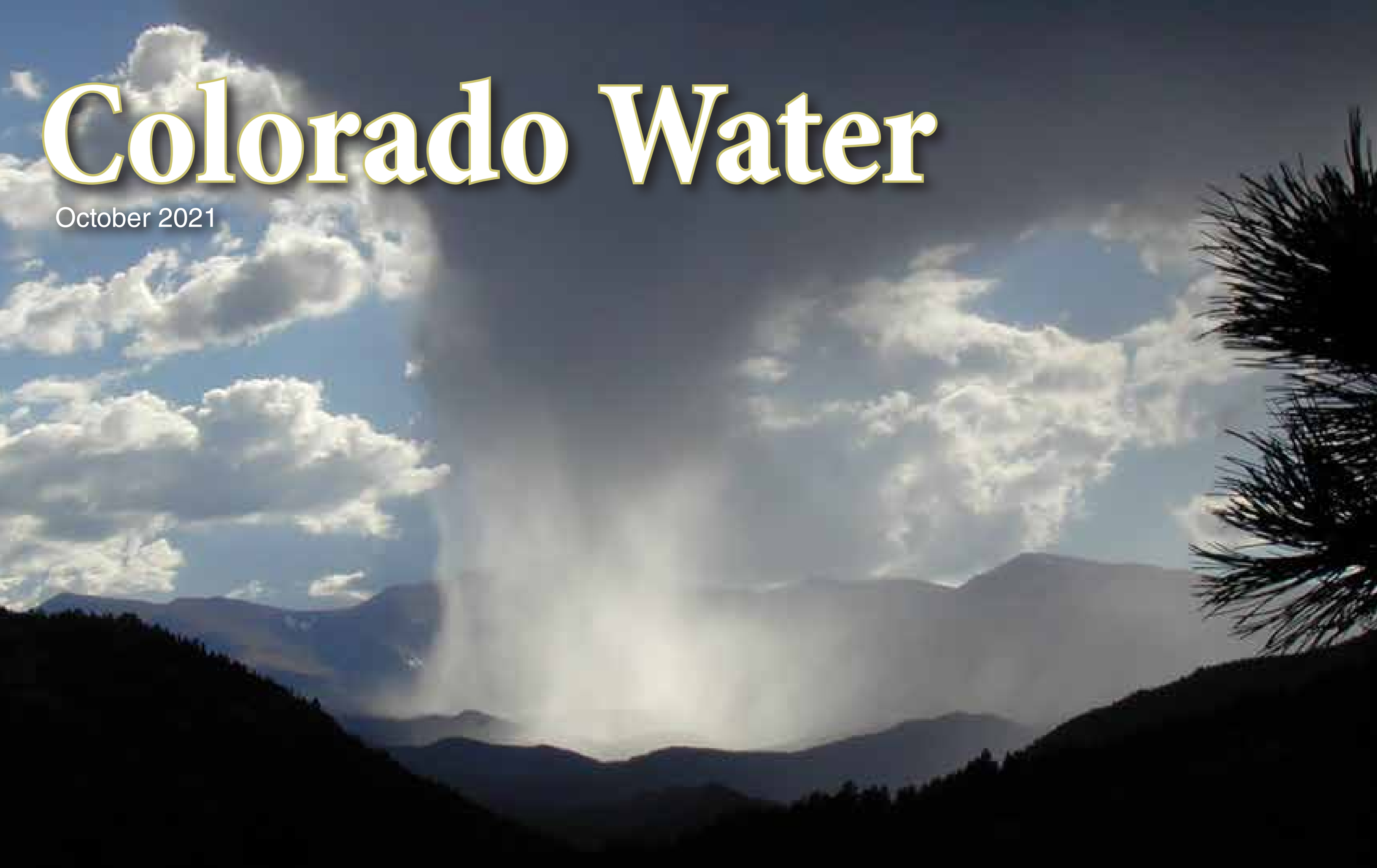
Colorado Water

October 2021



AGU Hydrology Days 2021

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

COLORADO **WATER**

Volume 38, Issue 2

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Jennifer Gimbel, Interim Director

Julie Kallenberger, Associate Director

Editor
Melissa Mokry

Design
R. Emmett Jordan

Production Director
Nancy Grice

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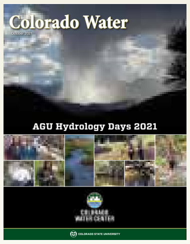


On the cover—The inset images are from Hydrology Days student projects.

Background photo of Mount Evans by Greg Younger/Wikimedia Commons.

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

Hydrology Days, Paving Water Resources, Education, and Service

Sarah Millonig, Assistant Director, One Water Solutions Institute, Colorado State University and
Dr. Mazdak Arabi, Professor, Civil and Environmental Engineering, Colorado State University

Spearheaded by Professor Hubert Morel-Seytoux in 1981, Colorado State University (CSU) has hosted the Annual American Geophysical Union (AGU) Hydrology Days meeting for the last 40 consecutive years. Each spring, Hydrology Days expands the University's reputation as a leader in water research, education, and service. Despite the global Coronavirus pandemic, the 41st Annual AGU Hydrology Days tradition continued, and the meeting was hosted online by the Civil and Environmental Engineering Department and One Water Solutions Institute at CSU with support from the Colorado Water Center (CoWC), U.S. Department of Agriculture (USDA) Agricultural Research Services (ARS), and university colleagues from the departments of Environmental Science and Sustainability, Geosciences, History, Soil and Crop Sciences, and Agricultural and Resource Economics.

Over the last year, we have all become accustomed to online platforms to communicate the activities and achievements of our vibrant water-related research community. The Hydrology Days sessions provided cutting-edge research presentations from numerous interdisciplinary fields, including agricultural water, groundwater, hydraulics and hydrologic systems, snow hydrology, climate and meteorology, urban water systems, and water quality. The two-day online conference was attended by 210 registered participants from nearly 75 organizations, including 21 national academic institutions, 28 international institutions, seven federal agencies, fifteen private/consulting firms, and two non-profit organizations.

The 2021 program showcased student presentations and offered 50 webinar presentations from seven academic institutions covering a range of topics delivered by eight undergraduates, 20 Masters degree students and 22 Doctoral students. This special issue of *Colorado Water* features student-authored articles selected for inclusion by the Hydrology Days conference committee. We applaud the hard work and dedication of all our student researchers for their participation in the online meeting.

Abstracts presented by webinar on March 30-31, 2021, have been published online in the 2021 Hydrology Days Proceedings (hydrologydays.colostate.edu/wp-content/uploads/2021/03/Hydrology-Days-Final-Program-2021.pdf), and the technical program is available for citation on CSU Mountain Scholar (mountainscholar.org/handle/10217/199983). Our gratitude goes to everyone who attended—it would not have been successful without your support.

Sarah Millonig

Dr. Mazdak Arabi

The organizing committee looks forward to next year when we plan to resume the in-person meeting and continue to enhance our vibrant research community. The committee plans to retain the award-winning world-class keynote speakers nominated in 2020 to be recognized during the 42nd Annual AGU Hydrology Days meeting:

Hydrology Days Award Recipient: **Dr. Soroosh Sorooshian**, Distinguished Professor—Departments of Civil and Environmental Engineering and Earth System Science, University of California, Irvine

Borland Hydraulics Award Recipient: **Dr. Ellen Wohl**, Distinguished Professor—Geology and Geosciences, Colorado State University

Borland Hydrology Award Recipient**: Dr. Ana Barros,** Distinguished Professor—Edmund T. Pratt, Jr. School of Civil and Environmental Engineering, Duke University

Dr. Norm Evans Lecture: **Dr. Jery Stedinger**—Dwight C. Baum Professor of Engineering, Department of Civil and Environmental Engineering, Cornell University

To learn more about these outstanding keynote speakers scheduled for 2022, please visit: hydrologydays.colostate.edu/keynote-speakers/

The 2022 AGU Hydrology Days event will be April 25-27, 2022 at the Lory Student Center, Colorado State University. For additional information about the event follow hydrologydays.colostate.edu/. We look forward to hosting the event in person next spring!

Connecting Irrigation Return Flow and Hydrologic Data to Riparian Greenness Using a Statistical Method

Dr. Matthew R. Lurtz, Professor, **Dr. Ryan R. Morrison**, Professor and
Dr. Timothy K. Gates, Professor, Civil and Environmental Engineering, Colorado State University

Introduction

Previous studies of riparian evapotranspiration (ET) (e.g., the sum of evaporated water and plant transpiration from vegetation on the banks of a river) in semi-arid irrigated river valleys acknowledge that changes in water use are related to energy demand, water availability, irrigation methodology, and pastoral practices. In Colorado, irrigation accounts for the largest water withdrawal, which includes water used by crops through ET and water lost through application and conveyance, most of which flows back to the river system. In southeastern Colorado, there is both surface water return flow from runoff into tributaries and canals and groundwater return flow derived from upland precipitation, irrigation deep percolation, and canal seepage. We assume that irrigation-derived return flows can significantly alter the water use patterns of riparian vegetation with implications on basin-scale water management. The objective of this study is to better understand how irrigation return flows impact riparian water use through the use of publicly available data and statistical methods.

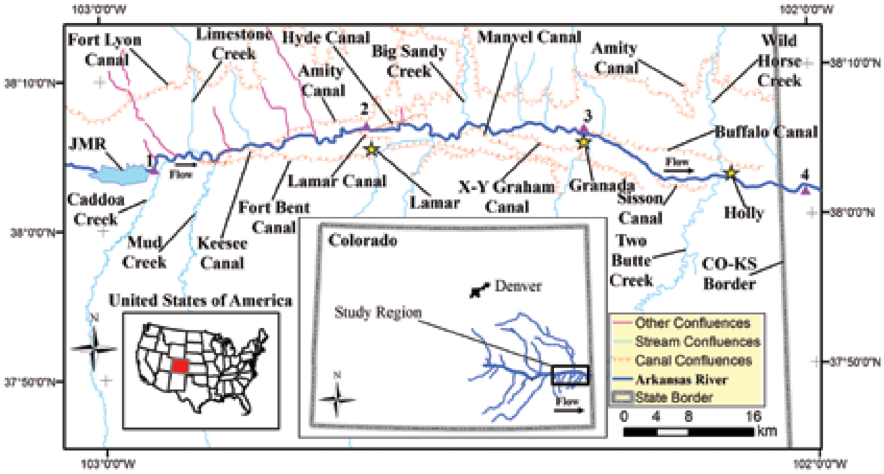


Figure 1. General location map of the 96-km segment of the Arkansas River located downstream of JMR. The Arkansas River flows from west to east (left to right). Significant canals and streams that intersect with the main stem of the Arkansas River in the study area are highlighted. Yellow stars indicate a township or city, and the purple triangles represent four U.S. Geological Survey gages used in this study.

Study Area and Methods

Riparian water use along the Arkansas River between John Martin Reservoir (JMR) and the Colorado-Kansas state line (Figure 1) is examined. The area of riparian vegetation under investigation is 52.5 km^2. With minimal rainfall in the area (343-394 mm annual average), the river valley aquifer supports the riparian vegetation. For analysis,

Furrow irrigation using siphon tubes from a lateral waterway. Photo courtesy of the NRCS.

we separated our dataset into eight subregions to be consistent with the rainfall-runoff model used by the Colorado Division of Water Resources.

We use a statistical method called Bayesian regression analyses to test hypotheses about socio-hydro-ecological system connections. We quantify monthly riparian greenness using the Landsat satellite normalized difference vegetation index (NDVI) and relate it to cumulative precipitation, temperature, river discharge, and canal discharge as a proxy for irrigation-influenced return flow. In the spatial analysis, time-integrated NDVI is used as a response variable to test the predictability of variables that categorically describe river confluence type, irrigation methodology, and other floodplain activities.

Results

Our results can be summarized in two components: (a) the time series results and (b) the spatial analysis results.

The time-series analysis indicates differences in riparian vegetative growth at distinct subregions in our study area. Additionally, riparian water use at a given time t is dependent on the average monthly temperature at time t, cumulative monthly precipitation at times t, t-1 and t-2, Arkansas River discharge at time t-2, and Arkansas River gain-loss at time t, t-3 and t-4. Figure 2 shows the time series of monthly riparian water use (as measured by NDVI) with an emphasis on temporal patterns of subregions No. 1 and No. 8 in different climatic years.

The spatial regression approach indicates that subregions of riparian vegetation intersecting with perennial tributaries have noticeably higher ET compared to subregions influenced by adjacent land use changes (Figure 3).

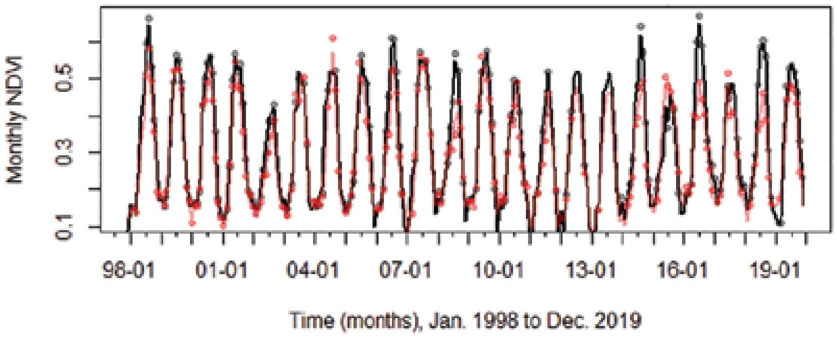


Figure 2. A time series of average monthly NDVI at subregions No. 1 and No. 8 from January 1998 to December 2019. Red points are monthly NDVI at subregion No. 1 and the black points represent subregion No. 8. We display this time period because 1999 was a historically wet year, and 2002-2003 are historically dry years. The red and black lines are the model predictions at subregions No. 1 and No. 8, respectively.

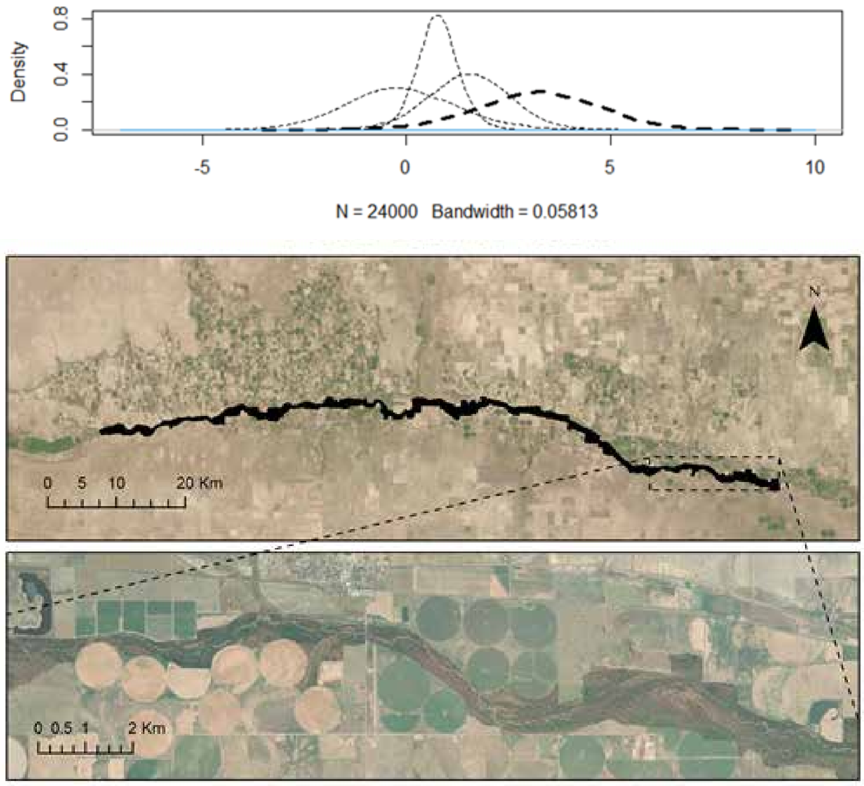


Figure 3. (Top) Posterior histograms from the spatial analysis using temporally integrated NDVI, and (Bottom) a two-part location map that shows our study area and a focused view of subregion No. 8 that is impacted by canal augmentation, return flows, and a confluence with a perennial river.

Conclusion

We were not able to show significant direct correspondence between canal discharge and riparian water use in time or space. However, we were able to quantify the temporal dependence of riparian water use on several hydrologic and meteorological variables. Additionally, the spatial analysis showed that riparian vegetation along the Arkansas River, intersected by a perennial tributary, has increased vegetation densities over time. The identification of these temporal and spatial dependencies in our irrigated river-aquifer system highlights the time lag between cause-and-effect and suggests riparian areas that may be suitable for restoration.

A Review on State of ‘One Water’ in Different Cities Across the World

Donya Dezfooli, Doctoral Student and **Dr. Mazdak Arabi**, Professor, Civil and Environmental Engineering, Colorado State University

Urban water management across the world has been plagued by various challenges, including a growing population, extreme events along with climate change, aging and inadequate infrastructures, sea-level rise, combined sewer overflows (CSOs), water supply limitations, and reliance on imported water. Due to the existing complexities, the previously known best practice, the linear “take-make-waste” approach, has been found to be unsustainable because of its dependence on the unlimited availability of energy and resources. Also, this approach does not possess robust regulations and overlooks the negative effects of greenhouse emissions and wastes (Novotny et al., 2010; Kennedy et al., 2011; Ferguson et al., 2013).

Therefore, it is necessary to change the current linear approach, which is dominant in most cities around the world, to one that utilizes a high degree of reuse and recycling. The suggested approach in current research, “One Water,” is being strategically probed and implemented around the planet. Unlike the linear approach, this multifaceted approach considers energy efficiency, material cycling, waste management, and infrastructure in urban systems. As a result of these substantial benefits, cities are implementing different programs to aid the transition from a traditional management approach to a One Water approach (Cardone & Howe, 2018).

Table 1. Summary of important challenges, potential solutions, and associated benefits to achieving the One Water approach in several cities.

Case Study	Important Challenges	Solutions	Benefits
Singapore	Severe floods—Imported water	NEWater and desalination	Providing reliable and resilient water supply
Melbourne	Acute shocks and chronic stresses	Stormwater management—Water efficiency and conservation programs	Cooler and greener city, Improved water quality, Flood mitigation
Philadelphia	Aging infrastructure—CSOs	Stormwater management	Economic, social, environmental, and water resources benefits
San Francisco	Droughts	Onsite Non-potable water use program—Stormwater management	Recharging of groundwater supplies, Climate-related benefits, Non-potable uses
Copenhagen	Flash floods	“Blue-green” solutions	Groundwater regeneration, Flood mitigation

For the purpose of this study, the state of the One Water approach was investigated in various cities across the world, such as Singapore, Melbourne, Philadelphia, San Francisco, and Copenhagen. The results indicate that these cities have successfully implemented several strategies to achieve this holistic approach. Major strategies include stormwater management and rainwater harvesting, implementation of green infrastructure, water reclamation and reuse, fit-for-purpose use of alternative water sources, water conservation, and desalination. These cities are making efforts to take the whole water cycle into account, leading to more co-benefits such as livability, air quality, greenhouse gas reduction, regulation of air temperature, water quality, and groundwater regeneration. Table 1 presents a summary of these strategies and the associated benefits of their implementation.

Singapore’s central business district as seen from the sky observation deck of the Marina Bay Sands skyscraper. Photo by Basile Morin/Wikimedia Commons.

San Francisco as photographed in Septeber of 2013. Photo by King of Hearts/Wikimedia.

However, investigations have revealed that these cities have encountered several barriers that inhibit the One Water transition. A review of the literature revealed that social and institutional barriers, the issue of path dependence, and lock-in are the greatest impediments. The term "cognitive lock-in" stems from the field of social psychology, where it has been used to investigate consumer habits and choices with respect to a product or service. In fact, historical investments into legacy infrastructure have yielded consistently high returns compared to those associated with alternative infrastructure. This phenomenon might discourage the future adoption of alternative technology and management practices. Regarding this matter, a cultural shift is another important element that should be considered when adopting One Water strategies. To illustrate, in terms of expanding the use of water recycling, a review of the literature revealed that public acceptance or the so-called "yuck factor" is one of the main barriers to reusing treated wastewater in households (Geels, 2004; Brown & Farrelly, 2009; Brown et al., 2011; Ferguson et al., 2013; Askarizadeh et al., 2015; Doung and Saphores, 2015; American Rivers, 2015; Cardone & Howe, 2018; Arabi et al., 2021).

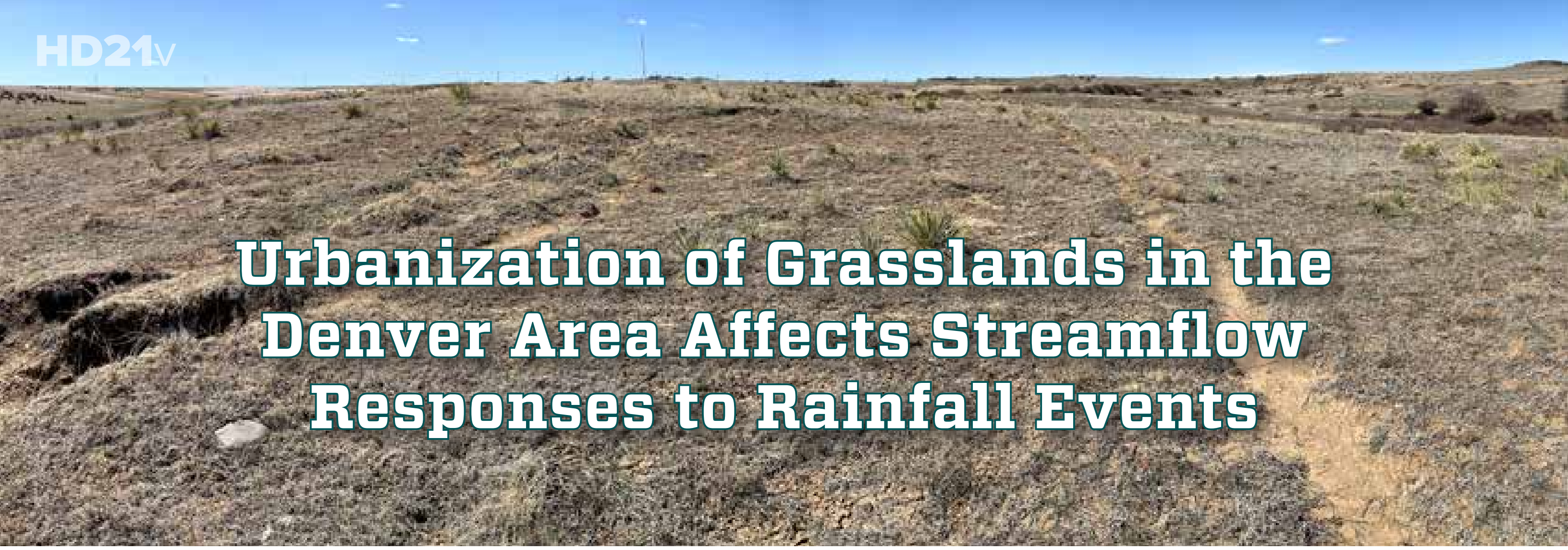
Nonetheless, characterization of pathways to facilitate transitions toward implementation of One Water approaches is necessary. It is obvious that the obstacles to achieve the paradigm shift do not always stem from inaccessibility of technological solutions and scientific knowledge, but instead, the social and institutional change process as well as a cultural shift are necessary to support any directional shifts. For example, successful case studies such as Singapore shows that the stigma related to "wastewater reuse" was removed using several measures such as changing the terminology from "wastewater" to "NEWater," gaining strong support from media, and promoting a public education campaign. Moreover, different actions, including public education on water issues, public engagement and awareness, adequate funding, collaboration among water service sectors, data management, regulations and legislation, partnerships between departments, changing cultural norms and technology can be conducted by water associations to facilitate the shift towards the One Water approach and the removal of existing barriers (Doung and Saphores, 2015; Arabi et al., 2021).

Acknowledgement

This work was supported by the Water Research Foundation (WRF) project #4969, "One Water Cities: Development of Guidance Documents and Assessment Metrics.

The Melbourne City Centre, Melbourne, Victoria, Australia photographed at night. Photo by Dietmar Rabich/Wikimedia Commons.

Urbanization of Grasslands in the Denver Area Affects Streamflow Responses to Rainfall Events



West Stroh Gulch rangeland in Parker, Colorado. Photo by Stacy Wilson.

Stacy Wilson, Research Assistant, **Benjamin Choat**, Graduate Student, and Graduate Research Assistant, and **Dr. Aditi Bhaskar**, Assistant Professor, Civil and Environmental Engineering, Colorado State University, **Dr. Stephanie Kampf**, Ecosystem Science and Sustainability, Colorado State University; **Dr. Kristina Hopkins**, Research Physical Scientist, South Atlantic Water Science Center, U.S. Geological Survey, **Dr. Timothy Green**, Research Agricultural Engineer, Water Management and Systems Research Unit, U.S. Department of Agriculture, Agricultural Research Service, **Dr. Andrew Earles**, Vice President of Water Resources, Wright Water Engineers, Inc.

Urbanization alters how streams respond to rain storms, increases urban flooding and causes detrimental effects on water quality, stream morphology, and ecosystem function. A thorough understanding of the hydrologic response to urbanization in semi-arid environments, like the Front Range in Colorado, is crucial for effective and sustainable water management as communities in semi-arid areas continue to grow and face drought conditions. Our goal was to contribute knowledge of the streamflow response in semi-arid streams before and after urban development. We used two approaches to accomplish this goal. The first approach was an analysis of the streamflow response of 21 watersheds with a range of urbanization in the Denver area. As development, or urbanization, occurs, permeable surfaces are replaced by impervious surfaces such as buildings, roads, and parking lots. We used the percent impervious area found in a watershed as a measure of the degree of urbanization and compared this to streamflow. For the second approach, we monitored streamflow conditions in a rangeland in Parker, Colorado.

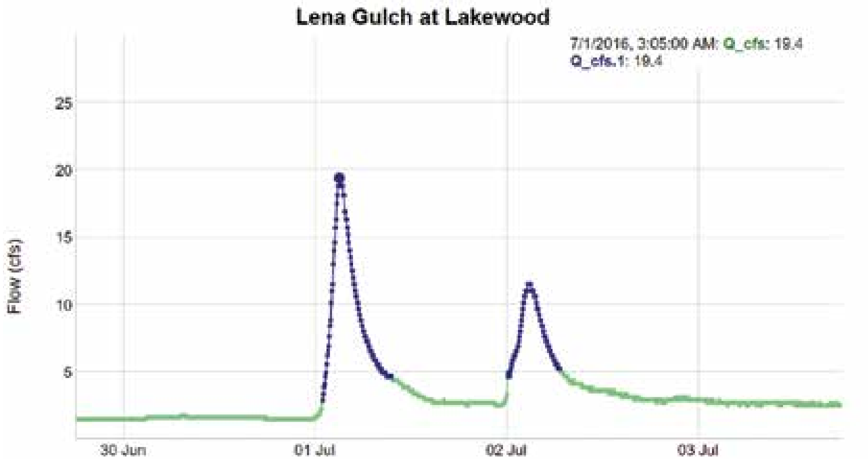


Figure 1. Runoff hydrograph of Lena Gulch at Lakewood in Denver, Colorado. The blue dots indicate a streamflow response to a rain storm. Graphic by Stacy Wilson.

Determining the Urbanization Effect on Streamflow in Denver

Using eight years of streamflow data for twenty-one watersheds ranging in size from 1 to 90 km^2 (0.5 to 35 square miles) with imperviousness ranging from 1 to 47%, this study provides a detailed analysis of hydrologic alteration occurring with urbanization in the semi-arid area of Denver, Colorado, USA. We used data from U.S. Geological Survey streamgages, which measure flow every 5 or 15 minutes at a point along a stream. We first identified when streamflow responded to rainfall at each streamgage by using the characteristics of the change of streamflow over time (Figure 1). We identified 3,644 streamflow responses to rainfall events, then analyzed how the number of streamflow events occurring in response to precipitation, peak streamflow, runoff depth, runoff ratio (calculated as the total runoff depth divided by the precipitation depth),

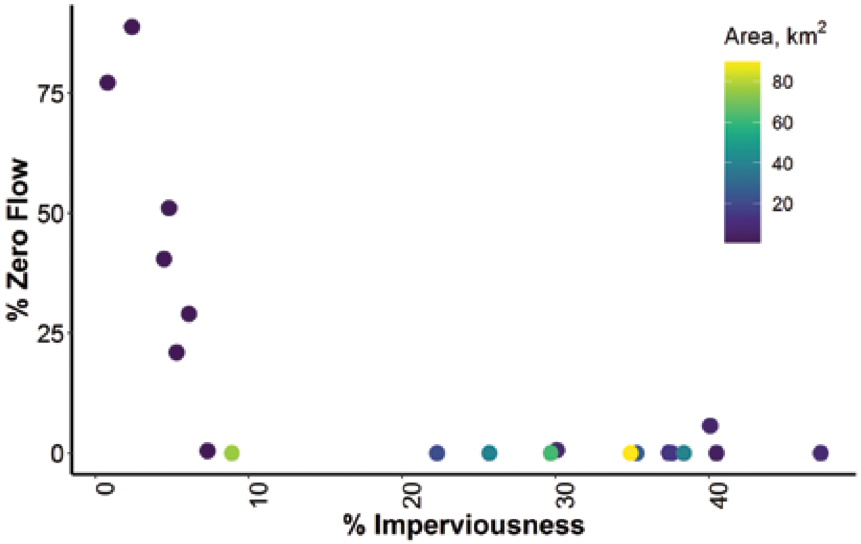


Figure 2. Percent of time with zero flow plotted against imperviousness with points color-coded based on watershed area (km2). Urban streams are more likely to have continuous flow than grassland streams.

time to peak streamflow, and the duration of the streamflow response to rainfall relate to urbanization, as represented by percent impervious area. We also determined the precipitation intensity needed to produce a streamflow response (or precipitation threshold) and the proportion of time channels had no streamflow.

We found that both the number of events and peak flow increased significantly with imperviousness, while the duration of streamflow response to rainfall, precipitation threshold, and proportion of time with no streamflow (zero flow) decreased significantly with imperviousness (Figure 2). Runoff depth, runoff ratio, and time to peak did not vary significantly with imperviousness. These results suggest urban watersheds in semi-arid environments are more efficient in the delivery of runoff to streams than their undeveloped counterparts, resulting in an increased number of streamflow events generated by smaller precipitation events, with a quicker delivery of higher peak flow to receiving streams. Therefore, stormwater management on the Front Range should focus on slowing the delivery of runoff, encouraging infiltration, and improving the capture of runoff that generates streamflow.

> ...stormwater management on the Front Range should focus on slowing the delivery of runoff, encouraging infiltration, and improving the capture of runoff that generates streamflow.

Using Time-Lapse Photography to Track Ephemeral Streamflow

This research also characterized the flow in West Stroh Gulch rangeland in Parker, Colorado, through time-lapse photography in conjunction with rainfall data. West Stroh Gulch is scheduled for residential development in the next two years. The planned development includes the incorpo-

West Stroh Gulch rangeland in Parker, Colorado. Photo by Stacy Wilson.

This research also characterized the flow in West Stroh Gulch rangeland in Parker, Colorado, through time-lapse photography in conjunction with rainfall data.

Figure 3. A game camera was installed next to and aimed toward an ephemeral channel in West Stroh Gulch. A staff gauge installed in the center of the channel provides an approximation of flow depth. Photo by Stacy Wilson.

Figure 4. Example of day and night photos taken at West Stroh Gulch. Photos were taken every 5 minutes, 24 hours a day. Photos by Stacy Wilson.

ration of green infrastructure and low-impact development strategies, including maintaining or mimicking as much of the natural channel network as possible in order to preserve the area's natural stream hydrology. We positioned a game camera next to a path for streamflow and programmed the camera to take a photo every 5 minutes, 24 hours a day (Figure 3). Ephemeral channels are usually dry and only flow after rainfall or when snowmelt is occurring. When streams do flow, the flow is usually brief, and of small volume, so photos must be taken frequently to ensure no small events would be missed (Figure 4). No streamflow was observed over one year of monitoring, suggesting the precipitation depth to generate runoff in this undeveloped rangeland exceeds the largest rainfall event observed (30 mm depth).

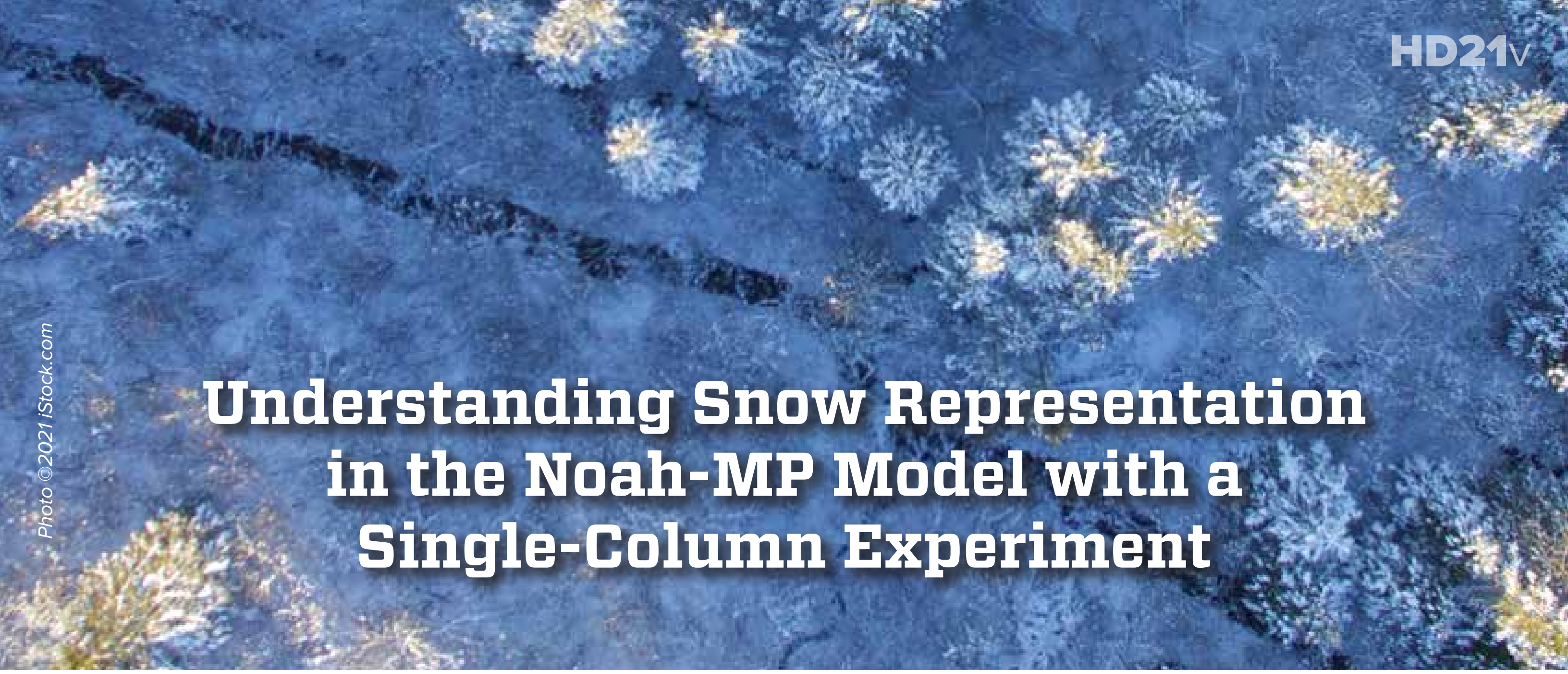
Our data provides important baseline information for future comparisons as development in semi-arid areas rapidly progresses, contributing physical data useful for model calibration. Overall, this research makes an important contribution to understanding the streamflow response to precipitation of grasslands and urban watersheds in semi-arid environments.

Implications for Growing Front Range Communities

Overall, our study demonstrates that grassland streams flow infrequently in the Denver area. The impervious surfaces such as roads and buildings added through urbanization cause streams to flow more frequently, with higher peak flow rates. The addition of irrigation or other changes in urbanized watersheds also causes streams to flow more continuously. These changes have important implications for flood risk and channel stability in a rapidly growing region.

Acknowledgement

This work was partly supported by National Science Foundation awards 1805340, 2045340, and U.S. Department of Agriculture, National Institute of Food and Agriculture Hatch project 1015939.



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Understanding Snow Representation in the Noah-MP Model with a Single-Column Experiment

Engela Sthapit, Graduate Research Fellow, **Dr. Tarendra Lakhankar**, Research Scientist and Adjunct Professor, **and Dr. Reza Khanbilvardi**, Professor, National Oceanic and Atmospheric Administration, Center for Earth System Sciences and Remote Sensing Technologies, Civil Engineering, City College of New York; **Dr. Mimi Hughes**, Research Scientist, **Dr. Rob Cifelli**, Team Lead, and **Dr. Kelly Mahoney**, Research Scientist, Hydrometeorology Modeling and Applications Team Physical Sciences Laboratory, National Oceanic and Atmospheric Administration, Earth System Research Laboratories-Boulder, Colorado

Introduction

Snow is one of the most important parameters of any hydrological model in snow-influenced areas but also one of the most difficult variables to estimate. Snowpack alters energy and mass balances, influencing surface heat fluxes, ground temperature, runoff, and soil moisture in land-surface processes. Calculating surface fluxes over snow-covered surfaces is a challenge in land surface models (LSMs) due to the poor simulation of snow and its evolution over time. Estimating snowpack properties, such as snow depth (SD) and snow water equivalent (SWE), from a model simulation, remains a challenge—in part due to uncertainties in atmospheric forcing variables, such as precipitation, irradiance, and temperature. Irradiance influences simulated snowpack melt rates, and precipitation and air temperature determine the quantity and phase (rain or snowfall) of modeled precipitation, which affects the accuracy of simulated snow accumulation and subsequent runoff.

This research focused on understanding snow representation in the Noah-Multi Parameterization (Noah-MP) LSM, through a single column experiment, and ultimately its representation in the National Oceanic Atmospheric Administration's (NOAA) National Water Model (NWM). NWM is a hydrologic model, operationalized in August 2016 to simulate observed and forecast streamflow over the CONUS. It is based on the Weather Research Forecasting-Hydro model, configured with the Noah-MP LSM. As a single-column experiment, the terrain routing, channel streamflow and groundwater flow were all deactivated in the model, resulting in snow output unaffected by lateral water transfer mechanisms. The single-column model's parameterization schemes, and calibration of those schemes, are the same as NWM.

The goal of this study was to understand the differences in SWE and SD from two single-column simulations driven by two sets of atmospheric forcing variables—North American Land Data Assimilation System Version 2 (NLDAS2) and in-situ station (Station) measurements. In addition, to help interpret differences between simulations, we also relate differences in snow simulation to differences in the forcing variables themselves. The comparison of the snow-specific performance of Noah-MP with different forcing datasets provides insight into physical reasons underlying LSM deficiencies, which could help improve future versions of NWM.

> The goal of this study was to understand the differences in SWE and SD from two single-column simulations driven by two sets of atmospheric forcing variables.

Study Area and Methods

The in-situ snow observations are from the CUNY-Snow Analysis and Field Experiment (CUNY-SAFE) site in Caribou, Maine, located at 46°52'00.9N and 68°00'47.9W. The meteorological observations were from the CUNY-SAFE and NWS office located nearby. The data are available here: star.nesdis.noaa.gov/smcd/emb/snow/caribou/microwave.html

SWE and SD from Noah-MP with atmospheric forcing from NLDAS2 and the in-situ station (referred to as NLDAS2-Noah-MP and Station-Noah-MP models hereafter) were simulated for six water years (2014-2019; 2013 as model spin-up). We also examined the relevant forcing variables—incoming longwave radiation (LW), incoming shortwave radiation (SW), near-surface temperature (NST, 2 m above ground), precipitation, and wind speed. For water year 2019, observed CUNY-SAFE SWE and SD values were compared with the values from the two model simulations.

The significant differences were tested with paired Student's t-test at 0.05 significance level for all water years (1 Oct – 30 Sept) and snow accumulation (Dec-Mar) and melt (Apr-Jun) times within each water year.

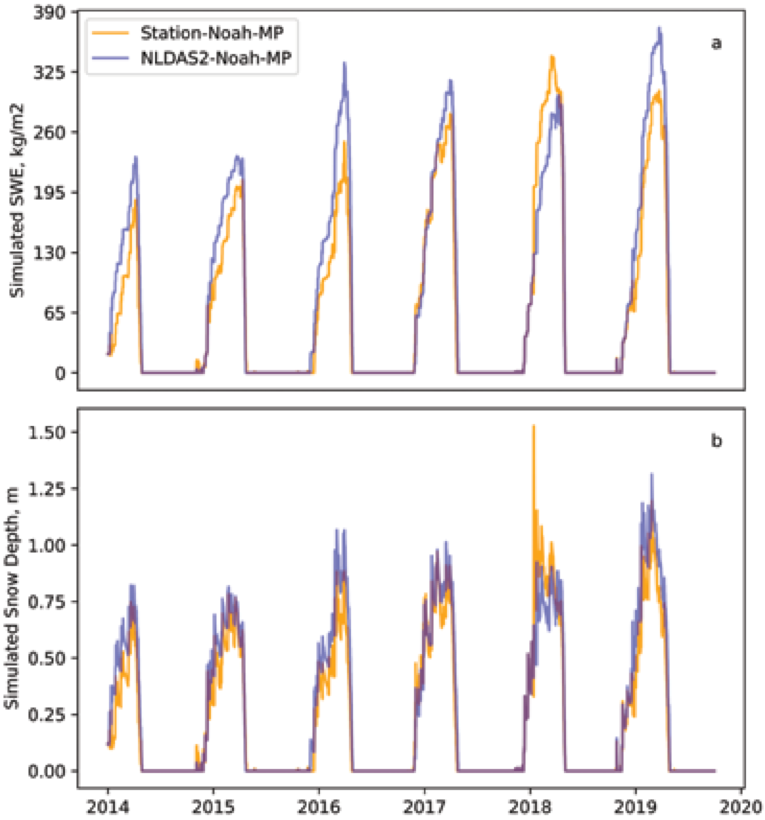

Figure 1: Simulated a) Snow Water Equivalent (SWE), and b) Snow Depth from Noah-MP Model, with NLDAS2 and Station meteorological forcing from WY2014-WY2019.

Discussion

Comparisons between the meteorological forcing and the resulting Noah-MP modeled snow were made to better understand the interrelationship, in-terms of sensitivities and the magnitude of biases. Briefly, the results are as follows:

1. SWE and SD simulated from NLDAS2-Noah-MP were significantly higher than Station-Noah-MP for the test period, except WY2018 (Figure 1a and 1b).
2. LW and NST (except WY2015) were significantly higher at the

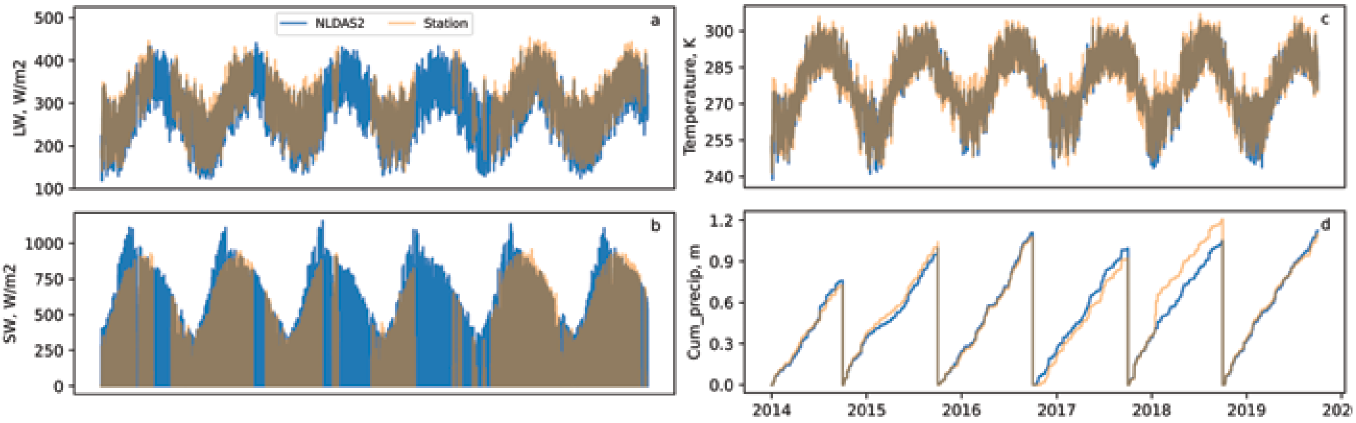

Figure 2: Comparison of a) outgoing longwave radiation (LW), b) incoming shortwave radiation (SW), c) near-surface temperature (NST), and d) cumulative precipitation (Cum_precip) from NLDAS2 versus those measured at the station from WY2014-WY2019 (Note: days where station values were missing are left blank).

Horsetooth Reservoir, Fort Collins. Photo ©2021 iStock.com

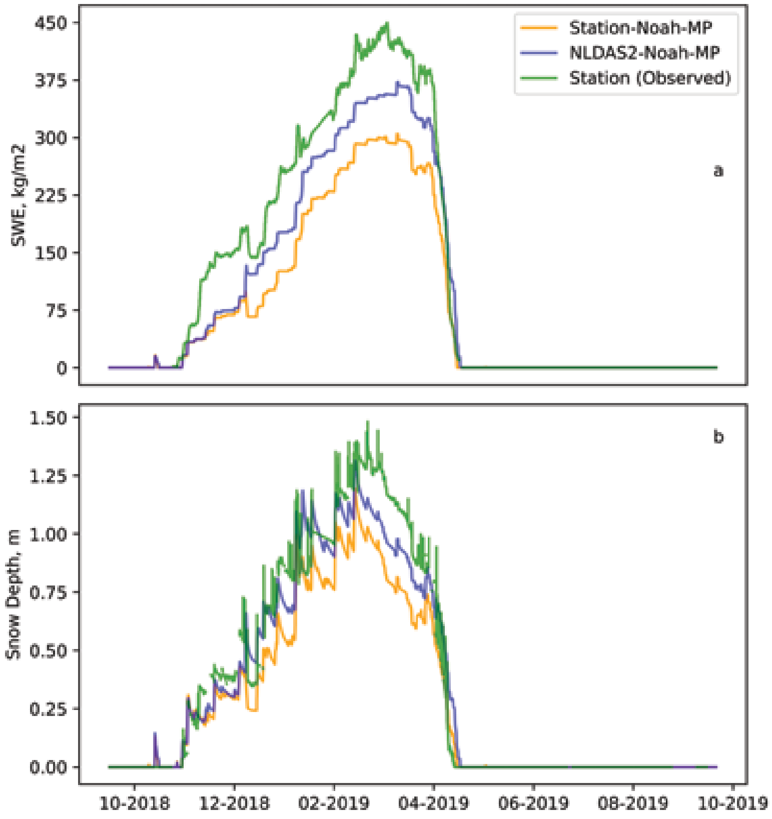

Figure 3: Comparison of a) snow water equivalent (SWE) and b) snow depth from Noah-MP Model, forced with NLDAS2 and station variables, and station (observed) values for WY2018-WY2019.

Station compared to NLDAS2 in the test period (Figure 2a, 2c). SW was significantly higher in NLDAS2 compared to Station in the test period (Figure 2b). Cumulative precipitation varied from year-to-year (Figure 2d).

3. For WY2019, although the measured SWE and SD were significantly higher than that simulated in both models (NLDAS2-Noah-MP and Station-Noah-MP), there was a general match in the timing of accumulation and melt events between all three timeseries (Figure 3a, 3b).

The higher SWE and SD simulated from NLDAS2-Noah-MP was consistent with the low bias in NST and LW in NLDAS2 compared with the station-measured forcing. Both higher NST and LW have the potential to reduce snow through decreased accumulation, increased melt, etc. The high bias in NLDAS2's SW did not appear to reduce SWE and SD as it might be expected (Figure 1, 2b).

The relationship of simulated SWE and SD with precipitation was less clear. However, higher cumulative precipitation in WY2018 seems to have contributed to higher SWE and SD for that year in Station-Noah-MP (Figure 1, Figure 2d). The influence of precipitation on snow depends not only on the intensity and accumulation but also on the precipitation partitioning into liquid rainfall and snowfall, which is affected by temperature.

The bias in meteorological forcing variables, especially temperature and precipitation, seems to significantly impact the modeled snow accumulation and melt. These inferences are further being studied at a watershed-level.

Acknowledgement

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Assessing Baseflow in Snow-Dominated Watersheds

Helen Flynn, Undergraduate Student; **Marin MacDonald**, Undergraduate Student,
Ecosystem Science and Sustainability, Colorado State University and **Dr. Steven Fassnacht**,
Professor, Watershed Science, Colorado State University

When the snow begins to fall in winter, people are excited about this change in the seasons. However, by spring, they cannot wait for that snow to melt, and the environment begins to respond to the disappearance of snow cover. In Colorado, watersheds are snow-dominated systems, and snowmelt acts as an essential water source within the system and for downstream users. As temperatures warm in spring, melt water either moves across the surface, through the shallow subsurface, or into the groundwater. These first two processes yield an almost direct runoff, and the latter recharges the subsurface, although groundwater from the previous years and current year both also contribute to streamflow (Figure 1). The higher snowmelt flows only last for a few months, with summer storms adding some limited amount of runoff, with the exception of large events such as the September 2013 storm. After the rainfall-based runoff, streams return to baseflow conditions that continue until snowmelt runoff begins in the following spring. Baseflow is fed by groundwater and maintains stream ecology, as well as providing water for downstream users in low flow periods. This research aims to evaluate the correlation between the snowpack and baseflow.

Figure 1. Photograph of Helen Flynn (left) and Marin MacDonald examining streamflow characteristics in the Cache la Poudre River at Poudre Falls on April 3, 2021. Photograph by Patrick Noe.

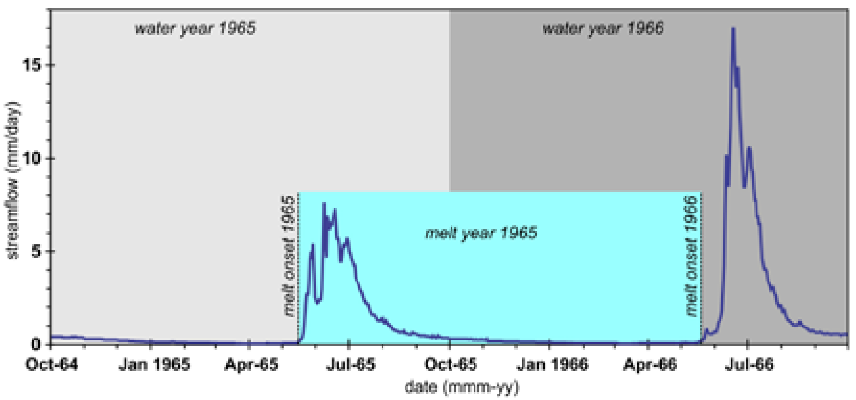

Figure 2. Hydrograph on the South Fork of the Cache la Poudre River for two water years illustrating the peak and baseflow in each year, and the new concept of a melt year, which is the period from the start of melt in one year to the start of melt in the following year. Graphic by Dr. Steven Fassnacht; Helen Flynn and Marin MacDonald prepared the data.

We considered the organization of the time series of data; the U.S. Geological Survey (USGS) uses the water year (WY) from October 1st of the preceding year to September 30th of that WY. The dates are static, and two years of baseflow are being analyzed: the tail-end of a previous spring melt and the beginning of a new cycle of melt (Figure 2). When examining the hydrograph, the peak flow occurs towards the end of the WY, with most of the subsequent groundwater-fed baseflow being included in the next WY (Figure 2). A new time period called a "melt year" (MY), was defined that starts with the onset of snowmelt in the spring and ends at the onset of the next melt, thus including one season of snowmelt streamflow and the subsequent baseflows (Figure 2). The MY is not static as the start date depends on the amount of winter snow accumulation and the timing of melt. While each melt year has a different length, it provides a chronological approach to the movement of water through the watershed.

We analyzed data from four watersheds nested within the South Fork of the Cache la Poudre River in Northern Colorado for the period 1961 to 1972 (data: nwis.waterdata.usgs.gov/nwis/sw). We compared the mean annual base-

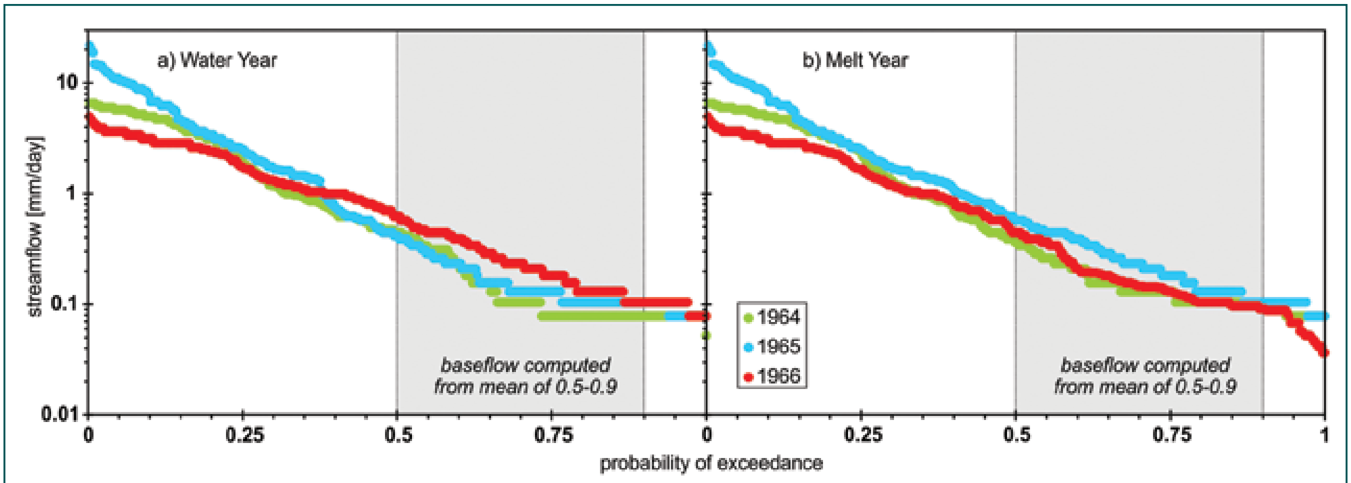

Figure 3. Flow duration curves based on the a) water year (WY) and b) melt year (MY) for Fall Creek at Cirque Meadows for sample years 1964, 1965, and 1966. Baseflow is computed from the mean flow for the probability of exceedance from 0.5 to 0.9 (grey area). Graphic by Dr. Steven Fassnacht; Helen Flynn and Marin MacDonald prepared the data.

flow extracted from the WY versus the MY, and then correlated these flows to snowpack properties. First of the month, snow water equivalent (SWE) measured at two nearby snow course stations were used to estimate peak snow accumulation (data: nrcs.usda.gov/wps/portal/wcc/home/).

Flow duration curves (FDC) were created for each annual time series (WY and MY separately) of daily streamflow by ranking daily streamflow by magnitude and plotting versus the probability of exceedance (Figure 3). Each average annual baseflow value was computed as the mean of the streamflow values over the 0.5 to 0.9 probability range (Figure 3). Depending on the elevation of the snow course, either April 1st or May 1st snow course was used to determine the correlation coefficient (R) between SWE and baseflow. Possible lags between snowmelt and baseflow were estimated, as R values, for SWE in a year and the baseflow in the same and also subsequent years, for up to five years.

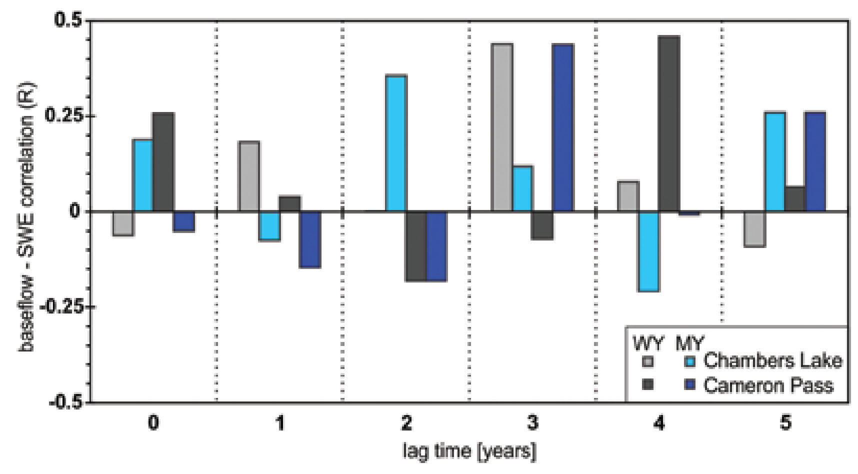

Figure 4. Correlation (as R) between baseflow and SWE for lags from 0 to 5 years for Fall Creek at Cirque Meadows from the years 1961 to 1972 based on the a) water year (WY) and b) melt year (MY). SWE was used for April 1st at Chambers Lake (lighter grey for WY and lighter blue for MY) and May 1st at Cameron Pass snow course stations.Graphic by Dr. Steven Fassnacht; Helen Flynn and Marin MacDonald prepared the data.

Using the melt year allows for better tracking of each spring melt and the subsequent baseflow period that follows, while a traditional water year would lump two spring melts worth of baseflow into one average period (Figure 2). From the FDCs, the high flows are the same for both melt and water years, but lower, i.e., baseflows, are different (Figure 3). For example, the baseflow for WY 1966 (red in Figure 3a) is the same as the baseflow for MY1965 (blue in Figure 3b).

We found that there was a lag between the correlation of baseflow values and SWE values in relation to the melt and water years (Figure 4). The strongest correlation was between current baseflow values and SWE data collected three years earlier. There were some delays in the lag. For example, the zero lag R value for baseflow—Chambers Lake SWE (light blue) was about the same as the one-year lag R value (light grey), the two-year MY Chambers Lake had a similar R value to three-year WY Chambers Lake, and the three MY Cameron Pass had a similar R value to the four-year WY Cameron Pass (Figure 4). Understanding the correlation between snowpack accumulation patterns and subsequent baseflows is important for water management during low flows periods, which in Colorado, occur a majority of the time (Figures 2 and 3).

Seasonal Fluctuations of Coarse Particulate Organic Matter Transport in a Snowmelt-Dominated Stream

Anna Marshall, Masters Student, Geosciences, Colorado State University and
Dr. Ellen Wohl, Professor, Geosciences, Colorado State University

Introduction

Leaves, branches, and wood fragments entering stream channels from adjacent forests create coarse particulate organic matter (CPOM: diameter 1 mm to 10 cm). CPOM can be transported downstream or stored in logjam backwaters or in eddies, where microbes and stream insects feed on it. Even transient CPOM storage over minutes to hours facilitates microorganism access to CPOM. However, CPOM is typically of lower density than mineral sediment and therefore readily transported unless it enters a portion of the stream with lower velocity. Streams with less large wood are significantly less retentive of CPOM and less physically complex than streams with abundant wood. Headwater streams are particularly important in CPOM dynamics because of their proximity to upland sources of CPOM and their limited transport capacity for large wood.

Transport of CPOM as bedload increases rapidly with the increasing flow in small streams. In snowmelt runoff regimes, nearly all annual CPOM exports may occur during the seasonal high flow. The peak of sediment transport is commonly temporally offset from the peak of discharge – a phenomenon described as hysteresis. We hypothesized that CPOM moving in suspension could display hysteresis, although the greater buoyancy of CPOM could create different hysteresis patterns than those for sediment. Greater understanding of the temporal scales of hysteresis would improve estimates of total CPOM transport.

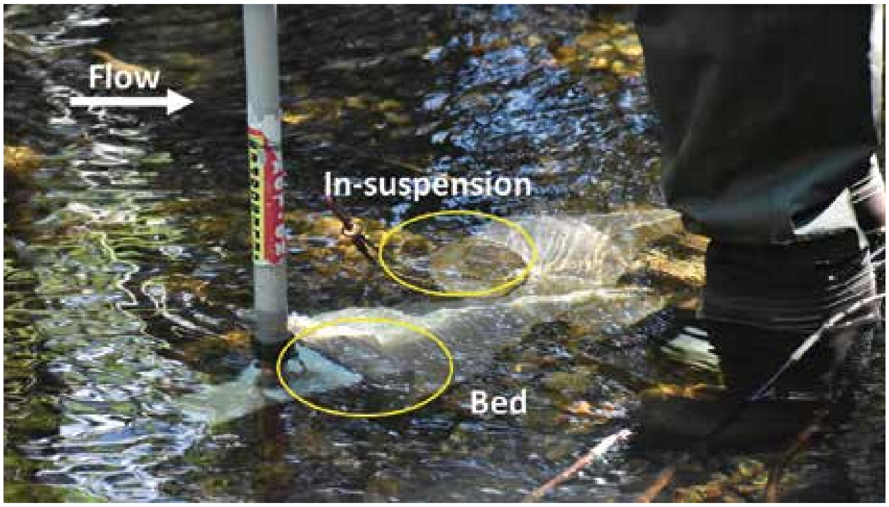

Figure 1. Helley-Smith bedload sampler and surface seine with expanded orifice used for CPOM sampling at surface, midpoint, and bed depths. Three nets were used at high flows at the surface, midpoint, and bed depths and only surface and bed nets were used at low flows. This photo, taken at base flow, shows surface and bed nets. Photo by Emily Iskin Photography.

Working in a snowmelt-dominated stream in the Southern Rockies of Colorado, we measured CPOM moving in suspension and in contact with the stream bed at 4-hour intervals during the rising and recessional limbs of the snowmelt hydrograph. Our sampling strategy was designed to test two hypotheses.

> *CPOM mass in suspension will be greater than CPOM mass moving as bedload.*
>
> *Seasonal CPOM transport is greater during the rising limb of the annual snowmelt hydrograph than during equivalent discharge on the recessional limb.*

We expect CPOM stored in the channel and overbank areas to be mobilized as the stage rises and snowmelt runoff enters the channel, and thus we expect the supply of CPOM to be depleted as the stage declines after peak flow. Suspended transport may equate to greater travel distances and, therefore, headwater subsidies of CPOM to downstream portions of the river network. Understanding the relative locations and timing of CPOM transport at the reach scale is critical to river management designed to enhance CPOM retention and processing. If the majority of CPOM is moving in suspension, this implies that river restoration designed to enhance CPOM retention should incorporate retention structures (i.e., logjams) that span the channel at high flows.

Methods

We measured CPOM transport at three sites: (1) in the backwater pool upstream from a channel-spanning logjam; (2) immediately downstream from the logjam; and (3) in a riffle

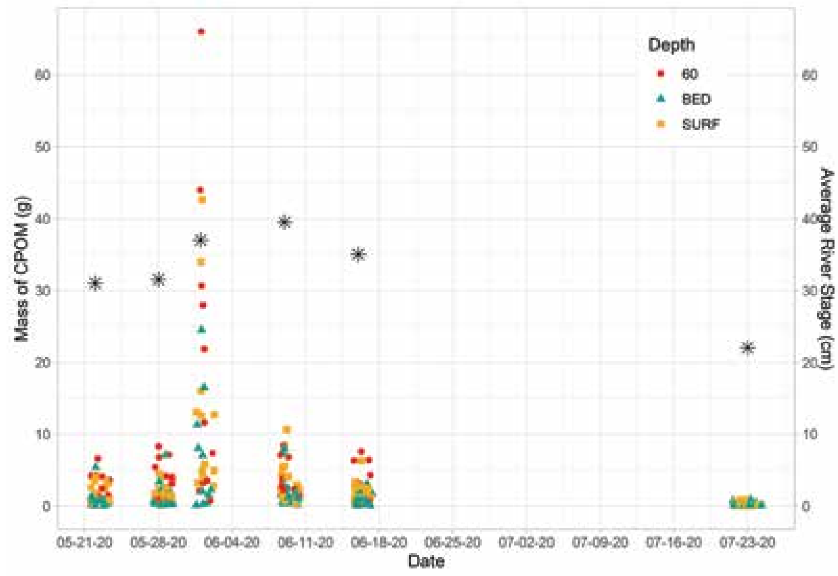

Figure 2. Mass of CPOM and corresponding average stage during the sampling event. Black stars indicate the average stage for each sampling period. Each data point in this plot represents an individual sample with respect to sampling depth, time interval, and date.

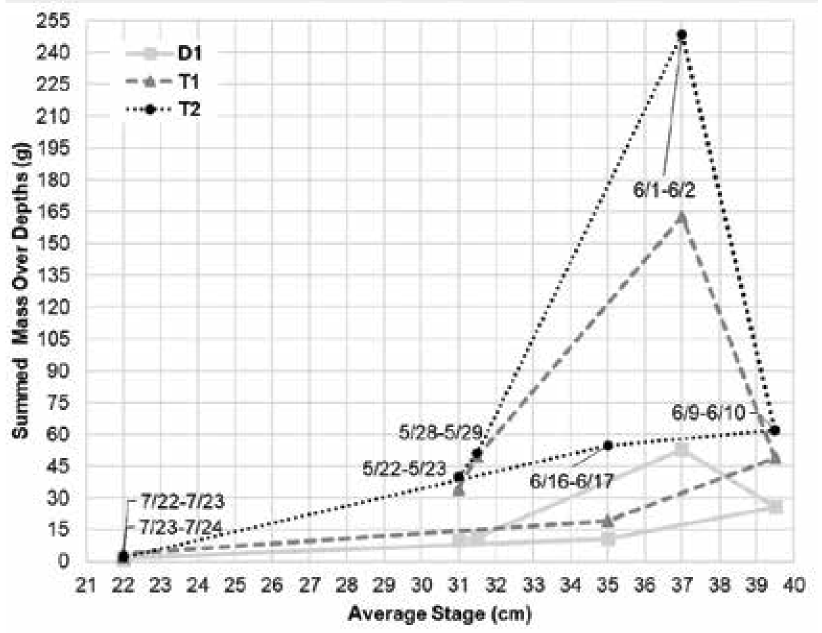

Figure 3. Hysteresis plot of mass corresponding with stage. Each data point represents the sum of all samples at a particular location during the 24-hour sampling period. The curves for each reach suggest clockwise hysteresis loops. Yellow arrows indicate a clockwise direction.

about ten bankfull-channel-widths downstream from any channel-spanning logjams. CPOM was collected at the water surface, 60% of flow depth, and the channel bed (Figure 1). Sampling occurred in sequence with the snowmelt hydrograph from May through August 2020.

Results

Analyzing 298 samples, we found that CPOM mass transported in suspension is significantly greater than mass transported as bedload, supporting the first hypothesis. There is a more pronounced seasonal curve in the largest values of CPOM transport than in the average stage (Figure 2). The peak CPOM precedes the peak stage (Figure 3), with the most pronounced hysteresis curve in the transport reaches. This supports the second hypothesis, indicating substantially greater CPOM transport during the final portion of the rising limb than at the equivalent stage on the falling limb, likely because CPOM stored in the channel and overbank areas is mobilized as with snowmelt runoff and rising stage, whereas the supply of CPOM is depleted as the snowmelt hydrograph continues.

Conclusions

Because a substantial portion of CPOM is transported in suspension, flow obstructions such as logjams that have a vertical dimension similar to peak flow depth are likely to be particularly effective in retaining CPOM. Similarly, areas of flow separation with substantially reduced flow velocity are more likely to retain CPOM in suspension. Current installations of large wood and engineered logjams typically do not include channel-spanning logjams, which greatly increase retention of CPOM.

Because CPOM is a primary energy source in the food webs of shaded forest streams, management designed to foster the sustainability of stream ecosystems can benefit from maintaining or creating features that enhance CPOM retention. Understanding patterns of seasonal hysteresis of CPOM transport can improve estimates of total CPOM export from watersheds and associated estimates of carbon storage and exports from rivers; and inform management designed to enhance CPOM retention in anthropogenically simplified streams.

Acknowledgements

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Does it Get Cooler Going Down the Hill?

Measuring Hillslope-Scale Temperature Gradients

Davis Rice, Undergraduate Student, Ecosystem Science and Sustainability, Colorado State University, **Dr. Steven Fassnacht**, Professor, Watershed Science, Colorado State University

Usually, when you go higher, it gets colder; the environmental lapse rate is -6.5˚C/km (18.8˚F per mile, negative indicates cooler temperatures as elevation increases). But at small scales, it can become colder as you go down. This is seen in small ditches that are often much colder than the area above them in the early morning. On the morning of July 5, 2019, author Dr. Steven Fassnacht was walking from an upper cabin at the Colorado State University Mountain Campus (CSU-MC) in Northern Colorado down the hill to the dining hall (Figure 1) when he felt a wall of different air. He looked down and saw a zone of frost, including on a strawberry (*Fragaria ovalis*) plant (Figure 2). This prompted the question: what are the gradients at the hillslope scale above the South Fork of the Cache la Poudre River?

Figure 2: Frost on a strawberry (Fragaria ovalis) plant at about 06:30 MDT on July 5, 2019 at the CSU-MC. Photo by Dr. Steven Fassnacht.

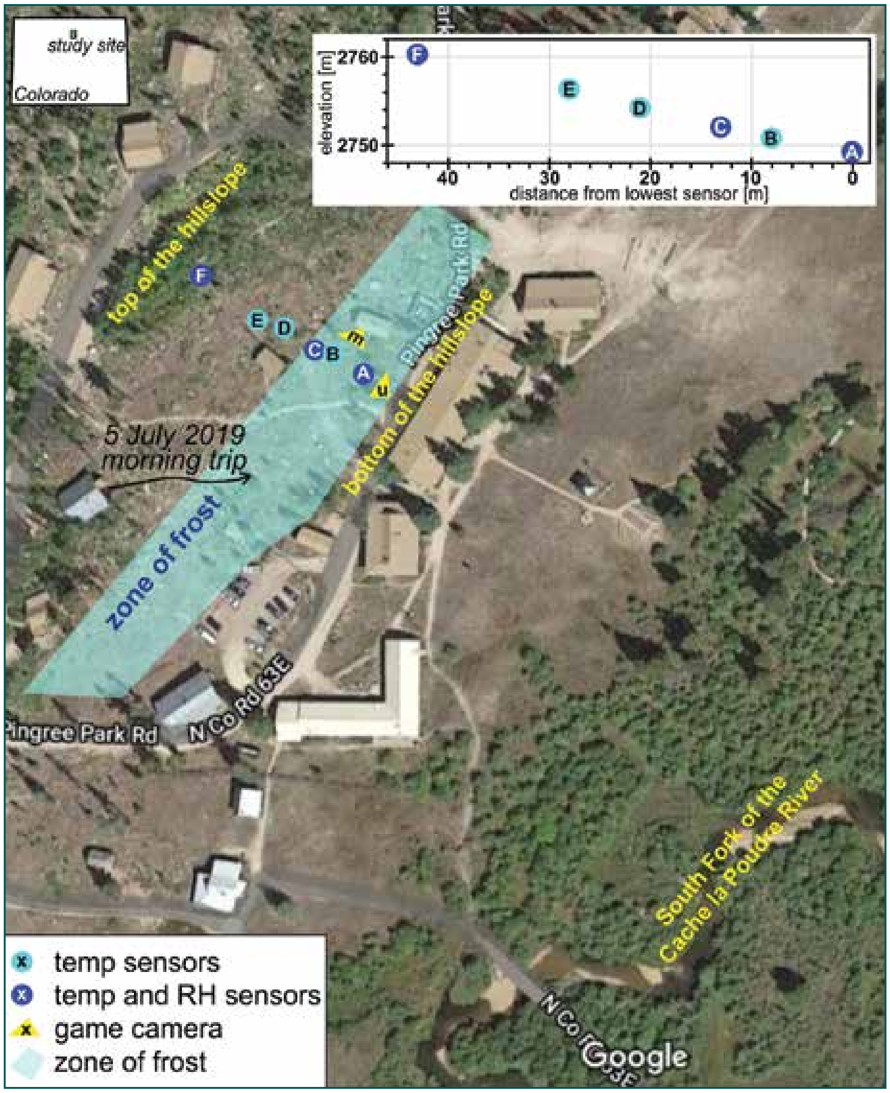

Figure 1: Site map showing the location of the Colorado State University Mountain Campus (CSU-MC) in Northern Colorado (upper left) and the location of the temperature sensors along the hillslope between the CSU-MC faculty cabins and the dining hall. The elevation of the sensors is presented in the upper right inset. Map by Google, other images by Dr. Steven Fassnacht.

Methodology

Six T-posts were installed along the hillslope (Figures 1 and 3) on July 22, 2020, with two to four temperature sensors (iButtons) on each post. The horizontal location of each T-post was determined from a handheld Global Positioning System (GPS), and the elevation was extracted from a 1-m resolution digital elevation model. Each sensor was placed in a double-funnel radiation shield to measure ambient air temperature at 20-minute intervals (see Collados-Lara et al., 2021; Kings-

Figure 3: T-posts with double-funnel radiation shields holding the temperature sensors along the hillslope, at the CSU-MC. Photo by Dr. Steven Fassnacht.

Figure 4: Game camera image of the Mummy Range on September 7, 2020 when the Cameron Peak Fire spread through the area at the CSU-MC. Photograph retrieved by Dr. Steven Fassnacht.

ton et al., 2021). The lowest sensors were placed about 20 cm above the ground, and the highest sensors were about 140 cm above the ground.

The temperature gradient was computed as the linear slope from the temperature versus elevation; the coefficient of determination (R^2) was computed for each 20-minute interval. Two game cameras were installed; one looking across the hillslope and the other up the hillslope (Figure 1). These were set to capture hillslope images from 05:30 to 07:30 in the morning so that the presence of dew or frost could be identified.

Results

Due to the Cameron Peak Fire (Figure 4), data collection was limited to a three-week period in late July and early August 2020 and four weeks in October 2020. Over a day, there is variability in temperature among the different (T-post) locations (Figure 5a). At night and into the morning (Figure 5b), and similarly in the evening (Figure 5c), the higher elevation T-posts (highest sensors on F and E) are warmest, while the lower elevation T-posts (A and B) are coolest; the middle location is a middle temperature. This sample date (August 9, 2020) reflected what was observed for the July-August study period (Figures 6ai and 6bi). There

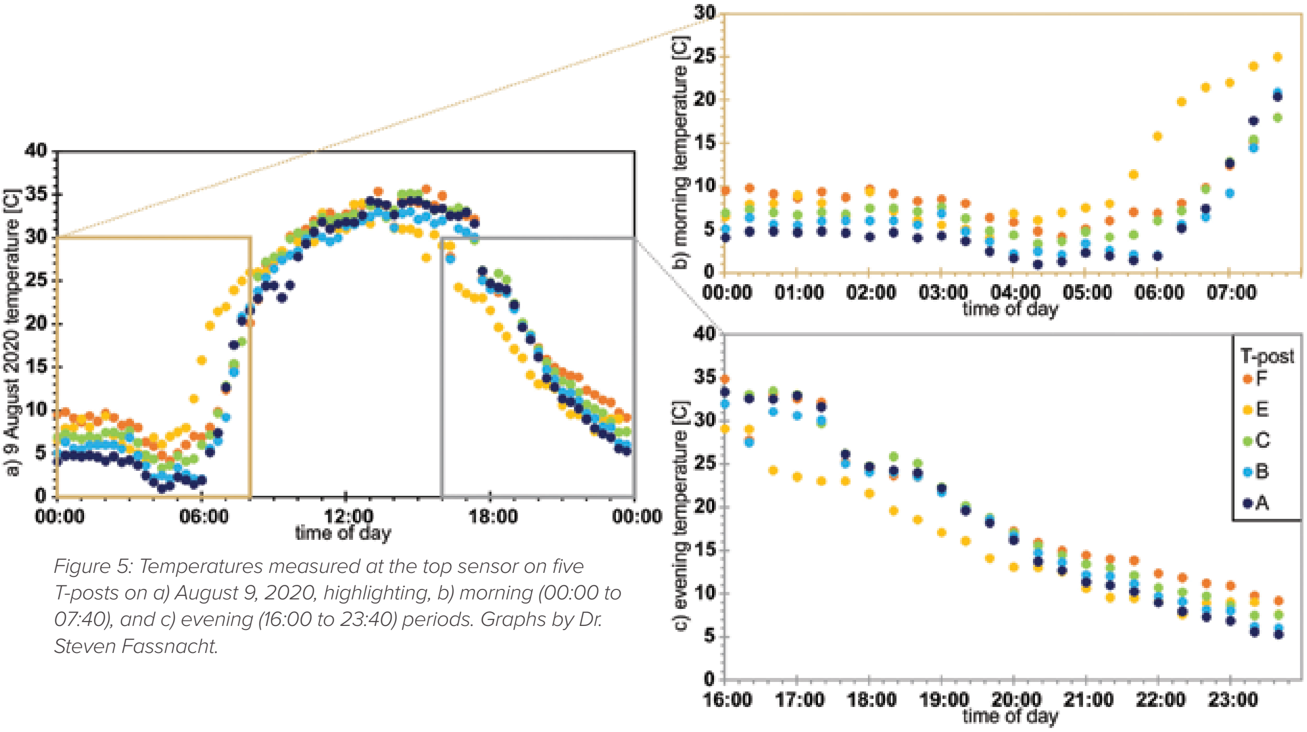

Figure 5: Temperatures measured at the top sensor on five T-posts on a) August 9, 2020, highlighting, b) morning (00:00 to 07:40), and c) evening (16:00 to 23:40) periods. Graphs by Dr. Steven Fassnacht.

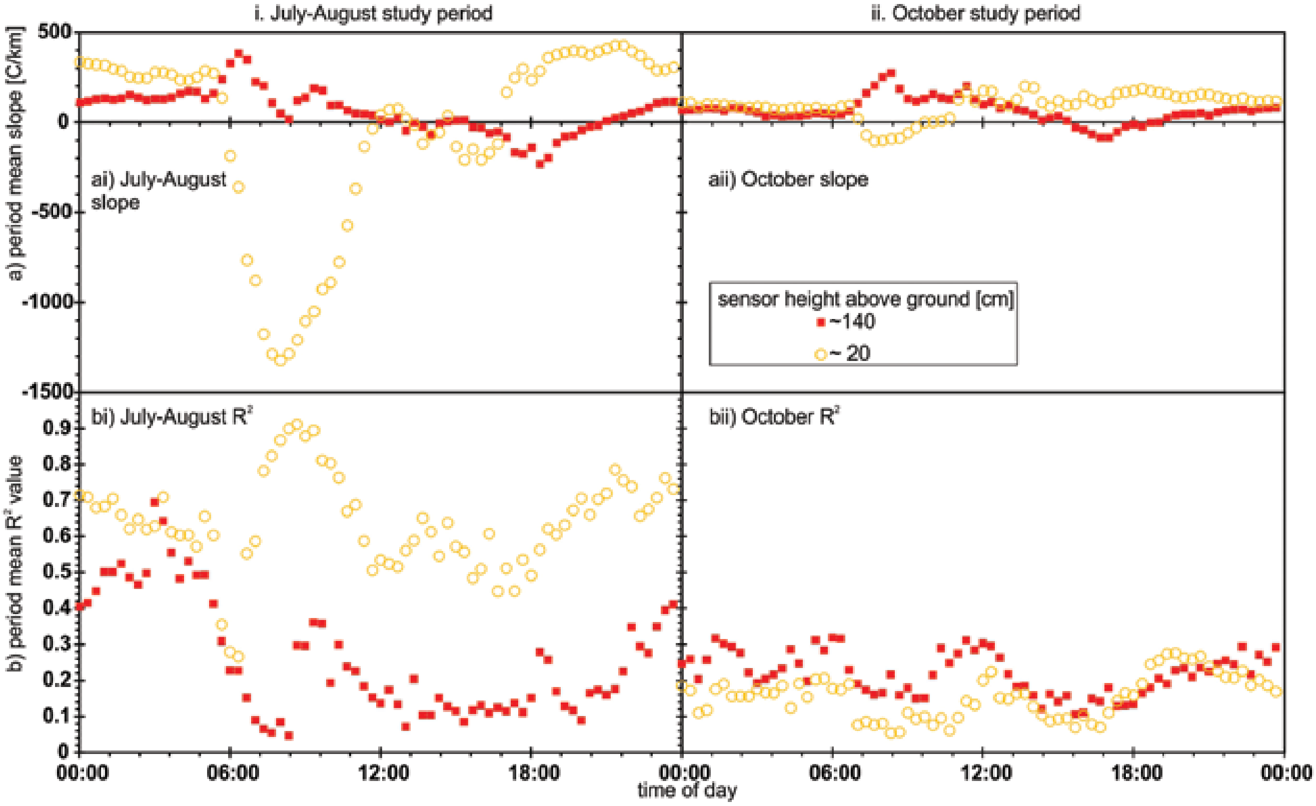

Figure 6: Mean a) slope and b) coefficient of determination (R2) value for the i. July-August and ii. October study periods. Graph by Dr. Steven Fassnacht.

When you go out in the morning and see dew on the grass or frost on the car, these are downward latent heat fluxes that have a hydrological and climatological significance.

is a large range in slope and large variability in the correlation (Figure 6); this was seen less for the October study period (Figures 6aii and 6bii).

The game cameras only captured one likely occurrence of frost (October 23). Other periods may have occurred between August 13th and October 3rd when temperature sensor data could not be retrieved due to the Cameron Peak Fire (Figure 4). However, the occurrence of the earliest snowfall event on record (September 8, 2020) and other snowfall events were captured.

Discussion

Previous work (Collados-Lara et al., 2021) examining temperature gradients across the lateral moraine at the CSU-MC found morning temperature gradients of +30 to +100˚C/km. Here, individual gradients varied from +/-2,000˚C/km for the sensors closest to the ground (~20 cm) and about one-third of this range for the sensors furthest from the ground (~140 cm) (Figures 5 and 6).

In July and August, ground heating occurs once the sun comes up, and it is likely that the sensors warm disproportionally. While the gradient, given as degrees Celsius per kilometer, may be misleading (as the gradient is only over an elevation of 11 m), the gradient does exist, and it tends to be positive, i.e., it is an inversion. Temperature inversions are consistent overnight and into the morning (Figure 6).

When you go out in the morning and see dew on the grass or frost on the car, these are downward latent heat fluxes that have a hydrological and climatological significance. This work collects data that starts to address the occurrence of such events. Further, strong inversions can be present over short distances. Their presence precludes the use of standard temperature lapse rates, and thus the possible presence of temperature inversions must be considered when interpolating temperature data, especially in the early morning.

Acknowledgements

We thank Dr. James R. Meiman for his financial support, and CSU-MC Director Seth Webb for logistical support.

Exploring the Connection Between Heavy Rainfall and Embedded Rotation in Tropical Storm Imelda (2019)

Allie Mazurek, Masters Student, Atmospheric Science, Colorado State University; **Dr. Russ Schumacher**, Professor, Atmospheric Science, Colorado State University, Colorado State Climatologist, Colorado Climate Center and **Dr. Erik Nielsen**, Assistant Professor, Atmospheric Sciences, Texas A&M University

Tropical cyclones are one of Earth's most destructive phenomena, bringing a multitude of hazards from violent winds and heavy rain to storm surges and tornadoes. These hazards can last for days in some cases, and they frequently occur at the same time, creating a particularly dangerous situation for lives and properties in the storm's path. Tropical Storm Imelda, which impacted the Southeast Texas and Southern Louisiana coasts in September 2019, was one of these cases. On September 19, as the storm system continued to deliver heavy rainfall and flooding for the third day, some of the same areas also began to see tornado warnings, indicating that a tornado was imminent or occurring. While ultimately, there were only two confirmed tornadoes that resulted from Imelda, many other areas of non-tornadic rotation could be seen on the radar throughout the event, often in the same areas where heavy rainfall was occurring (see Figure 1 for an example). These observations brought forth the question: is there some relationship between rotation in the atmosphere and rainfall at the surface in a landfalling tropical cyclone?

Previous scientists have already explored why rotating storms may be able to produce more rainfall than non-rotating storms. For example, Nielsen and Schumacher (2018) demonstrated using computer simulations that rotation in thunderstorms can lift more air upwards, where it can cool and saturate into liquid and grow into raindrops, effectively increasing the amount of rain that falls.

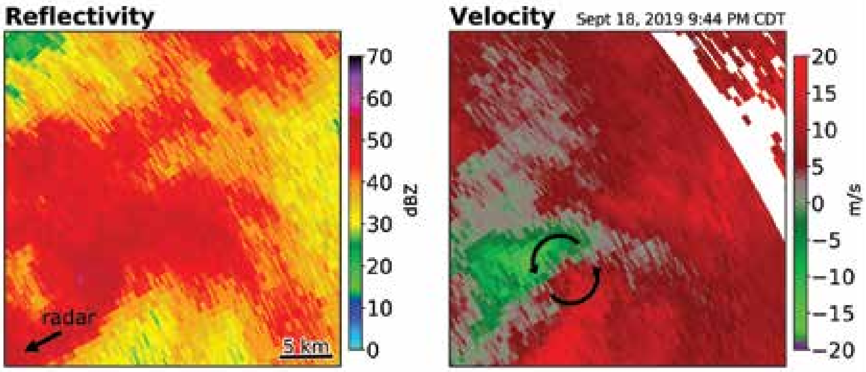

Figure 1: Reflectivity (left) and velocity (right) products from the radar in League City, Texas, on September 18, 2019, at 9:44 PM CDT. In the left panel, red and orange pixels suggest the presence of heavy rainfall (in decibels, or dBZ), and the arrow shows the direction of where the radar is located. On the right, green pixels indicate storm motion (in meters per second) towards the radar, and red pixels indicate storm motion away from the radar. Bright red and bright green pixels close to each other suggest rotation in the storm, as indicated by the arrows.

Tropical Storm Imelda shortly after making landfall near Freeport, Texas, on September 17, 2019. Photo courtesy of NASA.

To explore whether the relationship between rainfall and rotation can be found in observations, we can use the Multi-Radar Multi-Sensor (MRMS) dataset. This dataset combines information from radars, satellites, and surface weather stations to create products for rainfall and storm rotation. For the analysis on Imelda, these two products are examined together in time and space to assess if there is some association between the amount of rain that falls and the amount of rotation in the lower part of the atmosphere.

First, the rotation and rainfall datasets are overlaid with each other for each hour over an 18-hour period. Because these data can be noisy, we make them slightly smoother by averaging adjacent points together (see Figure 2 for an example). Then, the rotation and rainfall values at each smoothed point on the plot are graphed against each other. This process is repeated for each plot of hourly data in the 18-hour period, then points are removed if rainfall and/or rotation are zero. At first glance, we can see from the results in Figure 3 that, in general, when there is a greater amount of rainfall within a given pixel, the amount of rotation in that pixel is often greater. The calculated correlation coefficient (also known as "r") of 0.62 shows mathematically that a relatively strong positive relationship between these two variables exists. These results suggest that in Tropical Storm Imelda, locations where there was a greater amount of rotation in the lower part of the atmosphere also tended to see higher rainfall totals.

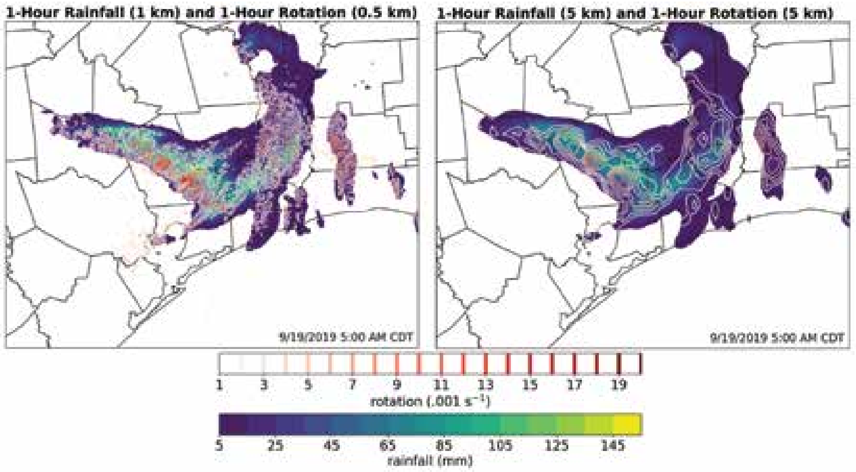

Figure 2: One-hour rotation (contours) and rainfall (shading) from the MRMS dataset on September 19, 2019, at 5:00 AM for southeast Texas and southwest Louisiana. The left panel shows the datasets in their original form (1 km and 0.5 km spatial resolution for rainfall and rotation, respectively), and the right panel shows the data after smoothing was applied (5 km spatial resolution for rainfall and rotation).

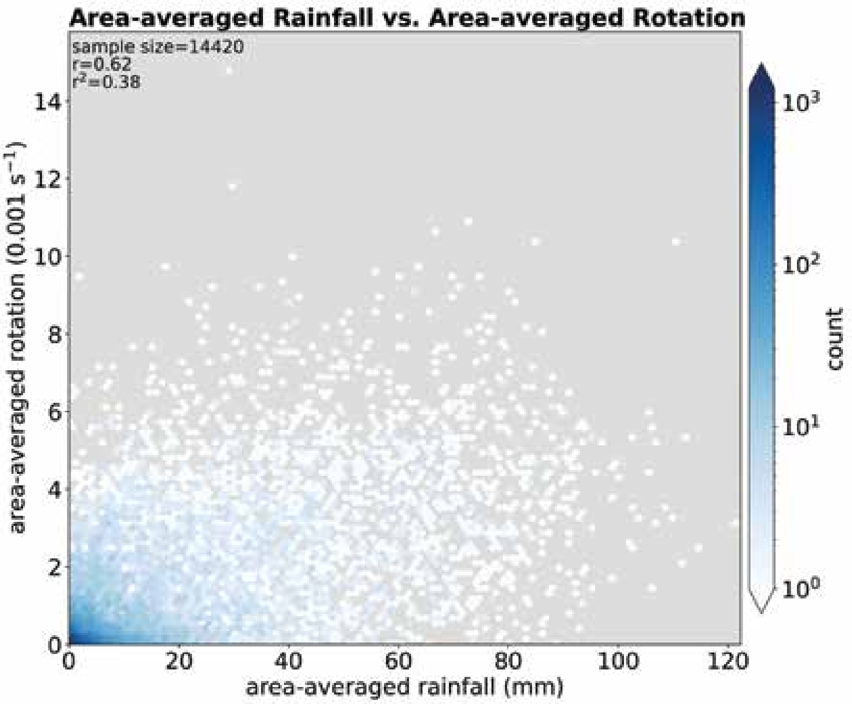

Figure 3: Hourly rainfall versus hourly rotation for all non-zero pixels from September 18, 2019, at 7:00 PM to September 19, 2019, at 1:00 PM. The number of pixels (shown as the sample size) and the r (correlation coefficient) and r2 (amount of variance explained by a linear model) values are noted in the upper left of the plot.

This study aims to support research on the causes of heavy rainfall and relationships among multiple hazards in tropical cyclones. It is important for meteorologists to be familiar with the science behind rotation and heavy rainfall as they are monitoring significant weather because both can be precursors to more life-threatening events: tornadoes and flooding. Additionally, understanding if there is a connection between these two phenomena—that is, whether rotation increases rainfall—would be even more beneficial to forecasters who monitor tropical cyclones and deliver information to the public on the hazards that accompany them. While this analysis does not assess whether the rotation is causing the heavier rainfall, it does suggest that when there is stronger rotation within a storm, there tends to be larger rainfall totals in that area.

Acknowledgements

This research is supported by NOAA VORTEX-SE grant NA18OAR4590308 and an AMS Graduate Research Fellowship sponsored by the NOAA Climate Program Office.

The Michigan Ditch flows across Cameron Pass on the border between Jackson and Larimer counties, Colorado. Photo by Jeffrey Beall/Wikimedia Commons.

The Timing of Peak Streamflow in a Small River Versus Snowpack Melt-Out

Maryam Sahaar, Undergraduate Student, Watershed Science, Colorado State University and
Dr. Steven Fassnacht, Professor, Watershed Science, Colorado State University

Introduction

The timing of peaks in snowmelt streamflow have been correlated to the disappearance of the snowpack; for the 386 km^2 (149 mi^2) Uncompahgre River in Southwest Colorado snow-all-gone (SAG) dates (Duncan et al., 2021) in forest and alpine areas matched the timing of two distinct streamflow peaks (Doskocil et al., 2021). Based on the streamflow-SAG correlation, the end goal of Doskocil et al. (2021) built on the premise that estimating the SAG date could provide a simple estimate of the timing of peak flow. Here, the idea is to examine the correlation between the timing of peak flow and snowpack melt-out or SAG for a smaller river, where there is usually only one main peak streamflow.

This work uses a time series of daily streamflow data from a small headwaters basin and daily snowpack data from a neighboring hydro-niveological station. It builds on the work of Fassnacht et al. (2014) that correlated snowpack and streamflow characteristics. The specific objectives are as follows: (1) determine the correlation between streamflow and snow water equivalent (SWE), and (2) determine the correlation between the timing of peak streamflow ($t_{Q\text{-peak}}$) and the SAG date.

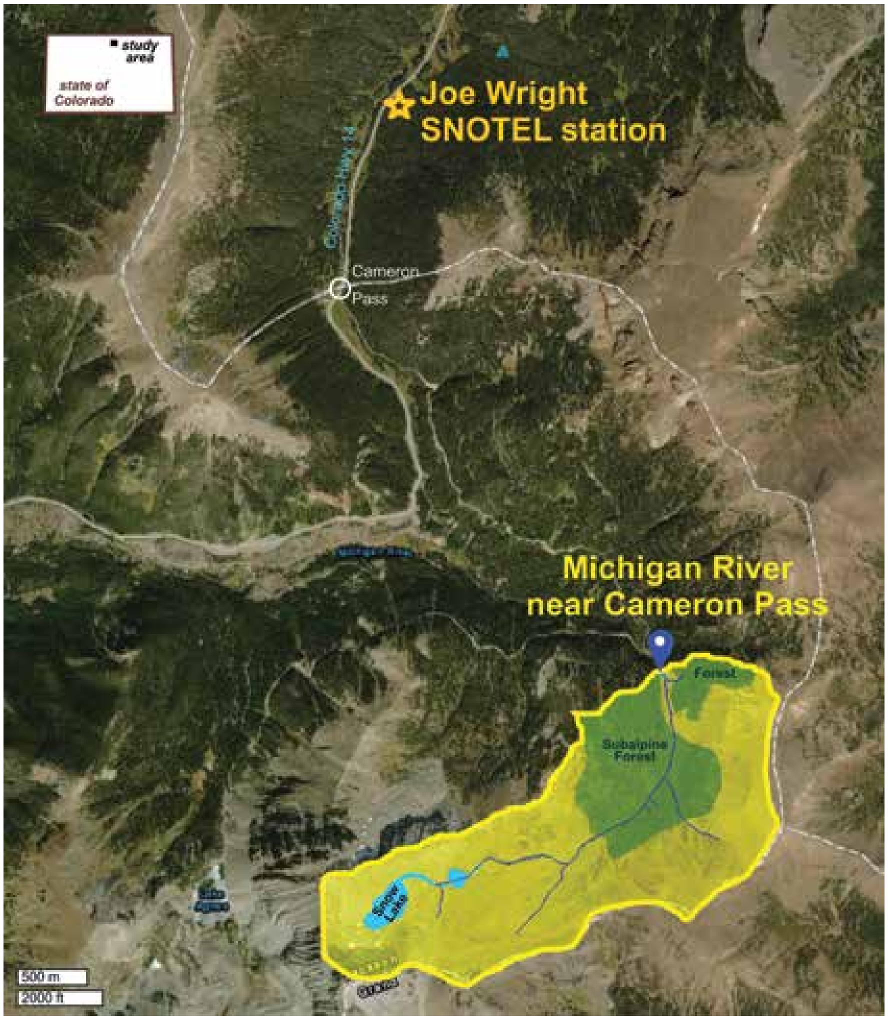

Figure 1. Location map of the study basin (Michigan River near Cameron Pass) and the SNOTEL station (Joe Wright). The background image and basin delineation are from the U.S. Geological Survey StreamStats (streamstats.usgs.gov/ss/) and additional information was prepared by Dr. Steven Fassnacht.

> For each year [of the study], the amount and date of peak streamflow, the amount and date of peak SWE, and the date of snow-all-gone were determined

Table 1. Correlation coefficient (R) between SWE-based (Joe Wright SNOTEL) and streamflow-based variables (Michigan River near Cameron Pass).

	Peak SWE Date	Date of SAG	Days From Peak to SAG	Peak Q	Peak Q Date
Peak SWE	0.66	0.75	-0.23	0.61	0.59
Peak SWE Date		0.79	-0.74	0.57	0.55
Date of SAG			-0.16	0.58	0.83
Days from Peak to SAG				-0.28	0.02
Peak Q					0.41

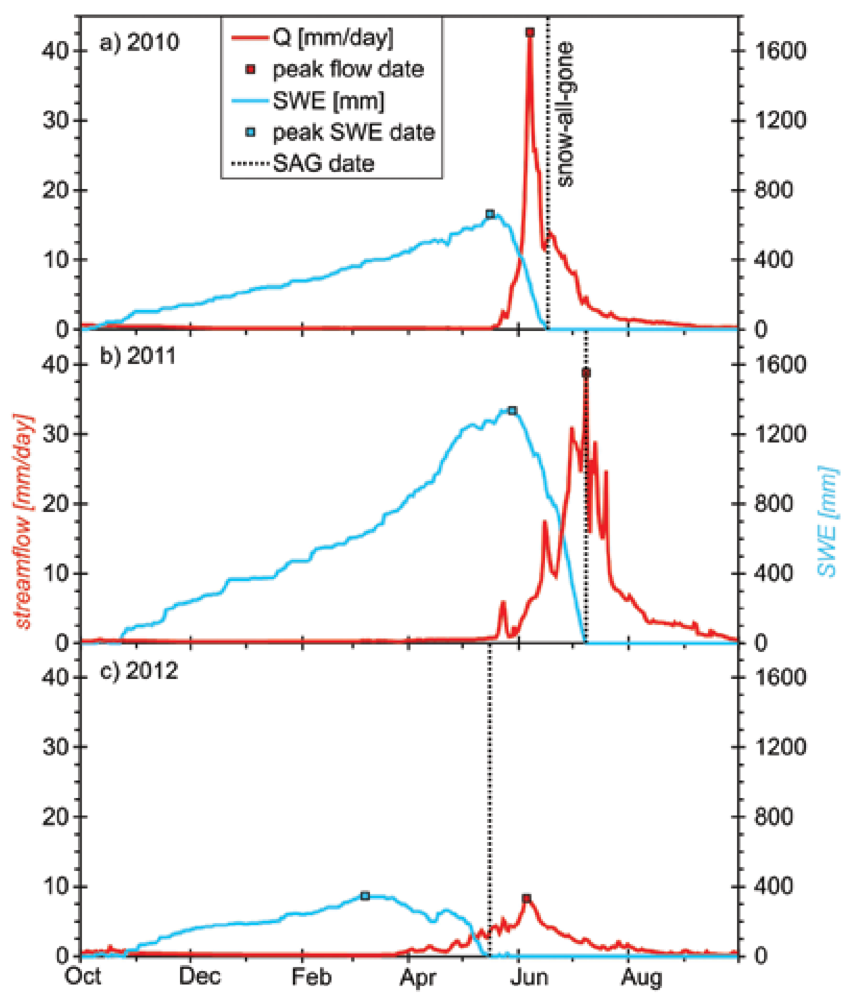

Figure 2. Daily time series of streamflow on the Michigan River near Cameron Pass Watershed (left axis and lines in red), and snow water equivalent (SWE) at the Joe Wright SNOTEL station (right axis and blue line) plus date of snow-all-gone date (dashed line) for 2010 (average year), 2011 (wettest year), and 2012 (driest year). Analysis was done by Maryam Sahaar and the image was prepared by Dr. Steven Fassnacht.

Study Area

The Michigan River near Cameron Pass Watershed (U.S. Geological Survey gauge 06614800; data available at nwis.waterdata.usgs.gov/nwis/sw) was paired with the Joe Wright snow telemetry (SNOTEL) station (National Resources Conservation Service station 551; data available at nrcs.usda.gov/wps/portal/wcc/home/). The watershed has a drainage area of 3.96 km^2 (1.54 mi^2), with a majority of the basin being in the alpine, with the tarn, Snow Lake, located at the headwaters (Figure 1). The lower elevation areas are forested, mostly by Engelmann Spruce (*Picea engelmanii*) and Subalpine Fir (*Abies lasiocarpa*).

Methodology

A 40-year time series of daily streamflow and SWE data were used for water years (1 October through 30 September) from 1981 to 2020. For each year, the amount and date of peak streamflow, the amount and date of peak SWE, and the date of snow-all-gone were determined (the variables are listed in Table 1). These variables were correlated to one another using the coefficient of determination; it also shows the sign of the correlation. The key correlation is between the date of peak streamflow and the SAG date, where the difference between the two dates was assessed. A linear regression was fit between the two variables, and further, a new regression was fit once outliers were removed. Three different snow years were highlighted: 2010 was an average snow year, while 2011 was the highest snow year in the 40-year period of record, and 2012 was the lowest on record.

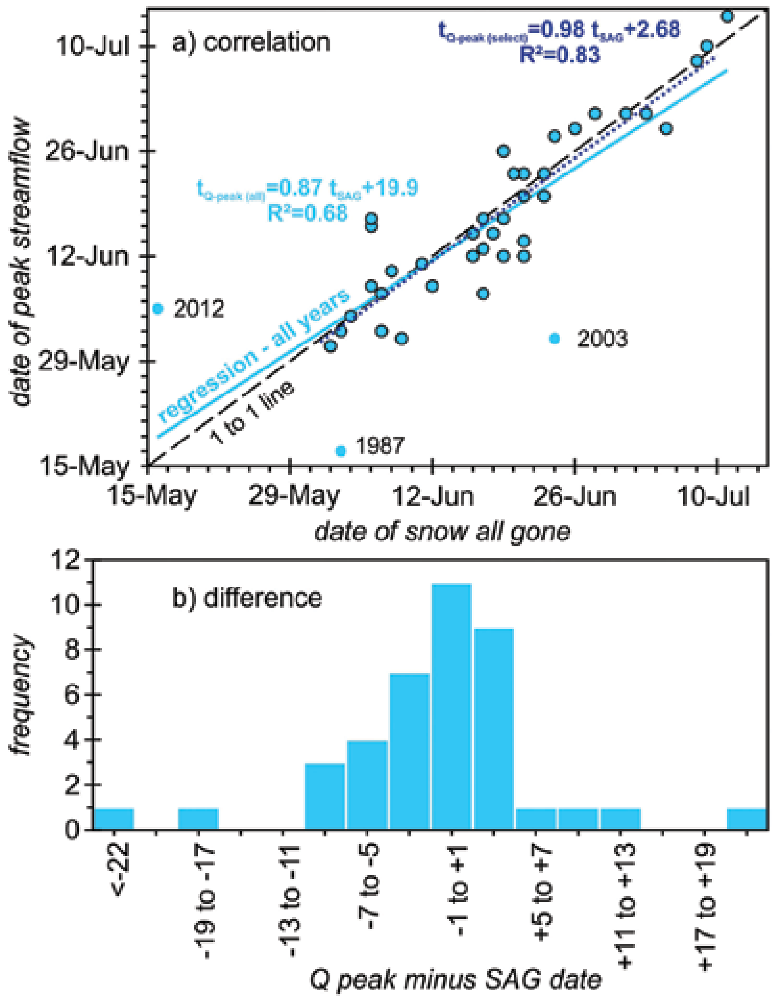

Figure 3. a) Correlation between date of peak streamflow (tQ-peak) on the Michigan River near Cameron Pass Watershed and date of snow-all-gone (tSAG) at the Joe Wright SNOTEL station. The lighter blue line is the best fit for all data, while the darker blue line is for the regression with the years 1987, 2003, and 2012 removed; and b) histogram of differences between tQ-peak and tSAG. The analysis was done by Maryam Sahaar, and the image was prepared by Dr. Steven Fassnacht.

Figure 4. Maryam Sahaa photographed near the Michigan River.
Photo by Dr. Steven Fassnacht.

Results and Discussion

The three snow years had different accumulation, peak SWE, the onset of melt, and streamflow characteristics (Figure 2). Peak SWE occurred more than two months later in 2011 (Figure 2b) than in 2012 (Figure 2c). In 2010, peak streamflow was only 22 days after peak SWE; it doubled this in 2011 and doubled again in 2012. Multiple larger streamflow peaks occurred in 2011, likely due to more differential melting across the basin than in other years.

For this headwater basin, the SAG date represented the timing of peak streamflow well (Figure 3a), within two days of one another for 18 of the 40 years. The mean (median) difference was SAG occurring 1.2 (0.5) days after peak streamflow (Figure 3b). The date of peak streamflow and SAG are well correlated ($R^2 = 0.68$). Three years were outliers; removing these three-year yielded the best fit that was almost along the 1:1 line (Figure 3a).

In 1987 and 2003, there were two streamflow peaks, and SAG matched the second smaller magnitude peak better. The other outlier was 2012 (Figure 2c); in that year, melt started three weeks earlier than any other year and almost two months earlier than the average start of melt. The SNOTEL station represents the forested area, and a majority of this basin is higher than the treeline (Figure 1). Snowpack measurements in the alpine could improve the understanding of melt-out (Doskocil et al., 2021).

Implications

The three demonstration years (Figure 2) illustrated the inter-annual variability in snowpack accumulation, snowmelt, and streamflow characteristics. Forty years of data can represent a vast range of hydro-climatic conditions. Using snowpack melt-out to estimate the timing of peak streamflow is a simple approach that does not consider all the complex hydrological processes that occur in a snow-dominated system. However, due to spatial variability, extrapolating meteorological data from a single station for use in a hydrological model would not necessarily improve the estimation of peak streamflow. A simple approach can provide some initial insight into the functioning of a small headwater basin.

Analysis of Uncertainty in Hydrometeorological Ensemble Forecasts

Carolien Mossel, Masters Student, Earth and Atmospheric Science, The City College of New York, National Oceanic and Atmospheric Administration, Center for Earth System Science and Remote Sensing Technologies

Figure 1. The study area of three drainage basins encompassing seven U.S. Geological Survey streamflow station sites.

Introduction

California's catastrophically wet 2017 water year ended a preceding years-long drought through many intense precipitation events that caused fast-rising rivers, floods, and infrastructure disasters such as the Oroville Dam Spillway failure. Extreme weather and climate patterns combined with the region's ongoing water shortage and California's highly-managed water systems highlight the need for accurate short-to medium-range water predictions.

The National Oceanic and Atmospheric Administration (NOAA) National Water Model (NWM) is an operational hydrologic model that generates hourly streamflow forecasts across the continental United States. Hydrologic model forecasts, like those made with the NWM, can be deterministic, with a single streamflow prediction for each forecast cycle, or probabilistic, with multiple (ensemble) streamflow forecasts for each cycle which yield a probabilistic forecast distribution. Current NWM forecasts are either deterministic or generated using a relatively simple, time-lagged ensemble method.

This project explores the value of using ensemble meteorological forecasts to drive experimental ensemble NWM forecasts. We examine both precipitation and the resulting ensemble streamflow for the entire wet season, as well as focusing on ten discrete high streamflow events.

Data and Methods

The objective of the research was to evaluate the performance of an experimental downscaled forecast ensemble for the period of October 2016 - March 2017. The meteorological forecasts used to force the NWM were originally produced by NOAA's Global Ensemble Forecast System (GEFS). However, to achieve higher resolution, more skillful forecasts that better represent the effects of western U.S. terrain, the forecasts were downscaled and post-processed using a method summarized by Scheuerer and Hamill (2018).

Two types of data were used as comparisons to evaluate the forecasted observations of precipitation, and streamflow were used in tandem with analysis data (the North American Land Data Assimilation System (NLDAS) meteorological analysis product and an NLDAS-driven NWM simulation). The downscaled ensemble was trained on NLDAS, and by using multiple "ground-truth" datasets, we can better decouple the error between ensemble forecast inputs versus NWM outputs.

To focus on errors between precipitation inputs and streamflow outputs, we selected coastal, rain-dominated drainage basins in California (Figure 1) to remove the added complexity of snow processes from the analysis. Across the three selected basins (Figure 1), there are seven U.S. Geological Survey (USGS) streamflow observation sites. To connect the hydrology (streamflow) to the precipitation, we compare streamflow observations and point forecasts to basin-average precipitation, which is calculated from both forecast and analysis gridded data.

The high streamflow events that occurred across the 2016 – 2017 wet season often had multiple peaks, requiring a systematic and reproducible approach for event definition (Figure 2). To define these high streamflow events, we used a method recently published by Kim et al. (2019) and selected high flow events are shown in Figure 2. These events were evaluated using a suite of metrics and diagnostics, including Normalized Bias:

$$\text{Normalized Bias}=\text{Average}(\text{Model}-\text{Observation})/\text{Average}(\text{Observation})$$

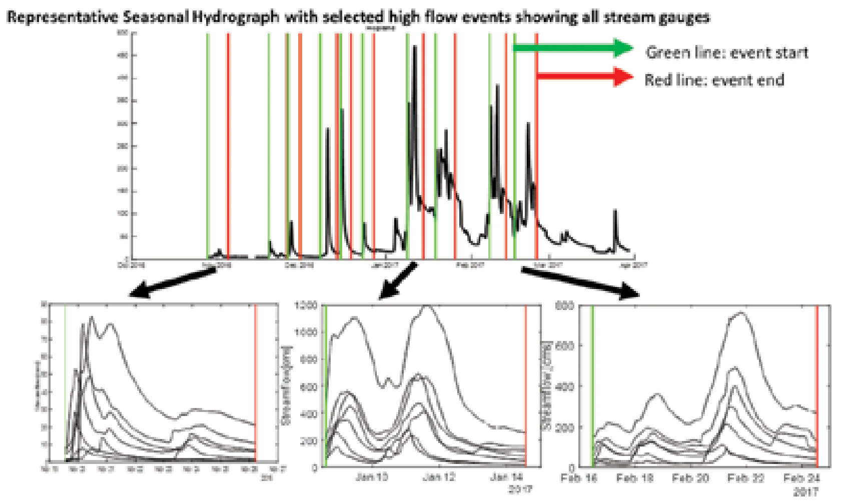

Figure 2. Representative seasonal hydrograph illustrates the magnitude and frequency of streamflow, with lines indicating the start and end of high flow events chosen by the algorithm. The green line indicates the start selected by the algorithm, and the red line marks the end. Selected high flow events are shown, with each black line representing the hydrograph provided by a U.S. Geological Survey streamflow recording station.

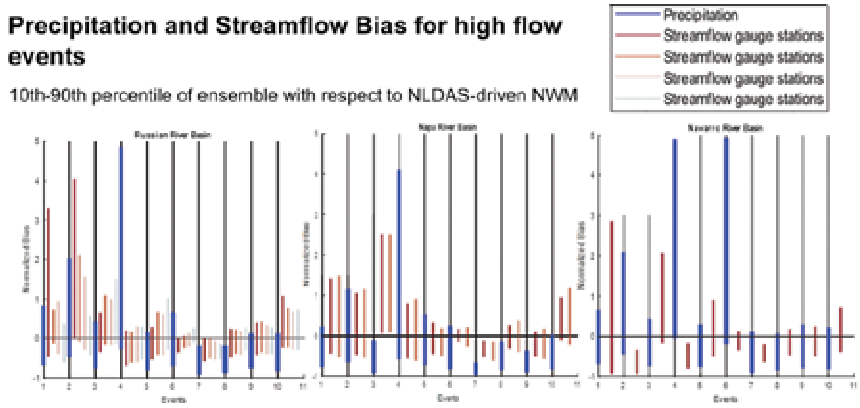

Figure 3. Range of normalized bias of the 10-90th percentile of ensemble data with respect to the NLDAS-driven NWM. The normalized bias value is calculated for each high flow event period defined in Figure 2, with extra time beforehand for precipitation only. Each graph shows the basin-wide precipitation bias for each event preceding the values of each respective streamflow gauge station.

Table 1. The percent coverage of the middle 80% of the ensemble precipitation compared to the observations (QPE) and the NLDAS-driven NWM for the entire cool season.

	Navarro	Napa	Russian
NLDAS (hourly)	59%	70%	64%
QPE (6 hourly)	56%	66%	62%

Results

The characterization of ensemble forecast performance results presented here fall into two categories: first via seasonal statistics and then with a focus on a subset of the high streamflow events. Seasonal statistics show that the middle 80% of the ensemble precipitation forecast "envelope" captured the NLDAS precipitation analysis better than it did the raw precipitation observations (Table 1), but that relative to either, the ensemble captured 10 – 25% less than the "expected" perfect result of 80%. This may be partially explained by the fact that the ensemble dataset was trained on NLDAS during drought years but then was used to forecast a non-drought year.

To illustrate the range in bias across the ensemble forecast during high streamflow periods, we calculate the Normalized Bias for each high flow event at the 10th and 90th percentile of the ensemble distribution compared to the NLDAS-driven NWM analysis simulation. Precipitation bias and the resulting streamflow bias for each river basin's set of streamflow stations (Figure 3) reveal differences in general trends from the early season to the late season. Higher biases are most prevalent at the 90th percentile for the early season, meaning that the upper end of ensemble streamflow was overestimated. Possible factors for this include soil moisture transition processes from dry to wet conditions and resulting effects on runoff. General trends in the range of biases over the length of the river can be seen in the Russian River basin, where the four streamflow stations are presented in the order that the river runs. Events 3 – 6 show that the range in bias trends toward overestimation further downstream, while events 2, 7, and 9 show the opposite.

Further work will explore how trends in meteorological and hydrologic over- and under-estimation are connected, and to what extent resulting hydrologic ensemble error and spread characteristics can be attributed to spread and errors determined by precipitation inputs. These preliminary results will improve our understanding of how ensembles can be designed and interpreted to provide more accurate and usable hydrologic forecasts.

Acknowledgments

This study is supported and monitored by The National Oceanic and Atmospheric Administration—Cooperative Science Center for Earth System Sciences and Remote Sensing Technologies under the Cooperative Agreement Grant #: NA16SEC4810008. The authors would like to thank The City College of New York, NOAA Center for Earth System Sciences and Remote Sensing Technologies, and NOAA Office of Education, Educational Partnership Program for full fellowship support for Carolien Mossel. The statements contained within the report are not the opinions of the funding agency or the U.S. government but reflect the author's opinions.

Upper Yampa Water Conservancy District Announces 2021-2022 John Fetcher Scholarship Recipients

The Colorado Water Center partners in supporting the John Fetcher Upper Yampa Water Conservancy District Scholarship each academic year.

The Upper Yampa Water Conservancy District provides two $2,000 one-year scholarships for full-time university student(s) who are pursuing a water-related career in any major at a public university within the state of Colorado. The Colorado Water Center administers the scholarship.

This year's scholarship recipients are Kaydee Barker and Daniel Cleveland.

Kaydee Barker

Kaydee Barker

Kaydee Barker is an accomplished student researcher and community volunteer who was motivated by firsthand experience to learn about the effects of climate change and mitigation. Kaydee earned an AA in Business from Colorado Mountain College in Steamboat Springs and balances her time between an impressive array of student organizations, classes, and research projects. She is a Western Slope native and has a personal appreciation for the value of water in Colorado communities.

There are few people who are as passionate about the environment as Kaydee. Not only is she actively involved in environmental research, but she is also involved with several environmentally-oriented student organizations such as the Society of Women Environmental Professionals (Vice President), Watershed Club, the Society for Ecological Restoration, and Strategies for Ecology Education, and the Diversity and Sustainability Club. Outside of that, Kaydee loves outdoor recreation activities such as kayaking, swimming, and fishing.

Kaydee has returned to school at Colorado State University in Fort Collins and is pursuing a BS in Ecosystems Science and Sustainability with a minor in Soil Science. Currently, she is working with Dr. Jill Baron, the Cortufo Soil Ecology Lab, and the Paustian Soil Lab, all at CSU. We are extremely interested to learn where Kaydee's research takes her!

Daniel Cleveland

Daniel Cleveland

Daniel Cleveland is a seasoned engineer who has spent the past five years working extensively on agricultural water projects all around the world. Graduating with a BS in Engineering from the University of Tennessee at Knoxville, Daniel combines technical knowledge with a passion for natural resource work that has taken him from India to Sweden to the Philippines and three different US states.

Daniel's belief in the importance of effective and sustainable water management drove him to leave a successful career in engineering and devote his life to sustainable agriculture and water management. Daniel is particularly interested in ecosystem resilience and how to ensure that watersheds can deal with ecological stress and climate change. He is currently working on restoring the land around Utterback Ranch, located just north of the Yampa River on Tow Creek.

In order to continue working towards his career aspirations, Daniel has enrolled in Colorado State University's Graduate Program in Ecology. Daniel spends his time working with Dr. Paul Evangelista and the Natural Resource Ecology Laboratory, and he hopes that his work will lead him to work to benefit those in stressed watersheds, especially watersheds that support indigenous and marginalized communities. We are excited to see where Daniel's work takes him next!

Congratulations to this year's Yampa Scholarship recipients. To learn more about the scholarship program, visit watercenter.colostate.edu/john-fetcher-scholarship

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Engaging Community Leaders in Critical Water Decisions

Julie Kallenberger, Associate Director, Colorado Water Center

Among the many important values of Northern Colorado citizens are preserving agricultural land and open space, ensuring high-quality drinking water, healthy rivers and environment, vibrant communities, and robust economies. For local leaders to make sound decisions related to water issues, they seek relationships with others throughout our Region and reliable, unbiased information from water experts.

Recognizing this need, the Colorado Water Center (CoWC; watercenter.colostate.edu/) developed the Water Literate Leaders of Northern Colorado program in partnership with the Community Foundation of Northern Colorado's Hach Center for Regional Engagement (nocofoundation.org/the-hach-center/). To date, the program has cultivated three cohorts consisting of 63 leaders from different sectors with the goal of raising the level of dialogue about water to the top decision-makers in the region. Participants in the program engage in nine months of learning about the many facets of water, discuss complex issues and associated tradeoffs, exchange ideas, and work towards how Northern Colorado can best achieve its goals for regional water collaboration.

Water Literate Leaders of Northern Colorado Welcomes New Cohort

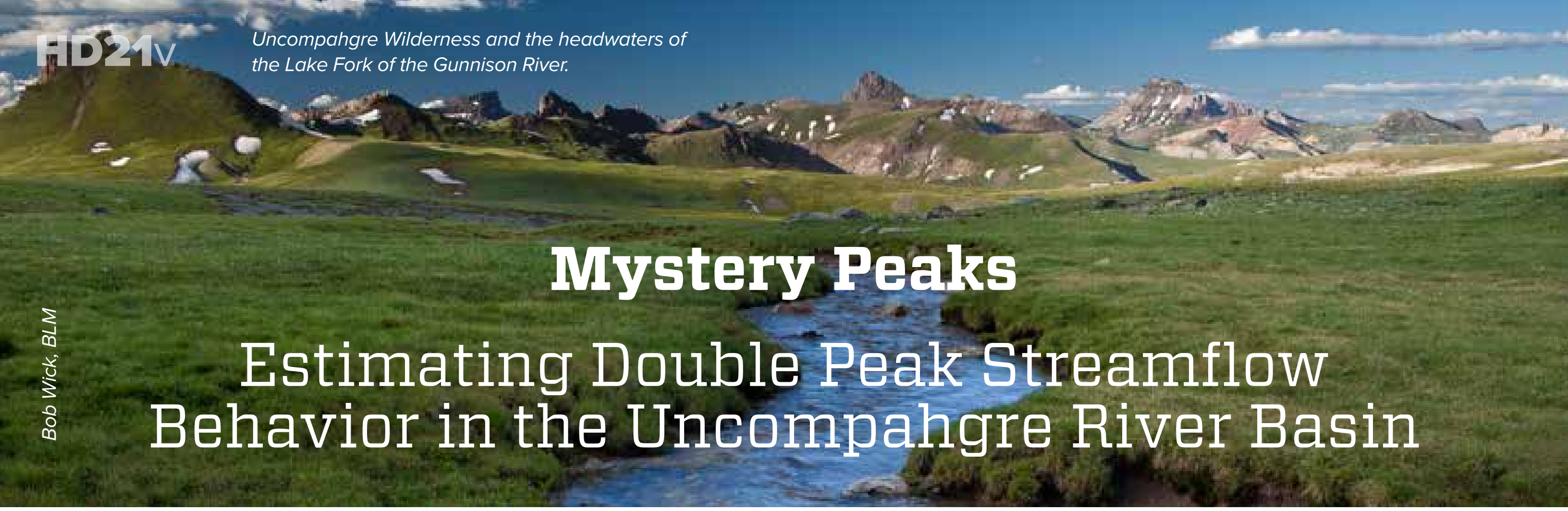
We are pleased to welcome our 2021-2022 cohort of Water Literate Leaders. These 20 individuals have committed to investing their time and energy to learn from experts and empower themselves to meet the ever-changing water needs of our communities.

Name, Title, Affiliation	*Community*
Dave Beede, Chapter Vice President, Chair of Grants Subcommittee Rocky Mountain Flycasters/Trout Unlimited	Northern Colorado/ Fort Collins
Tricia Canonico, Council Member, City of Fort Collins	Fort Collins
Ella Fahrlander, Chief Engagement Officer, Community Foundation of Northern Colorado	Northern Colorado/ Fort Collins
Wilynn Formeller, Program & Development Coordinator, Estes Valley Watershed Coalition	Estes Park
Patti Garcia, Town Administrator, Town of Wellington	Wellington
Travis Goeglein, Senior Vice President First FarmBank	Greeley/Evans
Amber Graves, Manager/Farm Hand, Colorado General Assembly/ Morning Fresh Dairy Farm	Bellvue
Jaime Henning, President and CEO, Greeley Area Chamber of Commerce	Greeley
Hunter Hoshiko, Director of Development—Great Western Industrial Park, BROE Real Estate Group	Windsor
Wyatt Knutson, Regional Manager/Water Task Force Member, CTL Thompson/Town of Wellington	Wellington
John Kolanz, Partner Otis & Bedingfield, LLC	Loveland
Matt LeCerf, Town Manager, Town of Johnstown	Johnstown
Eric Lucas, Public Services Director, Town of Windsor	Windsor
Dawson Metcalf, Program Coordinator for Conservation Leadership, Colorado State University	Fort Collins
Christian Morgan, Town Manager, Town of Kersey	Kersey
Don Overcash, City Councilor, Mayor Pro Tem, City of Loveland	Loveland
Kim Perry, Vice President Community Design and Neighborhood Development, McWhinney	Loveland
Kevin Ross, Vice President, Poudre Valley Capital	Greeley
Tim Whitehouse, Trustee and Planning Commissioner, Town of Wellington	Wellington
Janene Willey, Secretary, Town of Windsor Water and Sewer Board	Windsor

Interested in learning more about Water Literate Leaders? Visit our website at watercenter.colostate.edu/wll

The Water Literate Leaders program is made possible through the following partners and sponsors:

Community Foundation of Northern Colorado, City of Evans, City of Fort Collins, City of Greeley, City of Loveland, City of Thornton, Town of Windsor, North Weld County Water District



Uncompahgre Wilderness and the headwaters of the Lake Fork of the Gunnison River.

Bob Wick, BLM

Mystery Peaks

Estimating Double Peak Streamflow Behavior in the Uncompahgre River Basin

Lenka G.Doskocil, Undergraduate Student and Research Assistant, and **Dr. Steven Fassnacht, Professor**, Watershed Science, Colorado State University, **Jeffrey E. Derry**, Executive Director, Center for Snow and Avalanche Studies

In snowmelt dominated river systems, streamflow increases through the spring, peaks in late spring to early summer, and then declines through the summer and fall. Water resource managers and scientists typically describe these river systems, which characterize most river basins in the Rocky Mountain West, as having one single peak. However, some rivers, such as Colorado's Upper Uncompahgre River that flows into Ridgeway Reservoir (Figure 1), often peaks twice during the water year (Figure 2). Unpublished research suggests that using snowpack metrics from high-elevation snow stations operated by the Center for Snow and Avalanche Studies (CSAS) near the headwaters on Red Mountain Pass could yield good estimates of both the first and second hydrograph peaks.

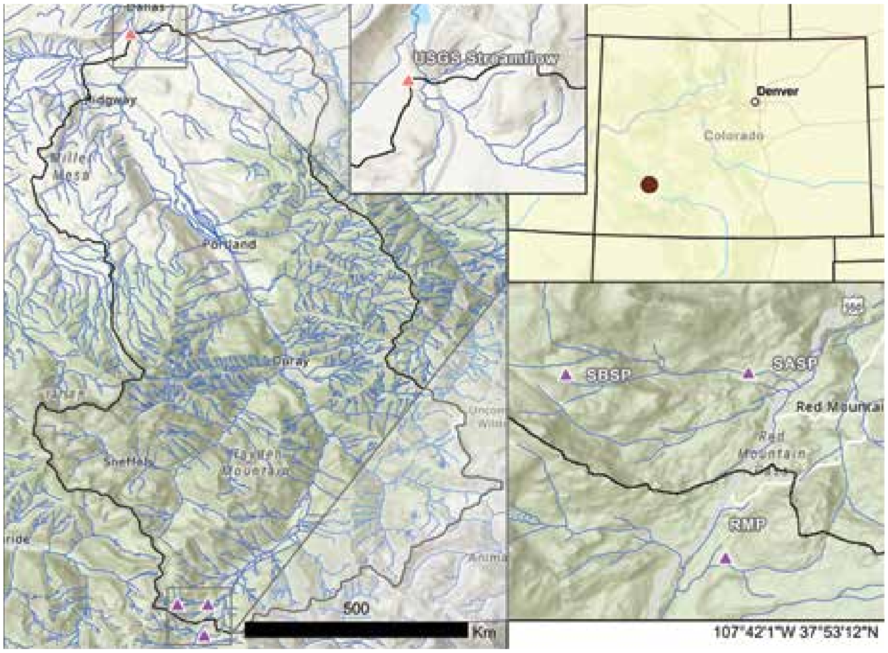


Figure 1. Uncompahgre Watershed (HUC 14020006) and relevant snow and streamflow stations: SBSP is CSAS Senator Beck Study Plot SBSP, SASP is CSAS Swamp Angel Study Plot, and RMP is NRCS Red Mountain Pass SNOTEL station. Data retrieved from ESRI and National Hydrography Dataset. Graphic by Lenka Doskocil.

Water resource managers and scientists have not yet developed a good understanding of what drives dual-peak behavior. Lenka Doskocil, a recent Watershed Science graduate and honors student from Colorado State University, examined the correlation between snowpack melt-out from alpine (above treeline) and sub-alpine (below treeline) biomes and peak streamflow events in the Uncompahgre as one potential mechanism. Snow generally disappears from sub-alpine areas before it fades from the alpine, producing a one-to-three-week window where consistent snow exists above the treeline but has melted below it. This same gap occurs between the Uncompahgre's two streamflow peaks (Figure 2), suggesting that peak flow may relate to snow disappearance. Using daily streamflow data from the U.S. Geological Survey (USGS) stream gauging station in Ridgeway (waterdata.usgs.gov/nwis) and snowpack data from two CSAS stations snowstudies.org and one Natural Resources Conservation Service (NRCS) snow telemetry (SNOTEL) station nrcs.usda.gov/wps/portal/wcc/home/ over a 16-year span, Doskocil extracted annual peak flow and snow-all-gone, or snow disappearance, dates. Each of the three annual snow-all-gone dates corresponded to a snow station: two located in the sub-alpine (see Figure 4 for one station) and one located in the alpine.

Results told a slightly unexpected story. Snow-all-gone dates, regardless of biome, estimated the Uncompahgre's second peak well (see Figure 3 for an example). The snow

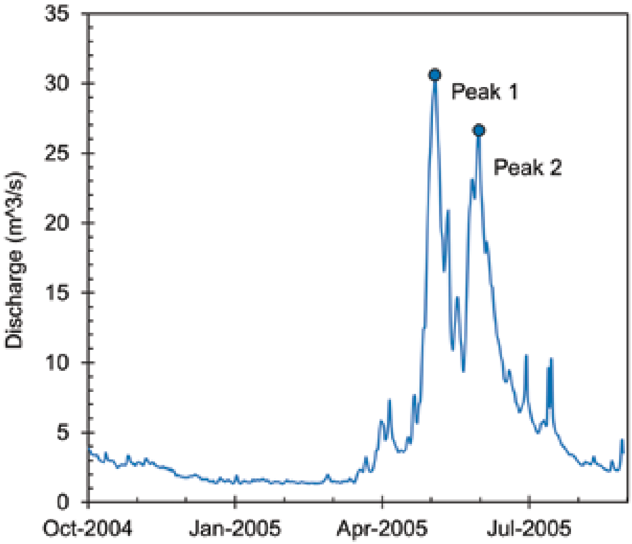


Figure 2. Hydrograph for U.S. Geological Survey (Station 09146200) for water year 2005, demonstrating double peak behavior in the Uncompahgre River near Ridgway, Colorado. Graphic by Lenka Doskocil.

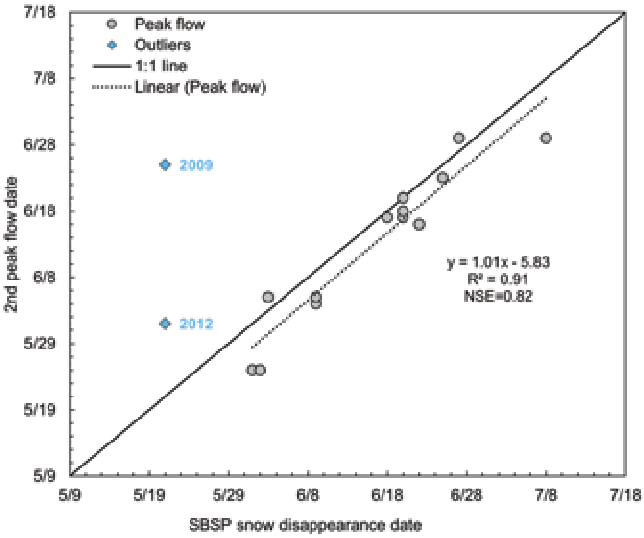


Figure 3. Correlation between snow disappearance date at Senator Beck Study Plot (SBSP) and the second peak flow event to occur in the Uncompahgre River near Ridgway, Colorado (U.S. Geological Survey 09146200). Years 2009 and 2012 omitted from reported R2 values. Figure by Lenka Doskocil.

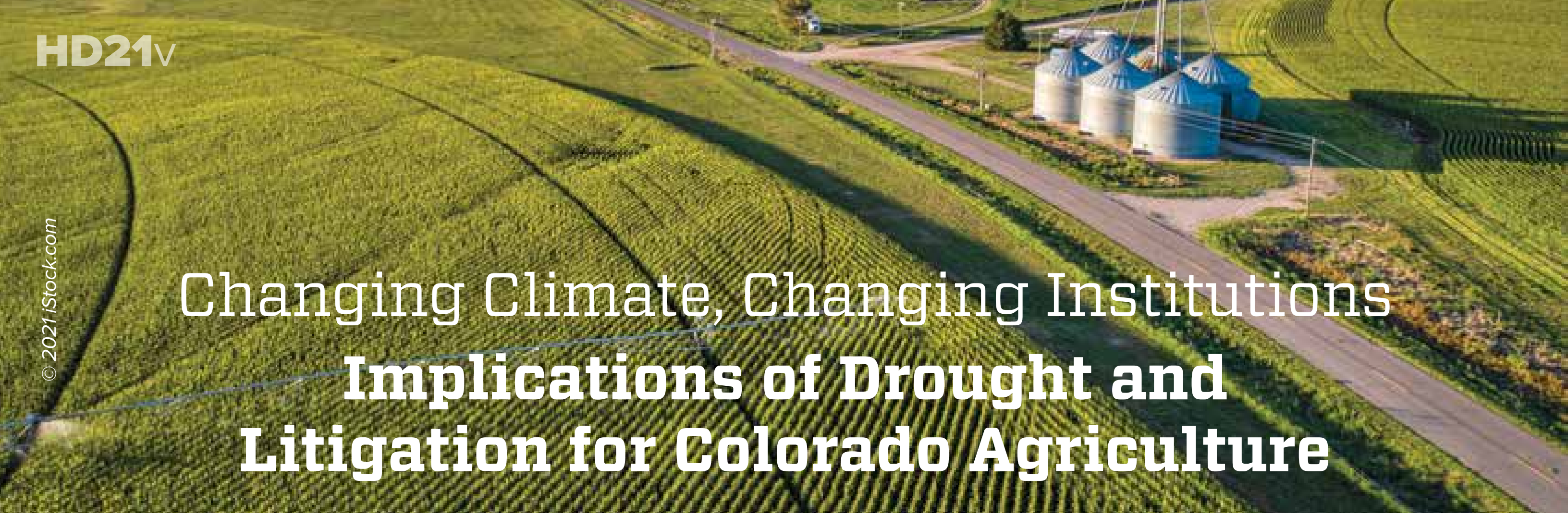
Figure 4. Lenka Doskocil and Dr. Steven Fassnacht at Swamp Angel Study Plot near the Uncompahgre's headwaters. Photo by Dylan Doskocil.

disappeared from the sub-alpine stations a few days before the second peak and from the alpine station up to a week and a half after. Years 2012 and 2009 broke that pattern across all stations, with snow-all-gone occurring two to four weeks before the second peak event. These years did contain a high number of dust-on-snow events, highlighting the degree dust deposition can impact streamflow dynamics in snowmelt dominated systems (Duncan et al., 2021).

The pattern connecting snow-all-gone dates to the second peak flow event did not hold true for the first peak flow event: no significant correlation existed. Fifty-percent peak snow depth from two stations (the alpine location and one sub-alpine location) provided better estimations of the first peak streamflow date. This suggests that melt-out from the two different biomes does not fully explain the Uncompahgre's dual peaks.

Further research exploring melt-out timing from different aspects or major tributaries could provide more detailed answers. For example, solar radiation variations between differing aspects substantially impact maximum snow accumulation and annual snowpack duration. This difference could cause a noticeable discrepancy in snowmelt timing from these different slopes, thereby impacting flow further downstream. Melt-out timing discrepancies from major tributaries or sub-basins could produce the same effect. The upper Uncompahgre River Basin contains two to three major sub-basins that drain generally different aspects, potentially driving the river's dual peak behavior.

Understanding peak flow timing, particularly in over-allocated basins across the West, provides water managers another decision-making tool. Forecasting peak flows using snowpack metrics, like snow disappearance and peak depth dates, rather than hydrologic modeling could prove less complicated. The NRCS operates over 900 SNOTEL sites in high elevation watersheds across the West, providing substantial data for snow-based estimation of peak flows.



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Changing Climate, Changing Institutions

Implications of Drought and Litigation for Colorado Agriculture

Joey Blumberg, Doctoral Student, **Dr. Chris Goemans**, Associate Professor, and
Dr. Dale Manning, Associate Professor, Agricultural and Resource Economics, Colorado State University

Introduction

Climate change and expanding populations place continued stress on Colorado's natural systems and meeting future agricultural water demands depends on the development of sustainable management strategies. While there exists ample research on the impacts of climate change on agriculture, little focus has been given to the interrelation between hydrological systems and institutional water administration. Understanding historical water user responses to supply conditions and changes in water law is critical for future planning. This article explores trends in irrigation efficiency from 1976-2015 in northeastern Colorado, focusing on a period in the early 2000s in which record drought and litigation between water users triggered an institutional change that led to an unprecedented curtailment of water rights.

Figure 1. Map of Colorado Water Divisions. Graphic courtesy of the Colorado Division of Water Resources, Geographic Information Systems (GIS) and Maps.

Context and Study Area

Water allocation in Colorado is governed by the Prior Appropriation Doctrine, a legal framework that rules over all surface water and tributary groundwater use. To divert water from Colorado's natural systems, one must obtain a water right from a court. Rights are ranked by a system of priority determined by the date on which a user appropriated and diverted water for beneficial use. During a shortage, the State Engineer places a "call" that requires users below a determined priority to cease water diversions.

Water Division 1 (WD1), the study area for this analysis, contains the South Platte River, Republican River, and Laramie River basins (Figure 1). Irrigated agriculture accounts for ~85% of all water withdrawals within WD1, with supplies originating in mountain snowpack along the Continental Divide (Colorado Water Plan, 2015). The basins in WD1 are over-appropriated, meaning the total allotted volume of water rights exceeds the current average supply.

Litigation and the Severe Drought of 2002

The Water Right Determination and Administration Act of 1969 introduced "augmentation plans" that allow for out-of-priority diversions so long as sufficient replacement water is supplied for river recharge. Augmentation plans require approval through a decree of the water court, but the State Engineer could temporarily approve less-regulated substitute water supply plans (SWSPs). SWSPs were used unsustainably throughout the 1980s and 1990s, but exceptional precipitation and snowpack (McKee et al., 2000) veiled potential water shortages.

Then, in 1999-2000, Colorado experienced low winter snowpack and above average spring temperatures that led to drought conditions across the state (Pielke et al., 2005). This made apparent that existing replacement efforts under SWSPs were inadequate, and litigation was launched between two water users. The outcome of Empire Lodge Homeowner's Association v. Moyer, 39 P.3d 1139 (Colo. 2001) ultimately stripped the State Engineer's authority to approve SWSPs on an annual basis, and the number of decreed augmentation plans that require formal records of actual diversions increased dramatically in subsequent years. As more water rights recorded daily diversions, the likelihood of calls along mainstream rivers increased.

Following the court's ruling, drought conditions persisted, with the most intense period occurring in 2002 (Figure 2, top panel). In 2002, the April snowpack was estimated at 52% of the previous 30-year average (Pielke et al., 2005), and all of Colorado was in extreme drought conditions (NOAA). Combined with severe drought, the institutional change resulted in a permanent change to the call regime (Figure 2, bottom panel), and many historically secure water rights were curtailed in subsequent years (Waskom, 2013). These events highlight how sudden changes within an interconnected system can have multiplicative effects.

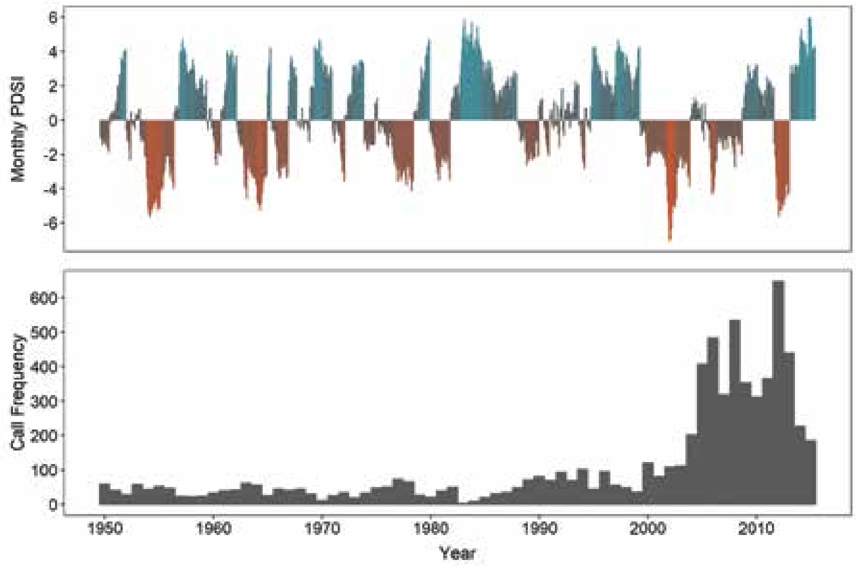

Figure 2. Drought Severity and Frequency of Calls by State Engineer, Water Division 1, 1950-2015. The Palmer Drought Severity Index (PDSI) estimates relative dryness with negative values indicating below average water supplies. A call represents an instance in which some water users are forced to stop irrigating.

Siphon tubes are used to draw water from an irrigation ditch to flood irrigate a crop. Photo by Dan Ogle, USDA Natural Resources Conservation Service.

Center pivot irrigation photographed in Adams County, Colorado. Photo by Jeffrey Beall/Wikimedia Commons.

Table 1. Trends in Irrigated Agricultural Lands, Water Division 1. The largest average annual changes are emboldened. Typical water application efficiencies for flood irrigation systems range from 20-50%, whereas pressurized sprinkler systems range from 75-90% (Bauder et al., 2014).

	Irrigated Acres			Average Annual Change		
Year	**Flood**	**Sprinkler**	**Total**	**Flood**	**Sprinkler**	**Total**
1976	871,595	140,538	1,012,133	-	-	-
1987	765,662 (-12%)	214,839 (+53%)	980,501 (-3%)	-9,630	6,755	-2,876
1997	658,123 (-14%)	258,095 (+20%)	916,218 (-7%)	-10,754	4,326	-6,428
2005	499,376 (-24%)	330,099 (+28%)	829,475 (-9%)	-19,843	9,000	-10,843
2015	394,601 (-21%)	414,642 (+26%)	809,243 (-2%)	-10,477	8,454	-2,023

…this article highlights the importance of understanding the linkages between individual behavior, scarcity, and water allocation institutions when designing water management strategies.

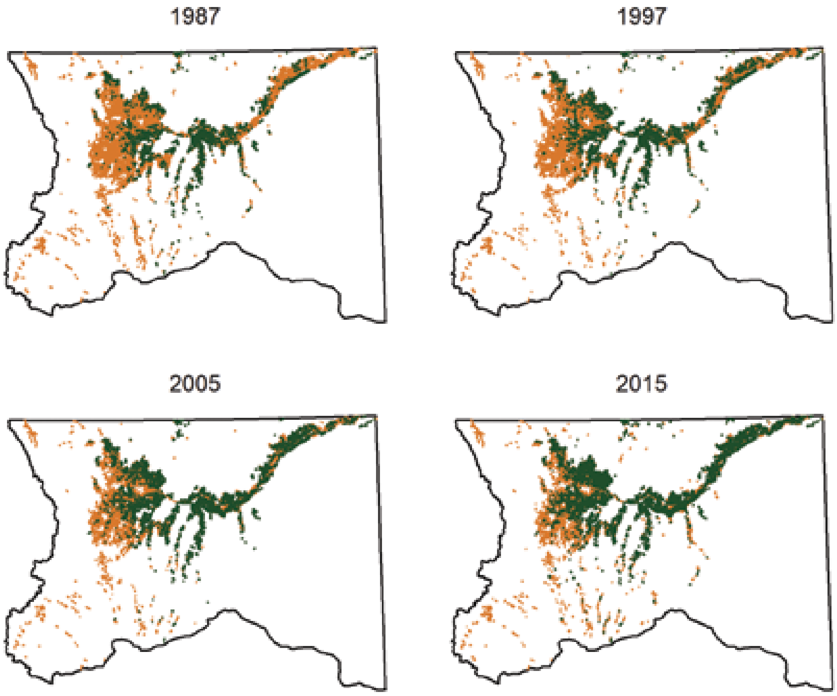

Figure 3. The transition from Flood to Sprinkler Irrigation Systems, Water Division 1, 1987-2015.

Trends in Irrigation Efficiency

To examine the potential impacts of the sudden hydrological and institutional changes on agricultural practices, we obtain data on irrigated cropland from Colorado's Decision Support System (see cdss.colorado.gov/). Changes in irrigated acreage and irrigation systems are reported in Table 1 and presented visually in Figure 3. Average annual increases in sprinkler-irrigated acreage range from ~4,300-6,800 prior to the shock and ~8,500-9,000 after. Flood-irrigated acreage underwent a rapid decrease during the years immediately following the shock but returned to the historical rate of decline over 2005-2015. Trends suggest that the change to water availability may have prompted a short-run decrease in the scale of agricultural production; however steady improvements in irrigation efficiency indicate a more persistent, long-run response. By 2015, 51.2% of irrigated lands in WD1 were equipped with sprinkler systems.

Conclusion

Agricultural producers in Colorado face uncertainty in water availability from two sources. First, water supplies in the arid West will be largely affected by climate change as the length and severity of droughts are projected to worsen (Gutzler and Robbins, 2010). Second, water administration is complex and constantly evolving. Colorado is experiencing increasing water demands for a variety of diverse uses, and the application of water law changes continually as insufficiencies in current institutions emerge. Our findings emphasize that trends in agricultural practices are influenced by changing water supply conditions and water management institutions. Overall, this article highlights the importance of understanding the linkages between individual behavior, scarcity, and water allocation institutions when designing water management strategies.

Acknowledgments

This material is based upon work supported by the National Institute for Food and Agriculture under Award No. 2018-69011-28369 and the National Science Foundation under Grant No. 1828902.

The "Pi Day" Storm of March 2021 and the Start of Drought Relief in Eastern Colorado

Dr. Russ Schumacher, Professor, Atmospheric Science, Colorado State University, Colorado State Climatologist, Colorado Climate Center

Introduction

For much of northern Colorado, March is the snowiest month of the year on average, but it can also be hit or miss. The epic snowstorm of March 2003 (see Wesley et al. 2003; nwafiles.nwas.org/jom/articles/2013/2013-JOM4/2013-JOM4.pdf) and the 'bomb cyclone' of March 2019 (see ncdc.noaa.gov/monitoring-content/extremes/scec/reports/20200508-Colorado-Mean-Sea-Level-Pressure.pdf) is still discussed by many residents of the Front Range, but several Marches in the 2010s had very little snowfall. Coming into March of 2021, Colorado had been experiencing a significant drought originating from the extremely hot and dry summer of 2020, and seasonal outlooks pointed to continued warm and dry conditions across the state.

But the situation for eastern Colorado started to turn in mid-March, as a major storm brought heavy snow to the Front Range and substantial rain to the eastern plains. This storm, nicknamed the "Pi Day" storm because it caused most of its impacts on March 14 (3.14), kicked off a wet spring for eastern Colorado that alleviated drought conditions. Unfortunately, extreme drought persisted in western Colorado, as these storms did not bring much moisture west of the Continental Divide. This article will summarize the Pi Day storm and its role in drought relief in eastern Colorado.

"Pi Day" snow drifts in Weld County, Colorado. Photo by Emmett Jordan.

COLORADO CLIMATE CENTER

The Meteorology

The March 2021 snowstorm was associated with a region of low pressure at the middle and upper levels of the troposphere that developed near the area known as the "Four Corners" and then intensified as it moved eastward across southern Colorado. On the morning of March 14, this low pressure center was located over southeast Colorado at 700 hPa (around 1,500 m or 4,900 feet above ground, Figure 1a), with strong easterly upslope winds extending over a deep layer. At the surface, the low pressure was centered in eastern Colorado (Figure 1b). Strong low pressure systems centered over southeast Colorado are ideal for producing high snowfall amounts over the northern Front Range. Owing to the earth's rotation, air flows counterclockwise around low pressure systems in the Northern Hemisphere. This brings moisture-rich air from the Gulf of Mexico to Colorado. As the air is lifted over Colorado's high terrain, it cools and condenses, bringing rain or snow. This atmospheric pressure pattern is seen in many of the largest Front Range snowstorms.

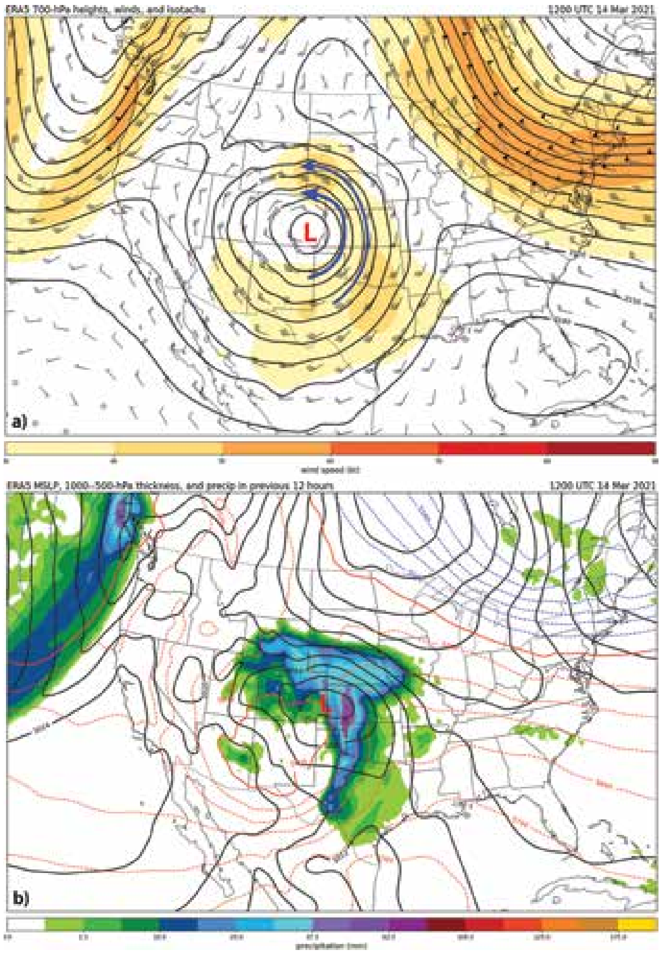

Figure 1: (a) Geopotential height (m, contours), wind barbs (knots), and wind speeds (color shading in knots) at 700 hPa and (b) mean sea level pressure (hPa), 1,000--500-hPa thickness (m), and precipitation in the previous 12 hours (mm) from the ERA5 analysis at 1200 UTC (6:00 am MDT) on March 14, 2021.

Snow began to fall on the afternoon of Saturday, March 13, but at lower elevations, it remained too warm for much accumulation. This led to many complaints toward meteorologists on social media, suggesting that the storm may end up being an over-hyped dud. But forecasters knew the event was far from over. Overnight on the 13th and through the day on the 14th, extremely heavy snow fell in the urban corridor and foothills, with snowfall rates of 2-3" per hour in many locations. Meanwhile, on the eastern plains, it remained too warm for snow, but unusually heavy rain for March fell across many drought-stricken areas.

In total, from March 13 to 15, over 4 feet of snow fell in the foothills west of Fort Collins, with the urban corridor from Fort Collins south through Denver and the Palmer Divide generally receiving 12-30" (Figure 2a). This snow contained over an inch of liquid precipitation across the region, with some parts of the northern Front Range reporting over 4" of liquid. On the far eastern plains, there was a broad band of 2-3" of rainfall (Figure 2b).

One notable aspect of the Pi Day storm was the indication about a week in advance that a significant and potentially historic storm was on the way. As early as March 8, meteorologists were already marveling at the pattern that weather forecast models were showing for the following weekend, and some models were hinting at truly extreme amounts of precipitation and snow. Some forecasts from the Global Forecast System (GFS) model showed snowfall totals well beyond any historical precedent, such as storm totals near 100" in the northern foothills, and in excess of 48" for the northern Front Range cities like Fort Collins and Boulder. Most meteorologists viewed these with considerable skepticism (see denverite.com/2021/03/09/how-much-should-you-be-freaking-out-about-the-weekends-snowstorm/). The details came into clearer focus as the storm neared, with the National Weather Service (NWS) consistently predicting over 18" for the Front Range beginning on March 10 and issuing a Winter Storm Warning on March 11. As noted above, the slow start to the snow accumulation on March 13 led some to think that these forecasts were overblown, but in the end, they were largely accurate (see twitter.com/ClimateBecky/status/1371625706472415234?s=20).

How Did this Storm Compare to Past Major Snowstorms?

The snowfall totals from the March 2021 storm were impressive by any measure, though they did not end up breaking too many records in Colorado. At Denver International Airport, the storm total was 27.1" of snow, which was the 4th largest snowstorm in Denver's long-term record. However, Denver's official record includes data from stations in several locations that are not particularly close to one another. If considering data from Central Park (formerly Stapleton), with a consistent record back to 1948, the 18.4" from the Pi Day 2021 storm ranks in 9th place. The Fort Collins weather station on the Colorado State University

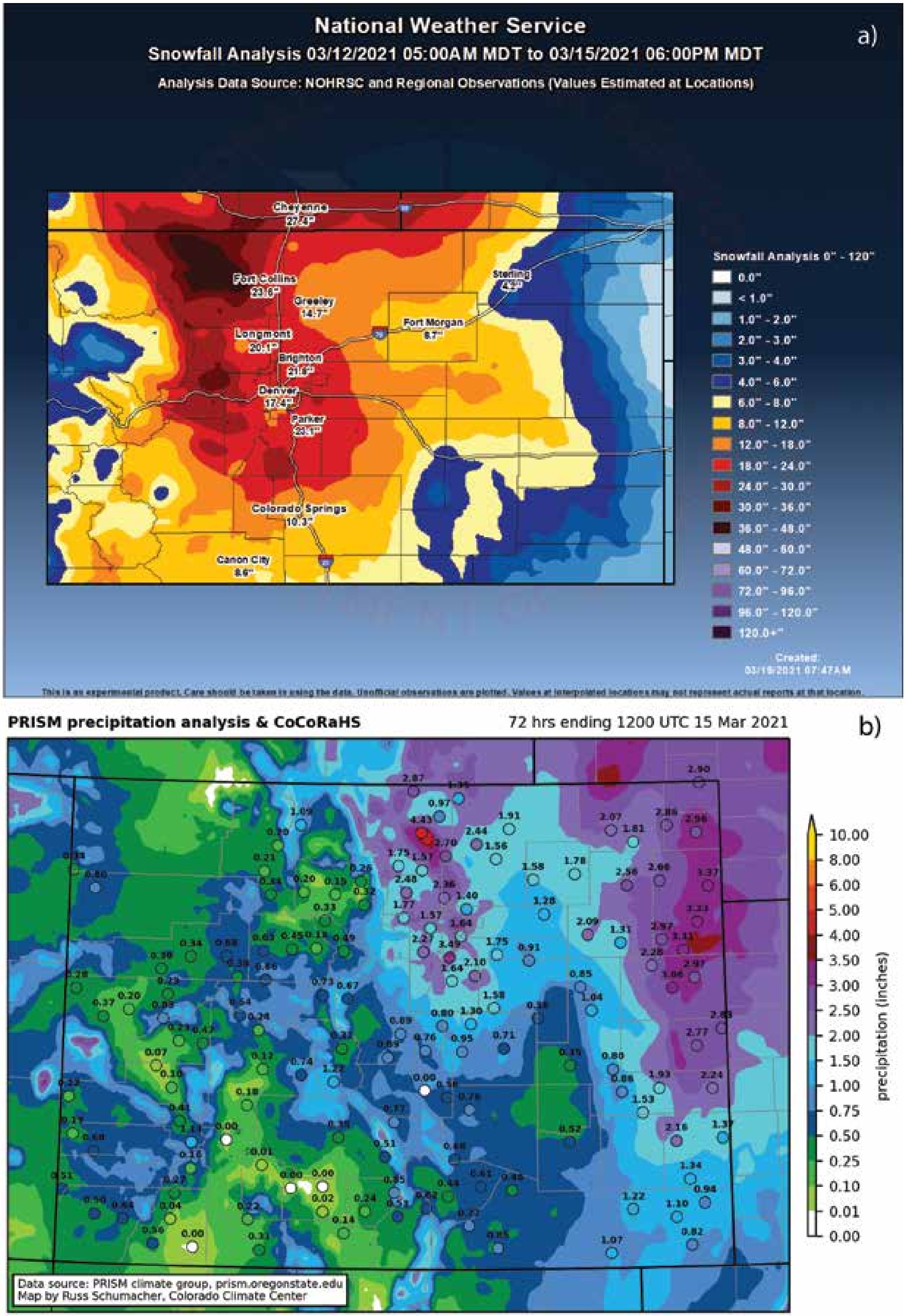

Figure 2: (a) Snowfall analysis for the period from 5:00 am MDT on March 12, 2021 to 6:00 am MDT March 15, 2021. Obtained from the National Weather Service at weather.gov/bou/March13_14_2021Storm; and (b) precipitation analysis from the PRISM climate group (prism.oregonstate.edu) and select CoCoRaHS observations for the 72-h period ending at 1200 UTC (6: 00 am MDT) on March 15, 2021.

…we will have to wait and see whether eastern Colorado can remain drought-free for long.

(CSU) campus recorded a storm total of 19.5", which is tied for the 11th biggest snowstorm on record. Some locations on the west side of Fort Collins recorded substantially more snow than campus did. One location that did break records during the Pi Day storm was Cheyenne, Wyoming. The 22.7" that piled up on March 14 in Cheyenne was the most ever for a single day, and the total of 33.7" from March 10-14 smashed the previous record for a snowstorm of 25.6".

Rainfall totals on the eastern plains were also impressive. On March 14, Burlington, Sedgwick, Holyoke, Idalia, and Yuma all recorded their rainiest March day on record, with between 2-3" of rain falling at all of these stations.

Drought Relief

In the places that received the most precipitation from the Pi Day storm, like the northern Front Range and the eastern plains, this single storm brought drought relief, with widespread improvements of 1-2 categories on the U.S. Drought Monitor in a single week. Furthermore, this was the first of a string of upslope storms during spring 2021. These additional storms throughout April and May, some bringing snow and others steady rain, resulted in spring precipitation that was much above normal (Figure 3) and the elimination of drought in the eastern half of Colorado (Figure 4). Unfortunately, the nature of these spring storms, in which moisture from the Gulf of Mexico is transported northward and westward and rises along the east slopes of the Rocky Mountains, left western Colorado in the “rain shadow” and provided no real improvement in the severe drought conditions in that half of the state (Figure 4).

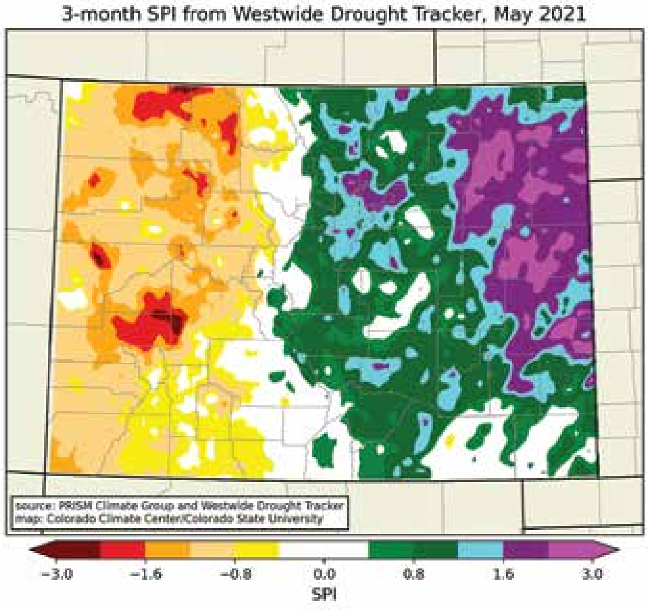

Figure 3: Standardized precipitation index for March-April-May 2021 in Colorado. Positive values indicate above-normal precipitation; negative values below normal. Data obtained from the Westwide Drought Tracker based on data from the PRISM climate group.

For significant drought relief to occur in western Colorado, a return of a wet summer monsoon season (which has been non-existent for the last three years) will be needed, along with above-average snowfall in the mountains in upcoming winters. And with a hot start to the summer underway and outlooks pointing toward continued warm and dry conditions, we will have to wait and see whether eastern Colorado can remain drought-free for long.

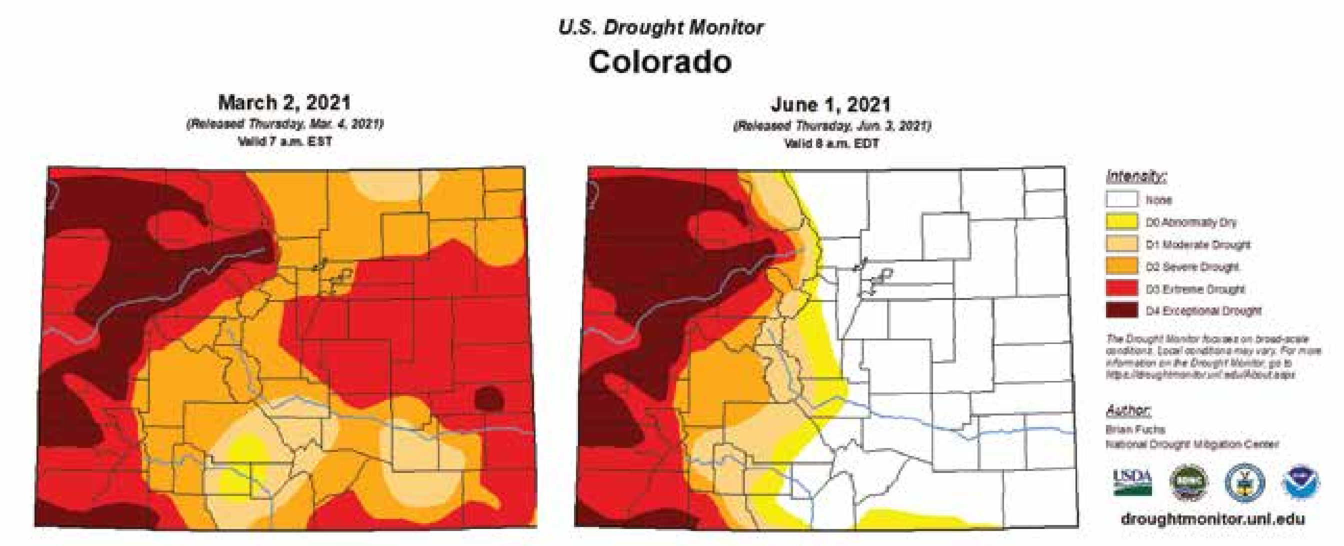

Figure 4: Comparison of the U.S. Drought Monitor in March 2, 2021 (left) and June 1, 2021 (right), illustrating the elimination of drought in eastern Colorado as a result of multiple spring storms. Obtained from droughtmonitor.unl.edu/.

Andrea Hanson Rhoades

Research Scientist II, Civil and Environmental Engineering, Center for
Contaminant Hydrology, Colorado State University

Andrea Hanson Rhoades

The intrinsic value of environmental conservation and stewardship was instilled in me from a young age, being born and raised in a rural North Dakota multi-generational cattle country. My deeply rooted commitment to the environment was a natural segue to pursue a profession that seeks to protect our natural world and repair it when necessary. Through multiple opportunities, I have found a niche at Colorado State University at the Center for Contaminant Hydrology (CCH) housed within the Department of Civil and Environmental Engineering. Here, my research employs microbiology, molecular biology, multi-omics approaches, and analytical instrumentation to characterize microbial communities and contaminant environments in engineered and natural systems to inform remedial action design, implementation, and monitoring.

Since joining the CCH in the summer of 2018, I have been involved in several groundwater research projects primarily aimed at remediation. My initial work focused on the electrochemical treatment of groundwater contaminated with perchlorate, a compound primarily used as an ingredient in explosives that may interfere with normal thyroid functioning when ingested. We used mesh electrodes to generate food for microbes to stimulate the biological reduction of perchlorate. Like other electrochemical-based treatment technologies being developed in our group, our results showed promise as a sustainable groundwater treatment technology.

We have several active field sites where pilot-scale tests are being conducted. I am heavily involved in a pilot test addressing substituted aromatic compounds via biosparging or the introduction of oxygen to the subsurface to stimulate the biodegradation of these compounds' naturally occurring bacteria. At this site, we also installed multi-level sampling devices equipped with continuous, real-time sensors that monitor select subsurface parameters. Our preliminary biosparing results have been exciting, plus we have gained unprecedented insights from the modern Internet of Things (IoT) sensor data. In support of this project, I also developed molecular tools for advanced bioprocess performance monitoring, which is one of my primary research interests. I also support two other pilot-scale tests in different parts of the U.S., both of which utilize treatment trains to enhance contaminant removal, namely, one,4-dioxane and per- and polyfluoroalkyl substances (PFAS). PFAS pose several challenges as emerging contaminants, therefore, are a major research topic of mine. I support a variety of PFAS projects, primarily through developing analytical pipelines, as the identification and quantification of PFAS is not trivial. We are also developing destructive treatment technologies for PFAS, such as electrochemical oxidation.

Lastly, building on my work as a postdoctoral research scientist, I support research into the beneficial reuse of produced water generated as a wastewater stream by the oil and gas industry. Working with multiple collaborators, my focus has been on developing analytical capabilities and high-resolution mass spectrometry pipelines to pinpoint the chemicals in produced water that cause challenges during treatment for reuse, such as membrane distillation.

In addition to active research projects, I support the daily operation of our CCH lab. We house several analytical instruments, such as a gas chromatograph with a mass spectrometer and ion chromatograph and maintain a large experimental space. I also mentor students and assist our faculty and research personnel. With multiple field tests, students, and ongoing projects, there is never a dull moment!

The cornerstone of our research at the CCH is collaboration. Our group thrives on several inter-campus and external collaborations ranging from other universities in the U.S. and abroad to engineering firms and chemical companies. These working relationships form the foundation of our overarching goal of leading the way to new frontiers in sustainable groundwater remediation, performance monitoring, and developing solutions for emerging contaminants.

Andrea Hanson Rhoades
Research Scientist II
Civil and Environmental
Engineering, Center for
Contaminant Hydrology
Colorado State University
andrea.hanson@colostate.edu

Water Research Awards 2/22-6/4 2021

Anderson, Jennie Adale, Center for Environmental Management Military Lands, U.S. Department of Agriculture, U.S. Forest Service-Rocky Mountain Research Station, Colorado. Ecological Surveys, Waters of the U.S. Mapping and Jurisdictional Determination at Hanscom Airforce Base (HAFB). $166,323

Arabi, Mazdak, Civil and Environmental Engineering. Colorado Department of Public Health and Environment. Colorado Stormwater Control Measures-Training, Education, and Community Outreach. $50,000

Arabi, Mazdak, Civil and Environmental Engineering, Colorado Department of Public Health and Environment. eRAMS Tools for CDPHE-WQCD. $149,53

Arabi, Mazdak, Civil and Environmental Engineering, ESSA Technologies, Ltd. Missouri River Recovery Management Plan Adaptive Management Decision Support System. $450,000

Arabi, Mazdak, Civil and Environmental Engineering, U.S. Department of Agriculture, Agricultural Research Service. Modeling Ecosystem Services in Agricultural Watersheds. $52,211

Bagley, Calvin F., Center for Environmental Management Military Lands, Department of Defense, Army Corps of Engineers Alaska. Natural Resource Support, Hemlock and Wetlands, JBER Alaska. $52,465

Bailey, Ryan T., Civil and Environmental Engineering, Texas A&M University, BLM-NOC, Enhancement of APEX Model for Simulating Soil Erosion and Salt Transport in the Colorado River Basin. $75,000

Barnes, Elizabeth Adrianne, Cooperative Institute for Research in the Atmosphere, Department of Commerce, National Oceanic and Atmospheric Administration. MJO and QB) Contributions to U.S. Precipitation Skill at S2S Leads. $174,474

Bayham, Jude, Agricultural and Resource Economics, University of Idaho. Agricultural Practices and Policies: Particulate Matter and Rural Health. $29,442

Burkhardt, Jesse Brodie, Agricultural and Resource Economics, Lynker Technologies. Developing Multi-Sector Drought Impact Models for the Intermountain West DEWS: Towards an Impact- and Data-Driven Approach for Drought Management. $31,541

Chen, Haonan, Cooperative Institute for Research in the Atmosphere, Department of Commerce, National Oceanic and Atmospheric Administration. Hydrometeorological and Water Resources Research. $44,960

Forsythe, John M., Cooperative Institute for Research in the Atmosphere, Department of Commerce, National Oceanic and Atmospheric Administration. CIRA Support to ATMS Precipitable Water Algorithms and Products (MIRS). $55,351

Gallen, Sean F., Geosciences, National Science Foundations, Geosciences. CAREER: Data-Driven Inversion of Subduction Zone Topography Using Tectonic Geomorphology. $199,279

Greenwell, Amy, E., Colorado Natural Heritage Program. Department of the Interior, Bureau of Reclamation. CESU-CP: Development of a Centralized PIT Tag Database for the San Juan and Upper Basin Recovery Programs 2020-2024. $48,199

Hall, Ed K., Natural Resource Ecology Laboratory, National Science Foundation. RAPID: Impact of Hurricanes ETA and IOTA on Lake Yojoa. $188,597

Ham, Jay M., Soil and Crop Sciences, Western Sugar Cooperative. Monitoring Edge-of-Field (EOF) Water Quality in Surface-Irrigated Sugarbeets: Identifying BMPs for Reducing Nutrient Runoff. $14,100

Hooten, Mevin, B., Cooperative Fish and Wildlife Research, Department of the Interior, U.S. Geological Survey. RWO123 Modeling Brook Trout Population Responses to Climate Variation in the Southeast USA. $181,294

Ippolito, Jim, Soil and Crop Sciences, U.S. Department of Agriculture, Agricultural Research Service. Understanding Soil and Environmental Effects on Crop Species and Rangeland Ecosystems Under Water Limitation, Water Quality, Soil Health, and Regenerative Agriculture: A Nexus for Sustainability. $88,465

Julien, Pierre Y., Civil and Environmental Engineering, Department of the Interior, Bureau of Reclamation. Linking Morpho-Dynamic and Biological-Habitat Conditions on the Middle Rio Grande. $278,956

Kanno, Yoichiro, Fish, Wildlife and Conservation Biology, Audubon Society of Greater Denver. Experimental Test of Condition-Specific Competition Between Native Plains Topminnow and Non-Native Mosquitofish. $3,000

Water Research Awards 2/22-6/4 2021

Keys, Patrick W., School of Global Environmental Sustainability, National Aeronautics and Space Administration. Research Proposal Type A-Cross-Scale Impacts of SDG15-Achievement: Household Decisions, Ecosystem Change, and Atmospheric Water Recycling. $215,742

Kummerow, Christian D., Atmospheric Science, National Aeronautics and Space Administration, Understanding GMI Observations in Orographic Precipitation Rain and Snow. $151,654

Lemly, Joanna, Colorado Natural Heritage Program, Colorado Department of Public Health and Environment. Colorado National Wetland Condition Assessment (CO NWCA). $92,000

Lemly, Joanna, Colorado Natural Heritage Program, University of Montana. 2021 BLM Western Rivers and Streams Assessment (WRSA). $72,037

Lemly, Joanna, Colorado Natural Heritage Program, University of Montana. 2021 BLM Wyoming Aquatic AIM Sampling. $215,140

Lemly, Joanna, Colorado Natural Heritage Program, University of Montana. 2021 BLM Utah Aquatic AIM Sampling. $266,283

Levinger, Nancy E., Chemistry, National Science Foundation. Collaborative Research: Unraveling Interactions that Drive Water-Osmolyte Interactions in Confinement and Impact Self-Assembly. $51,202

Liston, Glen E., Cooperative Institute for Research in the Atmosphere, University of Colorado. Bridging the Snow: Sea Ice Gap: A Snow on Sea Ice Assimilation System for the Arctic. $32,987

Myrick, Christopher A., Fish, Wildlife and Conservation Biology, Department of the Interior, U.S. Fish and Wildlife Service. CESU-RM: Developing Rock Ramp Fishway Design Parameters for Fish Species of Conservation Concern. $222,554

Osborn, Blake Justin, Colorado State University Extension, Colorado Department of Public Health and Environment. Nonpoint Source Program Project Implementation Plan (PIP) Template for Post-Wildfire Implementation Projects. $99,569

Preston, Daniel. Fish, Wildlife, and Conservation Biology, Wisconsin Department of Natural Resource. Effects of New Zealand Mud Snails on Wisconsin Stream Food Webs. $185,951

Randall, David A., Atmospheric Science, Department of Commerce, National Oceanic and Atmospheric Administration, S2S Forecasting of North American Precipitation Anomalies: Using Empirical Forecasts to Challenge Dynamical Forecasts. $213,345

Ross, Matthew Richard Voss, Ecosystem Science and Sustainability, University of Wyoming. Identifying, Predicting, and Managing the Occurrence of Harmful Algal Blooms in Wyoming Reservoirs. $25,236

Selby, Diana C., Colorado State Forest Service, U.S. Department of Agriculture, U.S. Forest Service Research. Pike Watershed Protection Fuels Project GNA. $5,792

Smith, Melinda Dianne, Biology, Department of the Interior, U.S. Geological Survey, CESU-RM: A Global Synthesis of Multi-Year Drought Effects on Terrestrial Ecosystem. $149,988

Sovell, John Raymond, Colorado Natural Heritage Program, Colorado Department of Public Health and Environment. Freshwater Mussels in Colorado- State of Knowledge Report. $20,082

Sueltenfuss, Jeremy, Forest and Rangeland Stewardship, Colorado Department of Transportation. Wetland Water Loss to Inform CDOT Mitigation Strategies. $99,807

Suter, Jordan, Agricultural and Resource Economics, Clemson University, Management of a Spatial Externality in an Irrigated Agricultural Region. $184,964

Thornton, Christopher I., Civil and Environmental Engineering, AECOM, Hydraulic-Model Study of the Los Vaqueros Dam Spillway and Sluice Outlet Works, California. $107,845

Wilkins, Mike James, Soil and Crop Sciences, National Science Found. New Roles for Reactive Oxygen Species in Mediating Carbon Fluxes at the Terrestrial-Aquatic Interface. $199,724

Wohl, Ellen E. Geosciences, National Science Foundation. Collaborative Research: Emergent Hydrological Properties Associated with Multiple Channel-Spanning Logjams. $39,695

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Water Calendar

December 2021

7-8 **National Groundwater Association Groundwater Summit**

Virtual

This groundwater summit will provide the opportunity for attendees to listen to conference and poster sessions, along with workshops and attended learning sessions. Emphasis will be on groundwater remediation, aquifer recharge, geophysical imaging techniques, and other groundwater-related content.

pheedloop.com/Summit2021/site/home/

9 **South Platte Forum**

Westminster, CO

This conference will provide the opportunity for individuals to discuss and learn about issues relevant to the South Platte River Basin.

southplatteforum.org/

9-10 **Colorado Agriculture Water Summit**

Winter Park, CO

Join farmers, ranchers, and water managers around the state to discuss water issues impacting the agricultural community.

coagwater.org/summit

13-17 **American Geophysical Union Fall Meeting**

New Orleans, LA and Virtual

This fall meeting will be an opportunity for Earth and space scientists, students, and those in affiliated fields to share key scientific research and identify innovative solutions. This year there will be in-person and virtual opportunities to attend and network.

agu.org/Fall-Meeting

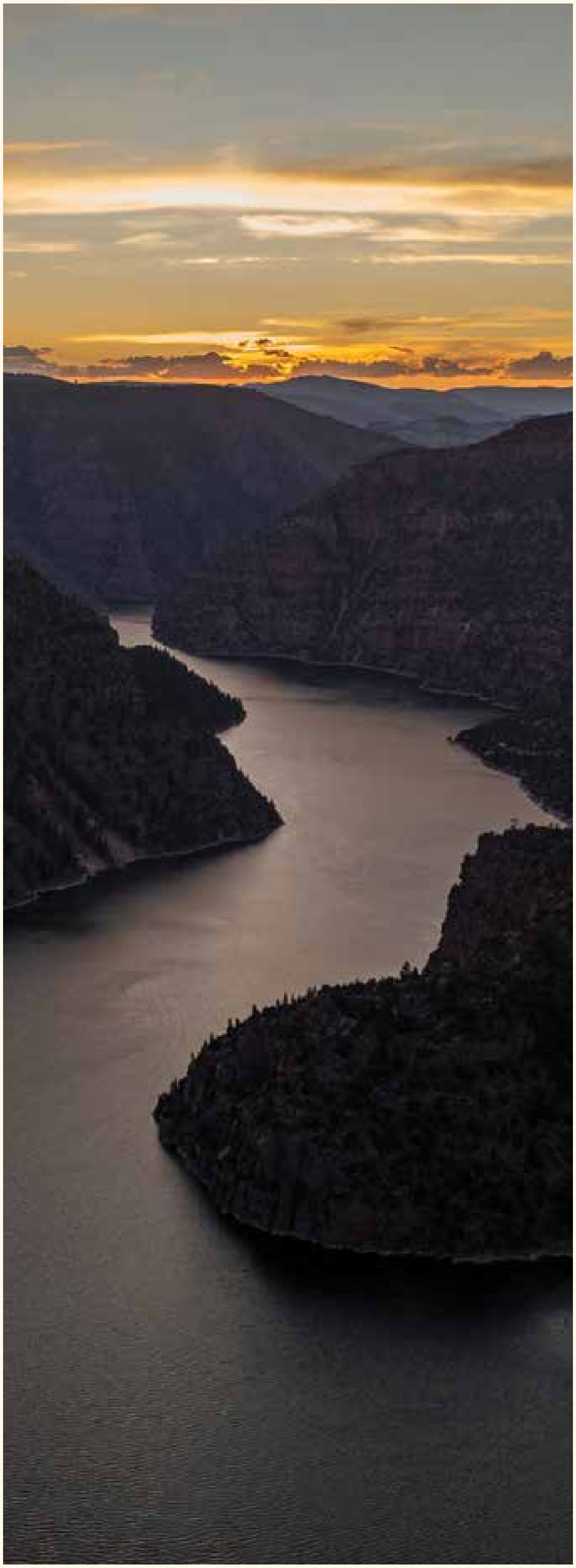
April 2022

25-27 **American Geophysical Union Hydrology Days**

Fort Collins, CO

This conference provides the opportunity for students, faculty, and practitioners to engage in a wide range of water-related interdisciplinary research topics. This is a great opportunity to hear about cutting-edge research and engage with a diverse array of professionals and students.

hydrologydays.colostate.edu



Flaming Gorge Reservoir (right) as photographed from the Red Canyon Overlook in Colorado National Monument. The reservoir is located in Wyoming and Utah on the Green River, a tributary of the Colorado River. Photo by RuggyBearLA/Wikimedia Commons.

USGS Recent Publications

Data Releases

Assessment of dissolved-selenium concentrations and loads in the lower Gunnison River Basin, Colorado, as part of the Selenium Management Program; 2021, U.S. Geological Survey data release; M.F. Henneberg
doi.org/10.5066/P92UIS8X

Elevation data from Fountain Creek between Colorado Springs and the Confluence of Fountain Creek at the Arkansas River, Colorado, 2020 (version 2.0); 2021, L.A. Hempel, A.L. Creighton, and Z.D. Kisfalusi
doi.org/10.5066/P98J7DRO

Geochemical data from batch experiments to test mobility of trace elements downgradient from breccia-pipe uranium deposits; 2021, U.S. Geological Survey data release; C.R. Bern, K.M., Campbell, K. Walton-Day, and G.L. Keith
doi.org/10.5066/P9VILVZY

Input and output data from streamflow and water-quality regression models used to characterize streamflow and water-quality conditions in the Upper Yampa River Basin, Colorado from 1992 to 2018; 2021, U.S. Geological Survey data release; N.K. Day
doi.org/10.5066/P9L7S3NQ

Near-surface geophysical data collected along French Gulch near Breckenridge, Colorado, USA, September 2020; 2021, U.S. Geological Survey data release; H.F. Malenda, N.C. Terry, and S. Paschke
doi.org/10.5066/P9LZN192

Orthoimagery, digital elevation, digital terrain, final surface, and vegetation classification models for four stream catchments in western Colorado 2016; 2021, U.S. Geological Survey data release; T.M. Preston, N.K. Day, J.D. Adams, and C.L. Holmquist-Johnson
doi.org/10.5066/P91KRAAD

Journal Articles

Water-quality change following remediation using structural bulkheads in abandoned draining mines, upper Arkansas River and upper Animas River, Colorado USA; 2021, Applied Geochemistry 127; K. Walton-Day, M.A. Mast, R.L. Runkel
doi.org/10.1016/j.apgeochem.2021.104872

Natural and anthropogenic geochemical tracers to investigate residence times and groundwater-surface-water interactions in an urban alluvial aquifer; 2021, Water 13(6), C.P. Newman, S.S. Paschke, G. Keith
doi.org/10.3390/w13060871

U.S. Geological Survey Scientific Investigations Reports and Maps

Characterization of water-resource threats and needs for U.S. Fish and Wildlife Service National Wildlife Refuges in the Legacy Mountain-Prairie Region, 2020; 2021, U.S. Geological Survey Open-File Report 2021-1007, 46, N.J. Bauch, M.S. Kohn, B.S. Caruso
doi.org/10.3133/ofr20211007

This view shows the confluence of the Green and Yampa rivers at the base of Steamboat Rock in Echo Park, Moffat County, Colorado. Photo courtesy of the National Park Service.

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Changing Climate, Changing Institutions: Implications of Drought and Litigation for Colorado Agriculture

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The Timing of Peak Streamflow in a Small River Versus Snowpack Melt-Out

Maryam Sahaar, Undergraduate Student, Watershed Science, Colorado State University; **Dr. Steven Fassnacht,** Professor, Watershed Science, Colorado State University

Doskocil, L.G., Fassnacht, S.R., & Derry, J.E. (2021). Mystery peaks: estimating the unusual double peak streamflow behavior in the Uncompahgre River Basin. *Colorado Water*, 38(2).

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A Review on State of 'One Water' in Different Cities Across the World

Donya Dezfooli, Doctoral Student and **Dr. Mazdak Arabi**, Professor, Civil and Environmental Engineering, Colorado State University

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Does It Get Cooler Going Down the Hill? Measuring Hillslope-Scale Temperature Gradients

Davis Rice, Undergraduate Student, Ecosystem Science and Sustainability, Colorado State University; **Dr. Steven Fassnacht**, Professor, Watershed Science, Colorado State University

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Analysis of Uncertainty in Hydrometeorological Ensemble Forecasts

Carolien Mossel, Masters Student, Earth and Atmospheric Science, The City College of New York; National Oceanic and Atmospheric Administration, Center for Earth System Science and Remote Sensing Technologies

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Mystery Peaks: Estimating Double Peak Streamflow Behavior in the Uncompahgre River Basin

Lenka G.Doskocil, Undergraduate Student and Research Assistant, and **Dr. Steven Fassnacht,** Professor, Watershed Science, Colorado State University; **Jeffrey E. Derry,** Executive Director, Center for Snow and Avalanche Studies

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Exploring the Connection Between Heavy Rainfall and Embedded Rotation in Tropical Storm Imelda (2019)

Allie Mazurek, Masters Student, Atmospheric Science, Colorado State University; **Dr. Russ Schumacher**, Professor, Atmospheric Science, Colorado State University, Colorado State Climatologist, Colorado Climate Center and **Dr. Erik Nielsen**, Assistant Professor, Atmospheric Sciences, Texas A&M University

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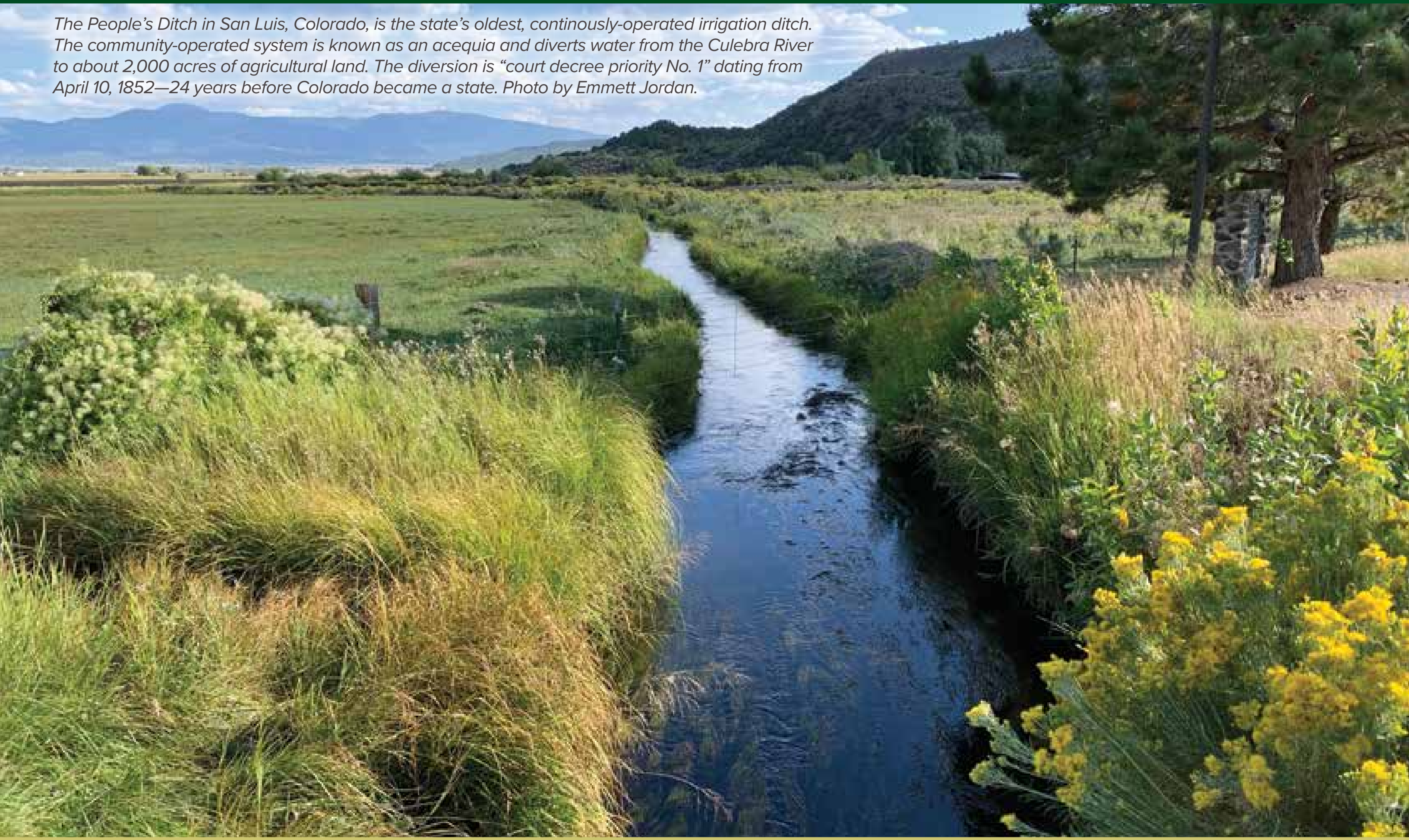

The People's Ditch in San Luis, Colorado, is the state's oldest, continously-operated irrigation ditch. The community-operated system is known as an acequia and diverts water from the Culebra River to about 2,000 acres of agricultural land. The diversion is "court decree priority No. 1" dating from April 10, 1852—24 years before Colorado became a state. Photo by Emmett Jordan.