we reviewed over 50 detailed logs for wells in the Denver Basin. Well-log data were obtained from the Colorado Geological Survey and the Colorado Division of Water Resources. Thus far, our site-specific analysis has focused on Douglas County, Colorado, a region with high groundwater pumping. Data compiled from well logs have been used to constrain geostatistical simulations of the aquifer structure. Three-dimensional examples provided in Figure 2 repre-

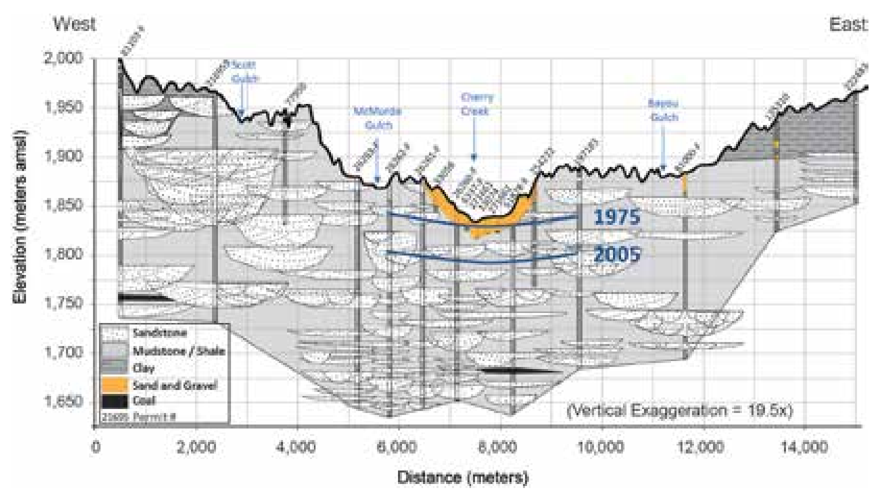

Figure 1. Hydrogeologic cross-section in the vicinity of Cherry Creek, Douglas County, Colorado. Water levels from state well records are plotted for the bedrock aquifer and indicate hydraulic head declines of roughly 50 meters since 1975.

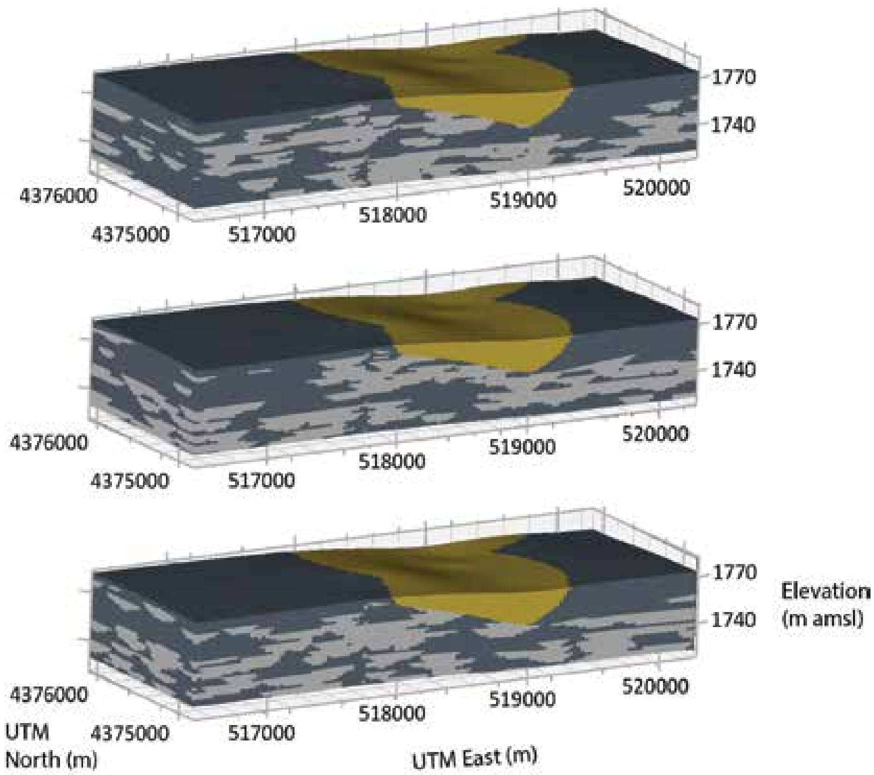

Figure 2. Simulated realizations of the subsurface heterogeneity within the Denver Basin Aquifer System. Alluvial sand and gravel at the top are underlain by channelized sandstone (lighter color) and mudstone/shale matrix.

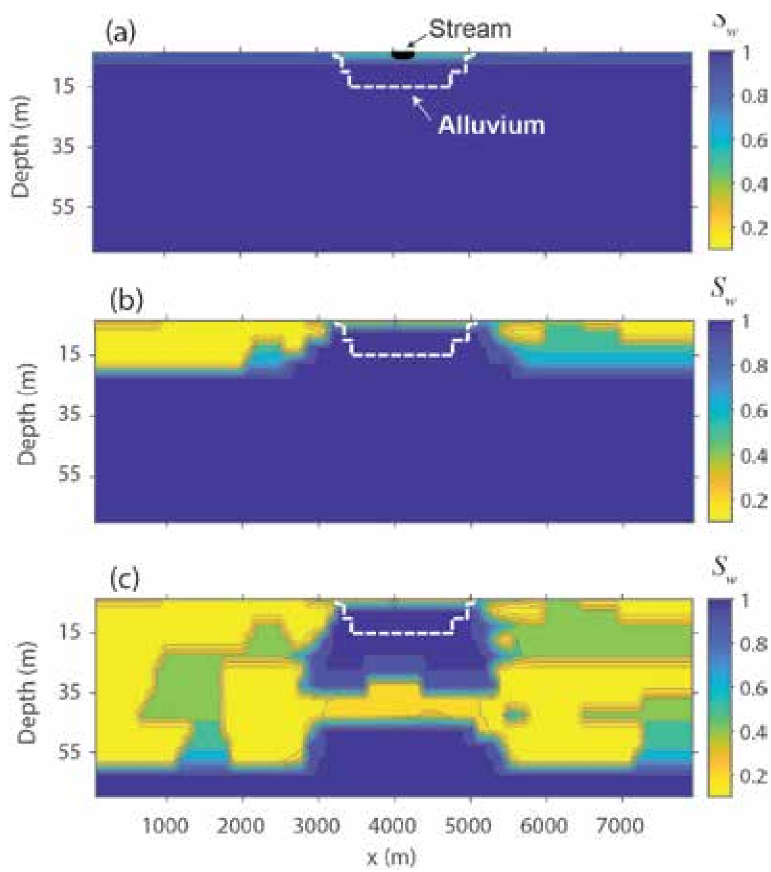

Figure 3. Modeled water saturations (Sw) for three scenarios with progressively lower (a → b → c) water-table positions in the bedrock aquifer.

sent a few plausible (albeit simplified) realizations of the geologic heterogeneity. Each of the realizations, which were generated using object-based geostatistical modeling, contains the general style of heterogeneity that occurs within the DBAS. The primary hydrogeologic units within the bedrock aquifer are sandstone and mudstone/shale. The abundance of sandstone and thickness of sandstone channels, along with some specific locations, are constrained by the well data.

Flow Modeling to Assess Evolving Water Budgets

The simulated subsurface heterogeneity (e.g., Figure 2) provides the architectural framework for groundwater flow modeling. Our modeling encompasses the stream-alluvium-bedrock aquifer sequence. Depending on the regional (bedrock aquifer) water-table position, groundwater may enter the alluvial aquifer and stream (vertically upward flow) or, alternatively, flow may be directed downward from the alluvium into the bedrock aquifer. We developed numerous modeling scenarios to simulate gradual changes in the regional water-table position, following historical water level records from monitored Denver Basin wells.

Variably-saturated flow modeling was performed to allow for the occurrence of unsaturated conditions. The major hydrogeologic units (alluvium, sandstone, and mudstone/shale) have very different hydraulic properties, including water-retention properties. For example, mudstone and shale tend to retain water, whereas the alluvium and sandstone have much greater potential to drain when aquifer hydraulic heads decrease. Given the importance of these properties for understanding hydrologic fluxes and water budgets, detailed spatial variability in hydraulic properties was incorporated into the modeling; the distribution of assigned properties followed the simulated geologic heterogeneity.

Figure 3 shows example flow modeling results within a 2D cross-section. The three scenarios correspond to early, intermediate, and later-time scenarios where the regional water table is 15 meters above, 5 meters below, and 45 meters below the base of alluvium, respectively. The modeling results highlight the potential for unsaturated conditions within the bedrock aquifer. In the deep water-table scenario (Figure 3c), coarse sandstone units become partially dewatered.

Pumping-induced water level decline changes the inputs and outputs to/from each aquifer. For the bedrock aquifer specifically, the amount of recharge increases with a declining regional water table (Figure 4). This is due to an increasing downward hydraulic gradient between the alluvial and bedrock aquifers. Initially, there is a linear relationship between recharge and water-table position. As unsaturated conditions develop in the bedrock aquifer, the relationship becomes nonlinear (Figure 4). Eventually, the recharge rate stabilizes (i.e., it is no longer dependent on the water table position in the bedrock aquifer). This is analogous to a hydraulic disconnection scenario that has been described for stream-aquifer systems. In this work, we demonstrate the potential for aquifer-aquifer disconnection, and we explore the associated water budget implications.

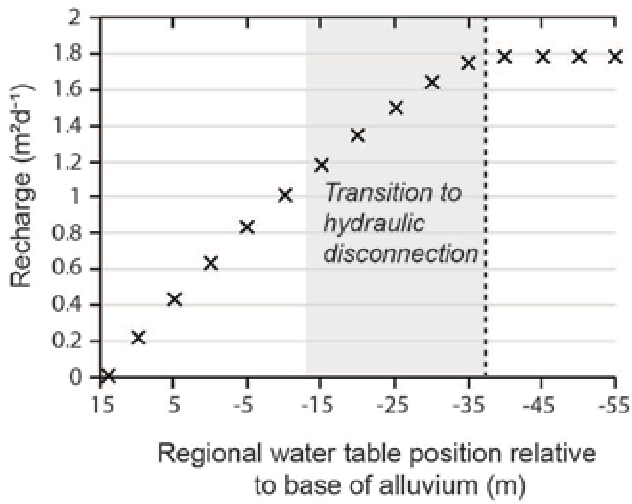

Figure 4. Simulated bedrock aquifer recharge for 2D cross-sectional modeling scenario. As the regional water table declines, groundwater recharge increases and then eventually stabilizes.

Dawson Formation sandstone in Castlewood Canyon State Park. Photo by Kristen Cognac.

Research Impact and Next Steps

Like many other aquifer systems worldwide, the DBAS has experienced substantial groundwater depletion, accompanied by declining water levels. This project investigated how these long-term changes impact alluvial-bedrock interaction. Variably-saturated flow modeling was performed to investigate the major controls on bedrock groundwater recharge, including the aquifer architecture, hydraulic properties, and regional water-table position. Model simulations with realistic geologic heterogeneity demonstrate the potential for unsaturated conditions within the bedrock aquifer. This may eventually produce a hydraulic disconnection between the alluvial and bedrock aquifers, limiting further pumping-induced changes in recharge. By describing long term changes in aquifer water budgets and sources of groundwater recharge, these results have important implications for water management in Colorado.

A portion of the work described in this article was recently published in Hydrogeology Journal (Cognac and Ronayne, 2020), and it will serve as the basis for external proposals focused on how heterogeneous multi-aquifer systems respond to long-term pumping. This project has allowed us to expand existing relationships with municipal partners in the Denver Basin. In a current municipal partnership, we are sampling surface water, alluvial aquifer water, and bedrock aquifer water for stable isotopes in an effort to further constrain sources of groundwater recharge in the DBAS. Through this work, we've also enjoyed new opportunities to interact and collaborate with colleagues at CSU and the Colorado Geological Survey.

Acknowledgments: Support from the Colorado Water Center is gratefully acknowledged. Special thanks to Heather Justus at Castle Rock Water, Peter Barkmann at Colorado Geological Survey, and professors Lisa Stright (CSU) and Tom Sale (CSU) for helpful discussions related to hydrogeologic data availability and well log analysis.

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COLORADO MASTER IRRIGATOR

Fostering Farmer Engagement with Irrigation Technology and Advanced Water Management

Susie Hutton and Amy Kremen, Department of Soil and Crop Sciences, Colorado State University

▼ SYNOPSIS

The Colorado Master Irrigator program aims to offer comprehensive education and an excellent forum for in-depth discussion related to a wide range of proven methods, strategies, and tools for increasing water- and energy-use efficiency and conservation in irrigated production systems. This course targets Colorado Republican River Basin irrigators farming in the northeast corner of the state.

Project Background

Colorado's agricultural sector that relies on the Ogallala/High Plains Aquifer has, for decades, pumped this limited source of groundwater faster than it can be recharged. Ongoing aquifer declines in water quantity and quality are anticipated to diminish future agriculture profit potential and land values, and threaten the long-term vitality of many communities.

Several proven irrigation technologies and strategies available to assist farmers in reducing their consumptive water use, while maintaining profitable yields, have primarily been adopted by a minority of innovative producers. For instance, most farmers tend to visually inspect their crops and gauge soil moisture by hand-feel to determine when and how much to irrigate, rather than trusting soil moisture probe or evapotranspiration (ET) data to inform their irrigation decisions. As a result, producers are potentially using more water than needed, especially during normal-to-wet years, incurring unnecessary expenses, as well as wear and tear on irrigation systems, and possibly leaching expensive applications of nutrients down beyond the plant-root zone.

Effective training opportunities are needed to support and engage producers in discovering and evaluating opportunities and options that can help make it possible to steward limited groundwater resources more effectively as part of maximizing their operations' profitability.

Project Rationale

Producer resistance to integrating data-centric decision-support tools is multifaceted. For example, farmers are unlikely to invest in system upgrades or adopt new technology solutions (hardware and/or software) and management practices if they do not see a clear time- or money-saving benefit, or see that their peers are using them. Producers will abandon these tools if they are not familiar with how to interpret data and as a result, cannot determine how to use these tools to their fullest potential on their operations. Given the widespread proliferation and constant evolution of tools, platforms, and ownership of technologies, it is not surprising that farmers struggle to identify options they think will suit their operations.

Meanwhile, over time it is common for irrigation system hardware to deteriorate and diverge from initial optimal performance specifications. There is enormous opportunity in agriculture, to save energy and water. But situations such as lack of timely and comprehensive review of irrigation systems, initial system design being out of sync with current needs, oversizing of pumps and control valves due to a lack of system standards, along with other common factors, all contribute to irrigation system inefficiencies. Few irrigators have had their systems audited in a timely way. Nor do they keep up with identifying necessary hardware replacement needs that could minimize operation costs year-over-year, and improve system reliability.

Methods

Modeled after an award-winning Master Irrigator program created in 2016 by the North Plains Groundwater Conservation District in the Texas Panhandle (northplainsgcd.org/conservationprograms/communityedu/master-irrigator/), Colorado Master Irrigator is a four-day classroom-based learning experience that takes place over four, eight-hour sessions. The program format is shaped with the input of a program advisory committee (PAC) of local producers, university extension personnel, groundwater management district leaders, technical service providers, and others who volunteer their time and who are responsible in large part for recruiting participants and sponsors.

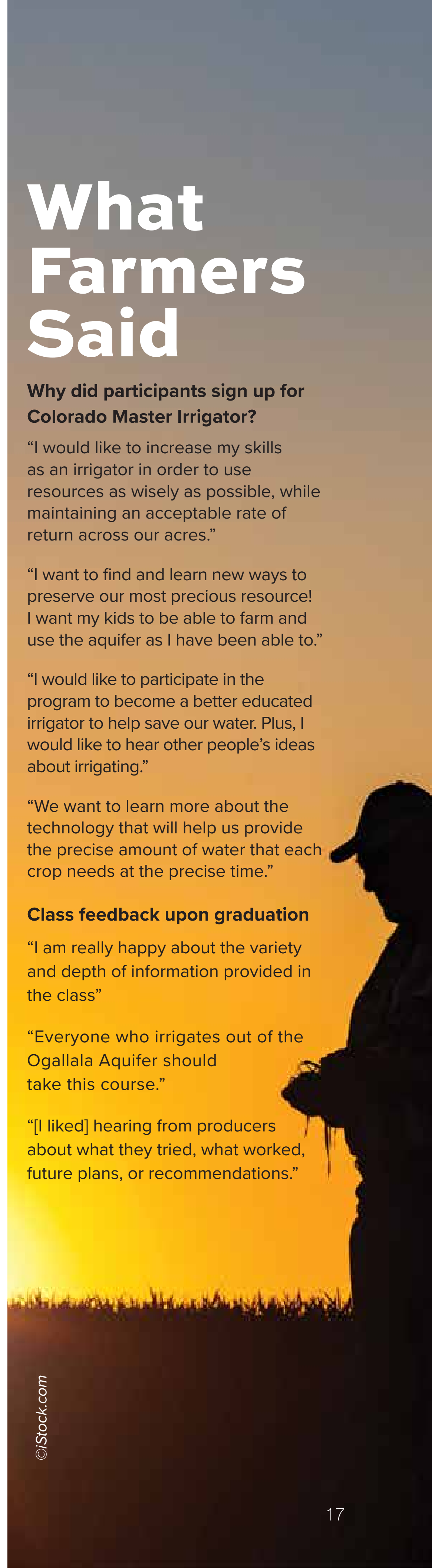
The course covers a wide range of fundamental-to-advanced topics and practical economic aspects related to optimizing water use, including: irrigation scheduling, crop choice and planting density, soil and plant sensors, remote monitoring systems, pivot-related maintenance for improved water use efficiency, residue management, soil health, and more. The program uses an interactive learning approach, with the class size limited to 25 participants to encourage peer-to-peer exchange.

Thanks to the financial support provided through a Colorado Water Conservation Board (CWCB) Colorado Water Plan grant, program graduates are eligible to receive a $2,000 participation stipend. “In return for accepting this stipend, our graduates will provide quantitative and qualitative information for three growing seasons about their thinking and efforts to manage energy and water use on their operations. We’ll use these valuable insights to improve our program, and we hope that they will also help advance water management in our region, benefitting the aquifer and our communities over the long term,” says Brandi Baquera, Colorado Master Irrigator program coordinator. Graduates can also take advantage of other financial assistance opportunities made available by program sponsors and partners. For example, recognizing Colorado Master Irrigator graduates’ training, the Natural Resources Conservation Service provides a 20% criteria ranking bump when they apply to a Republican River Basin Targeted Conservation Project that awards Environmental Quality Incentives Program-funded financial assistance to support the adoption and integration of conservation-oriented tools and practices.

Results and Impacts

The inaugural Colorado Master Irrigator class comprised 22 producers and farm managers who are involved in the management of approximately 20,000 irrigated acres located across all eight of the groundwater management districts in Colorado’s Republican River Basin. In completing program exit surveys, participants noted that the program expanded their knowledge and exposed them to new tools, such as relatively low-cost weather stations and satellite-based imaging. When asked what new tools and strategies they would be willing to try in the future, they mentioned soil moisture probes, ET data-based irrigation scheduling, Variable Frequency Drives, and cover crops. Participants also mentioned being interested in using telemetry to remotely monitor fields and irrigation systems, using Variable Rate Irrigation to precisely apply nutrients and water, and updating nozzle packages to improve irrigation application uniformity.

The engagement of a diverse group of presenters including researchers, extension educators, groundwater management district representatives, and producers was a critical factor in the program’s success. Many colleagues connected to the USDA National Institute of Food and Agriculture-funded, multistate Ogallala Water Coordinated Agriculture Project team (ogallalawater.org) based at CSU were tapped to serve as presenters. Their expertise and dynamic presentation of topics were well-received. A particularly notable outcome related to this cross-state engagement is that the coordinator for a new Master Irrigator program expected to launch later this year in western Oklahoma attended and observed part of Colorado’s program. The Colorado program is sharing budget information and other supporting documentation as templates,



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What Farmers Said

Why did participants sign up for Colorado Master Irrigator?

“I would like to increase my skills as an irrigator in order to use resources as wisely as possible, while maintaining an acceptable rate of return across our acres.”

“I want to find and learn new ways to preserve our most precious resource! I want my kids to be able to farm and use the aquifer as I have been able to.”

“I would like to participate in the program to become a better educated irrigator to help save our water. Plus, I would like to hear other people’s ideas about irrigating.”

“We want to learn more about the technology that will help us provide the precise amount of water that each crop needs at the precise time.”

Class feedback upon graduation

“I am really happy about the variety and depth of information provided in the class”

“Everyone who irrigates out of the Ogallala Aquifer should take this course.”

“[I liked] hearing from producers about what they tried, what worked, future plans, or recommendations.”

... two producers from Kansas ... made a huge impression by sharing how they have adapted to using less water.

Interactive small-group activities built into each day of the program provided terrific opportunities for participants to explore questions in greater depth and exchange ideas and expertise with one another. Photo by Amy Kremen.

Colorado Master Irrigator coordinator Brandi Baquera congratulates Burlington-area producer Brian Lengel as the program's graduation ceremony. Brian also served on the Colorado Master Irrigator PAC and was instrumental in contributing his time, creative ideas, and grounded input critical to the program's success. Photo by Hannah Moshay.

The inaugural Colorado Master Irrigator class of 22 producers and farm managers are involved in the management of approximately 20,000 irrigated acres located across the Republican River Basin, within all eight of the Basin's groundwater management districts. Photo by Hannah Moshay.

passing forward to the Oklahoma team the same kind of support that the original Master Irrigator program in Texas provided in 2018-2019, when the effort to start Colorado's Master Irrigator program was just getting underway.

In another terrific cross-state development, two producers from Kansas' Groundwater Management District #4 (GMD4) in northwestern Kansas, just across the state border, made a huge impression by sharing how they have adapted to using less water. These producers farm within the Sheridan-6 Local Enhanced Management Area, which limits producers to using 55 ac-in of water over five years. The Colorado Master Irrigator participants found it very interesting to hear how these two farmers have managed. In turn, the Kansans appreciated the educational approach to Master Irrigator so much that, upon returning home, they immediately pitched a plan to their district manager to offer a similar program for irrigators farming in their district. As a result, GMD4 now plans to launch a Master Irrigator program within the coming year or two.

Next Steps

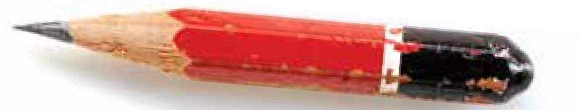
Seven graduates expressed interest in joining the Colorado Master Irrigator PAC which will reconvene in late summer 2020 to review the successes and lessons learned from the inaugural 2020 program, work to adjust the curriculum and program logistics, line up speakers, and engage sponsors for the 2021 program.

Colorado Master Irrigator awarded three special awards of $4,000 each to support three graduates who submitted applications describing especially strong commitments and clear plans for achieving specific water conservation goals on their operations. To be eligible for this award, these individuals all agreed to be program spokespeople and to serve on the PAC. Pandemic conditions permitting, the Colorado Master Irrigator program team will visit them later this growing season to film them on their operations and capture their stories to share through Colorado Master Irrigator's website and social media outreach efforts.

That collection of information will be part of a larger effort by the program team to follow up with 2020 graduates to find out how they have used or followed up on the information and networking connections they made through participating in the program. This material will be used to update the program's website and advertise the program. Follow the program's news and updates at comasterirrigator.org and via Twitter (@ColIrrigator) and Facebook (@comasterirrigator).

Acknowledgments: A 2019-2020 Colorado Water Center Education and Engagement grant of $7,500, combined with other seed funding, made it possible to develop this program throughout 2019 and launch it in early 2020. This funding was also used to leverage an additional $200,000+ in state funding through the CWCB to support the program's ongoing development and delivery through 2023.

Kids Using Water as a Metaphor to Write Poetry and Experience Nature



Steven R. Fassnacht, Ecosystem Science and Sustainability, Natural Resources Ecology Laboratory, Colorado State University; Cooperative Institute for Research in the Atmosphere
Elayna (Ella) R. Bump, Ecosystem Science and Sustainability, Natural Resources Ecology Laboratory, Colorado State University
Jim Glenn, Rocky Mountain High School
Jonathan Carlyon, Languages, Literatures and Cultures, Colorado State University

▼ SYNOPSIS

Poetry offers connections between science and the human experience. Using this motivation, the goals of this Education and Engagement project were to engage K-12 students by combining the creativity of writing poetry with the exploration of nature and provide hands-on experiences with water and early exposure to water science.

Inspiration

Nature provides a broad inspiration for poetry. Rivers are used as metaphors in many influential poems (Hughes, 1920; 1994), in philosophy (Heraclitus as discussed by Dietz, 2004), and short stories (Hemingway, 1927). Such metaphors have inspired others. The Heraclitus quote *Panta Rhei,* or "everything flows," was adopted by the International Association of Hydrological Sciences to investigate the changing interaction of hydrology and society over a decade (2013-2022) (Montanari et al., 2013). However, in the modern age, kids enjoy less time in nature. Louv (2008) quotes Wendell Berry: "our children no longer learn how to read the great book of Nature from their own direct experience ... they seldom learn where their water comes from or where it goes."

Hydrology and poetry are not so far apart; the use of the senses governs both fields. The poet examines the physical, and then takes it into abstraction. From the public's perspective, the scientist does the same. With these considerations, this project started as an opportunity to meld water science and poetry.

Materials

Does the young water expert ever wonder what happens to those old hard-copy journals that sit in the basement of an institution's library, in a professor's office, or tucked away in a lab? Since most journals are now available online, we decided to put some old ones to use (Figure 1).

Figure 1. Example of hard-copy water journals provided by Professor John Stednick upon his retirement in 2016. Photo by Steven Fassnacht.

Methods

CSU faculty and a graduate student partnered with an English Language Arts (ELA) instructor at Rocky Mountain High School (RMHS) in Fort Collins, Colorado to address the goal of kids writing poetry on water in a U.S. Literature and Poetry class. We implemented a three-part lesson plan at the end of October and beginning of November 2019.

Figure 2. A Rocky Mountain High School U.S. Literature and Poetry student reads through a Journal of the American Water Resources Association paper. Photo by Steven Fassnacht.

In the first class-period, CSU Professor Steven Fassnacht, and graduate student Ella Bump, attended the poetry class at RMHS. Fassnacht and Bump spoke to the students about rivers and natural landscapes. The students were given a hard copy journal article (Figure 2) to review and explore the words that scientists use to write about rivers. Specifically, they were asked to identify key words and descriptors from the scientific paper. The students were asked to write a poem from the coupled key words and descriptors using the previously learned concept of metaphors.

The second day was a field trip to Picnic Rock Natural Area along Col-

Figure 3. RMHS students exploring the Cache la Poudre River at Picnic Rock Natural Area. Photo by Steven Fassnacht.

Figure 4a. Students pondering the Poudre River. Photo by Steven Fassnacht.

Table 1. River-personification poem from the Picnic Rock field trip "River Poems: 1 Personification" by TB

Water inked to glaring darkness,
shines with light as though
a thousand stars danced in its depth.

Glittering rapids swirl and swing,
bending and building the path they run,
while joyful laughter comes from beneath.

Capped with ice, seemingly slowed,
the River flows strong and ready
to devour any who sink into deep.

orado Highway 14 near the mouth of the Cache la Poudre River Canyon (about 15 miles from RMHS). ELA instructor Glenn reminded his students of the common adage that "you can't write about what you don't know, or you will be faking it." This field trip gave the students an opportunity to look at the river and the surrounding landscape (Figure 3). On the bus ride to Picnic Rock, Fassnacht provided a brief overview of the Poudre River and suggested the students ponder the varying landscape from Fort Collins to the Poudre Canyon. The students then explored the river and its surrounding landscape (Figure 4a). They were advised to make observations and take notes (Figure 4b) on what they experienced, including what they saw, heard, smelled, felt, etc. From these notes, they were asked to write a poem using personification of the river (Table 1). During the bus ride back to RMHS, several students shared the poems they had written.

The third water poetry exercise was to use a journal article to create a "found poem" by highlighting words and linking them together (Figure 5). They identified words to use in their poem, blacked-out all the other words, and through this redaction, created something like a ransom note.

Outcomes

There were 23 students in the class, and all submitted poems for the project. Most of the students attended the field trip. Since the trip to Picnic Rock took the entire afternoon, those who had other in-school commitments could not attend. The trip participants stated that they enjoyed the experience; this appreciation was also borne out from the poetry that they read during the bus ride.

The river-personification poems varied, but all spoke to the students' experiences at Picnic Rock (Table 1). The "found poems" appeared to be more of a challenge due to the confines of specific text on one page. However, with some grammatical interpretation, the students were able to craft a "found poem" based on a journal article focusing on water science (Table 2 and Figure 5). Word-cloud analysis of the terms used in the nine "found poems," illustrated the key water terms that resonated with the students, including: *development, measurements,* and *deprive* (Figure 6).

Table 2. Found poem" by MA (after Yoffe et al., 2003), as per Figure 5.

Conflict and Cooperation …
freshwater lies
in highlights in the
likelihood of war boundaries infer borders
between proximity
and other relations may share interactions.
with potential serve to immediate conflict

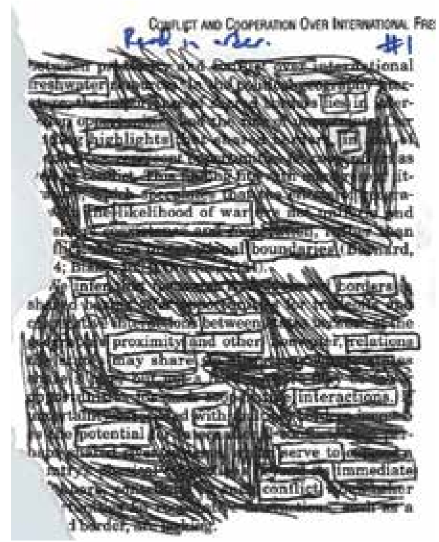


Figure 5. Sample "found poem" from the journal article by Yoffe et al. (2003).

Figure 4b. Students pondering the Poudre River's riparian landscape. Photo by Steven Fassnacht.

Figure 6. Word cloud for the "found poems" written in the class.

Discussion

Poetry is one of the earliest forms of documentation: first sung, then written. Documentation is at the heart of science, as the scientist observes and records. The two are connected through the sensory experience of being a human in nature — and being in nature is something that has been scientifically proven to have psychological and physical benefits to the human body. This integration of hydrology and poetry not only introduces kids to a scientific discipline, but it is also a scholarly exercise for young students to practice their writing skills, and a beneficial excursion into nature for developing minds.

There are numerous examples of grade school children helping collect hydrology data for research (Peck et al., 1974), and such opportunities provide students with a window into the science of water and data collection. However, such efforts should go beyond data collection into the unguided exploration of nature (Fassnacht et al., 1998). An example of this method is seen in a writing class at Plymouth State University, offered by English Professor Richard Chisholm (1997), who taught scientific writing through hands-on observations and basic measurements of the snowpack, and thus combined both the writing and science components. The melding of water science and poetry provides k-12 students a basic understanding of rivers (hydraulics, geomorphology) and the interaction of water with the landscape (hydrology), and helps improve writing skills.

Word-cloud analysis of the terms used in the nine "found poems," illustrated the key water terms that resonated with the students, including: development, measurements, and deprive.

WAVE

Watershed Assessment and Vulnerability Evaluations

Post-wildfire Land Health Assessments through a Hydrologic Lens

Blake Osborn, Southern Region Water Resources Specialist, Colorado Water Center and CSU Extension

It is no secret that Colorado's montane forests have evolved with fire regimes of predictive intervals and intensities. It is also widely accepted by the scientific community, that policies and management practices implemented over the past two centuries have, in many cases but not all, altered these regimes (Prichard et al. 2017). The American West, over the last several decades, has seen more wildland-urban development, extreme drought events, pest pressure, and wildfire suppression (Moritz et al. 2014). It is to be expected that at some point, environmental and management pressure could lead to the "perfect conditions" (or, in reality, not-so-perfect conditions) for large wildfires of greater intensities and severities. Then came 2020.

The global COVID-19 pandemic shifted our working environments and led to many logistical challenges for land managers, not the least of which was wildfire response and suppression. Worsening drought conditions, anomalous wind events, and years of fuel accumulation created the right (or wrong) conditions for an explosive growth in wildfire activity in Colorado, specifically north of the I-70 corridor. Three record-breaking fires (Pine Gulch, soon surpassed by the Cameron Peak; then by fast-moving East Troublesome) burned through a host of different ecosystems, including pinyon-juniper woodlands, shrublands, and sub-alpine forests. Still not fully contained at the time of this writing, the three biggest fires in Colorado during 2020 have burned more than 540,000 acres. And that is not including the highly visible Cal-Wood and Grizzly Creek fires. Suffice it to say, 2020 has been a record-breaking year for wildfire activity.

Three record breaking fires in Colorado burned through a host of different ecosystems including pinyon-juniper woodlands, shrublands, and sub-alpine forests.

In some cases, fires are confined exclusively to public lands. In other cases, they cross over to privately held lands. But no matter the jurisdictional ownership, the goods and services these lands provide (clean air and water, biological diversity, open space) are enjoyed by most of the public. Private landowners are vital partners in a well-functioning and healthy watershed environment,

and much of the natural resources we depend on in our daily lives are dependent on a healthy watershed.

The Watershed Assessment and Vulnerability Evaluation (WAVE) program was specifically designed to help private landowners recover from wildfire. This program benefits landowners by giving them personalized recovery plans to meet their land management goals, and could include forest regeneration, infrastructure protection, water quality protection, wildlife recovery, etc. The landowner's goals are evaluated through a set of criteria that determine their role in the watersheds' water cycle, and priorities are recommended to achieve their goals, always with the stabilization of the water cycle in mind. Most land management objectives depend on a healthy and functioning water cycle, and a healthy water cycle depends often on a healthy and productive ecosystem. It is a self-driving feedback generator. When one of the mechanisms is limited, it can affect the proper functioning of watersheds as systems.

The WAVE program was designed to fill gaps in other government agencies' post-wildfire response programs. WAVE was specifically designed to complement existing post-wildfire programs like the Natural Resources Conservation Services Emergency Watershed Protection (EWP) program, and works with local entities to provide outreach and assessment services to landowners around the state. What makes WAVE unique from other post-fire assistance is the ability to provide post-wildfire restoration technical assistance to landowners quickly, and at various scales. The program is also flexible to reflect priorities of the landowners, as well as making recommendations about how restoration treatments on their lands impact processes at the watershed scale. Finally, the program deploys through a network of local experts around the state, principally CSU Extension and the Colorado State Forest Service. Below is an example of two WAVE assessments that can be used as case studies.

A large ranch was impacted by a fire with 100% of the land burned to varying severities. A series of assessments, as well as a detailed list of recommendations, was given to the landowner. Finally, the WAVE team followed up with funding recommendations.

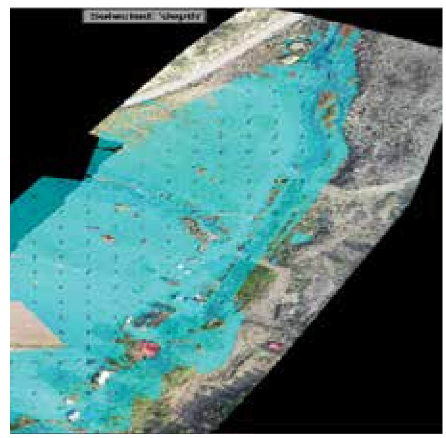
Hillslope and Channel Treatment Recommendations

A large ranch was impacted by a fire with 100% of the land burned to varying severities. The initial assessment included soil-burn severity tests and mapping, areas vulnerable to flooding and sediment transport, and infrastructure protection. A secondary GIS assessment was performed to identify soil characteristics, slope analysis, and priority areas for treatments. Finally, a basin-scale rainfall/runoff model was calibrated to offer a range of scenarios and impacts based on existing conditions. The findings of this effort, as well as a detailed list of recommendations, was given to the landowner. Finally, the WAVE team followed up with funding recommendations.

The WAVE program was designed to fill gaps in other government agencies' post-wildfire response programs.

Hydrologic Modeling

A small piece of land was just on the boundary of a large 2020 fire. Only a few acres of the property burned, and at low/moderate severity. However, a creek with a large contributing area transected the middle of the property near several buildings and other structures. The landowners were most concerned about the potential impacts of flooding and debris flow events in the creek. A basin-scale rainfall/runoff model was used to estimate stream flows under a variety of conditions, and a second flood model was calibrated with aerial drone photographs to produce a high-resolution digital surface model for flood analysis.



For private landowners concerned about post-fire flooding, a basin-scale rainfall/runoff model was used to estimate stream flows under a variety of conditions, and a second flood model was calibrated with aerial drone photographs to produce a high-resolution digital surface model for flood analysis.

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The Drought of 2020 in Colorado

Russ Schumacher, Peter Goble, and Becky Bolinger, Colorado Climate Center

▼ SYNOPSIS

After a near-average winter in terms of snowpack in Colorado, drought emerged and intensified quickly through the spring, summer, and autumn of 2020. Precipitation was well below average, but the drought was especially characterized by hot conditions through the summer and fall. This contributed to unprecedented wildfire growth, along with significant impacts on agriculture and water supply. In this article, we will summarize the development of one of the most intense droughts in Colorado's history, which persists as of this writing.

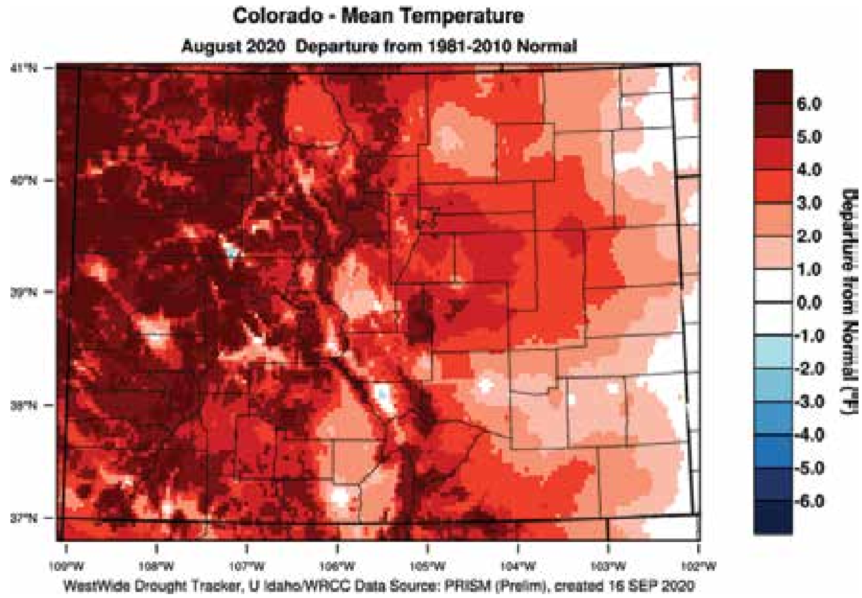

Figure 1: August 2020 departure from the 1981-2010 normal temperature (°F). Image from Westwide Drought Tracker, based on data from the PRISM Climate Group.

Development of the 2020 Colorado Drought

To set the stage for the development of drought in 2020, let's first look back at the extreme variations of the last few years. The winter of 2017-18 had very little snow in the southern mountains, and the Four Corners area had a failed monsoon in the summer of 2018. These combined to produce exceptional drought and a very active wildfire season (including the 416 and Spring Creek fires, both in the top 10 largest fires in state history). The winter of 2018-19 was the complete opposite, with February and March 2019 bringing huge storms, record snowpack in some areas, and a historic avalanche season in many mountain areas. Cool, wet conditions persisted into the spring, and in May 2019, the entire state of Colorado was free of drought or abnormally dry conditions for the first time since the U.S. Drought Monitor was established in

2020 precipitation was well below average, but the drought was especially characterized by hot conditions through the summer and fall. The result of wind erosion was visible in northeast Colorado. Photo by Emmett Jordan.

2000. Then the monsoon failed again in western Colorado (Defined here as Colorado climate division 2; all areas in Colorado that drain into the Colorado River system), and the late summer of 2019 set records for being hot and dry. In this context, the winter of 2019-20 was surprisingly normal, with snowpack in all basins in Colorado peaking within a few percent of average.

But in April, conditions started to turn warm and dry. Statewide, the April-May period was the fifth driest on record, and with temperatures well above average, the snowpack melted sooner than average, and the lack of spring rains on the eastern plains caused significant agricultural impacts. Along with some severe storms in early June (including an unusual derecho on the Western Slope and a major downburst in Akron), a string of hot, windy days led to drought intensification, and by the end of June, roughly the southern third of the state was in extreme drought. An episode of monsoon rainfall arrived in late July, bringing hopes of relief in some areas. But by the end of July, nearly the entire state was in at least abnormally dry conditions according to the U.S. Drought Monitor, with a quarter of the state in extreme drought (Fig. 1).

Photograph of the Cameron Peak fire plume, October 14. Photo by Henry Reges.

Then came August—by many measures considering temperature and precipitation, the most extreme summer month on record for western Colorado. Statewide, it was the hottest and fifth driest August on record. In western Colorado, it was the driest August on record, and exceeded the previous hottest August by 2°F (Figures. 1 and 2). The wildfire season typically slows down in August, as regular afternoon clouds and monsoon rains arrive in the mountains. But not in 2020: the Pine Gulch fire north of Grand Junction (which ignited on July 31) grew to become the largest wildfire in state history, a record that lasted only a short time. On August 13, the Cameron Peak fire started in the high elevations of Larimer County, and grew quickly in the hot, dry, and windy conditions.

Early September 2020 brought extremes, as the first several days of the month smashed records for heat, and smoke shrouded Fort Collins in darkness at midday on Labor Day.

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Early September brought more extremes, as the first several days of the month smashed records for heat, and smoke shrouded Fort Collins in darkness at midday on Labor Day. This was abruptly followed by snow two days later, including over a foot of snow in the San Luis Valley, where it had never snowed so early in the fall before. Growth of the active wildfires was slowed by the September snowstorm, but warm, dry, and windy weather returned, and the fires regained their momentum. The Cameron Peak fire became the largest in state history on October 14, and on that same day, the East Troublesome fire started in Grand County. Within ten days, it grew to become the second largest in state history, with terrifyingly fast growth through Grand Lake and into Rocky Mountain National Park. By late November 2020, the entire state remained in drought and over a quarter of the state was in the D4 (Exceptional Drought) category (Fig. 4). The most striking images of the 2020 drought in Colorado were the development of the three largest wildfires in state history (along with several other very large fires), but other wide-ranging impacts were felt as well.

From a water resources standpoint, it is worth revisiting both the spring and fall of 2019. The onslaught of winter storms in February, March, and even May produced a banner runoff year. This wet period

Colorado CD2 (Colorado River drainage) average temperature and precipitation August 2020.

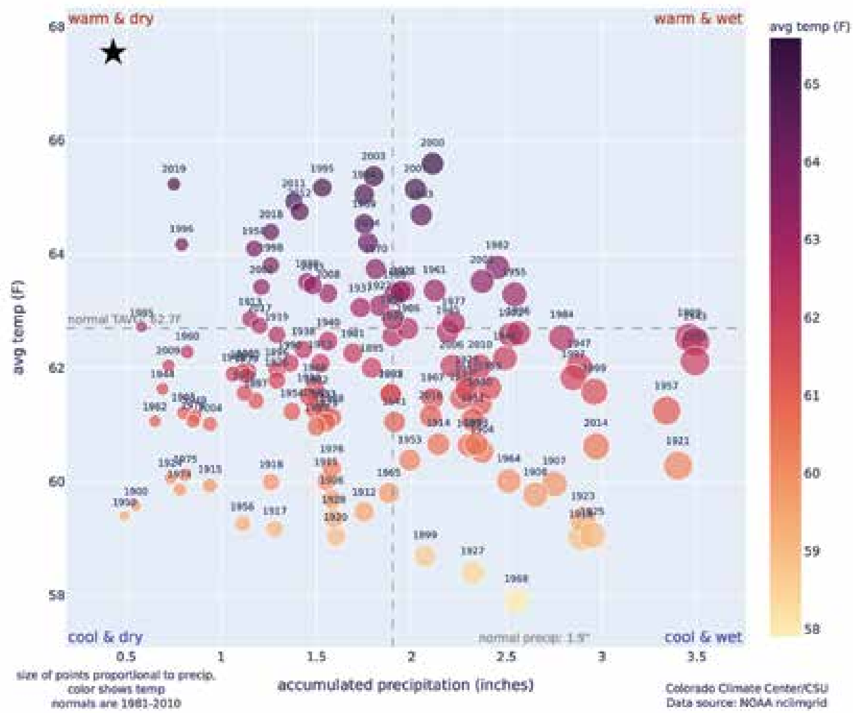


Figure 2: Precipitation (on x-axis) and temperature (on y-axis, and dot colors are proportional to temperature) for Colorado climate division 2 (western Colorado) for all years 1895-2020; the 2020 value is denoted by a star.

U.S. Drought Monitor—Colorado

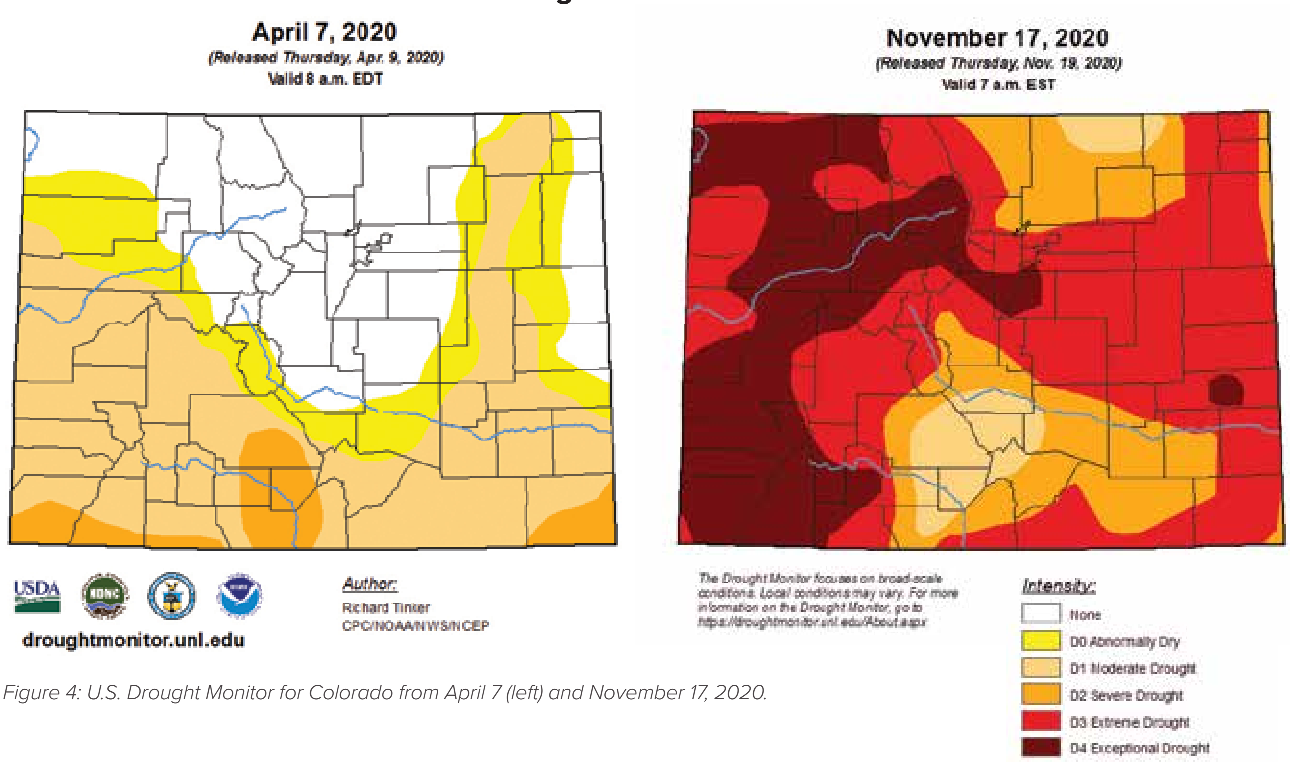


Figure 4: U.S. Drought Monitor for Colorado from April 7 (left) and November 17, 2020.

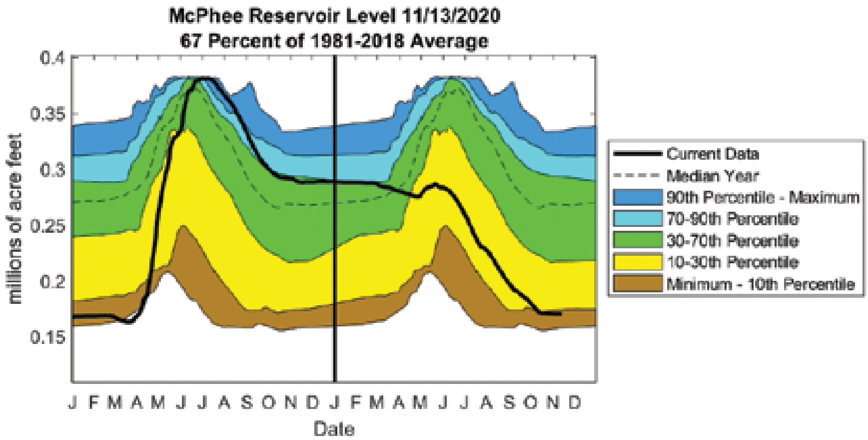


Figure 5: McPhee Reservoir Storage 2019-2020. Solid black line indicates 2019-2020 storage. Shaded regions indicate percentile ranges.

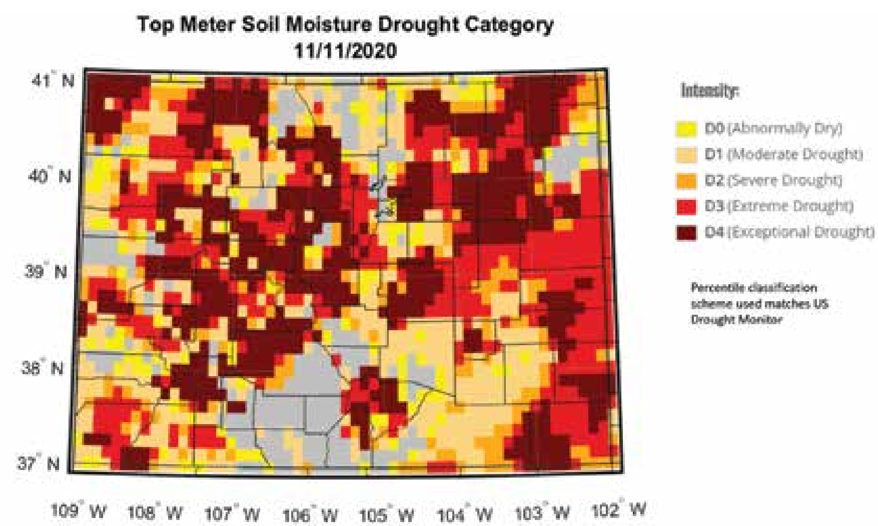


Figure 6: Colorado root zone (top meter) soil volumetric water content map. Color scheme designed to match US Drought Monitor. Dark red = 0-2nd percentile, red = 3-5th percentile, orange=6-10th percentile, tan = 11-20th percentile, yellow = 21-30th percentile, gray = 31-100th percentile.

... the summer of 2020 was characterized by a rapidly intensifying drought, with extremely high temperatures and another failed monsoon in much of Colorado. These conditions led to a record wildfire year for Colorado, and widespread impacts on agriculture and water resources.

recharged ailing reservoir systems across Colorado. Larger bodies of water still benefit from 2019 carry-over storage today. However, late summer and fall of 2019 was dry, which also had important consequences for 2020. Soil moisture storage was well below average leading into water year 2020's snowpack season. This, in combination with a dry April and May 2020 produced peak runoff values generally ranging between the 20th and 40th percentile. Some portions of southwest Colorado fared even worse, reflected in the storage in McPhee Reservoir (Fig. 5).

The month of July brought some temporary relief in the form of thunderstorm complexes, particularly to southeast Colorado. However, water resources simultaneously continued to weaken in western Colorado. Following the last week of July, the North American Monsoon again failed to materialize in Colorado. Statewide, soil and vegetation became critically dry, contributing to both agricultural and ecological drought. While temperatures have cooled through the fall as the days have shorted, our water resources remain low (Fig. 6).

Summary

In summary, the summer of 2020 was characterized by a rapidly intensifying drought, with extremely high temperatures and another failed monsoon in much of Colorado. These conditions led to a record wildfire year for Colorado, and widespread impacts on agriculture and water resources. Future research will likely identify the specific influences of a warming climate on summer droughts such as these. Considering that western Colorado is among the places in the country that has warmed the most , and the sensitivity of our water resources to increases in temperature, continued warming raises considerable concerns about the potential for more intense droughts in the future.

Hugo Lezama, Colorado State University Civil and Environmental Engineering student and Water Sustainability Fellow, speaks at the 2017 Stories of Environmental Justice Symposium on diversifying voices and raising awareness though the National Western Center youth water project. Photo by Beth Plombon, Colorado State University.

Research Experience and Mentorship Opportunities

Nora Flynn, Agriculture Water Specialist, Colorado Water Center

Once again, the Colorado Water Center will be offering hands-on research experience and mentorship through the Water Sustainability Fellowship Program this spring. Each cohort of Water Sustainability Fellows partners with CSU faculty, staff, and community members to explore topics in water sustainability and environmental justice and equity. The spring 2021 cohort will focus on water quality in the South Platte River Basin in historically disadvantaged communities in Denver. Future cohorts may explore tribal water issues, climate change impacts, or sustainable food systems.

The Water Sustainability Fellows Program is also designed to elevate previously underrepresented voices in conversations and decision-making around water. Undergraduate students from underrepresented minority groups, and/or students who have been trained in diversity and inclusion principles, are highly encouraged to apply. The Fellows work with community members to support projects that benefit the environment and improve livelihoods. Students interested in participating should send an email to nora.flynn@colostate.edu.

We rely on generous donations from the Colorado water community to support scholarships for our Fellows and the projects we work on. Are you or your organization interested in supporting a Fellow's stipend, project, or conference registration? Please contact Nora Flynn at nora.flynn@colostate.edu.

Colorado Water Center's Water Sustainability Fellows engage with water professionals throughout the state. Photos by MaryLou Smith.

Congratulations to the 2020-2021 **CSU Competitive Grant Program Awardees**

Sara Rathburn photographed at the CSU Mountain Campus. Photo by Bill Cotton.

Water Research Teams

Building a long-term watershed research site at CSU Mountain Campus

Sara Rathburn is an Associate Professor in the Department of Geosciences. She is leading a large team of faculty, students, and partners to build a long-term watershed research site at CSU Mountain Campus. Rathburn and this team of researchers will study the headwaters of the South Fork of the Cache la Poudre River, and make that information available for wider use. Through this project, the team will coordinate data collection, storage, and analysis, and will also develop teaching content for CSU and the Poudre School District.

Rathburn described the team's motivation: "The award leverages an initial investment from Dean Hayes in Warner College of Natural Resources to install surface-water gages, as well as groundwater wells along the South Fork Cache la Poudre River, two weather stations, and telemetry equipment. The Colorado Water Center funding will allow us to launch a full year of coordinated data collection, interpretation, analysis, and visualization to foster broad interdisciplinary research, collaborate with City of Ft. Collins stakeholders, develop relevant teaching content for CSU and public school students enrolled in classes at the Mountain Campus, and promote the Mountain Campus as a long-term research site. We look forward to building synergy between the Mountain Campus and the Colorado Water Center to address pressing water issues through research and teaching."

Team Investigators

PI: Sara Rathburn, Geosciences

Co-PIs: Kira Puntenney-Desmond, Stephanie Kampf, Steven Fassnacht, and Matthew Ross, Ecosystem Science & Sustainability

Michael Ronayne and Daniel McGrath, Geosciences

Ryan Morrison, Civil & Environmental Engineering

Kristen Rasmussen, Atmospheric Science

Seth Webb, CSU Mountain Campus

Jared Heath, City of Fort Collins

Mike Wilkins (right) with Thomas Borch (left) and Holly Roth

Beaver-generated wetlands as ecosystem control points for post-fire transport of sediment, carbon, nutrients, and toxic metals into Rocky Mountain headwaters

Assistant Professor Mike Wilkins in the Soil & Crop Sciences Department is partnering with CSU faculty and the U.S. Forest Service to conduct field and laboratory research in order to better understand water quality changes in post-fire landscapes. Specifically, the team will investigate ecosystem impacts of burned landscapes in beaver-generated wetlands in Colorado and Wyoming.

Team Investigators

PI: Michael Wilkins, Soil & Crop Sciences

Co-PIs: Thomas Borch and Charles Rhoades, United States Forest Service

Water Fellows

Integrating low-tech, process-based restoration techniques to a degraded perennial stream system: A community-driven research model

Blake Osborn, Water Resources Specialist with CSU Extension and the Colorado Water Center, is exploring restoration of degraded stream systems through collaborations with myriad community members including local water experts, Cañon City High School, private landowners, local municipal water providers, and NGOs. "The number one goal for our project is to quantify the impacts of novel stream restoration techniques on groundwater/surface water relationships. Working with the local high school, and giving students intensive hands-on training in applied research, are just icing on the cake," Osborn explains.

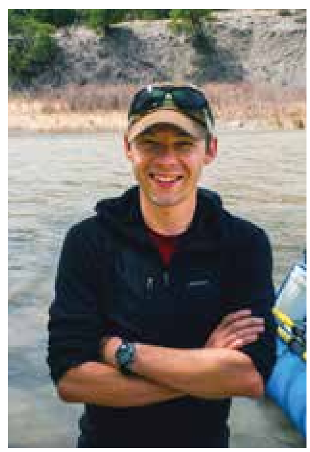
Cañon City High School students are part of the collaboration effort integrating low-tech, process-based restoration for degraded stream systems.

Blake Osborn

The project seeks to educate and train students and water professionals in natural river processes and restoration, improve hydrogeomorphic conditions in a two-mile stretch of Oak Creek in southeast Colorado, and provide data to inform state water managers about process-based restoration on stream-system hydrology. Project impacts will be achieved by developing a new high school course that offers integrated STEM subjects and case studies.

Fellow

Blake Osborn, CSU Extension and Colorado Water Center



Ryan Morrison

Toward understanding the global impacts of human activities on floodplain integrity

Civil and Environmental Engineering Assistant Professor Ryan Morrison is joining forces internationally to understand human impacts on floodplain integrity. Leveraging previous research, Morrison will identify and compile global datasets, and develop methodology to assess global floodplain integrity. Ultimately, Morrison and collaborators aim to help water and land managers target efforts toward the most impaired floodplains.

Fellow

Ryan Morrison, Civil & Environmental Engineering

Learn more about the CSU Competitive Grant Program

watercenter.colostate.edu/grants

2020 CSU Water Research Awards

Principal Investigator	Project Title	Sponsor	Amount
Thornton, Christopher	Design Variable Development for Transverse Features in the Middle Rio Grande	DOI-Bureau of Reclamation	$390,000
Flynn, Nora	Alternative Transfer Method (ATM) Strategic Plan Development	Colorado Water Conservation Board	$15,040
Bailey, Ryan	BLM-NOC, Enhancement of APEX Model for Simulating Soil Erosion and Salt Transport in the Colorado River Basin	Texas A and M University	$75,000
Sueltenfuss, Jeremy	Creation of Hydrologic Performance Standards Training Manual	DOD-ARMY-Corps of Engineers	$50,000
Arabi, Mazdak	Tools for CDPHE	Colorado Department of Public Health and Environment	$150,000
Dell, Tyler Adam	E.Coli Sampling in Denver Streams	Colorado Department of Public Health and Environment	$112,082
Flynn, Nora	McKinley Ditch Pilot Project	Colorado Water Trust	$144,041
Winkelman, Dana	Quantitative Assessment of Pelagic Fishes in Colorado Reservoirs	Colorado Division of Parks and Wildlife	$71,667
Sanford, William	CESU-RM: NPS Groundwater Data Management	DOI-NPS-National Park Service	$65,000
Wrighton, Kelly	Development of a Microbiome Resource to Discern the Microbial Impacts across Dynamic River Systems	DOE-Pacific Northwest National Laboratory	$49,000
West, Daniel Robert	2020CPG Forest Health Monitoring	USDA-USFS-Forest Research	$52,000
Ham, Jay	Monitoring Edge-of-Field (EOF) Water Quality in Surface-Irrigated Sugarbeets: Identifying BMPs for Reducing Nutrient Runoff	Western Sugar Cooperative	$14,100
Goemans, Christopher	Evaluating Alternative Water Institution Performance in Snow-Dominated Basins: Are Food Productions Systems at Risk from Changing Snow Water Availability?	University of Nevada	$108,372
Arabi, Mazdak	Missouri River Recovery Management Plan Adaptive Management Decision Support System	ESSA Technologies, Ltd.	$168,000
Baker, Ian	Advancing Understanding of Drought Prediction from Environmental Stressors	DOC-NOAA-Natl Oceanic and Atmospheric Admn	$75,194
Kendall, William	RWO120 Developing Fish Population Models for the Little Colorado River from Integrated Data Sources	DOI-US Department of the Interior	$19,868
Covino, Timothy	CAREER: From the Forest to the Stream: Exploring Forest Land Cover Controls on Dissolved Organic Matter Character and Aquatic Ecosystem Respiration in Headwater Streams	NSF-National Science Foundation	$423,487
Arabi, Mazdak	Modeling Ecosystem Services in Agricultural Watersheds	USDA-ARS-Agricultural Research Service	$54,000
Wardle, Erik	CSA(5392771-5391376) Training and Education for Agricultural Chemicals and Groundwater Protection - FY20	Colorado Department of Agriculture	$390,237
Levinger, Nancy	Collaborative Research: Unraveling Interactions that Drive Water-Osmolyte Interactions in Confinement and Impact Self-Assembly	NSF-National Science Foundation	$382,279
Winkelman, Dana	TO# 2001 Control of Sucker Spawning Migrations in a Major Tributary of the Gunnison River to Increase the Production of Native Sucker Larvae	Colorado Division of Parks and Wildlife	$60,323

2020 CSU Water Research Awards (Cont.)

Principal Investigator	Project Title	Sponsor	Amount
Winkelman, Dana	TO 2002 Field Examination of Wastewater Treatment Effluent Thermal Regimes and Effects on Reproduction of Johnny Darter Etheostoma Nigrum	Colorado Division of Parks and Wildlife	$66,323
Winkelman, Dana	Laboratory Study of Temperature and Winter Duration Requirements for Reproductive Success in Johnny Darter, Etheostoma Nigrum (Percidae), in the South Platte River Basin, Colorado	Colorado Division of Parks and Wildlife	$18,652
Morrison, Ryan	Verde River Wild and Scenic River Riverine Environmental Flow Decision Support System (REFDSS)	USDA-USFS-Forest Research	$70,000
Gannon, Benjamin	Peaks to People Water Fund Science Support	Peaks to People Water Fund	$97,437
Myrick, Christopher	Native Fish Passage in Front Range Transition Zone Streams	Colorado Division of Parks and Wildlife	$26,523
Miller, Janet	Evaluating the Effects of Piscicide Use on Aquatic Insects for Greenback Cutthroat Recovery	USDA-USFS-Forest Research	$46,000
Arabi, Mazdak	Denver One Water Plan	Carollo Engineers	$30,000
Arabi, Mazdak	(CSA for 5302142) North Weld County Water District (NWCWD) - CWCB: A System and Process for Assessing Water Use of Land Use Decisions	North Weld County Water District	$5,000
Koons, David	Productivity of Breeding Waterfowl on Working Lands in a Flood Irrigated System	Ducks Unlimited	$3,750
Qian, Yaling	Turfgrass UnderEeffluent Water Irrigation: Long-term Data Collection and Model Simulation to Predict Management Effectiveness for Minimizing Salinization and Sodificaiton Risks	US Golf Association - Green Section Research	$10,000
Bestgen, Kevin	BOR New 5 year agreement: KR143006- Proj. 22f Larva Fish Monitoring	DOI-Bureau of Reclamation	$133,070
Hawkins, John	BOR New 5 year agreement: KR143007- Proj. #125NNF Management Yampa River	DOI-Bureau of Reclamation	$439,790
Bestgen, Kevin	BOR New 5 year agreement: KR143008 - proj.# 128 Green River PikeMinnow Est.	DOI-Bureau of Reclamation	$76,106
Bestgen, Kevin	BOR New 5 year agreement: KR143009- proj.#140 ; Native Fish Reponse	DOI-Bureau of Reclamation	$67,515
Bestgen, Kevin	BOR New 5 year agreement: KR143010 - proj. #FR-115 Lodore Whirlpool Monitoring	DOI-Bureau of Reclamation	$108,900
Kremen, Amy	Organizing and Synthesizing Ogallala Aquifer Data to Facilitate Research and Resource Management	University of Oklahoma	$78,858
Arabi, Mazdak	Hydrological Modeling to Assess Vulnerability of Water Supply in the Contiguous US	USDA-USFS-Rocky Mtn. Rsrch Station - CO	$35,000
Bruegger, Margaretta	Compost for Carbon Sequestration on Irrigated Pasture	Montana State University	$49,746
Myrick, Christopher	Developing "Freshwater Cod" or Burbot (Lota lota) into a Viable Commercial Aquaculture Species in the United States	University of Washington	$41,348
Arabi, Mazdak	A System and Process for Assessing Water Use of Land Use Decisions	Colorado Water Conservation Board	$149,249
Covino, Timothy	Using Landsat Imagery to Assess Riparian Wetland Condition in the Southern Rockies	NASA-National Aeronautics and Space Administration	$45,000
Koons, David	Productivity of Breeding Waterfowl on Working Lands in a Flood-Irrigated System	Ducks Unlimited	$116,000
Clements, William	Post-Restoration Assessment of the Upper Arkansas River: A Watershed-Level Analysis of Responses to Improvements in Habitat and Water Quality	Colorado Division of Parks and Wildlife	$80,456

2020 CSU Water Research Awards (Cont.)

Principal Investigator	Project Title	Sponsor	Amount
Myrick, Christopher	Triploid Walleye: A New Frontier for Managing Cool Water Predators in the West	Colorado Division of Parks and Wildlife	$45,247
Kummerow, Christian	Untangling Changes in the West Pacific Water Cycle	NASA-National Aeronautics and Space Administration	$1,438,971
Cooper, David	Summit Lake Wetland Study	Colorado Department of Transportation	$45,000
Bolinger, Rebecca	Identifying Drought-Related Triggers and Impacts on Decision Calendars for the Ski Industry	DOC-NOAA-Natl Oceanic and Atmospheric Admn	$74,270
Arabi, Mazdak	A Comprehensive Assessment Framework and Rating System for One Water Cities	Water Research Foundation	$89,999
Kanno, Yoichiro	Field Investigations for Greenback Cutthroat Trout Recovery	USDA-USFS-Forest Research	$7,243
Venkatachalam, Chandrasekaran	Hydrometeorological and Water Resources Research	DOC-NOAA-Natl Oceanic and Atmospheric Admn	$62,263
Ross, Matthew	COVID-19: RAPID: Collaborative Research: Increased Access to Infrastructure for Distance Education in Hydrologic Science	NSF-National Science Foundation	$20,552
Arabi, Mazdak	Modeling Ecosystem Services in Agricultural Watersheds	USDA-ARS-Agricultural Research Service	$55,300
Cooper, David	CESU-RM: Hydrologic Monitoring of Reference and Degraded Wetlands in Big Thicket National Preserve	DOI-NPS-National Park Service	$36,557
Lemly, Joanna	2020 Utah Aquatic AIM Sampling	University of Montana	$70,005
Bauder, Troy	Training and Education for Agricultural Chemicals and Groundwater Protection - FY20	Colorado Department of Agriculture	$78,630
Bestgen, Kevin	Passage and Estimation Studies of Native Fishes, Green River Basin	DOI-Bureau of Reclamation	$200,000
Bailey, Ryan	Improved Crop Yield and Soil Salinity by Cost-Effective Integration of Microbial Community, Hydrology, Desalination, and Renewable Power	University of North Texas	$178,775
Andales, Allan	Understanding Water Use and Plant Responses of Crops Due to Deficit Irrigation	USDA-ARS-Agricultural Research Service	$55,000
Smith, Melinda	Synthesizing the Effects of Multiyear Drought Across a Coordinated Global Experiment	USDA-NIFA-National Institute of Food and Agriculture	$165,000
Cabot, Perry	Installation of Soil Moisture Sensors and Data Loggers to Monitor Industrial Hemp CU Rates	Colorado Water Conservation Board	$9,975
Bailey, Ryan	Integration of SWAT+/MODFLOW and Inclusion in the Geospatial Modeling Interface	USDA-ARS-Agricultural Research Service	$40,000
Kampf, Stephanie	RAPID: Wildfire Impacts on Snowpack, Flow Paths, and Sediment Dynamics across an Elevation Gradient	NSF-National Science Foundation	$49,990
Wardle, Erik	Ag. NPS BMP Implementation and Monitoring Project	Colorado Department of Public Health and Environment	$335,280
Cabot, Perry	Evaluating Conserved Consumptive Use in the Upper Colorado River	Trout Unlimited	$45,632
Toll, Weston	20CPG Water Quality Assessment Tool	USDA-USFS-Forest Research	$18,181
Schumacher, Russ	Colorado Mesonet COAGMET CSU Climate Center FY21 CMS#163750	Colorado Water Conservation Board	$150,000

COLORADO WATER CENTER
COLORADO STATE UNIVERSITY

In Memory of
Robert A. Longenbaugh

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

In a 2017 oral history interview, available through the Water Resources Archive, Robert A. Longenbaugh stated: "The reason why I'm here today is because I feel strongly, very strongly, that we need to get the facts, and people need the facts. They need the education. And if I can help provide that, that makes me have a good night's sleep." (https://hdl.handle.net/10217/186225)

Bob Longenbaugh talking at Fred Fassler farm south of Akron in regard to modification of Playa lakes, 1963. From the Groundwater Data Collection, CSU Libraries.

Longenbaugh's contributions included artificial recharge projects, studying the impacts of pumping on streamflow, and mathematical modeling of groundwater systems.

This statement, taken in the context of an interview focused on his experiences with and knowledge of Colorado groundwater, summarizes Longenbaugh's life's work. He conducted extensive research to obtain the facts and worked to disseminate them through a variety of educational venues.

Born in 1935, Longenbaugh, former Colorado State University civil engineering faculty member and assistant state engineer, passed away October 17, 2020. He will be remembered by those in the water community who knew him for his passionate discussions. Especially toward the end, he wanted to pass on his knowledge and experience to others for the betterment of wise use of Colorado's water resources.

From his college days in the 1950s at Colorado A&M (later Colorado State University) to his final years—one cannot say that Bob ever actually retired—he lived firsthand the development of groundwater science, technology, law, and administration. Even while doing research, whether collecting water level data at the edge of a farmer's field or working with early computers in windowless rooms, he educated others, and that continued until the end of his life.

Having learned from and worked with those who shaped the understanding of Colorado groundwater, Longenbaugh's contributions included artificial recharge projects, studying the impacts of pumping on streamflow, and mathematical modeling of groundwater systems. Across these areas, he educated others in his roles as a CSU professor, as an Extension Service specialist, and as a manager of the groundwater section within the State Engineer's Office, as well as through his service on the Colorado Ground Water Commission and committees of professional organizations.

Portrait of Robert A. Longenbaugh, CSU engineering professor, 1974. From the University Historical Photograph Collection, CSU Libraries.

In addition to his decades of research and educational contributions, Bob leaves an endowed scholarship in the Department of Civil and Environmental Engineering to help further the education of students with an interest in water resources. He also leaves an endowment for the Water Resources Archive to help further the documentation and study of Colorado's water history. In addition, his lifetime of accumulated papers, data, maps, and more will be housed in the Archive, which will organize and make it available for continued research and education on groundwater.

Bob will long be remembered for this extensive legacy left for the benefit of future Colorado water resources students and professionals.

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Data Releases

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Beyond the pandemic, 2020 will be remembered in Colorado for fire, high temperatures and drought. A lack of fall moisture, dryland farming practices, and high winds combined in Weld County in November to form clouds of soil reminiscent of the Dust Bowl. See page 24 for a recap of the 2020 drought in Colorado. Photo by Emmett Jordan.