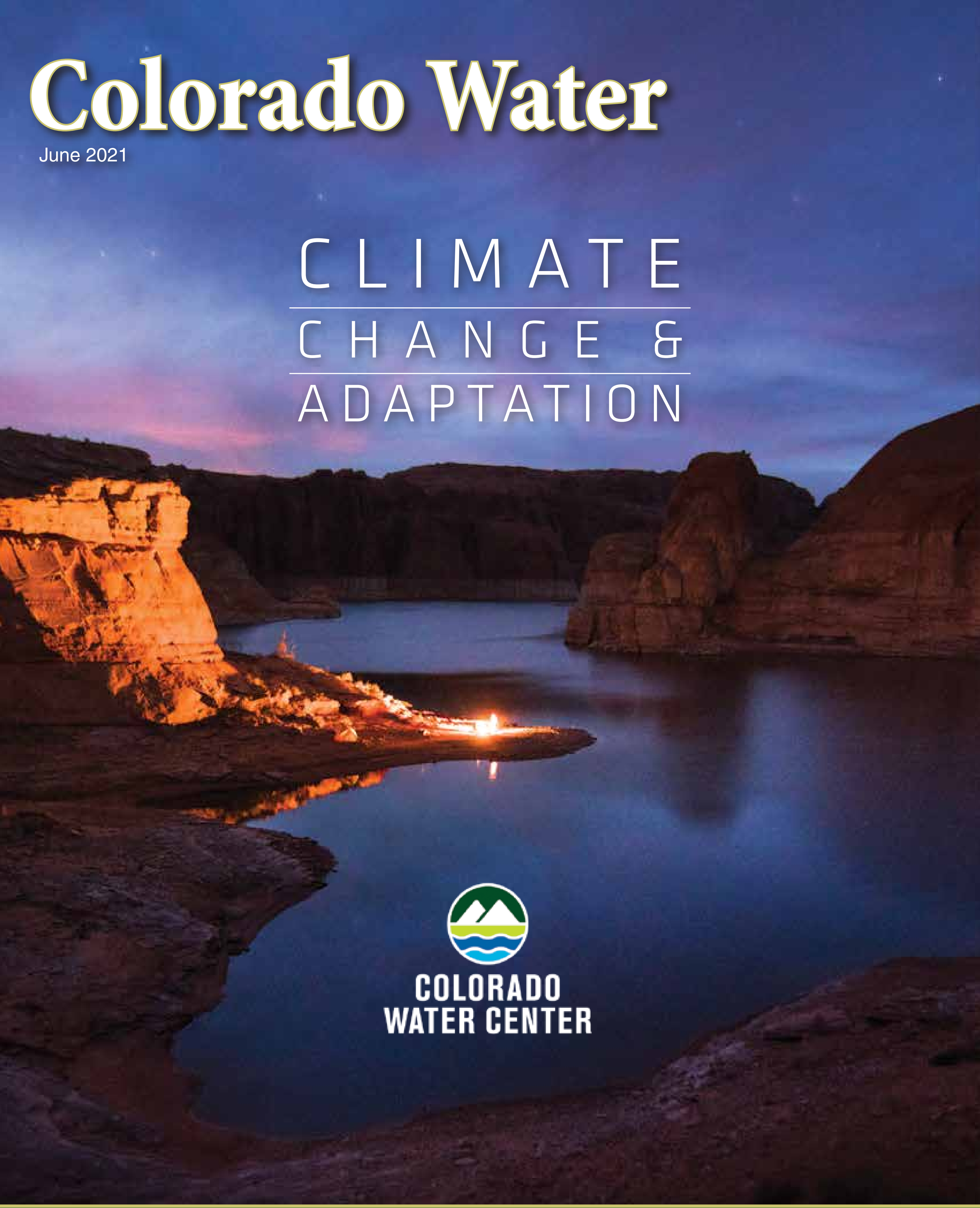
Colorado Water

June 2021



CLIMATE CHANGE & ADAPTATION

COLORADO WATER CENTER

COLORADO STATE UNIVERSITY

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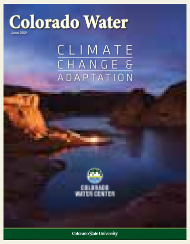

References can be found in the online version of this newsletter at watercenter.colostate.edu/water-news

On the cover— A campfire on the shore of Lake Powell pictured at night. ©iStock.com.

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

COLORADO **WATER**

Volume 38, Issue 1

Colorado Water is a publication of the Colorado Water Center. The newsletter is devoted to highlighting water research and activities at CSU and throughout Colorado.

Colorado Water. (2021). Colorado Water Center, Colorado State University

Published by
Colorado Water Center
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Supported by
This publication is financed in part by the U.S. Department of the Interior Geological Survey, through the Colorado Water Center and CSU's College of Agriculture, Warner College of Natural Resources, Agricultural Experiment Station, and Extension.

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Director's LETTER

Jennifer Gimbel, JD

Welcome to our Spring edition of the Colorado Water Center (CoWC) newsletter focused on climate change and adaptation. It has been over five years since we focused on climate change and adaptation. Scientists have continued to research and study climate change and its effects. Thanks to the CoWC's own Brad Udall and his colleagues for all their work and for sharing that information in this newsletter.

In December's edition Dr. Reagan Waskom, former Director of the CoWC, eloquently talked about his 34 years at Colorado State University (CSU), including 20 years at the CoWC. He spearheaded the research, education, and outreach of water sustainability and created a "safe" environment for discussions on many contentious issues in academia, Colorado, and the western water world. I personally respected Reagan for his kindness, thoughtfulness, insight, and ability to lead difficult conversations by speaking softly and making quiet suggestions. Most of our readers interacted with Reagan in his many years of service. One aspect that has not been shared is what Reagan meant to the people who worked for him, or as he would say with him.

"The thing about Reagan is that he was a kind person, above all else. He inspired me perhaps the most by showing that a person with great intellect and authority can also nurture positive relationships at every level, from undergraduate students all the way to the highest levels of state government. There are many other things to admire about Reagan, such as his tireless work to improve the Colorado Water Center, his encyclopedic knowledge of water literature, and his enthusiasm for all forms of water research, he inspired me the most through his humility. His career will be defined by countless successes and achievements, but I believe that the larger legacy he leaves behind is the standard he set for courtesy and respect, whether things were collegial or controversial. He never wavered from his belief that positive relationships are the foundation for a successful and happy career."

—Perry Cabot,
Research Scientist and Extension Specialist

"The thing Reagan taught me most was to be unwaveringly committed to the objective truth. He was very good at cutting through the fray and getting to the heart of a matter to analyze the facts in an objective and unbiased way. And Reagan was fiercely committed to the facts."

—Blake Osborne,
Water Resources Specialist-Southern Region

"Reagan was always a trusted source to throw ideas and thoughts at and always gave you great responses back as well as items to think about. If Reagan knew issues were coming forward, he always made sure you were in the loop, so there weren't any surprises coming at you."

—Joel Schneekloth,
Water Resource Specialist-Northern Region.

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Horsetooth Reservoir, ©iStock.com

"It's challenging to summarize the influence Reagan's leadership and mentorship had on both my professional and personal growth in only a few sentences. Reagan provided invaluable support and inspiration throughout my graduate studies and our work at CoWC. Like many others, I am the beneficiary of Reagan's many talents, including his ability to impart his vast water knowledge and shape the next generation of water professionals. I am blessed to have worked with one of our community's most respected and committed public servants."

—Julie Kallenberger,
Associate Director

"I really valued and respected that no matter how busy Reagan Waskom's schedule was, he always made time to meet with faculty, students, and the public. He was happy to mentor students and new faculty, and he enjoyed watching them develop their education and research careers."

—Nancy Grice,
Assistant to the Director

"As I reflect on the days when Reagan was my advisor, I realize how crucial his guidance impacted and empowered my growth as a scientist and as a person. Reagan is a generous mentor, passionate to share his knowledge, and was always willing to share his valuable insights for building a successful career. I am grateful for his continued support."

—Panagiotis (Takis) Oikonomou,
Colorado Water Center Affiliate and
Former Civil and Environmental
Engineering Post-Doctoral Researcher

"What was so valuable for me, working with Reagan, is that not only is he an extraordinary listener, he has a holistic perspective to bring to whatever issue is at hand. Rather than jump to easy answers, he was willing to spend some time with me, probing, looking for underlying factors, historical significance, and societal implications. I miss having his perspective—and his wisdom."

—MaryLou Smith,
Former Water Policy and Collaboration Specialist

Reagan's legacy can be found in every aspect of CoWC: students, employees, academia, water users, western water discussions, and finally, in his vision of a new Western Water Policy Institute to be part of the SPUR campus in Denver. Thank you, Reagan. Your influence has given CoWC a solid foundation to move forward.

Jennifer Gimbel, JD

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

How is Climate Change Impacting Colorado River Flow?

Brad Udall, Climate Scientist and Scholar, Colorado Water Center
Dr. Jonathan Overpeck, Samuel A. Graham Dean and Collegiate Professor, School of Environment and Sustainability, University of Michigan

Since the 1970s, scientists have been interested in how runoff in the Colorado River Basin (CR Basin) would change as the climate warms. Many of these studies strongly suggested that the Colorado River (CR) would lose flow with warming, but in the last few years, scientists have been able to analyze a declining 22-year flow record, the ongoing 2000-2021 "Millennium Drought". Multiple studies since 2016 have now found human fingerprints on the nearly 20% loss in flow since 2000 and attribute up to half of that loss to the approximately 1.2°C or more warming that has occurred during the last century. This article summarizes six key peer-reviewed studies related to the topic of CR flow loss. These studies have found declines in runoff efficiency, investigated the causes of flow loss, and in some cases made projections about future flow declines based on the 21st-century climate model projected temperatures.

A high-water mark or "bathtub ring" is visible at Lake Powell, the second largest reservoir on the Colorado River. The bathtub ring is white because of the leaching of minerals on previously submerged surfaces. ©iStock.com

Lake Granby stores Colorado River water and is the largest storage reservoir in the Colorado-Big Thompson Project and the second largest water body in Colorado. Water is pumped from Lake Granby via the Farr Pump Plant to the Granby Pump Canal, where it flows to Shadow Mountain Reservoir through a connecting channel to Grand Lake and into the West Portal of the Alva B. Adams Tunnel on its way to users on the east side of the Continental Divide. ©iStock.com

In 2016, Connie Woodhouse of the University of Arizona published "Increasing Influence of Air Temperatures on upper Colorado Streamflow" in *Geophysical Research Letters.* Woodhouse and her team found that since 1988, flows at Lees Ferry were less than expected for a given amount of winter precipitation in both high flow and low flow years. They concluded that temperature, in addition to precipitation, can be a major driver of river flow. In addition, the paper reported that warm temperatures exacerbated the modest precipitation drought (see Figure 1).

In 2017, Jonathan Overpeck and I published "The Colorado River Hot Drought and Implications for the Future" in *Water Resources Research*. We found that a lack of precipitation could not fully explain the 19% CR flow loss between 2000 and 2014. We attributed about one-third to one-half of the flow reduction to higher temperatures, approximately 1°C over the 20°C average. Using projected temperatures from climate models, we then determined that by 2050 the river could lose 20% or more, and by 2100 35% or more flow solely from temperature increases. Were these flow decreases to occur with the same precipitation that occurred from 2000-2014, flow losses

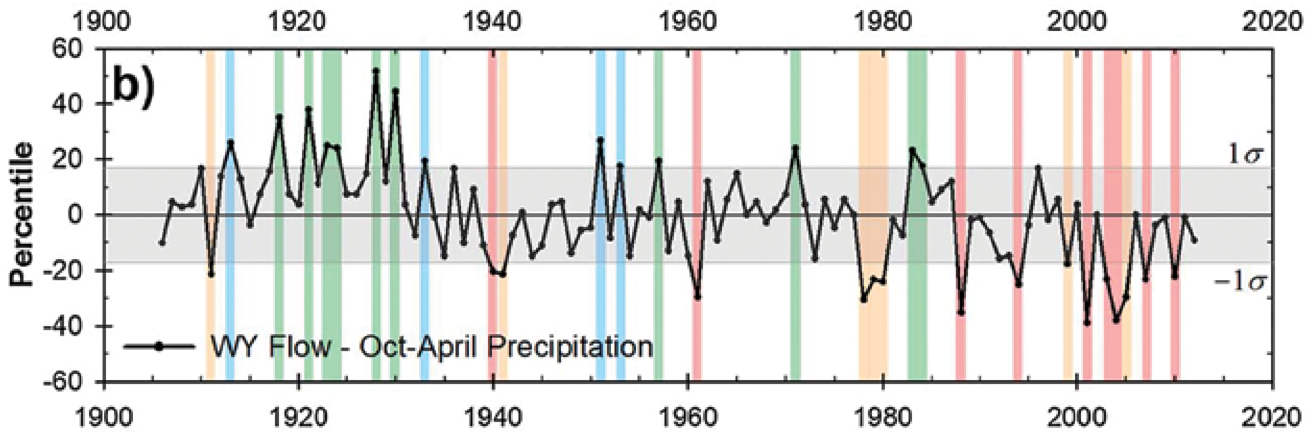

Figure 1. Declining Runoff Efficiency 1906 to 2012. The black line is the difference between the annual Colorado Lees Ferry flow minus the October to April precipitation, with both measured as percentiles. When the line is above zero, there is anomalously high runoff relative to the precipitation and when the line is less than zero there is anomalously low runoff relative to the precipitation. Years marked with green (higher than median flow) and blue (lower than median flow) represent high runoff efficiency years. Years marked with orange (higher than median flow), and pink (lower than median flow) represent low efficiency years. Note that the high efficiency years overwhelmingly occurred in the early part of the 20th century and that low efficiency years are almost always after 1988 with many clustering after 2000. Low efficiency years are characterized by higher March-July temperatures than high efficiency years. Source: Woodhouse et al. (2016).

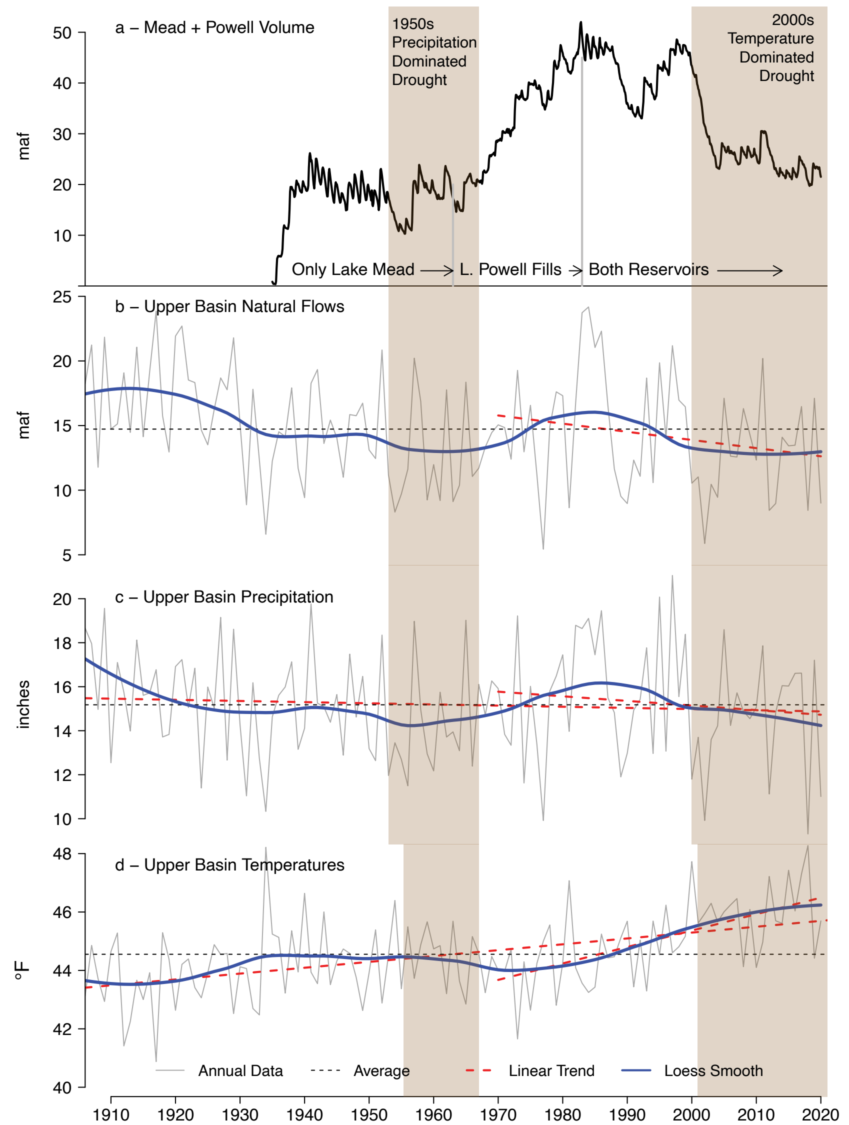

Figure 2. Critical Colorado River Basin measurements thru end of the Water Year 2020. (a). Combined Contents of Lakes Mead and Powell. (b) Upper Basin Natural Flows at Lees Ferry. (c) Upper Basin Precipitation. (d) Upper Basin Temperatures. Note that Lakes Mead and Powell have lost over half of their contents since 2000. River flows are down sharply in the ongoing Millennium Drought (since 2000). Precipitation is only down slightly, and Upper Basin temperatures are up sharply. After Udall and Overpeck (2017), but extended to end of the water year 2020.

would be 30% and 45%, respectively. Higher temperatures increase evaporation of all kinds and thus decrease water available for the river. Increases in precipitation could alleviate these losses somewhat were they to occur. However, climate models do not agree that precipitation will increase (some have increases, some decreases), and climate theory suggests that storm tracks will move northwards, diminishing precipitation in more southerly parts of the CR Basin (see Figure 2).

In 2018, the well-known University of California, Los Angeles (UCLA) Hydrologist Dennis Lettenmaier, his graduate student Mu Xiao, and I published "On the Causes of the Declining Colorado River Flows" in *Water Resources Research.* This study used a well-known hydrology model to first generate historical flows from 1916 to 2014 using historic temperature, precipitation, and wind. The model reliably generated these flows to within just a few percent of reconstructed gage flows at Lees Ferry. We then re-ran the model removing the increasing temperature trend from 1916 to 2014. In this run, the flows increased by about 10% relative to the historic run. By comparing the two runs, we concluded that approximately half of the 20% flow decline was due to warmer temperatures. The remaining 10% flow loss was due to shifting precipitation patterns from mountains to deserts.

Marty Hoerling of the National Oceanic and Atmospheric Administration (NOAA) and other authors from the University of Colorado wrote "Causes of the Century-Long Decline in Colorado River Flow" in the *Journal of Climate* in late 2019. Using a sophisticated suite of meteorological and hydrological models, this study attempted to calculate the CR temperature sensitivity—the flow loss per 1°C rise. Their temperature sensitivity estimates ranged from -2.5% to -6.5%, lower than many similar studies (e.g., Udall and Overpeck reported -3% to -10%). They found that of the approximately 20% decline in flow over the last century, about one-half (i.e., 10%) was due to human-caused climate change. They attributed about one-third of the decline (3% of flow) to higher temperatures and two-thirds of the flow loss to precipitation declines (7% of flow). This study is interesting in that it is the first study to attribute the slight decline in precipitation (~3%) to human-caused climate change. While the temperature sensitivity is lower than other studies, the attribution of precipitation declines to human causes is concerning because it implies this could continue or get worse. Additional precipitation declines combined with temperature-induced flow losses would result in significant flow declines. They did not attempt to make predictions about future changes in flows.

In March of 2020, longtime U.S. Geological Survey (USGS) Hydrologist Chris Milly and co-author Krista Dunne published "Colorado River

Flow Dwindles as Warming-Driven Loss of Reflective Snow Energizes Evaporation" in the nation's premier scientific journal, *Science*. Milly and Dunne attempted to reconcile different published temperature sensitivity estimates for the CR. Those estimates range from -2%/°C to -15%/°C. They created a high-resolution model of the river and recreated the historic flow of the river to within a few percent of the reported natural flow. Experimenting with many different model parameters, they determined that the temperature sensitivity is -9.3%/°C, among the higher sensitivities that have been calculated. Using projected temperature increases from climate models, they predicted that flows could drop by -14% to -31% at mid-century. Including temperature and precipitation projected by climate models, their estimates widened to +5% to -40%. As to be expected, increases in precipitation alleviate the losses while declines increase them. Their key insight is that as snow declines, the darker surface of the Earth heats up and drives more evapotranspiration, reducing water in the river (see Figure 3).

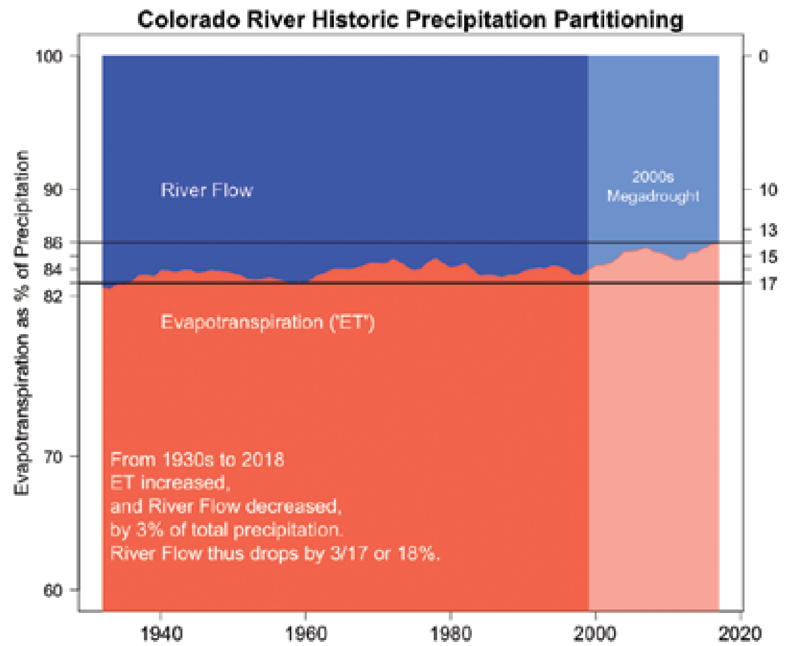

Figure 3. Small increases in evapotranspiration (all evaporation + all movement of water through plants into the atmosphere) can lead to large declines in river flow. Independent of the total annual precipitation amount, precipitation in the Colorado River each year can be broken into two components: water that leaves the Basin by (1) evapotranspiration ('ET', red) or by (2) river flow (blue). Measured as a percent of total precipitation in the Basin, evapotranspiration used approximately 83% of all precipitation in the Basin in the 1930s (left axis). River flow is the remainder, 17% (right axis). Note that numbers on the left and right axis add to 100, as they must if precipitation can only turn into either ET or river flow. By 2018, evapotranspiration increases by what seems to be small amount, 3%, to 86% of all precipitation, leaving 14% for river flow (left and right axis). Most of the increase occurs from 2000 to 2018 during the very warm Millennium Drought. As measured by the original 1930s amount, river flow is now 3/17 (18%) less than the original amount. Seemingly small increases in evapotranspiration (3%) can lead to large declines in river flow (18%). Data from Milly and Dunne (2020).

The Colorado River, as photographed from the Desert View viewpoint in Grand Canyon National Park, drains a 246,000 square-mile basin that includes parts of seven U.S. and two Mexican states. ©iStock.com

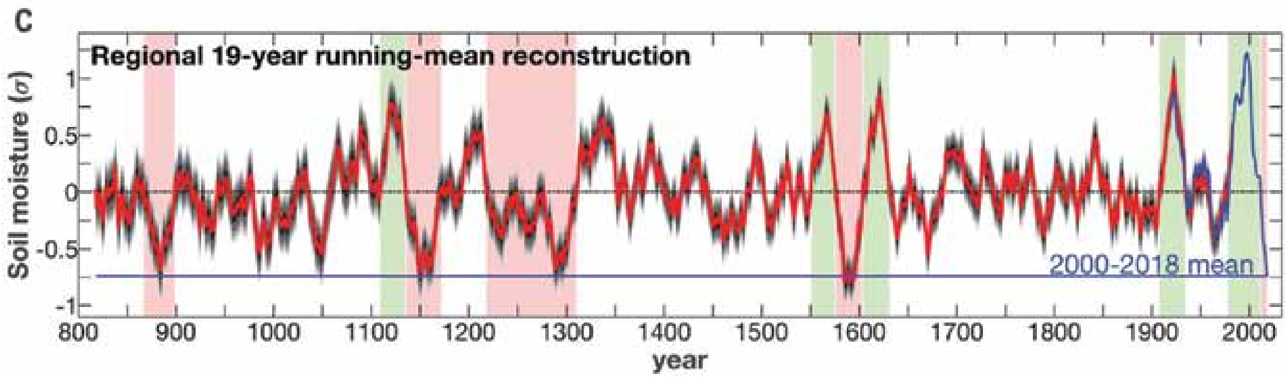

Figure 4. Summer soil moisture reconstruction for the American Southwest. The red line is a reconstructed 19-year running mean of summer soil moisture going back to 800 CE, and the blue time series from 1901 to 2018 represents modeled soil moisture. Gray represents the 95% confidence interval. The 2000-18 mean soil moisture value is the horizontal blue line. The lowest soil moisture periods are represented by the pink vertical bars. The 2000-18 period is the 2nd worst period in the last 1200 years, second only to the period before 1600 CE. Source: Williams et al. (2020).

A key finding is that temperature increases in the summer months decreased soil moisture immediately, and these soil moisture losses persisted into the following year, causing flow losses over an extended period of time.

In April of 2020, Park Williams and co-authors published a "Large Contribution from Anthropogenic Warming to an Emerging North American Megadrought" in *Science*. Some of these authors have previously published warnings about how the likelihood of megadrought in the Southwest will increase substantially in the 21st century as warming occurs, with the chances as high as 80% or more by some measures. This study said that 2000-2018 was the 2nd driest 19-year period since 800 AD as measured by reconstructed July to August soil moisture. The drought was caused by both natural variability and humans, with 50% of the cause attributed to higher temperatures. Without anthropogenic heating and drying, the drought would be modest. This study, while not expressly directed at the CR, has important implications for water managers because soil moisture declines have been linked to long-term reductions in runoff (see Figure 4).

A study in 2011 by Tapash Das and co-authors provided clues as to why reduced soil moisture should concern water managers and users. "The Importance of Warm Season Warming to Western U.S. Streamflow Changes" in *Geophysical Research Letters* investigated how increasing temperatures would affect the Colorado, Columbia, Northern Sierra, and the Southern Sierra Rivers. Using a hydrology model that produced streamflow when driven by temperature, precipitation, and wind speed, they explored how small temperature changes in a single month affected flows throughout the rest of the year. Changes in summer temperatures reduced river flow in all basins, but the Colorado was the most affected. A key finding is that temperature increases in the summer months decreased soil moisture immediately, and these soil moisture losses persisted into the following year, causing flow losses over an extended period of time.

How the flow of the CR will change as the climate warms in the 21st century has been a topic on intense scientific interest for decades. Since 2016, five different studies have attributed up to half of the almost 20% flow decline since 2000 to human-caused climate change. An additional study indicated that using soil moisture, the 19-year period from 2000-2018 was the 2nd driest in the last 1,200 years. All of these papers were published in well-regarded, peer-reviewed scientific journals, including two in the nation's premier journal, *Science*. The July to August period in 2020 in the Four Corners states was the warmest in the last 126 years, according to the National Weather Service (NWS). This comes on the heels of record-setting temperatures in 2018 in large parts of Colorado. Warm temperatures from human causes have already decreased the flow of the CR, and additional significant losses should be expected as the Earth continues to warm from human greenhouse gas emissions.

Research Technician Martin Schroeder (Utah State University) performing routine maintenance and data collection on eddy covariance instrumentation in Kremmling, Colorado. This instrumentation is located in a field where irrigation has been fully curtailed for an entire season, in order to perform intercomparisons with the OpenET ensemble modeling approach. Professor Larry Hipps and Professor Alfonso Torres (Utah State University) collaborate to interpret the data from this portion of the project.

Evaluating Conserved Consumptive Use on High-Elevation Pastures in the Upper Colorado Basin

Dr. Perry Cabot, Research Scientist**,** Colorado Water Center, Colorado State University Extension and Colorado State University Agricultural Experiment Station; **Aaron Derwingson,** Water Projects Director, The Nature Conservancy; **Matt Bromley,** Research Scientist, Desert Research Institute

Since 2000, the Colorado River Basin (CR Basin) has experienced significant drought conditions and warming temperatures. It is estimated that climate change will likely reduce flows in the Colorado River (CR) by a range of 5% to 20% by 2050 (Udall and Overpeck, 2017). Lakes Powell and Mead have also witnessed declines in the past two decades and are facing historically low levels. This trend is alarming for an economic engine as critical as the CR, which supplies drinking water to over 40 million people, irrigates over 5 million agricultural acres, and has 4,200 megawatts of hydropower generating capacity. It also fuels a multi-billion-dollar recreational economy and supports a diversity of wildlife and fish. Without determination and collaborative action to mitigate the impacts of aridification, persistent drought, and the effects of a changing climate on the CR Basin, all economic sectors are at risk.

The CR Basin states and Congress recently approved a Drought Contingency Plan that outlines the actions that water users will take to address the threat of declining water supplies (CR Drought Contingency Plan Authorization Act, P.L. 116-14). For the Upper Basin states of Colorado, New Mexico, Utah, and Wyoming, this plan includes exploring the feasibility arrangements that enroll landowners and water rights holders on a voluntary, temporary, and compensated basis to reduce consumptive water use to leave more water in the river. Over the past several years, several high-profile efforts in the Upper Basin have investigated how such a program could work administratively and legally to assure compliance with the CR Compact and improve water security (Grand Valley Water Users Association and J-U-B Engineers, 2017). Building on the success of these efforts, the Colorado Water Conservation Board (CWCB) established workgroups to address additional questions regarding drought contingency, further educate and involve stakeholders on water-sharing arrangements and promote larger statewide discussions.

In its capacity to direct research and outreach to inform these workgroups, the Colorado Basin Roundtable (CBRT) expressed their need to understand the scientific concerns, measurement and verification technology, and agronomic viability associated with programs that conserve consumptive use (CU). Irrigated pastures, particularly in the higher elevation regions of the CR Basin, comprise approximately 80% of total irrigated land and consume significant amounts of agricultural irrigation water in Colorado Water Divisions 4-7 that ultimately drain to the CR. The CBRT agreed that these irrigated pastures represent a dominant source of potentially conservable CU, but questions still exist regarding the measurability of actually conserved water, transferability of techniques to other regions, and most importantly, the impacts of reducing CU on the widely recognized importance of livestock producers that own this land. While this idea has been part of the drought contingency portfolio for decades in some form or another, a recent article published in *Politico,* entitled "The Rancher Trying to Solve the West's Water Crisis," captured what may be recognized as an inflection point in the development of water-sharing arrangements. In the piece, journalist Annie Snider focuses on the leadership of Paul Bruchez, a 5^{th} generation rancher, fly-fishing guide who serves as vice-chair of the CBRT, who advocates a paradigm shift in attitudes. "Instead of seeing agriculture and new suburbanites as locked in a zero-sum struggle over who gets the West's diminishing water," Ms. Snider highlights the insistence on collaboration that Mr. Bruchez advocates, "having spent the past two decades hatching a series of projects to help ranchers by making common cause with sportsmen, environmental groups and even some big city water officials and lawyers." Encouraged by the broad support for this research and outreach, a project to evaluate conserved CU (CCU) on high-elevation pastures was initiated in April 2020 in Grand County, Colorado with funding provided by American Rivers, The Nature Conservancy, Trout Unlimited, and the CWCB.

Research Implementation and Approach

Multiple landowners who operate irrigated parcels throughout Grand County signed up to support the project and were compensated for their participation in the project entitled "Evaluating Conserved Consumptive Use on High-Elevation Pastures in the Upper Colorado Basin." Irrigation was intentionally cut back on a total of 1,117.4 acres during the 2020 season, including 958.7 acres of full-season curtailment (no water applied) and 158.7 acres of split-season curtailment (irrigation cessation after June 15). The parcels were also granted SB13-019 protection status, which provides that any decrease in CU resulting from reduced irrigation rates will not be considered in any future judicial quantification of the historical CU (HCU) of the water rights for a maximum of five years out of the ten-year period.

This project presents a unique opportunity for researchers from Colorado State University (CSU), Utah State University (USU), and OpenET (openet-data.org/) to model evapotranspiration (ET)—often used interchangeably with CU in these discussions—over a considerably large land area subjected to irrigation curtailment. While there are multiple aspects of this project, including evaluation of impacts on forages subjected to irrigation curtailment, understanding of biomass yields and forage quality relative to CU rates, carbohydrate and nutrient carryover on stressed pastures, and of course, economic impacts, a primary goal of the project is the use of remote sensing technology to estimate heterogeneous ET patterns across the large field sizes common to high-elevation irrigated pastures. Participating fields are characterized by various grasses, forbs, and sedges, as well as differing soil and groundwater, representing conditions typical to these types of fields across the Western Slope.

Remote sensing data analysis methods have been advocated as an alternative method for estimating actual CU where diversion records are too coarse to make estimates at the parcel scale (URS, 2014). Similarly, empirical methods (Blaney, Criddle, Hargreaves, Penman-Monteith, 1962) can be used to estimate HCU with local weather data to calculate water balances for individual parcels but may not be suf-

This project presents a unique opportunity for researchers from Colorado State University (CSU), Utah State University (USU), and OpenET to model evapotranspiration (ET)—often used interchangeably with CU in these discussions—over a considerably large land area subjected to irrigation curtailment.

The partnership with OpenET has allowed the project to integrate with their intercomparison and accuracy assessment protocol, strengthened by the installation of an eddy covariance tower at one of the Grand County field sites, along with soil moisture sensing instrumentation at nine locations across the study area.

ficiently specific for regional business transactions and program monitoring (Cuenca et al., 2013). In some cases, these methods have exhibited estimation errors in semi-arid, high-altitude environments (Smith, 2008). Furthermore, point-based measurements obtainable from field sites equipped with lysimeter, eddy covariance, and soil monitoring instrumentation, are very effective but may be too costly to implement for multiple parcels across broad areas (Walter et al., 1990; Carlson et al., 1991; Tang et al., 2009). The importance of improving methods to evaluate CU is a major impetus behind the work of OpenET, which brands itself as a platform for "Filling the Biggest Data Gap in Water Management."

Using remotely sensed data for the study area, ET rates were estimated at the monthly timescale for years 2016-2020, which included the year of the irrigation curtailments. The OpenET platform (openetdata.org/) uses Landsat as the primary satellite dataset to produce an average ET estimate using an "ensemble" of four separate and diverse ET models: EEMETRIC (Allen et al., 2005; Allen et al., 2007), PT-JPL (Fisher et al., 2008), SIMS (Melton et al., 2012; Pereira et al., 2020), and SSEBop (Senay et al., 2014; Senay et al., 2018). The EEMETRIC, PT-JPL, and SSEBop models are based on the surface energy balance approach, which relies on satellite measurements of surface temperature and surface reflectance combined with other key land surface and weather variables to estimate ET. In contrast, the SIMS model relies on surface reflectance data and crop type information to compute ET using a crop coefficient approach for agricultural lands. Reference ET (ETo) was accounted for using the GridMET gridded meteorological product (Abatzoglou, 2013) and calculated ETo using the American Society of Civil Engineers Penman-Montieth equation (Walter, 2000). This makes possible a more detailed calculation of daily actual ET in between every 8-day Landsat satellite overpass by using the fraction of reference ET (EToF) values to linearly interpolate to a daily timestep.

Preliminary Results and Analysis

The 4-year period of data studied between 2016-2019 for these fields indicated a relatively stable pattern of annual ET for all sites in previous years. Not unexpectedly, the sites that experienced irrigation curtailment exhibited a reduction in ET rates for 2020. These reductions ranged from a -18.37% to -49.29% change in comparison to the baseline average for 2016-2019. This wide range in reduction is likely attributable to whether the particular study site was subjected to a full-season or split-season treatment. The fields used as companion references maintained 2020 annual rates of ET that were very similar to those observed in 2016-2019, exhibiting a percent change that ranged between -5.85% and 1.55%.

It is important to note that at the time of this report, the ET data are preliminary in nature, and a larger comprehensive report is being developed for review during 2021. The partnership with OpenET has allowed the project to integrate with their intercomparison and accuracy assessment protocol, strengthened by the installation of an eddy covariance tower at one of the Grand County field sites, along with soil moisture sensing instrumentation at nine locations across the study area. The intercomparison between field and remote sensing will allow the team to perform a valuable "use case study" to test the regional scalability and transferability of this technique to irrigated pastures under what is expected to be an ongoing challenge of changing climate conditions across the Western Slope.

This project is supported with funding from The Nature Conservancy, Trout Unlimited, American Rivers, and the Colorado Water Conservation Board Alternative Transfer Methods (ATM) program.

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The Agriculture Impact Task Force

Nora Flynn, Agriculture Water Specialist, Colorado Water Center

The Agriculture Impact Task Force (AITF), convened by Governor Polis in June 2020, is a coalition of state, federal, and agricultural association partners working together for the future of agriculture in Colorado. Co-led by Kate Greenberg, Commissioner of Agriculture, and Megan Holcomb, Senior Climate Scientist and Interagency Climate Coordinator at Colorado Water Conservation Board, the AITF's responsibility is to identify problems and potential threats to agriculture, assess impacts of drought, and coordinate across agencies and stakeholders for the greatest mutual benefit.

One of the first actions of the AITF was to create a comprehensive list of drought-related financial assistance to ensure producers experiencing challenges due to drought had a one-stop access point to explore available aid. The AITF members helped to ensure the distribution of this resource to producers. A list of drought-related financial assistance programs can be located here: bit.ly/3dI3liY

Throughout the growing season, members of AITF compile data and information about drought impacts around the state. In previous years, this information was utilized to coordinate drought tours for state legislators and policy leaders, providing the opportunity for them to witness the challenges of drought firsthand. However, this year, due to travel limitations during the COVID-19 pandemic, the AITF put together a virtual drought tour. This provided the opportunity to share 50 stories about agricultural drought in Colorado and the influences it has for farmers in a virtual format. This platform is readily available to policy makers and the general public. To check out the Colorado drought stories and information visit the following website: bit.ly/3a043qT

Most recently, the AITF created a briefing for the Colorado legislative session that highlights recommendations that precipitated from AITF reflections on important avenues for supporting resilience in the agricultural sector. Recommendations include providing drought adaptation support, mental health resources, and creating market opportunities for new and diverse revenue streams. The briefing can be found on CWCB's Agriculture Drought Response webpage or at bit.ly/3uBe31z.

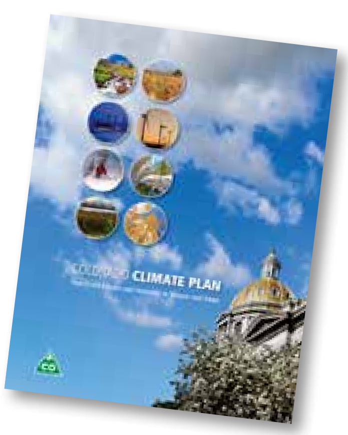
The AITF has remained active over the winter of 2020-2021 to prepare for continued drought conditions expected during the upcoming growing season. The AITF is also planning beyond this upcoming season because the effects of drought are widespread across the state, long-lasting, and increasing in severity. The AITF's efforts in the future will continue to elevate the innovation and resilience of Colorado's farmers and ranchers while promoting the many benefits agriculture creates for all Coloradans.

Green Mountain Reservoir, located near Kremmling, Colorado on the Blue River has seen reduced water levels due to low snowpack. ©iStock.com

Embracing Climate Change in the Colorado Water Plan and in Local Communities

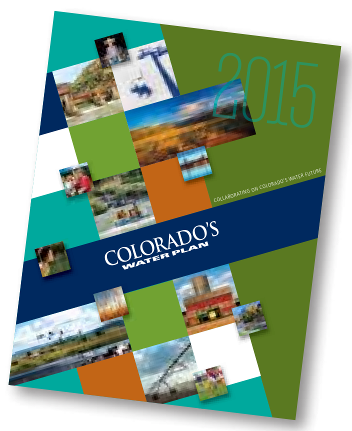
Russell Sands, Water Supply Planning Section Chief, Colorado Water Conservation Board

Colorado climate leaders are working to guide diverse communities and economies toward a resilient future by embracing climate action, and the Colorado Water Conservation Board (CWCB) is helping to spearhead that effort. Adaptive planning is critical to support a vibrant future, but the CWCB or even the state as a whole cannot do it alone. Meeting our future climate challenges, which includes climate's impact on water, will take leadership at local, state, and regional levels, as well as public and private involvement. Together, Colorado can work to minimize future climate risks and recognize new economic opportunities.



Current Climate Trends and Resilience

This past year was hot and dry—2020 was the eighth warmest year and second, driest calendar year on record, trailing only 2002. While the Colorado Climate Plan (bit.ly/3amaVz1) projects temperatures may rise a 2.5°F to 5°F by 2050, it is important to remember that the plan also notes that Colorado has already warmed 2°F in just the last 30 years. This effectively means we are not just planning for some distant climate future—in many ways, the future is here.



The Colorado Water Plan, which uses the same underlying climate modeling as the Colorado Climate Plan, envisions that a much warmer climate may have cascading impacts on cities, farms, streams, and the state as a whole. While climate modeling is less clear about whether the future will be wetter or dryer, most models show increasing warming trends, which certainly seems to be playing out. That warming stands to shift the runoff season up further, decrease the snowpack, and increase the chances of drought, wildfires, and floods.

Brad Udall, Senior Water and Climate Scientist and Scholar, Colorado Water Center once stated, "climate change is water change;" and while climate impacts are broad for Colorado, water is certainly on the frontlines of the climate discussion. This is why the Colorado Water Plan and its 2022 update will continue to focus on climate challenges and climate-related opportunities for adaptive planning.

CWCB online Future Avoided Cost Explorer (FACE) Hazards Tool

Understanding the Cost of Doing Nothing

A common barrier to climate action is cost. One way the CWCB is hoping to help remove that barrier is by helping local planners better make the financial case for climate action. In a partnership with other state agencies and the Federal Emergency Management Agency (FEMA), the CWCB recently developed the Future Avoided Cost Explorer (FACE) Hazards Tool (cwcb.colorado.gov/FACE). The tool helps frame-up sector-specific impacts and provides future estimated costs from increased natural hazards that may result from climate change. The result is a tool that puts a cost to inaction, helping local

Changes in global climate patterns show Colorado faces more frequent and intense natural hazards such as wildfires, droughts, and floods. The Grizzly Creek fire, above, burned more than 30,000 acres in Glenwood Canyon in 2021. Photo courtesy of the U.S. Forest Service.

communities make the case for why climate action actually pays dividends.

At the state level, climate science is increasingly leading policy discussions and planning resources such as guiding frameworks, technical tools, and assistance programs. While Colorado's climate leaders have made great strides in responding to, recovering from, and mitigating the impacts of hazards, the state's risk profile will continue to increase in the coming decades. Putting more science, data, and tools in the hands of local planners and community leaders can help build a ground-swell of the kinds of actions needed for Colorado to collectively meet its climate challenges.

Changes in global climate patterns show Colorado faces more frequent and intense natural hazards such as wildfires, droughts, and floods—each with its cascading impacts to water availability, energy demands, public health threats, transportation infrastructure, agricultural viability, and seasonal-dependent tourism such as skiing and rafting.

Coupled with steady increases in state population means Colorado faces constant pressure to decide how and where to develop communities. Combined all with other driving factors (e.g., economy), Colorado faces increased vulnerabilities. But we can work together to adapt and meet the challenge by implementing tangible, on-the-ground solutions. That work starts by highlighting the impacts in documents like the Colorado Water Plan and supporting and helping fund local projects that can build solutions.

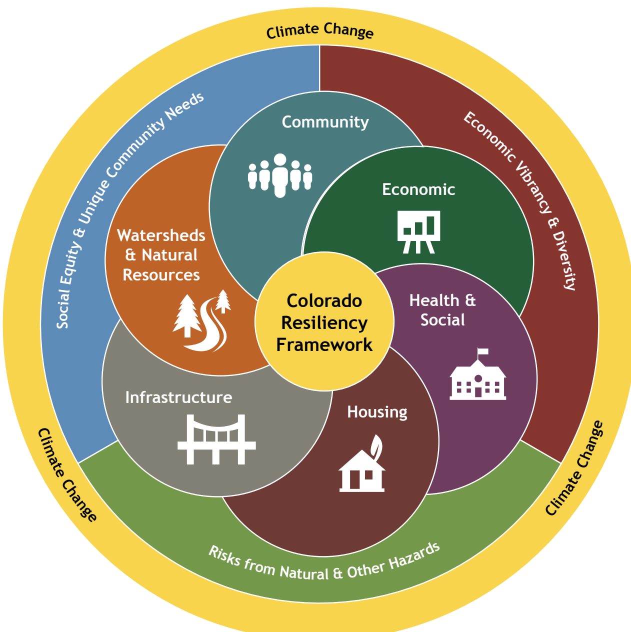
Local Efforts Support Climate Action

Because resilient systems can respond to and recover quickly from disturbances, local efforts to build resilience should be focused on minimizing risk and increasing preparedness to help lessen the impacts of future challenges. While this sounds logical, the discussion is often followed by questions like "where do I start?" and "who do I engage"? Sometimes the answers come in learning from other's stories and partnering to replicate that success.

Stories that demonstrate resilience in real-time provide exceedingly helpful lessons in action. When those stories offer local, "neighbor to neighbor" examples, they also hit home by offering actionable priorities with clear behavior changes attached to them. During the 2020-2021 drought, CWCB launched a "virtual drought tour" where local community members could share their experience. Those stories were put into an online story map (bit.ly/3dpqMPc) that allows anyone to look by region at local stories of impact and resilience. Some of these stories certainly speak to economic struggle and devastating climate impacts. But there are also stories of creative adaptation, reimagined management, and resilience.

In both disaster and non-disaster years, water users, stakeholders, and concerned citizens work tirelessly through Colorado's unique policy engagement structures, such as the state's nine basin roundtables and Interbasin Compact Committee—legislatively created water stakeholder groups across the state. These groups are committed to truly adaptive solutions.

Planning for the future means changing how we think, resetting expectations, and being increasingly adaptive. However, planning also needs to be increasingly integrated to maximize benefits, avoid unintended consequences and work towards greater synergies in planning.



An infographic from the the Colorado Department of Local Affairs' Resilience Plan illustrsates risks and vulernabuilites in a holisitic framework.

State Climate Planning is Increasingly Integrated

Since the 2015 Colorado Water Plan, a flurry of climate-informed state plans and roadmaps have emerged. Documents like The Analysis and Technical Update to the Colorado Water Plan aim to strike a balance between understanding risk, embracing opportunities, and setting actionable paths toward increased climate resilience. Climate mitigation is the primary approach (i.e., reducing greenhouse gas emissions) to prevent the planet from warming to more extreme temperatures, but climate adaptation is the primary approach to respond to climate impacts and to build resilience. The reality is both are necessary to meeting future climate needs.

While CWCB focuses on climate adaptation, staff also work to help to support an array of planning efforts, including a forthcoming climate action hub (climate.colorado.gov). Beyond the Colorado Water Plan update (slated for release at the end of 2022) and the creation of the FACE Hazards tool, there are many state documents and tools that collectively plot a path forward to greater preparedness. Some examples of recent efforts follow:

» In January 2021, Colorado set a path towards ambitious, multi-industry greenhouse gas mitigation (bit.ly/2QdebFZ) solidifying a commitment to climate action and clean air.

» The Colorado Energy Office developed a Rebuild and Re-energize Local Government Toolkit (bit.ly/3efcekm) to help empower communities with on the ground examples of innovative programs and policies throughout Colorado.

» The Colorado Department of Local Affairs' Resiliency Office updated its Resilience Plan (bit.ly/3gladWK) continues to host a climate adaptation webinar series (coresiliency.com/webinars) focused on real-time topics and actionable advice from communities around the state.

» The Colorado Department of Public Health and Environment is beta-testing the Climate Equity Data Viewer (bit.ly/32oAzPf), which uses data to prioritize equitable community engagement efforts.

Other plans and initiatives include efforts for resilient forests (csfs.colostate.edu/forest-action-plan/), resilient local governments (bit.ly/2RAn7FM), economic transition (bit.ly/3dprgF0), renewable energy (bit.ly/32rWgy1), reimagined infrastructure (bit.ly/2Qzpo3s), regenerative agriculture (ag.colorado.gov/conservation/soil-health), and frameworks that address racial equity and economic justice (bit.ly/3mXwhYP).

Many of these guides expand upon the formative Colorado Climate Plan, which developed a multi-sector policy vision to adapt our state to the realities of climate impacts and shifting ecosystem conditions. What made that effort successful was getting public buy-in through a robust public process (the Water Plan received 30,000 public comments) and a commitment to implementation after the Plan was released.

Local project development is essential. Plans and frameworks can help lead the way, our ability to minimize future climate risks and embrace new economic opportunities largely depends on the collective action of communities who feel empowered and resourced (financially, technically, and in human capacity) to try something new.

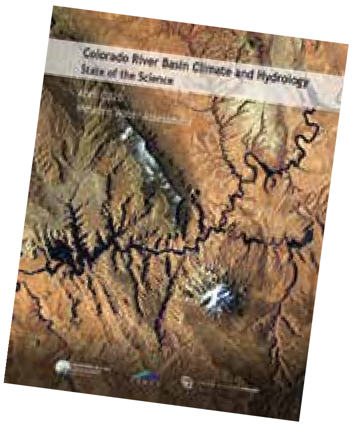
As CWCB Director Rebecca Mitchell noted, "Resilient planning must recognize the impacts that are felt across our communities and are disproportionately felt in our poorest communities. Understanding and supporting adaptive measures that mitigate risk and maximize benefits through projects that support all Coloradans is critical."

Colorado River Basin Climate and Hydrology

State of the Science

A Synthesis Report to Support Water Planning and Management

Elizabeth Payton, Water Resources Specialist, Western Water Assessment, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder; **Jeff Lukas,** Principal, Lukas Climate Research and Consulting



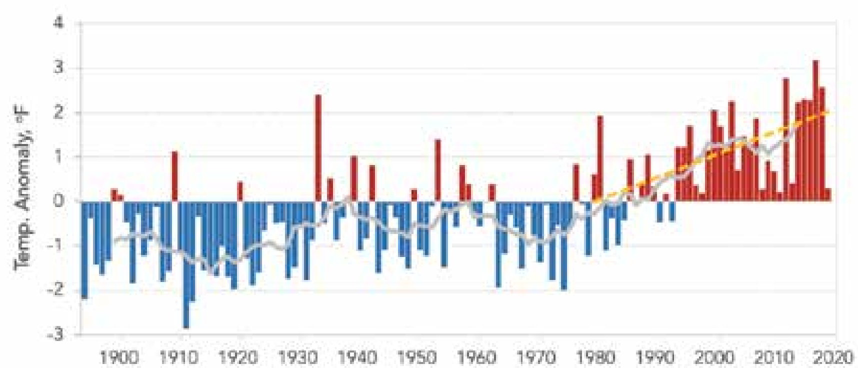


Figure 1. Annually averaged temperature for the Colorado River Basin, 1895–2019, shown as departures from a 1970–1999 average. (Data: NOAA NCEI)

Colorado River (CR) water managers and water users are facing the most challenging water supply conditions on record at a time when CR Basin (Basin) demand has risen to where it matches or exceeds the supply. Naturally, those managers and users are looking for scientific and technical guidance to navigate the future of the CR, but the vast array of complex climate and hydrology datasets and models presents its own challenges. The CR Climate and Hydrology Work Group, a consortium of major water agencies in the Basin, including the Bureau of Reclamation (Reclamation), Southern Nevada Water Authority, Colorado Water Conservation Board (CWCB), CR District, and Denver Water, initiated an effort to capture the current state of the science and technical practice in a form that would be more accessible to stakeholders. In 2018, the Work Group approached Western Water Assessment (WWA) to develop the *CR Basin Climate and Hydrology: State of the Science* report.

The overall goal of the report was to produce a broadly accepted and shared reference that managers, practitioners, and researchers could use to inform both near-term operations and long-term planning for an increasingly uncertain water supply future, including the upcoming renegotiations of the 2007 Interim Guidelines. To that end, the report conveys not only what is currently known and being implemented in each area of science and technical practice but also knowledge gaps and opportunities in those areas, which in turn also informs priorities for new research and research-to-operations activities.

The report is oriented around the hydroclimatic knowledge, data, and modeling that produces inputs to the three primary Reclamation operations and planning models for the Basin. Below, we have distilled a brief narrative from three of the main sections of the report, with the hope of encouraging you to explore these topics at greater length in the full report.

Current Understanding of Basin Climate and Hydrology

The Basin's hydrology is snowmelt-driven, and 85% of the annual Basin-wide runoff comes from 15% of the Basin's area located in the mountain headwaters. There is high year-to-year variability in headwaters precipitation and thus in runoff. Over the past 40 years, there has been a substantial warming trend (2°F) across the Basin (Figure 1). Some important changes in the Basin's hydrology have been linked to this warming, including decreasing spring snowpacks, shifts to earlier runoff timing, and declining runoff efficiency. The most recent studies indicate that the warming is partly responsible for the cumulative streamflow deficit since 2000 in the Upper Basin.

Primary Data and Models

Guidance for water operations and planning in the Basin depends on high-quality observations and

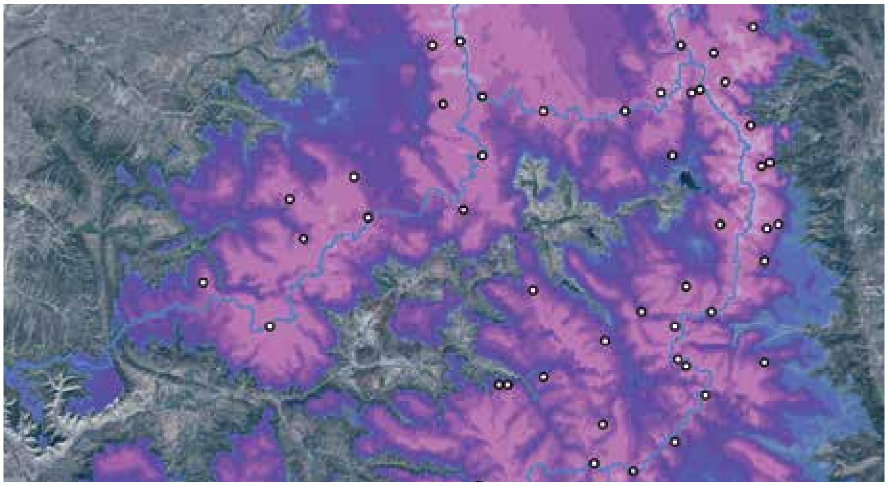


Figure 2. The SnowView map tool showing spatial snow-water equivalent (SWE) estimates for the Colorado River headwaters and portions of adjacent basins for April 1, 2018. The white circles show the individual NRCS SNOTEL sites that are used as the basis for the spatial estimates. (Source: SnowView, University of Arizona; climate.arizona.edu/snowview/).

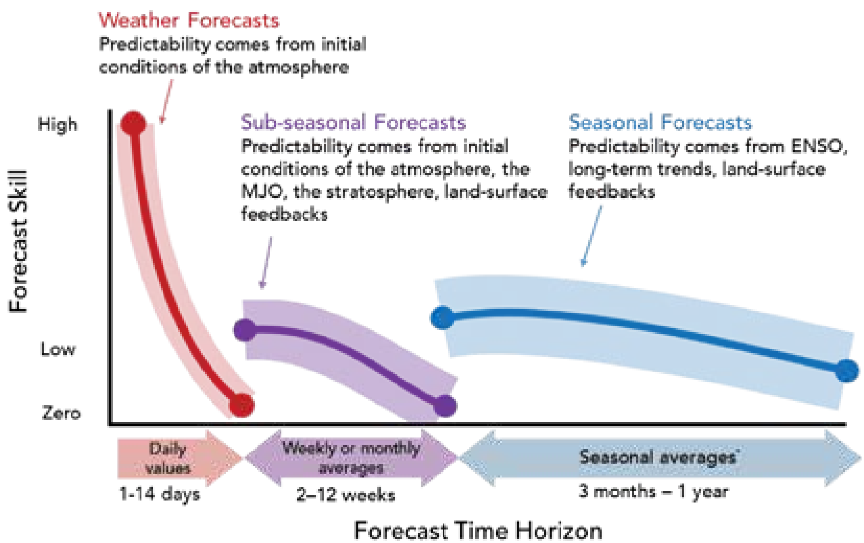


Figure 3. Schematic of typical forecast skill vs. forecast time horizon for three main types of weather and climate forecasts. The relatively low skill of sub-seasonal and seasonal forecasts limits their ability to inform streamflow forecasts. (Source: Adapted from a figure by Elisabeth Gawthrop and Tony Barnston, International Research Institute for Climate and Society).

historical records of weather, climate, and hydrology variables, including temperature, precipitation, snowpack, streamflow, soil moisture, and evaporation. The backbone of this observational capacity in the Basin remains the long-standing, on-the-ground measurement networks, such as the Cooperative Observer Program (COOP) and other weather stations, USGS and cooperator streamflow gages, and Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) snow observing sites.

Increasingly, data from these networks are being augmented by remote sensing data and spatial modeling, filling in gaps in observations in both space and time (Figure 2). This enhancement provides a more detailed view of the Basin's hydroclimatic variability and allows more sophisticated spatial analysis, but it does not lessen the importance of the on-the-ground networks. These new datasets also put some additional burden on data users when selecting and interpreting them; gridded, spatial climate, and hydrology products that interpolate between measurements are not equally accurate across all grid cells, especially at the highest elevations where observations are sparse.

Short- and Mid-Term Forecast Tools

Forecasts for the Basin hydrologic and water system outcomes over the mid-term (1 month to 2 years) dictate critical Basin-wide water management decisions, such as the operating tier in Reclamation's Annual Operating Plan. They also inform individual decisions by many other water managers and water users.

The relatively high skill of the seasonal streamflow forecasts from NOAA CR Basin Forecast Center (CBRFC) and NRCS arises from knowing the watershed moisture conditions at the time of the forecast, i.e., the relative state of the snowpack and, to a lesser extent, soil moisture. The quantification of these watershed moisture conditions has improved and will continue to improve as remote sensing, and spatial modeling of snowpack and soil moisture augment the point observations.

A key source of error in seasonal streamflow forecasts remains the large uncertainty in upcoming precipitation and temperature at timescales beyond about ten days (Figure 3). Climate forecasts for the upcoming month and season have relatively low skill but are improving, if slowly, and hydrologic forecasters may use them to "nudge" the seasonal streamflow forecasts in the near future. The seasonal precipitation outlooks in the Basin have more skill in winter and spring and during El Niño and La Niña events.

Hydrology Scenarios for Long-Term Planning

To guide long-term water planning at the Reclamation and many other water agencies, plausible hydrologic futures are run through system models to evaluate potential outcomes over the next 5 to 50 years. Traditional planning approaches have assumed hydrologic stationarity, i.e., that future streamflows will have characteristics (e.g.,

The Green River pictured in Dinosaur National Monument.
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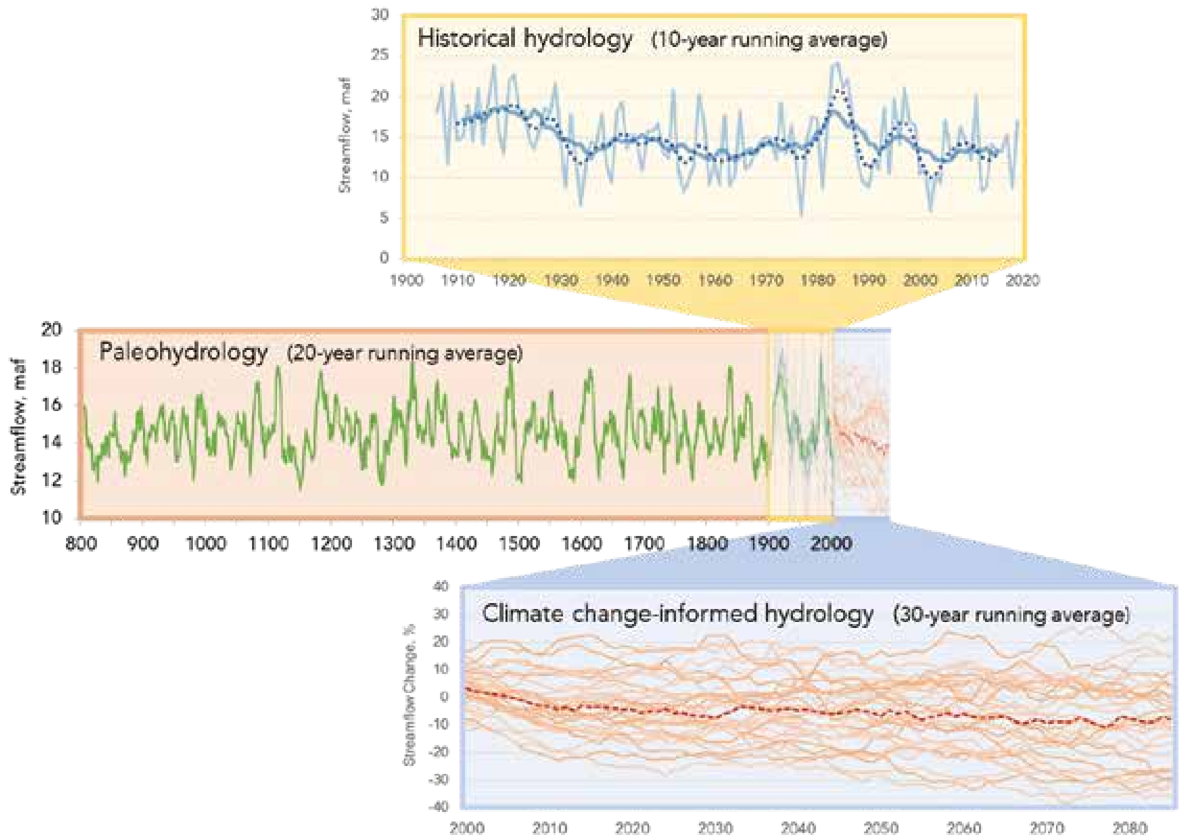


Figure 4. Three complementary sources of guidance for long-term basin planning: historical hydrology, paleohydrology, and climate-change informed hydrology. Annual streamflows for the Colorado River at Lees Ferry, Arizona, representing total Upper Basin natural runoff. (Data: Historical: Reclamation, usbr.gov/lc/region/g4000/NaturalFlow/; Paleo: Meko et al. 2007, treeflow.info/upper-colorado-basin; Climate change: Reclamation et al., CMIP5 LOCA, gdo-dcp.ucllnl.org/)

average, variance, extremes) similar to past streamflows; accordingly, the historical hydrology was the primary basis for planning.

The historically unprecedented streamflow deficits of 2000—2004 pointed to the need to consider additional sources of guidance. Tree-ring reconstructions of Basin streamflows extend the observed natural flow record up to 1,200 years and show a broader range of hydrologic variability and extremes, including multi-decadal megadroughts. The reconstructed record reveals that early 20th century high-flow years (1905—1930) may have been the wettest period in 500—1,000 years.

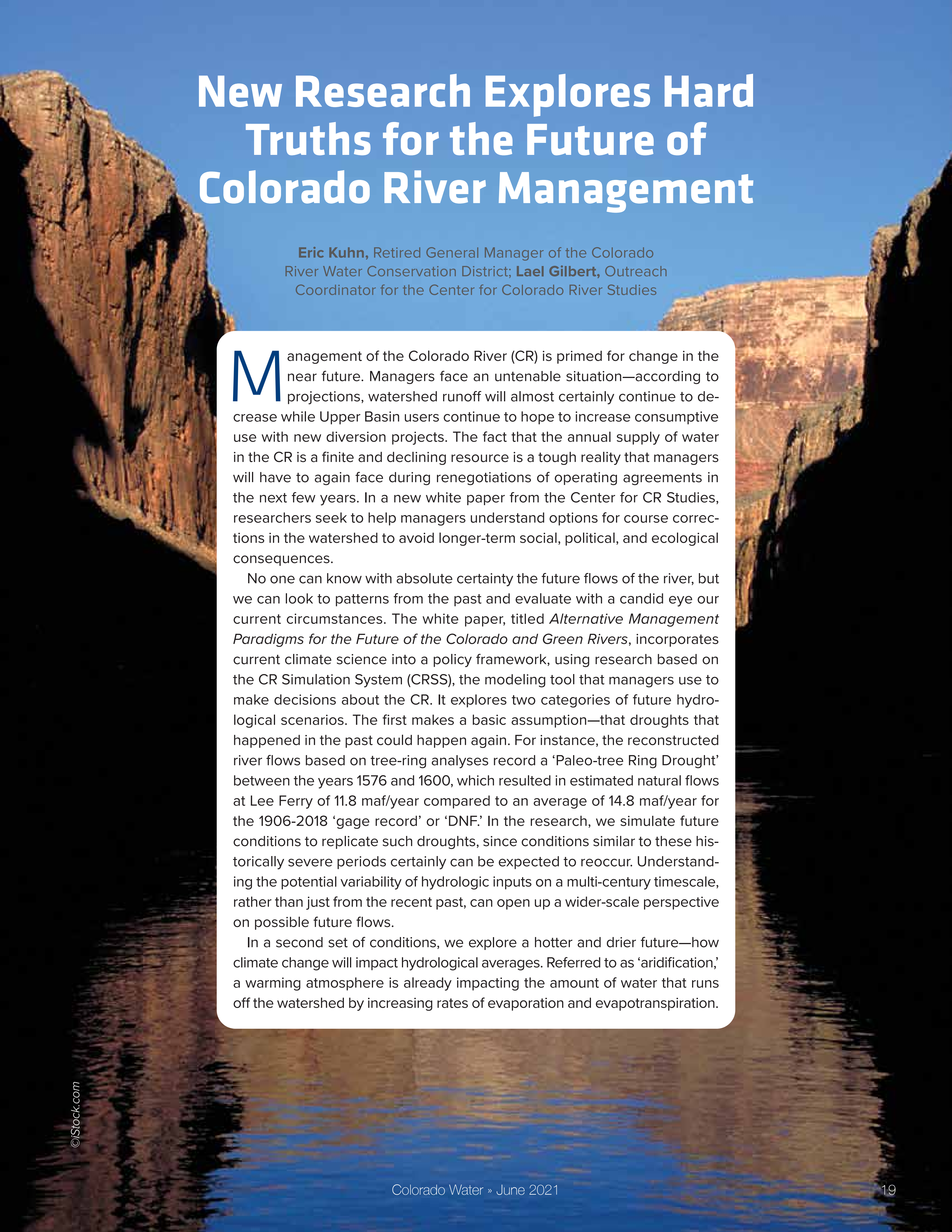
Since the early 2000s, studies using global climate models (GCMs) to project the future impacts of human-caused climate change on CR hydrology have consistently shown that annual flows are likely to decline by mid-century due to the impacts of warming. The GCM-based future projections indicate a much warmer future that will likely impact water supply—smaller spring snowpacks, earlier runoff, lower summer flows, and reduced annual runoff—and also lead to increased water use by crops and urban vegetation.

Challenges and Opportunities

A critical aspect of synthesizing the current state of the science and technical practice in the report was identifying persistent knowledge gaps and uncertainties, and then describing ongoing, planned, or potential activities and research directions for closing those gaps.

Opportunities to close knowledge gaps and reduce uncertainties exist across all of the areas of research and technical practice represented in the report. In many of these areas, Basin-specific activities are in progress, and in most cases, Basin water agencies and other stakeholders are collaborating with researchers to carry out studies and implement technical advances. In other areas, such as climate forecasting, progress will also depend on work by the scientific community well outside of the Basin.

Past scientific advances have led to improvements in the various links in the chain of data and models, and to more accurate and actionable information for decision making. The ongoing efforts documented in the report strongly suggest that this progress will continue, especially at shorter timescales. At longer timescales, the increasing impact of climate change means that Basin water planners will have to prepare for climatic and hydrologic futures never seen before, which is a more difficult challenge than preparing only for the past.



New Research Explores Hard Truths for the Future of Colorado River Management

Eric Kuhn, Retired General Manager of the Colorado River Water Conservation District; **Lael Gilbert,** Outreach Coordinator for the Center for Colorado River Studies

Management of the Colorado River (CR) is primed for change in the near future. Managers face an untenable situation—according to projections, watershed runoff will almost certainly continue to decrease while Upper Basin users continue to hope to increase consumptive use with new diversion projects. The fact that the annual supply of water in the CR is a finite and declining resource is a tough reality that managers will have to again face during renegotiations of operating agreements in the next few years. In a new white paper from the Center for CR Studies, researchers seek to help managers understand options for course corrections in the watershed to avoid longer-term social, political, and ecological consequences.

No one can know with absolute certainty the future flows of the river, but we can look to patterns from the past and evaluate with a candid eye our current circumstances. The white paper, titled *Alternative Management Paradigms for the Future of the Colorado and Green Rivers*, incorporates current climate science into a policy framework, using research based on the CR Simulation System (CRSS), the modeling tool that managers use to make decisions about the CR. It explores two categories of future hydrological scenarios. The first makes a basic assumption—that droughts that happened in the past could happen again. For instance, the reconstructed river flows based on tree-ring analyses record a 'Paleo-tree Ring Drought' between the years 1576 and 1600, which resulted in estimated natural flows at Lee Ferry of 11.8 maf/year compared to an average of 14.8 maf/year for the 1906-2018 'gage record' or 'DNF.' In the research, we simulate future conditions to replicate such droughts, since conditions similar to these historically severe periods certainly can be expected to reoccur. Understanding the potential variability of hydrologic inputs on a multi-century timescale, rather than just from the recent past, can open up a wider-scale perspective on possible future flows.

In a second set of conditions, we explore a hotter and drier future—how climate change will impact hydrological averages. Referred to as 'aridification,' a warming atmosphere is already impacting the amount of water that runs off the watershed by increasing rates of evaporation and evapotranspiration.

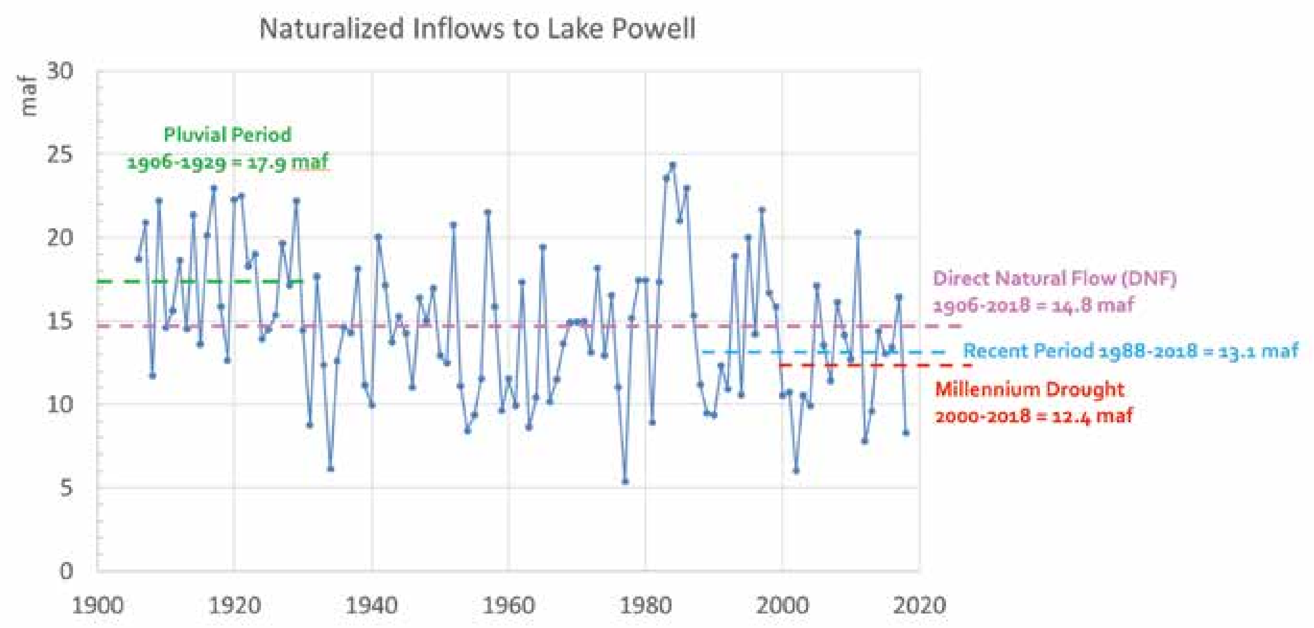


Figure 1. The graph showcases naturalized inflows to Lake Powell from the 1906-2018 DNF period, the 1906 -1929 pluvial period, and the 2000-2018 Millennium Drought.

Traditionally, almost all CR management decisions have used the concepts that future flows will look like the past (stationarity) and that the longer the period-of-record used, the better the data. Under the 1922 CR Compact, Lee Ferry (about one mile downstream of Lees Ferry and 15 miles downstream of Glen Canyon Dam) is the dividing line between the Upper and Lower Basins and the point on the river where the Upper Basin must meet compact flow obligations, thus both scientific and water management studies focus on this location. The estimated mean natural flow at Lee Ferry over the 1906-2018 period is 14.8 maf/year. This period includes both the pluvial period (1906-1929) with a mean natural flow of 17.9 maf/year (21% higher than the long-term mean) and the current Millennium Drought with a 2000-2018 mean of 12.4 maf/year (approximately 18% lower). We now recognize that the pluvial period was unusually wet and cool, and there is no indication that a flow period of a similar magnitude is likely to reoccur. Water planners will need to recognize, according to recent science, that the current hot and dry conditions of the Millennium Drought will be much more typical of the future conditions than the average of what has occurred over the last century-plus.

Indeed, if the Millennium Drought, which has now persisted for more than two decades, is our 'new abnormal,' or if the progressive decline of runoff resulting from climate change becomes even more apparent, major structural changes to water management in the basin will be urgently required. If, as modeled, each degree Celsius of warming brings flow declines of 6.5% (Figure 2), the average total reservoir storage in Lakes Mead and Powell will continue to drop approximately 0.25 maf/year under any fixed river management strategy. Adapting to this non-stationary river will require a revised strategy and restyling of the *Law of the River* to identify more sustainable and adaptive approaches that continually reduce consumptive use in both the Upper and Lower Basins.

Under these potential future scenarios, the white paper offers a wide variety of alternative management paradigms. Some describe significant modifications or entirely new approaches to the current incremental status quo management approach. The paper concludes that basin water managers need to be open to radical departures from existing strategies because, considering projected conditions, incremental change may not be enough.

Managers cannot control natural inflows into the basin reservoir system, but they can manage consumptive demands. If the Upper Basin was able to maintain current levels of water consumption, the impacts of future droughts and climate change could be substantially moderated. But this is not the current plan. Managers and State Water Agencies in the Upper Basin have historically and continue to this day, overestimate future use. They do so to protect their perceived entitlements under the basic assumption that there is "surplus" system water available for future development. They also favor policies that preferentially store water in the reservoirs considered 'theirs', such as Lake Powell. They do this to have a 'savings account' for future development and to satisfy their compact obligations

The only effective approach for the Upper Basin is to manage consumptive use demands at today's levels or less while simultaneously seeking an agreement with the Lower Basin where both basins share the burden of climate change.

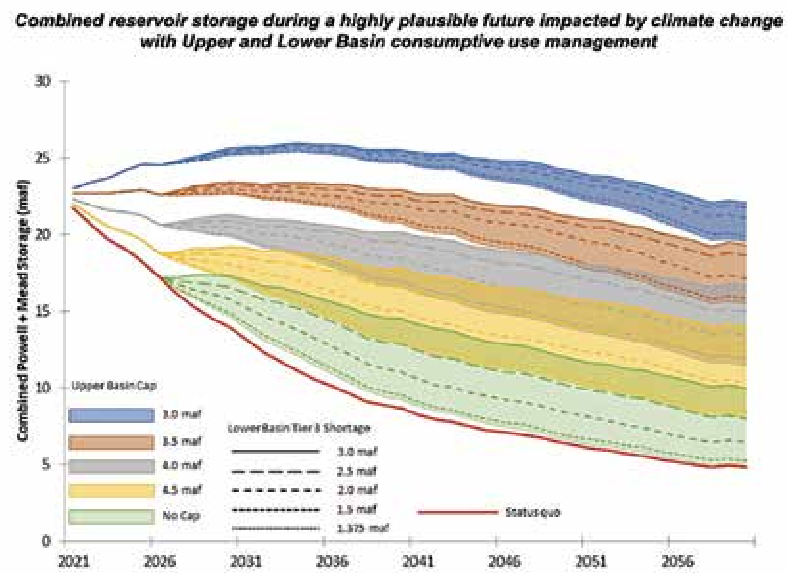


Figure 2. End-of-year combined Lake Powell + Lake Mead storage using the RCP45_065 hydrology (i.e., IPCC Representative Concentration Pathway 4.5 with 6.5% decrease of flow with each degree Celsius of warming) demonstrates the effects of a range of Upper Basin demand 'caps' along with a range of Lower Basin maximum shortages triggered when the combined storage falls below 15 maf. The status quo uses the 2007 UCRC Upper Basin schedule and elevation-based shortage triggers.

at Lee Ferry. Our models, however, show that under a continuation of the current Millennium Drought and a continued decline in mean natural flows caused by aridification, these strategies fail. The only effective approach for the Upper Basin is to manage consumptive use demands at today's levels or less while simultaneously seeking an agreement with the Lower Basin where both basins share the burden of climate change.

Others have suggested new radical reservoir management approaches such as *Fill Mead First* or *Fill Powell First*. But our results again show that these strategies do not have any significant impact on upstream or downstream water supply security. The savings these plans offer are minimal while creating major ecological impacts for ecosystems like the Grand Canyon. All of our alternative management paradigms point to a common result; changes in reservoir operations will not solve the supply-demand imbalance. The hard truths are that an increase of consumptive water use in the Upper Basin has the potential to be a more important determinant of the sustainable management of the CR's reservoirs than do other factors, and future shortages for Lower Basin users will have to be much greater than even the highest levels provided by the 2019 Lower Basin Drought Contingency Plan.

Our research found that there are significant advantages of using a combined storage metric for Lake Powell and Lake Mead as the principal determinant of Lower Basin shortages, rather than managing them separately as currently is practiced. Such a metric would encourage a more accurate perspective on the state and security of the CR's water supply and would discourage the currently fragmented view in which Lake Powell and Lake Mead are considered two separate reservoirs. Not only does this method provide a clearer and more logical way to declare shortages in the Lower Basin, but it also allows operational flexibility to benefit environmental conditions along the river in the Grand Canyon.

Managing the two reservoirs as one would also benefit ecosystems of rivers and tributaries by allowing timing of releases from Lake Powell to be on schedules that answer to ecosystem needs, rather than political ones, benefiting native fish and allowing for more flexibility to meet sediment transportation ideals.

The CR system is one of the most highly managed in the U.S., the lifeblood of the economic West, and spiritual bedrock for those who call it home. With this white paper, we hope to give managers a more complete, more candid look at where the river is heading at this major turning point in its history.

The white paper was produced through the Center for Colorado River Studies "Future of the Colorado River" project and was funded by Walton Family Foundation, the U.S. Geological Survey (USGS) Southwest Climate Adaptation Science Center, the Utah Water Research Laboratory private donors, and grants from the Catena Foundation.

Above: Denver Water's new LEED-Platinum administration building. Below: The From Forests to Faucets program at work thinning Lodgepole pine in the Dillon Reservoir watershed. This program proactively manages forests to reduce the impact of high intensity wildfires, as well as restores forested areas that have been heavily impacted by wildfire. Photos courtesy of Denver Water.

Climate Change Mainstreaming at Denver Water

Taylor Winchell, Water Resources Engineer, and **Laurna Kaatz,** Climate Program Manager, Denver Water

"Climate change is water change, and at Denver Water, where providing safe and reliable water is our business, climate change impacts our entire organization." That is what we—Denver Water's Climate Team—tell each new Denver Water employee during a Climate Change 101 Tutorial.

We developed this tutorial as part of our climate change mainstreaming efforts, to help streamline and embed climate adaptation within Denver Water's organizational practices, plans, and decisions. We recognize that climate change is currently—and will continue to—impact all water utility business functions. The best way to prepare the organization for a changing future is to work directly with experts throughout the organization and embed climate change thinking into their everyday work.

Climate change is both a risk enhancer and creates new risks, and its impacts to water utilities have traditionally been associated with the risks and uncertainties to water supply. As the West continues to experience trends of aridification and variation in annual precipitation, reliable water supplies are becoming continuously more precarious. Denver Water strives to make reliable water supply in an uncertain future a top priority for its long-range planning. Moreover, it is important to examine some of the other ways that climate change impacts drinking water utilities.

Water Quality

Just delivering water is not enough to fulfill our mission at Denver Water—that water must also be safe to drink and use. Climate change enhances many water quality risks, including increased algae blooms due to warmer water; large and high-intensity wildfires that result in difficult-to-treat contaminants and sediment build up in streams and reservoirs; extreme precipitation events that could damage water treatment infrastructure; and overloaded power grids that subsequently result in blackouts that could render treatment plants inoperable.

Watershed Health

Healthy watersheds naturally pre-treat water before its arrival to treatment plants, and they also moderate the timing of snowmelt runoff so that water is released in more of a sustained manner throughout the summer. Climate change poses direct threats to the health of Colorado's watersheds and the delicate balance of these mountain ecosystems through enhanced wildfire risks, rising temperatures creating new opportunities for invasive species, and rising temperatures potentially making species propagation more difficult for native flora and fauna.

Worker Health and Safety

A core component of water utilities throughout the world is the robust workforce that works outside installing infrastructure, fixing pipes, and maintaining the water utility systems. As heat waves and wildfires become more frequent, outdoor water utility workers will continue to face an increasing risk of heat stress, poor air quality, and other heat-related injuries.

Infrastructure Design and Management

Infrastructure can be vulnerable to extreme heat and cold, chronic heat and cold, as well as severe and hazardous weather such as flooding, wind, and hail. Additionally, HVAC systems will need to work harder and will cost more to operate as temperatures continue to warm. Water utilities are tasked with the challenge of maintaining, enhancing, and designing current and new infrastructure to ensure climate resilience.

Financial Stability

At Denver Water, annual revenue comes from three sources: 1) customer water bills, 2) new customer taps, and 3) hydropower revenues. Due to varying weather conditions and correlating water use needs, customer water bills fluctuate greatly depending on week-to-week and month-to-month weather patterns. As climate change introduces more variability into local weather patterns, revenue forecasting becomes increasingly difficult, making it more challenging to plan reliable annual operating and capital budgets.

So how is Denver Water addressing these risks and preparing for an uncertain climate future? The key for us is the climate change mainstreaming approach. How do we do this?... through educating and working together with as many experts throughout the organization as we can.

We have generally found that employees are concerned about climate change and want to consider it in their work, but also that they find it confusing and difficult to know where to start and rightfully so! That is why we created the Climate Change 101 Tutorial, which provides employees the opportunity to better understand what climate change is, what climate change means for the water cycle, and how climate change impacts various aspects of Denver Water. Toward the end of the tutorial, each participant is asked what climate change means for their work. This final step empowers staff to use what they have just learned to reframe their current work in terms of climate change threats and potential adaptations.

In the summer of 2020, we completed a climate adaptation tabletop exercise with over 25 Denver Water staff participants from four different business functions: finance, watersheds management, water quality and treatment, and distribution. This tabletop brought people together from across the organization to discuss three different climate change scenarios. This co-production approach allowed subject matter experts to share their specific climate change concerns and to propose potential adaptation solutions to address these concerns. Many of these solutions would never have been considered without hearing directly from these subject matter experts or without having created a space for cross-sectoral discussions.

Field operation team faces increasingly hot working conditions with climate change. Denver Water's Climate Team is working with field operations managers to progress solutions that ensure employees can remain safe and healthy under these changing conditions. Photo courtesy of Denver Water.

In our long-range planning, Denver Water has adopted scenario planning to plan for multiple ways in which the future might come to fruition. We understand that climate models show a range of plausible conditions and are projections, not predictions, and thus it is essential to embrace this uncertainty in our planning. In addition to climate uncertainties, there are uncertainties around the economy, technology, and social values, all of which have planning implications.

The Watershed Management Program at Denver Water has long been leading the way on climate change adaptation. Denver Water formed the From Forests to Faucets program partnership in the years following the 1996 Buffalo Creek wildfire, the severe drought of the early 2000s, and the 2002 Hayman wildfire that burned over 138,000 acres directly surrounding Denver Water's Cheesman Reservoir. This program—which is a partnership with the U.S. Forest Service (USFS), the Colorado State Forest Service (CSFS), and the Natural Resource Conservation Service (NRCS)—proactively manages forests to reduce the impact of high-intensity wildfires and also works to restore forested areas that have been heavily impacted by wildfire. This work has already proven to have real benefits in reducing wildfire impacts, and it will become even more crucial as the climate continues to warm.

On the infrastructure management side of things, the Denver Water Climate Team has been working directly with asset managers and engineers to plan for extreme heat. As Denver Water's engineering team was putting together an updated infrastructure master plan, the Climate Team worked to include a "climate change considerations" section for

Taylor Winchell, a member of Denver Water's Climate Team, working to install a stream temperature monitoring network in the Upper South Platte Basin, a collaboration project with Denver Water's Water Quality Operations group. Photo courtesy of Denver Water.

each primary infrastructure component of the system. This mainstreaming effort has helped Denver Water engineers consider how climate change impacts their work. The Climate Team has also worked with the Asset Management Team to conduct a heat impacts study that considered how rising temperatures could impact HVAC operations and motor functionality.

This same heat impacts study also provided an opportunity to think through how extreme heat will impact staff that work outdoors, a process through which the Climate Team sat down with field crew managers to listen to the concerns they have, the solutions they already implement, and their ideas for new solutions. The Climate Team will work directly with field crew managers to implement solutions that reduce the risk of heat and smoke-related injuries. The Climate Team also works directly with Denver Water's emergency management team to discuss how climate change enhances current system risks and introduces new risks.

Denver Water's Finance Team has already taken steps to increase revenue stability—which is threatened by climate change—through increasing the "fixed charge" that customers pay each month. The fixed charge is not impacted by how much water a customer uses and therefore provides some added revenue stability even when weather patterns are excessively variable. Additionally, the Finance Team is engaged in conversation with the Climate Team about continuing to plan for a more variable future.

And finally, Denver Water is a founding member of the Water Utility Climate Alliance (WUCA). WUCA is a collection of twelve water utilities from across the country that collectively serve over 50 million people, and its mission is to collaboratively advance water utility climate change adaptation. WUCA has helped build and progress the field of climate change adaptation and has made strides through working directly with the scientific research community to co-produce decision-relevant science for resource managers. WUCA will soon release a report on Leading Practices in Climate Change Adaptation, which provides an adaptation framework for any utility or organization interested in adapting to a changing climate. The tabletop exercise and heat impacts projects discussed above also both emerged from WUCA projects.

Climate change poses a direct threat to water utilities throughout the world, especially here in the western United States. At Denver Water, we view climate change as a threat not just to our water supply but also to every single organizational function. We are working hard to address this through our mainstreaming approach, which focuses on empowering experts throughout the organization to understand climate threats and respond by developing innovative adaptation solutions. Adapting to an uncertain climate future will not be easy, but if there is one thing we can be certain about, it is that it must be done.

COLORADO
Colorado Water Conservation Board
Department of Natural Resources

The Colorado Water Plan
Past, Present, and Future

Navajo State Park. Photo courtesy of Colorado Parks and Wildlife.

Rebecca Mitchell, Director, Colorado Water Conservation Board

Amidst a turbulent year across the United States, the Colorado Water Plan celebrated its fifth anniversary in 2020. Despite the low-profile celebration, the progress on the Colorado Water Plan over the last five years was no small accomplishment. Since 2015, the plan has helped support over 300 water projects across Colorado using close to $500 million in supporting grants from the Colorado Water Conservation Board (CWCB). Similarly, the plan helped spur drought planning and the integration of water and land use planning in cities, the creation of 26 or more stream management plans that support environmental needs, and enhancements to irrigation systems on farmlands. With over 76% of the actions in the Water Plan initiated to date, the progress is undeniable. However, drought, population growth, accelerating climate change, budget impacts, wildfires, and competing demands for water pose challenges as water planners in the state look to update the Water Plan.

Where It All Began

Though the first Colorado Water Plan was published in 2015, its roots go back to 2002-2003 when Colorado was faced with extreme drought that brought some municipalities to the brink of running out of water. At the same time, dry conditions helped fuel the Hayman wildfire, which incinerated 138,000 acres of forested headwaters across Douglas, Jefferson, Park, and Teller counties--all within the South Platte River drainage system. The aftermath of this burn included flooding and heavy sediment runoff into the river, which provides about 50% of the water supply for the Denver Metropolitan area. For the water community, these events cemented a need to analyze Colorado's water needs. This collective reckoning led to the first Statewide Water Supply Initiative (SWSI), published in 2004—an analysis of Colorado's potential for future water challenges.

In 2005, Colorado leaders passed the Water for the 21st Century Act to build transparent collaboration into state water planning. This created nine legislatively defined stakeholder groups called roundtables—one in each of Colorado's eight major river basins plus the Denver-metro region. The nine roundtables also elect members to represent them on the Interbasin Compact Committee (IBCC)—another legislatively defined group tasked with facilitating cross-basin discussion, education, and water planning.

Beyond establishing the roundtables and IBCC, the Act also set a vi-

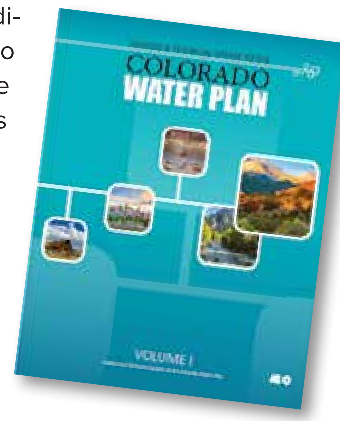
Navajo State Park. Photo courtesy of Colorado Parks and Wildlife.

sion for water planning at the grassroots level. The roundtables not only discuss water challenges, support local water projects through grant funding, and helps spur water planning by identifying needs and concerns. Similarly, the IBCC focuses on topics of state significance, such as an exercise that looked at possible future water/climate conditions and identified low-risk actions to prepare the state for those future conditions. Collectively, these efforts represented a foray into the scenario planning work that would form the basis for the Water Plan as well as helping establish the major focus areas in the plan (e.g., storage, conservation, watersheds, agriculture, etc.).

At the same time, on the heels of another dry winter 2012-2013, then-Governor John Hickenlooper took the unprecedented step to initiate the first Water Plan to further identify strategies that Colorado would need to meet its future water challenges. To complete this effort, each state's eight major river basins were tasked with producing a Basin Implementation Plan (BIP) in 2014. The BIPs used data to examine each basin's future water needs. They also identified projects and strategies for addressing those needs. The grassroots approach of the basin roundtables and the IBCC, combined with CWCB's commitment to collaboration, engaged hundreds of stakeholders across diverse sectors and regions, enabling citizens in each basin to share their vision for Colorado's water future. This effort provided a forum for building consensus and generated momentum towards forming the original Colorado Water Plan in 2015.

Recent Work

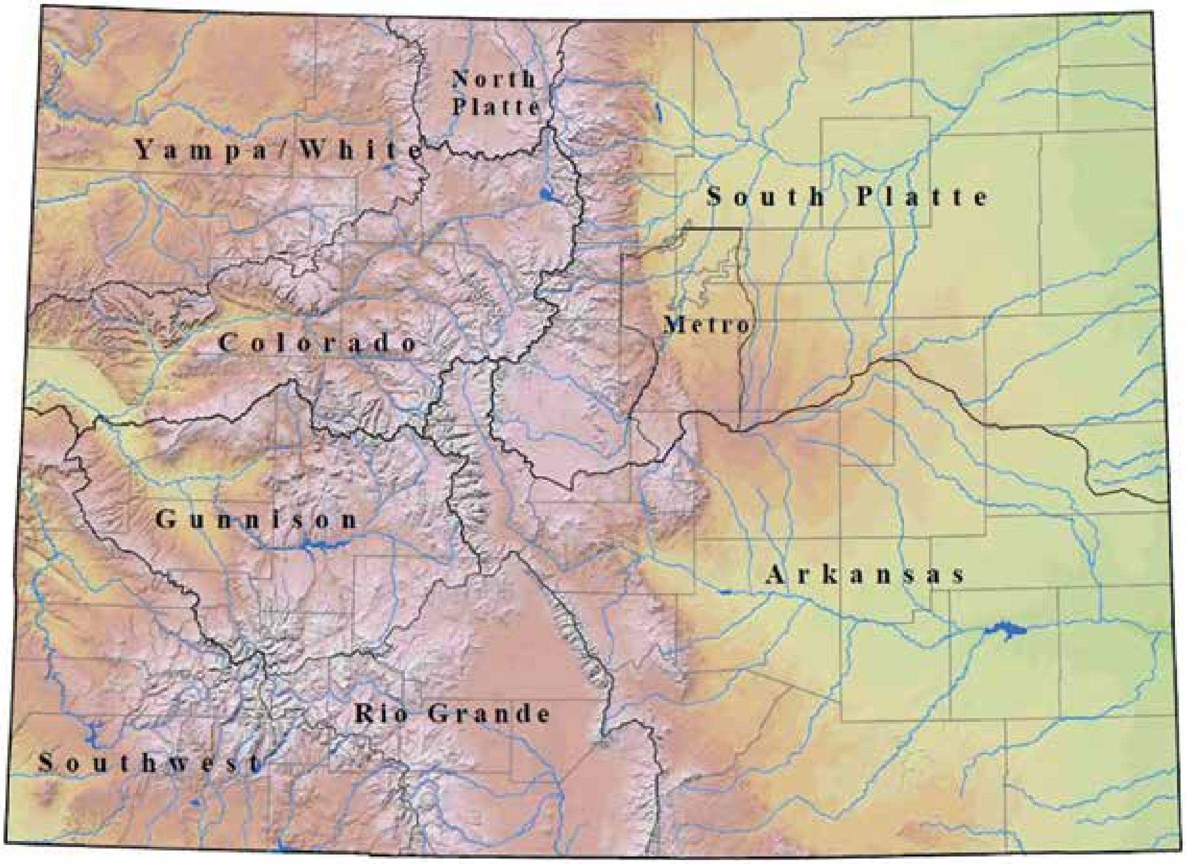
Following the release of the Water Plan in 2015, CWCB staff began using new data and state-of-the-art tools to develop the Analysis and Technical Update to the Colorado Water Plan (Technical Update). The Technical Update evaluated key drivers of future conditions—factors that stand to significantly change future water needs. These drivers include water supply and demand, economic growth, climate change, social values, and agricultural, municipal & industrial sector water demands. This refined modeling revealed that the most impactful drivers on future conditions were population growth and climate change, which allowed the CWCB to identify potential strategies, like conservation, to mitigate the worst of those impacts.



Of course, a range of mitigating actions are needed to meet our future water needs. Tools like conservation, storage, alternative transfer mechanisms (ATMs), stream restoration, and other future solutions often depend on local projects. Because the CWCB does not build projects directly, working to identify and support local efforts is critical. The roundtables are working now to revisit the original BIPs, including identifying any new basin strategies and updating project lists. This effort is central to meeting future water needs. The current basin planning will conclude at the end of 2021 and will support the Water Plan update to be released the following year.

Moving Forward

Building on the Technical Update and basin planning efforts, the Water Plan update will showcase the key themes of risk mitigation, adaptive planning, and protecting the Colorado way of life. These themes echo



In 2005, Colorado leaders passed the Water for the 21st Century Act to build transparent collaboration into state water planning. This created nine legislatively defined stakeholder groups called roundtables—one in each of Colorado's eight major river basins plus the Denver-Metro Region.

the original Water Plan values, including: (1) a productive economy that supports vibrant and sustainable cities, viable and productive agriculture, and a robust skiing, recreation, and tourism industry; (2) efficient and effective water infrastructure promoting smart land use; and (3) a strong environment that includes healthy watersheds, rivers and streams, and wildlife. The plan was a precedent-setting effort and has set a high bar for water planning across Colorado.

The legacy of work that built the first Water Plan provides context for today's effort, and the state is doubling down on the commitment to informed and collaborative planning that underscored the Water Plan from the start. CWCB staff are currently taking in feedback from stakeholders in advance of the forthcoming update. In January 2021, the CWCB announced an early vision for how the update might look, including a few concepts listed below:

» *Action-Focused:* The original Water Plan was organized around nine objectives with goals set for varying deadlines ranging out to 2050. This update will keep the same values of the original plan but re-orient them into four action areas that roughly align with cities (bit.ly/3esaFzZ), farms (bit.ly/3x3FK5p), streams (bit.ly/32moIRU), and planning (bit.ly/3syFoA1). Within these action areas, the plan will identify near-term steps (5-7 years) aimed at managing risks. These actions will collectively capture the spirit of the original Water Plan objectives while offering clear, actionable steps to manage Colorado's water wisely for the future.

» *Line of Sight:* The original Water Plan offered critical actions and objectives along with the history and context necessary to set the stage for such an unprecedented planning effort. The vision for the update includes streamlining the report and making it easier to see the line of sight between our values, action areas, and in turn, the actions recommended to achieve our long-term vision.

» *Increasingly Accessible:* While the original plan topped out at 540 pages, the update will include a two-volume format—one version concise and action-focused, and one version more explanatory of overarching concepts. Both Volume 1 and Volume 2 content will be available interactively online.

The Water Plan update will move into the drafting phase in Summer 2021 and will be finalized in 2022 after a robust public comment period.

CWCB encourages all Coloradans to learn more and share their input in order to ensure that voices from across the state are heard, incorporated into the Plan, and truly reflective of our state's collective vision for meeting future water challenges. To learn more, visit engagecwcb.org.

DIRTY SNOW

Turning Qualitative Assessments into Quantitative Factors for the Effect of Dust on Snow

Caroline (Rosie) Duncan, M.S. Student, Ecosystem Science, and Sustainability-Watershed Science, Colorado State University; **Dr. Steven R. Fassnacht**, Professor, Ecosystem Science and Sustainability-Watershed Science; **Jeffrey E. Derry,** Executive Director, Center for Snow and Avalanche Studies

Introduction

Water resources in Colorado depend primarily on snowmelt. The seasonal maximum of snow accumulation has a direct, downstream correlation to the amount of available water supplies. The Natural Resources Conservation Service (NRCS) and other agencies monitor the fluctuating amount of snow accumulation and collect daily measurements of snow water equivalent (SWE) to project total water content for monthly comparisons to previous years. This forecast of the absolute amount of water is critical, yet the anticipation of changes in melt rate is also necessary for efficient reservoir management. A variety of factors can change daily melt rates, including air temperature and the amount of solar radiation. This research project is primarily concerned with snow albedo, or the relative reflectivity of the snow surface, which determines the amount of incoming solar radiation absorbed by the snowpack. If the snow albedo is low due to dust or other particulates darkening the surface, then the amount of energy absorbed will be greater than a particulate-free snow surface, and the melt rate will increase. Our research objective is to develop a scaling factor quantifying the effects of buried dust layers on snow albedo to enable Colorado water resource planners to improve forecast changes in the rate of snow melt.

Background

Dust-on-snow occurs worldwide but is of particular concern in Colorado due to the combination of sunny winters, local dust sources, and snowmelt-dominated water supply. Most dust deposition events in the state occur in March and April, with each storm leaving a dust layer on the snow surface, which can then be buried by subsequent snow accumulation. In spring, the snowpack melts down to a buried dust layer, and the melt rate can increase suddenly due to the darker dust absorbing more solar energy than the previous layers of white snow. Dust-on-snow events were connected to faster melt rates and earlier snow disappearance as far back as 1913. National Weather Service staff at Wagon Wheel Gap, Colorado, theorized that a March dust deposition was responsible for the snow melting out a month earlier than average.

To better monitor continental alpine hydrology, an automated meteorological station was installed by the Cen-

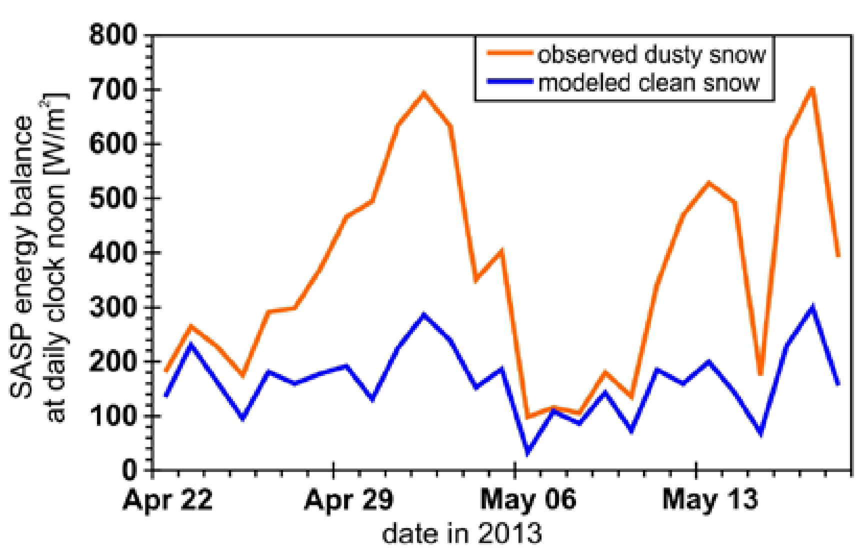


Figure 1. Comparison of dusty and clean net daily energy balances for the sub-alpine (lower elevation) automated tower from date of peak snowpack water content (April 22) to snow-all-gone (May 18). Three merged dust layers appeared at the snow surface on April 30 there was a light late-season snowfall in early May, and all remaining dust layers emerged in late May.

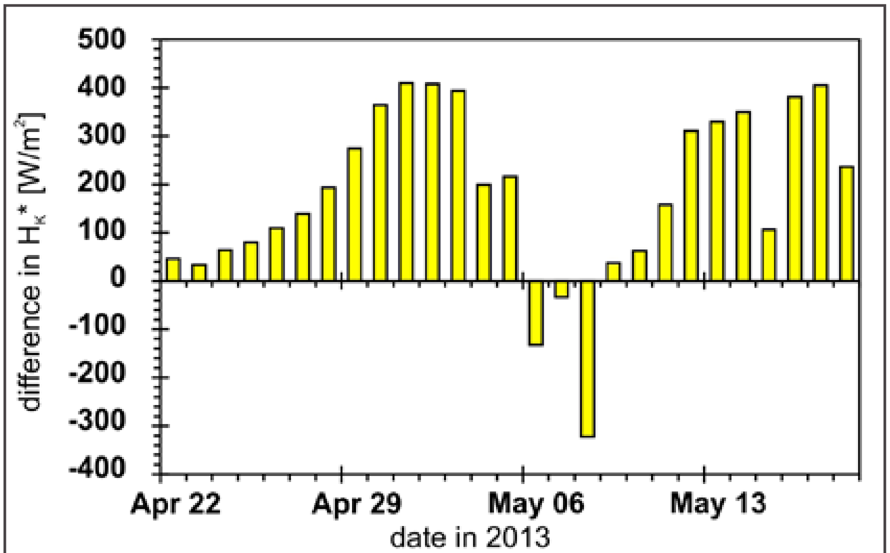


Figure 2. Net short-wave (HK) energy difference between actual and modeled snowpack for the sub-alpine tower. Positive difference implies greater energy absorption due to dust. Negative differences may be due to a late-season snowfall in early May which covered sensors and caused errors in albedo calculations.*

ter for Snow and Avalanche Studies (CSAS) in a small (<3km^2) high-elevation study basin near Silverton, Colorado, in 2005. This station collects hourly measurements of variables such as air temperature, snow depth, snow surface temperature, and wind speed. It also has paired radiation sensors that collect hourly measurements of incoming and outgoing radiation. This allows snow surface albedo (the ratio of outgoing to incoming radiation) to be calculated hourly. The automated tower data collection is supplemented by bi-weekly field observations of the snowpack during melt at ten additional locations (Figures 4 and 5 are two examples). These snow pit profiles record the location of dust layers within the snowpack, in addition to observations of snowpack characteristics such as depth, temperature, and structural evolution. Currently, CSAS issues a weekly report during the melt season with qualitative estimates of when dust layers will appear at the snow surface, based on weather forecasts and known dust layer locations. These point-based forecasts provide qualitative estimates that water resource planners such as the Colorado Basin River Forecast Center (CBRFC) attempt to quantify and distribute to make continent-scale streamflow forecasts. Our research has focused on translating CSAS qualitative assessments of melt rate into a quantitative factor that could be more efficiently used in larger-scale distributed hydrologic models.

Summary of Work Accomplished

Data Collection

Graduate student Caroline R. Duncan conducted three field site visits to established CSAS locations (Willow Creek, Berthoud Pass, and Hoosier Pass) to increase the temporal resolution of changes in snow characteristics (Figure 5). Daily National Oceanic and Atmospheric Administration (NOAA) weather forecasts were archived for the water year (WY) 2018 by undergraduate student Denna Martinez. The CSAS archive of discrete dust events (daily timestep, 2005-2018) was combined with the automated daily meteorological data collection archives for both study sites (2005-2018) to make future model simulations more efficient.

Data Analysis

The daily records for the low-elevation CSAS study site and Red Mountain Pass (Snowpack Telemetry) SNOTEL Station (NRCS) were compared for WY 2018 to inform our model development. Red Mountain Pass station is about 3km SE and 43m higher in elevation than the CSAS site and collects SWE measurements, whereas the CSAS sites only collect snow depth measurements. Understanding the amount of local variation in snowpack characteristics will allow broader distribution of point-based model results. Additionally, the snow's energy balance at the

CSAS tower was analyzed, focusing on the 4-6 weeks immediately preceding snow disappearance for WY 2013. This water year was selected since ten discrete dust events were deposited within the snowpack, which is the greatest number of dust events per accumulation season for the period of CSAS record (2005-2019). This large number of layers and amount of dust provided the strongest melt rate effect of dust-on-snow, and a "clean snow" model was run to compare net energy for clean snow and dust-laden snow (Figure 1 and 2). This model combined observed meteorological variables with a first-order decay equation to approximate the snow surface albedo under "clean" conditions. In cases where freshly deposited snow blocked sensors, manual adjustments were made to both the "dusty" and "clean" scenarios. Overall, we found that high concentrations of dust can increase the net energy available for late-season snowpack by hundreds of Watts per unit area (W/m^2). For example, immediately after a dust deposition event on May 1st, the lower-elevation site recorded a net energy balance of 400 W/m^2 higher than the modeled clean scenario (Figure 2).

Figure 3. Dr. Steven Fassnacht, Caroline Duncan, and Tyrus McLachlan surveying snow depth at Cameron Pass, Colorado in May 2019. Photo by Danielle Reimanis.

Figure 4. Center for Snow and Avalanche Studies Director Jeff Derry collecting snowpit profile data at Hoosier Pass in March 2019. Photo by Caroline Duncan.

Continuing Research

Our next research objective is to evaluate the range of additional energy input to the snowpack from dust-on-snow occurrences at the Silverton CSAS study site for WYs 2012-2019. The daily mean of these radiative forcing calculations will be compared to the total amount of dust present, the number of dust events, and the total amount of broadband irradiance recorded at the study site for each WY. We are trying to understand the relative effect of both dust concentration and melt season weather on the amount of additional energy absorbed by the snowpack. For example, is a high-dust year with predominantly cloudy days going to experience the same degree of shifts in melt rate as a low-dust year with mostly sunny days? Can we identify a principal driver of shifts in melt rate?

Additionally, we will use these energy calculations to model clean snowpack for WYs 2012-2019 and determine complete snow disappearance dates under "clean" conditions. These model results will facilitate comparisons with previous studies and allow us to determine interannual trends or variations. The difference in dirty snow and clean snow SAG dates can be combined with total seasonal SWE and our melt rate driver results to provide basic quantitative forecast results at coarse temporal resolution to water resource managers.

This project is supported by the Colorado Water Center from the U.S. Geological Survey and the Water Resources Research Act Program.

THE WATER PROBLEM

Historical Observations on Climate Change

Taylor Schulze, Undergraduate Student, Civil Engineering, Colorado State University, and Water Resources Archive, Colorado State University Libraries

WATER RESOURCES ARCHIVE

Center: Ralph Parshall with a gauge at a Parshall flume in 1946. From: The Ralph L. Parshall Collection, Water Resources Archive, Colorado State University Libraries at hdl.handle.net/10217/81845. Image ID: wrlp01204102

Background: The first page of Parshall's "The Water Problem" Rotary Club speech from 1956. From: The Ralph L. Parshall Collection, Water Resources Archive, Colorado State University Libraries at hdl.handle.net/10217/40928.

Climate change first became a national news story following James Hansen's June 23, 1988 testimony before the U.S. Senate Committee on Energy and Natural Resources. Hansen's remarks—particularly his statement that "the greenhouse effect has been detected, and it is changing our climate now"—propelled the issue of climate change into the public consciousness.

Remarkably, almost 32 years earlier, Ralph Parshall, the inventor of the Parshall flume, was also speaking out about the Earth's changing climate. On August 29, 1956, in a prescient speech on "The Water Problem" delivered to the Fort Collins Rotary Club, Parshall foreshadowed Hansen's message.

His talk begins: "About the beginning of the present century a change of climate and weather was in the making, but at that time the change was not noticeable and such variations were assumed to be the usual and natural fluctuations of the warm and cold or wet and dry years." In hydrology, the idea that mean values of hydroclimatic variables such as temperature and precipitation remain steady over time despite year-to-year fluctuations is known as stationarity.

At the time of his talk, Parshall, a 75-year-old retired irrigation engineer and former Colorado Agricultural College (now Colorado State University) Professor, clearly understood that the assumption of stationarity was no longer valid. This fact had Parshall expressly concerned about the impact of a changing climate on Colorado's water supply. He observed: "Our weather is changing and unfortunately in the wrong direction. Only during the past few years have we become conscious that something is going wrong, and each year, especially just at present, we are becoming more alarmed about our water supply. In view of what is known at present, we can conclude that mean temperatures are increasing, and precipitation is decreasing."

Having lived much of his life in Colorado, Parshall was uniquely well-positioned to survey the development of these alarming changes. Born July 2, 1881, in Golden, Colorado, he grew up in the state and spent the majority of his adult life in the Fort Collins area. He worked for over three decades as an irrigation engineer for the U.S. Department of Agriculture (USDA) Soil Conservation Service (now the Natural Resources Conservation Service, then housed at Colorado Agricultural College.

Sixty-four years later, part of what makes Parshall's talk so remarkable is its wide-ranging scope and foresight. His knowledge of the regional, national, and global impacts of climate change on water is compelling. His insight into the water problems facing Colorado and the arid West then and now is striking.

Looking back on his childhood and college years, Parshall draws on his "personal experience to indicate that we now have a very different climate from that of 50 years ago." As a young boy on the family ranch 16 miles west of Golden in the 1890s, he recalls "lush crops" grown without irrigation through dryland farming. He laments that this former abundance is "a thing of the past," something that would not be possible in 1956, given climatic changes.

As a college student in Fort Collins at the turn of the twentieth century, he remembers a climate "much the same as at my mountain home—cold with considerable snow and ice." Back then, it was commonplace to skate on Sheldon Lake (also known as City Park Lake) and other ponds throughout the City from Thanksgiving until late February. Fifty years later, he observes that the local lakes do not freeze enough to skate on until "the Christmas holidays or some time in January and then only for a short time."

Next, he turns to the global situation in the 1950s. Here, he comments on both the "rise in ocean temperatures'' and the "biological aspect" of climate change. Many aquatic and terrestrial species, he remarks, are "drifting northward" as warming occurs. He also makes note of phenomena that will sound immanently familiar to many of us today: "The arctic ice cap is gradually being dissipated to cause a rise in the sea level, the glaciers are retracting in some areas… [and] on the whole melting exceeds ice accumulation." Parshall recognizes these trends as indicators of climate change.

Shifting his attention from worldwide trends back to Colorado's water and climate, Parshall goes on to describe "what is happening in our immediate area." He continues, "A brief inspection trip down the South Platte Valley to Fort Morgan a few days ago revealed a rather startling water supply situation"—diminishing return flows to the South Platte River.

Return flow is water that returns to a river after being used for irrigation. As return flows decrease, stream flows dwindle, and reservoirs are being depleted earlier in the growing season. He links the disappearance of return flows with the rise of groundwater pumping along the South Platte River. At the time, "more than 4,000 irrigation wells" along the River between Kersey and Julesburg were being pumped at a volume large enough to fill Horsetooth Reservoir four times over. For Parshall, it is evident that irrigators "cannot continue this practice of depleting the underground reservoir at the present rate." He foresees the need to better manage groundwater resources as a bulwark against the increasing unpredictability of surface water availability in light of climate change.

Noting these unsustainable practices, Parshall can forecast how disconcerting water supply trends will be magnified by population growth.

Ralph Parshall demonstrating water measurement at a Parshall flume in 1946. From: The Ralph L. Parshall Collection, Water Resources Archive, Colorado State University Libraries at hdl.handle.net/10217/81845. Image ID: wrlp01204108

While Colorado's population grows "at a steady pace," the water supply is "gradually dropping." This divergence amounts to a "serious situation," one which Coloradoans are still grappling with to this day: "People are on the move to live in Colorado, farmers are to be supplied with water, industry is expanding to use more water, and we are going down hill on water supply." Parshall understands that the growing demand for water presents a complex set of challenges, particularly in light of climate change.

As he approaches the end of his talk, Parshall asks, "What are we going to do about this problem?" From his vantage point, a clear answer to this question remains elusive. He notes that while "many theories have been advanced as to the cause of the change in weather," a better understanding of its causes is still needed before the issue can be effectively addressed.

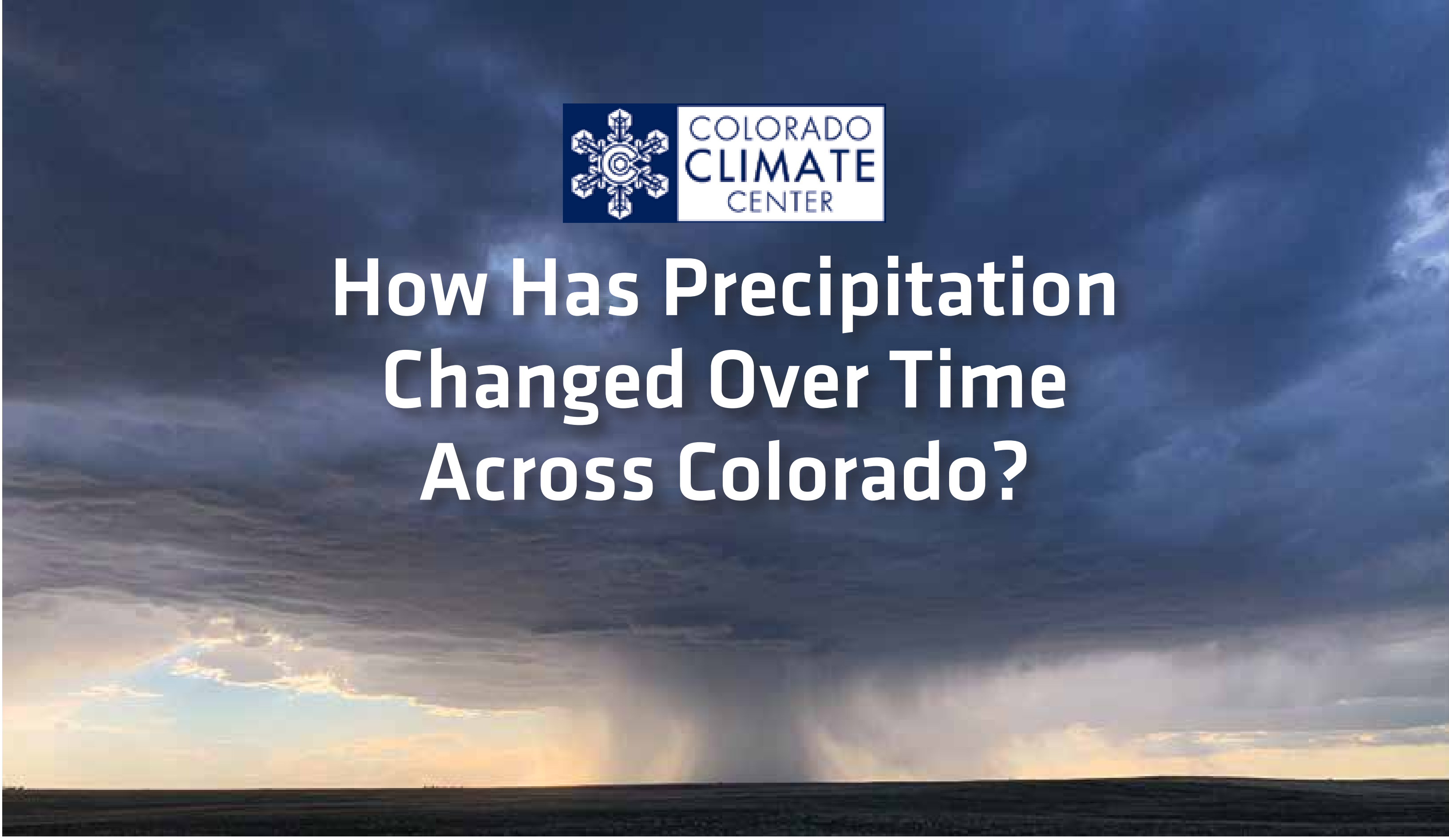
Parshall concludes his remarks with this arresting passage: "Carbon dioxide gas in the atmosphere is at present a tremendous quantity, 235 billion tons. We are now adding 10 billion tons per year. Every time you drive your car around the block, you make a contribution of this gas to the atmosphere. This gas, together with ozone, water vapor, and other gases at high altitude retards the radiation of heat from the earth's surface, which increases the temperature of the air somewhat in the nature of the glass roof on a greenhouse. These various natural effects have been known for a long time, but since man has little or no control, we can only bend our efforts in the direction of safeguarding ourselves in the best possible manner. At the moment, there does not appear to be a solution to this problem."

When one considers Parshall's comments about carbon dioxide and the greenhouse effect in a historical context, his observations foretell what it would take several more years for scientists to confirm. In 1958, Charles David Keeling began his systematic study aimed at measuring atmospheric carbon dioxide concentrations on Mauna Loa in Hawaii. The groundbreaking data he collected is widely regarded as the first definitive evidence that human activity is changing the composition of the atmosphere and having an effect on climate.

Today, we have reason to be more optimistic about solving the problem than Parshall appears to have been in 1956. Technological advancements and international agreements are signs that human beings are finding ways to adapt and respond to the challenges posed by climate change. Here in Colorado, the 2015 Colorado Climate Plan provides a framework for increasing the state's resilience to climate change across multiple sectors, water among them.

In its own way, Parshall's talk stands as a precursor to these positive developments. By raising awareness about the emergence of climate change and its impact on water, he inspires us to think beyond the here and now about the world that future generations will inherit.

More information about Ralph Parshall, water, and climate in Colorado is available at the Water Resources Archive website (lib.colostate.edu/archives/water/). The Archive is home to both the Ralph L. Parshall Collection and the Irrigation Research Papers, a collection documenting his research team's work in irrigation engineering. It is also home to the Colorado Climate Data Collection, which contains more than 130 years of climate data. To find the full text of Parshall's "The Water Problem" speech, go to hdl.handle.net/10217/40928



How Has Precipitation Changed Over Time Across Colorado?

A thunderstorm makes its way across the Eastern Plains of Colorado. Photo by Emmett Jordan.

Dr. Becky Bolinger, Assistant State Climatologist, Colorado Climate Center

Introduction

Climate change in Colorado has become quite evident in temperature observations. But the effects of climate change on precipitation in Colorado remain uncertain (Lukas et al., 2014). While statewide average temperatures have increased dramatically since 1895 (with the most notable increases since 1985), statewide precipitation has been much more variable (Figure 1). The recent wet periods during the 1980s and 1990s can be seen, and a downward shift since the turn of the century. With that downward shift, the three driest years on record have happened since 2000 (2002, 2012, and 2020). While research has suggested that these frequent dry periods in Colorado (and the Southwestern United States) have experienced part of aridification or a megadrought (Udall and Overpeck, 2017; Williams et al., 2020), we do not yet know what to expect for future precipitation. The goal of this study is to analyze less obvious precipitation behaviors and changes over the last 120 years and what the implications of these changes might mean for Colorado.

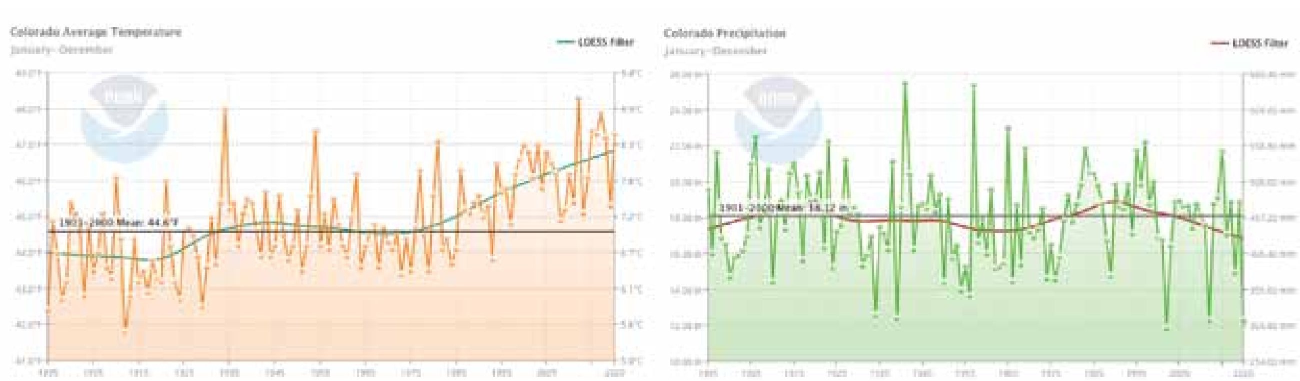


Figure 1. Colorado statewide averaged annual temperature (left) and precipitation (right) from 1895 to 2020. Also plotted – 1901-2000 mean (black line), and lowess fitted curve (green for temperature, maroon for precipitation).

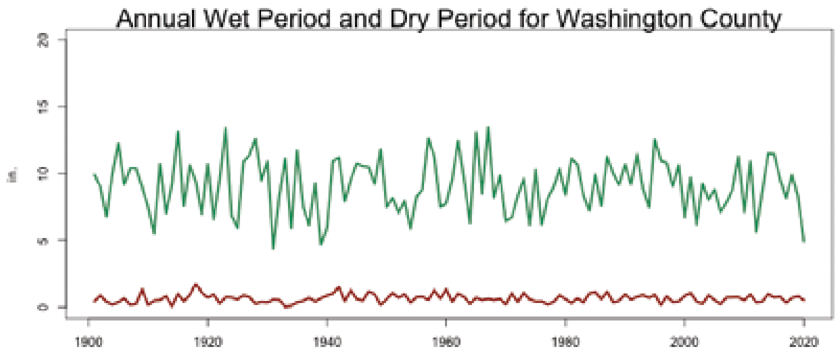


Figure 2. Annual wet period (wettest three months in the year) in green and dry period (driest three months in the year) in maroon, for Washington County, Colorado for 1901-2020.

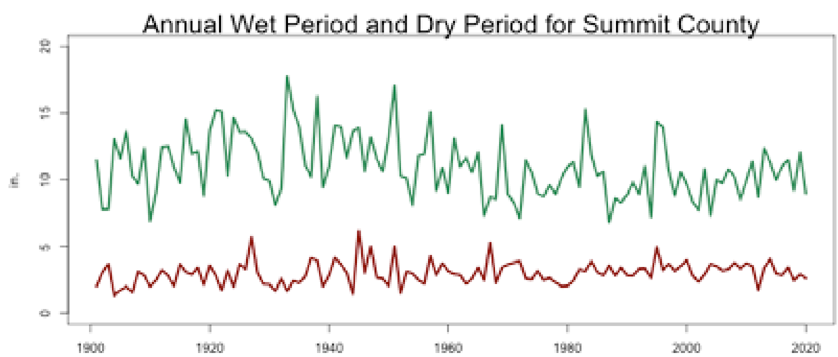


Figure 3. Annual wet period (wettest three months in the year) in green and dry period (driest three months in the year) in maroon, for Summit County, Colorado for 1901-2020.

The view as seen from Quandary Peak in Summit County. ©iStock.com

Precipitation Behavior

Many climate change studies focus on trends in annual temperature or annual precipitation across a region (Frankson et al., 2017). When focusing on precipitation over Colorado, it is important to remember two things—first, precipitation does not fall uniformly throughout the year; and second, different locations around the state have different seasonal cycles.

To assess the spatially and temporally different behaviors of precipitation across the state, I am defining wet months and dry months for every county, based on data from the National Oceanic and Atmospheric Administration (ncdc.noaa.gov/cag). In a given year, the wet period is the sum of accumulations for the top three wettest months, and the dry period is the sum of the lowest three accumulating months. The months within each period can change from year to year.

Figure 2 shows the wet period and dry period for Washington County (northeast Colorado) from 1901—2020. In most years, the dry period (i.e., driest three months) totals less than 1 inch of moisture (the maroon line in Figure 2). There is a lot more year-to-year variability in the wet period, which mostly ranges between 8 and 10 inches. Washington County displays a relatively strong seasonal cycle—there can be 10 to 20 times more moisture in the wettest three months than in the driest.

Figure 3 shows the wet and dry periods for each year for Summit County (north-central Colorado). The most significant geographic difference between these counties is elevation—Summit County is mostly mountainous and west of the Continental Divide. The differences between the wet and dry periods are not as large in Summit County. On average, the dry period is around 3 inches and the wet period has an average of 10 inches. Summit County does not have as strong of a seasonal cycle. Most of the time, the wet period gets less than 5 times as much precipitation as the dry period.

In Figure 4, we look at the ratio of wet to dry periods around the state, averaged over 1991-2020. The darkest colors are the lowest ratios between wet and dry periods, and the lightest colors highlight the largest ratios. Let's go over some of the patterns emerging from this map.

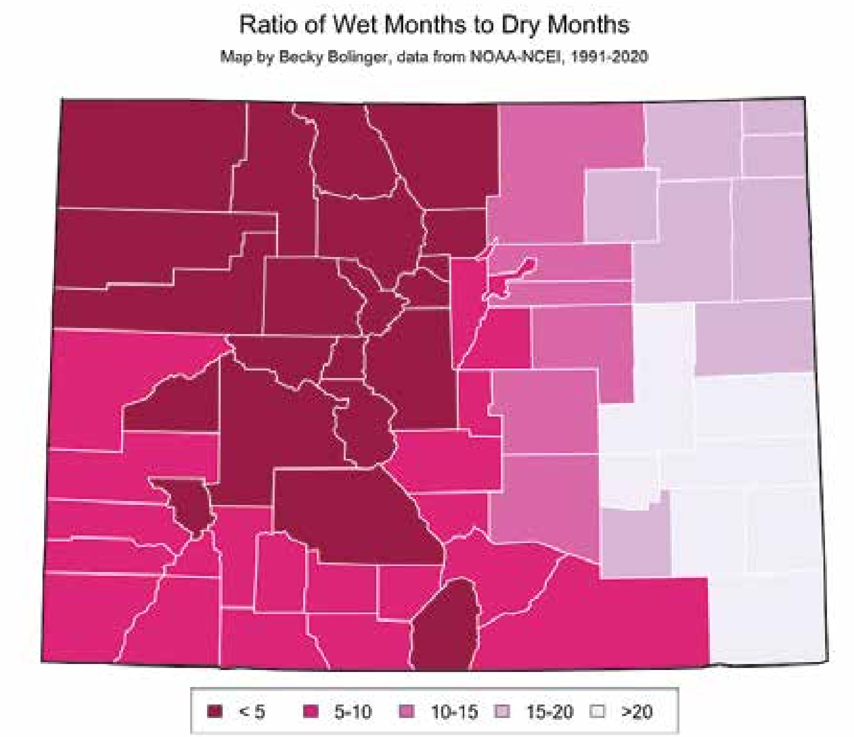


Figure 4. Average wet period divided by dry period for 1991-2020 for every county in Colorado.

Northwest Colorado

The lowest ratios spread across northwest Colorado and south along the Continental Divide counties. For these areas, it is harder to define a "wet season." The highest elevations of these counties likely moderate the seasonal variability. These counties are generally the wettest counties in the state. Every month has the potential to make a drought or break a drought.

Southwest Colorado

With a little more seasonal variability than to the north, these counties typically experience a wet period that is 5-10 times greater than the dry period. This region experiences two distinct wetter time periods—one during the winter season and also a monsoon season in the late summer and early fall. But the lower elevation dry periods may act to enhance the seasonal variability compared to northwest Colorado.

Central Plains Transition

From Weld County south to Pueblo County, this region is the transition from the mountain counties to the lowest elevation plains counties to the east. The seasonal variability also begins its transition here from the lower variability to the west and the higher variability to the east. The ratio between wet and dry periods is 10:1 to 15:1.

Northeast Colorado

Focused on the heart of the South Platte River valley, the counties in northeast Colorado experience high seasonal variability. Without the high elevation snows, winter precipitation is low. And far from the influence of the monsoon to the southwest, late summer precipitation is a bit more hit and miss. For this area, spring moisture dominates the annual precipitation totals. The wettest three months are 15 to 20 times greater than the driest three months.

Southeast Colorado

This region of the state is probably the most volatile, climatically speaking. The area, following along the Arkansas River Valley, is the lowest elevation, the hottest in the summer, and has the most variable seasonal cycles. For these counties, they get 20 (or more) times as much precipitation in their wettest months than their driest months. For this very brief period of wet weather, there is little margin for error in getting the moisture needed for the entire year.

Trends in Wet and Dry Periods

Are there trends in those wet periods and dry periods? Figure 5 shows the sign of the trend in the driest months, and Figure 6 shows trends for the wettest months. Trends were calculated over 120 years (1901-2020), where each year is the sum of 3 months of precipitation (the driest 3 months and the wettest 3 months). Using the Mann-Kendall Trend Test, we can detect increasing or decreasing trends and identify if the trend is significant or not. For both Figures 5 and 6, increasing trends are noted in green and decreasing trends are yellow. Focus on counties that are dark green for significant increasing trends and maroon for significant decreasing trends. The most interesting thing to note is there are only significant increasing trends in the dry periods, and there are only significantly decreasing trends in the wet periods.

Dry Period Trends

Seventeen counties show a significant increasing trend in their dry period totals. With the exception of one, all of the counties contain high elevation mountains. Also interesting, many of these counties comprise the

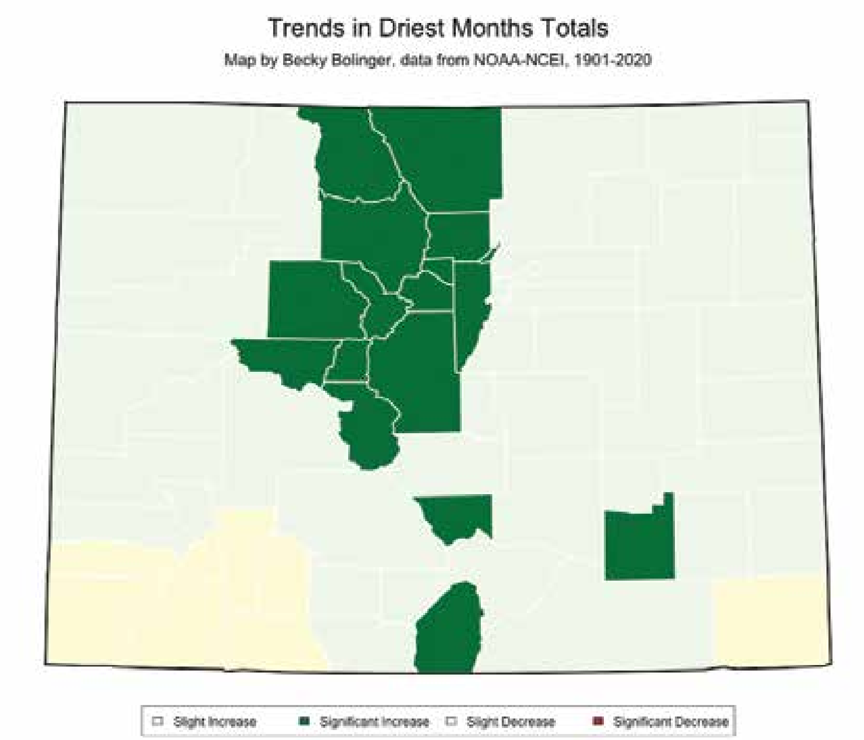


Figure 5. Positive (green) and negative (yellow) trends using the Mann-Kendall trend test on the driest months from 1901-2020 for every county. Counties in dark green exhibited a significant positive trend in their driest months.

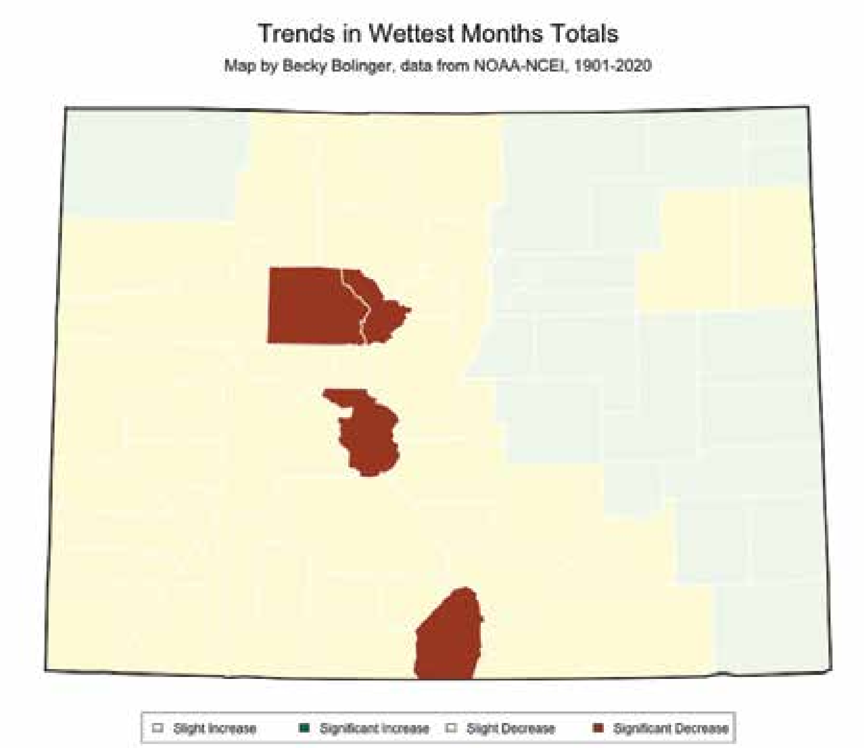


Figure 6. Same as Figure 5, for the wettest months. Counties in dark red exhibited a significant negative trend in their wettest months.

headwaters of major rivers, including the North Platte, South Platte, Colorado, and Arkansas Rivers.

Figure 7 shows the monthly average precipitation for Grand County (where the headwaters of the Colorado River are located). As expected, there is not a lot of variation between the months. Each month's precipitation contributes about 8% to the annual total, on average. When analyzing each month over time, no detectable trends are apparent. In Figure 8, there is an increasing trend, although significant, is not a very large trend.

Wet Period Trends

Focus on the counties with significant trends in Figure 5 when looking at Figure 6—note that with this significant increasing trend in precipitation in the dry periods, they are also experiencing a decreasing trend in the wet months. For most of the counties, this is not a significant trend. Four counties show a significant decreasing trend in wet periods (Figure 6) and show a significant increasing trend in dry periods.

Figure 9 shows the wet and dry periods over time for Costilla County (southern Colorado), with trend lines added for each. It is clear that the ratio between the wettest and driest months is decreasing.

Conclusions

Combining both of these trends, we can hypothesize that the seasonal variability in these counties is decreasing, with precipitation becoming more evenly distributed and uniform throughout the year. What are the implications of these trends? It is difficult to say with certainty, but one critical point should be mentioned: In these regions, the wettest months tend to occur during the cold season and the drier months during the warm season (Doesken et al., 2003). Even without changes in annual precipitation, with an increase

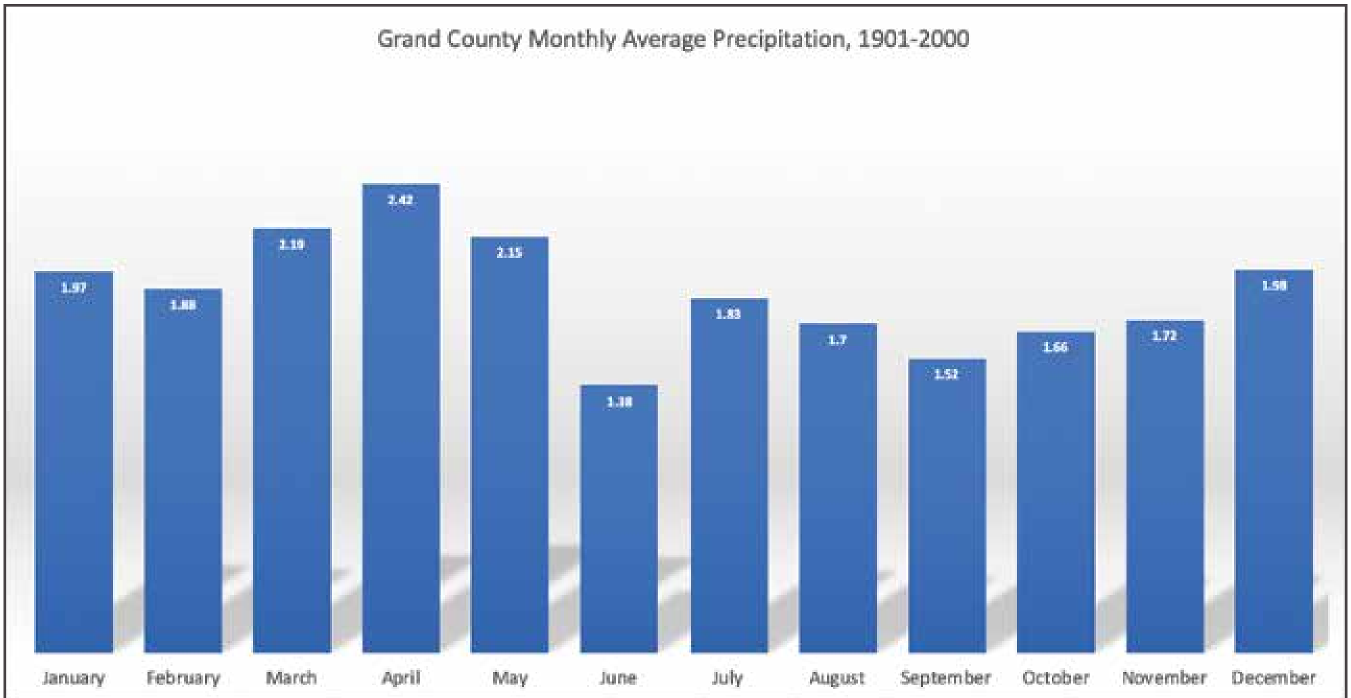


Figure 7. The seasonal cycle of precipitation for Grand County, Colorado. Average precipitation for each month calculated from 1901-2000 data.

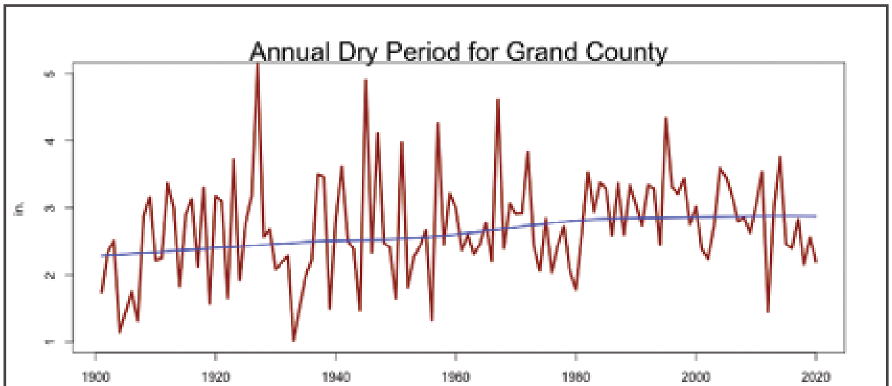


Figure 8. Annual dry period for Grand County, 1901-2020. Lowess fitted curve in blue.

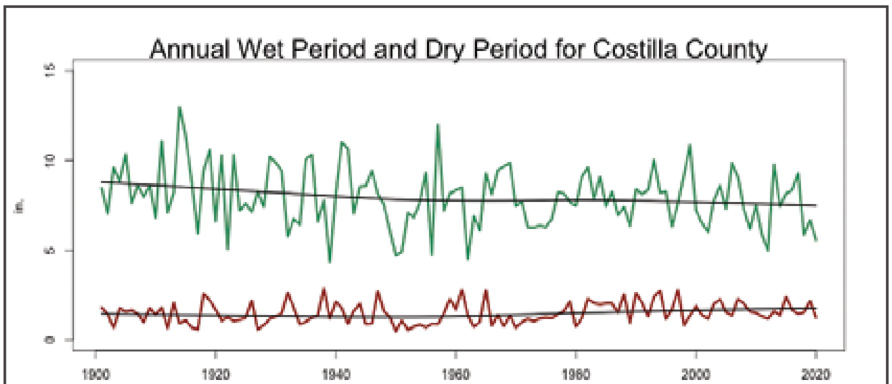


Figure 9. Annual wet period (green) and dry period (maroon), for Costilla County, 1901-2020. Lowess fitted curves added for both wet and dry periods.

in moisture during the dry months and a slight to significant decrease in moisture during the wet months, there is less opportunity for the moisture in these areas to manifest into useable water supply (i.e., snowpack to streamflow to reservoir, Barnett et al., 2005). A recent study by Julander and Clayton (2018) in Utah found that the majority of streamflow in Utah watersheds originated from melting snow. During low snow years, more annual precipitation did not produce the same streamflow. Given the similar climate and geography between Utah and Colorado, we can expect the same results here.

Regardless of how we analyze precipitation, what the future holds for Colorado's precipitation with a changing climate remains uncertain. One key takeaway from this study is that how precipitation falls throughout the year is changing. Despite the uncertainty in precipitation trends, our warming climate and changes in precipitation behavior will ultimately play a large role in our future water supply.

Climate Change and Forest Regeneration

What to Expect and Where to Go

Dr. Ethan Bucholz, Academic Liaison and Experiential Learning Specialist, Colorado State Forest Service, Warner College of Natural Resources, Colorado State University; **Dr. Amanda West Fordham,** Associate Director, Science, and Data Division, Colorado State Forest Service, Warner College of Natural Resources, Colorado State University

Climate change represents a persistent challenge to forest health and regeneration in Colorado, which presents an increasing threat to the ecosystem services that forests provide, such as water quality and quantity. Currently, rising temperatures and cumulative drought—and associated increases in insect and disease outbreaks and uncharacteristic wildfires—are increasing tree mortality.

This is especially important given the connection between water supplies and forests. Water is stored in forest soils, where tree roots collect and filter rainfall and runoff. Some of the water is taken up by trees and transpired through the leaves, which influences precipitation timing and quantity. Trees also influence snowpack dynamics and melt, affecting trees' survival in drier periods before spring and summer rains. In recent decades, the extent of wildfires has increased in Colorado, and the length of the wildfire season has increased with the changing climate. The loss of vegetation and potential for hydrophobic soils after high-severity wildfires can increase the risk of post-fire flooding, erosion, and heavy sediment loads, which can degrade water supplies.

Colorado's forested watersheds are the headwaters of four major rivers: the Colorado, Rio Grande, Arkansas, and Platte. The 2015 Colorado Water Plan indicated that approximately 80% of Colorado residents rely on forested watersheds to deliver municipal water supplies, and Colorado's forested watersheds provide water to Colorado, 18 other states, and Mexico.

Based on aerial detection survey data collected by the Colorado State Forest Service (CSFS) and the U.S. Department of Agriculture (USDA) Forest Service, more than 20% of Colorado's forests have been impacted by bark beetles since the year 2000, leaving millions of acres of standing dead trees (Figure 1). Additionally, between 2000 and 2019, 450 wildfires greater than 100 acres in size impacted approximately 1.8 million acres (Rocky Mountain Area Coordination Center). Of the ten largest wildfires in recorded state history, seven have occurred since 2010. Three of these were late-season fires in 2020, one of the hottest, driest years on record in the west. Climate change is increasing the frequency and severity

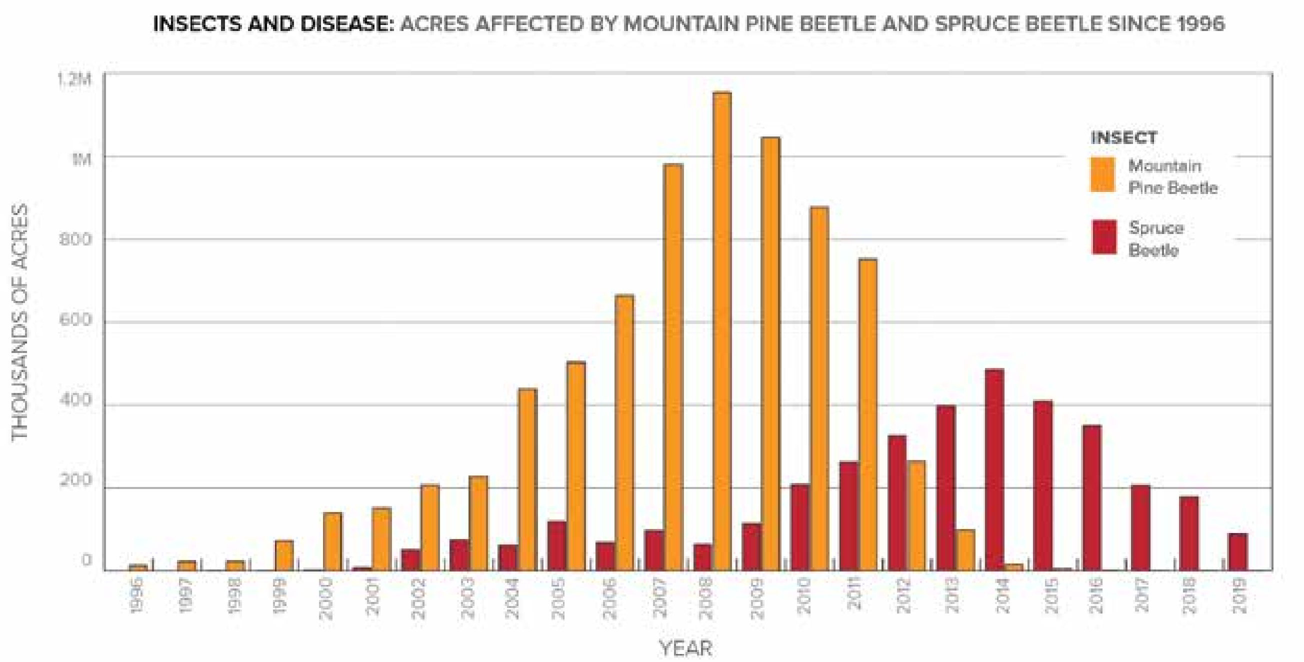


Figure 1. Acres affected in Colorado by mountain pine beetle and spruce beetle, as determined by aerial detection surveys conducted by the USDA Forest Service and Colorado State Forest Service. Graphic by Dan West, Colorado State Forest Service.

West of Grand Lake, only a house foundation and charred trees remain after the 2020 East Troublesome Fire. The second largest wildfire in state history left thousands of dead trees in critical watersheds along the Colorado River. Photo by Zach Wehr, Colorado State Forest Service.

of forest disturbances in some ecosystems and changing the seasonality of these events. Increased temperatures can stimulate faster generation cycles of bark beetles, and drought negatively impacts tree vigor, making forests more susceptible to outbreaks (Bentz et al,. 2010). Decreased winter snowpack and higher temperatures result in earlier melting; this coupled with cumulative drought is altering natural fire regimes across the west (Westerling et al., 2006).

One aspect of these disturbances needs more attention moving forward: forest recovery and regeneration. The regenerative abilities of forests, both natural and artificial (i.e., seedlings grown and then later planted), are challenged by changing climatic conditions and by the alteration of forested stands due to disturbance. Applied research in cooperation with forest managers offers a way forward to address these challenges—and ensure Colorado's forests continue to provide clean water.

Bark Beetles and Forest Recovery Trajectory

Bark beetles are native pests to Colorado forests. Since they target weakened trees, they can aid in forest thinning for areas where management is lacking. However, climate change and insufficient forest management couple to create drought-stressed, dense forest stands that put them in a "danger zone," enabling more intense bark beetle outbreaks with high levels of tree mortality. This demonstrates the complex manner in which management and disturbance interact. Simulated studies of recovery following mountain pine beetle outbreak in lodgepole pine forests demonstrate the importance of advanced regeneration (regeneration that establishes beneath a live overstory) in aiding the recovery of forests (Briggs et al. 2015; Kayes and Tinker, 2011). Therefore, management actions to promote and enhance tree regeneration are critically important.

Other studies agree with the importance of management considerations in forest recovery following bark beetle outbreak. Windmuller-Campione et al. (2015) found forest management strategies promoting spruce regeneration to be successful in increasing resilience to spruce bark beetle mortality. Post-mountain pine beetle outbreak stands in Fraser Experimental Forest, Colorado, differed in trajectory depending on management; stands harvested following mortality showed higher abundances of lodgepole pine and aspen, whereas those left untreated were dominated by subalpine fir (Collins et al., 2011). Therefore, management post-outbreak may help promote both species and age diversity within Colorado forests, reducing homogenous conditions that contribute to future beetle outbreaks.

The variables that control regeneration can change with bark beetle outbreaks. Recent research from Pettit et al. (2019) indicated that Engelmann spruce regeneration before a spruce bark beetle outbreak was driven by competition with overstory trees, while post-outbreak spruce regeneration density was driven by high summer soil moisture content. This indicates that forest structure and climate interact with disturbance to produce viable regeneration. Similarly, Carlson et al. (2020) found spruce regeneration decreasing since the outbreak, and suggested the loss of overstory seed sources, as well as drought and warming, impacts seedling success. To promote forest health and thereby bolster their ecosystem services, such as improved water supplies, the physical characteristics within a forested stand, as well as the manner in which disturbance alters climatic conditions, must be considered to facilitate regeneration.

Wildfire and Forest Regeneration

Some wildfires have positive impacts on Colorado's forests, stimulating regeneration. In others where tree mortality is high, and slopes are steep, rates of erosion and sedimentation in streams increase, negatively impacting downstream water quality. The 1996 Buffalo Creek Fire and the 2002 Hayman Fire cost Denver Water more than $27.7 million for restoration and repairs to its collection system, due largely to sedimentation. The Hayman Fire shocked the state of Colorado as it was the largest wildfire in recorded state history at the time. Both the size of the wildfire and the intensity with which it burned during the drought of 2002, foreshadowed the altered fire regimes Colorado has experienced since that time. Looking at the Hayman Fire burn scar today is important; forest recovery has been slow over the past 20 years, and the future is uncertain.

There are numerous factors influencing forest recovery following wildfire. These include proximity to surviving forests (Chambers et al., 2016), changes to annual moisture content (Stevens-Rumann et al., 2018), elevation, slope, aspect, and plant competition. Davis et al. (2019) studied regeneration in 33 wildfires across the western U.S., finding climatic conditions conducive to regeneration success becoming more infrequent over the past three decades. These studies provide information to forest managers on where to prioritize planting post-fire and which species and genotypes should be considered based on climatic conditions to improve seedling success. Considering the fine-scale climatic changes across current tree species' ranges is important in determining what and where to plant moving forward in the future—targeted reforestation can improve seedling survival and forest resilience following severe wildfires.

Where Do We Go From Here?

Increasing collaboration between researchers and forest managers is essential to addressing the compounding effects of climate change and disturbance on forests and the ecosystem services they provide. For example, Coop et al. (2020) synthesizes research to evaluate regeneration success and failure in fire scars, providing a tool that can be integrated into land management decisions. With climate change, forest managers also need to understand that tree species have limited options in terms of their ability to persist in a given area. Assisted migration (Aitken et al., 2008) and assisted gene flow (Aitken and Whitlock, 2013) are two ideas that can facilitate seedling success. Assisted migration focuses on human-assisted movement of species into areas currently outside their zone of compatibility that are likely to be suitable habitat in the future. Assisted gene flow aims to protect existing species' ranges by introducing specific individuals that carry beneficial genes for tolerance to specific disturbances, which helps future populations adapt through sexual reproduction with these genetic introductions.

Mike Till, a Forester with the Colorado State Forest Service, plants a seedling as part of a reforestation effort near La Veta in 2020. Photo by Luke Cherney, Colorado State Forest Service

By considering the trade-offs of different management actions and planning for future potential climate and disturbance, forest managers can leverage different scientific concepts into their toolbox to improve regeneration success in Colorado's forests. Long-term experimental trials, such as adaptive silviculture for climate change (ASCC—see Nagel et al., 2017), bring land managers and scientists together to discuss management goals and develop management strategies to both maintain and provide for adaptive responses within different forested systems. The Colorado State Forest Service is collaborating with the CSU Forest and Rangeland Stewardship Department, Northern Institute of Applied Climate Science, Colorado Forest Restoration Institute, USDA Forest Service, and Colorado Parks and Wildlife on an ASCC study at the Colorado State Forest near Walden.

The 2020 Colorado Forest Action Plan (Colorado State Forest Service; csfs.colostate.edu/forest-action-plan/) outlines goals, strategies, and approaches for climate-adaptive forest management that can be employed to address the impacts of climate change to forest health, including regeneration. As we move forward, researchers and managers must work together to monitor successes and failures of new approaches that address persistent challenges to forest health and regeneration in Colorado—and the ecosystem services that forests provide, including clean water.

The CSU Climate Adaptation Partnership

Connecting Research and Policy to Address the Challenges of Living with Climate Change

Dr. Courtney Schultz, **Dr. Leisl Carr Childers, Dr. Niki vonHedemann,** and **Tamera Breidenbach,** Colorado State University; Climate Adaptation Partnership for Policy Innovation and Research Coordination

Addressing Climate Adaptation

Climate change presents profound and unprecedented challenges in navigating the human-environment relationship. For decades, social and political leaders have focused on reducing greenhouse gas concentrations, or "mitigating" climate change, with the hope that society could forestall significant warming. It is now apparent that the increase in average global temperatures will very likely exceed 2°C even with aggressive mitigation (Intergovernmental Panel on Climate Change, 2018). The Intergovernmental Panel on Climate Change (IPCC) predicts that crossing this threshold makes it much more likely that the Earth's natural environments and human communities will experience catastrophic effects (Intergovernmental Panel on Climate Change, 2018). As a result, there is an urgent, growing need to focus more on climate "adaptation," or "the process of adjustment to actual or expected climate and its effects" (Intergovernmental Panel on Climate Change, 2014).

We are forming a Climate Adaptation Partnership (CAP) for Policy Innovation and Research Coordination at Colorado State University (CSU), in partnership with other campus entities, including the Colorado Water Center (CoWC). Our primary aim is to coordinate and cultivate dialogue among researchers and policymakers to address the grand challenge of how social and ecological systems can successfully adapt in the face of climate change. Specifically, we will: 1) coordinate research to form high-capacity, interdisciplinary teams to pursue unique fundraising and research opportunities related to climate adaptation, and 2) train researchers to engage more effectively with federal and state policymakers to increase the relevance of our work and our ability to respond to policymakers' needs. CSU lacks an identifiable home for climate adaptation research and outreach. While adaptation research is conducted by individual researchers doing outstanding work across campus, unlike other major land grant universities, we have no climate adaptation center. Given that adapting to climate change is the most pressing challenge of our era, this is a gap that we seek to fill.

Climate adaptation is an issue that requires interdisciplinary, applied research that is policy relevant. Climate-driven disturbances (e.g., heat waves, wildfire, floods, hurricanes, drought, and insect/disease outbreaks) and their interactive effects are increasingly disruptive to global social and ecological systems, with disproportionate impacts falling on economically disadvantaged and socially marginalized people (Davies et al., 2018; Millar & Stephenson, 2015). The 2020 wildfire season in Colorado and across the West demonstrates that climate-driven disturbances are happening now, threatening ecosystems, water resources, infrastructure, and human health (Gonzalez et al., 2018). With proper preparation, these events can present opportunities to improve the ability of both social and ecological systems to persist in the face of disturbance, ideally in ways that increase equity and access for historically disadvantaged community members to promote social justice (Gonzalez et al., 2018; Buma & Schultz, 2020; McWethy et al., 2019; Schultz, & Moseley, 2019; Hassan & Mahmoud, 2020). Communities need strategies to rapidly adapt to changing conditions, and policymakers at all levels must address these issues immediately.

Addressing Climate Adaptation with Diverse Expertise

An interdisciplinary perspective is crucial to effectively tackling climate adaptation, in light of the complexity and diversity of impacts to our social and ecological systems. Building as we grow and based on our team's expertise, the CAP will focus across five areas of research: 1) climate adaptive public land policy and management, particularly around wildfire management; 2) strategies to support healthy air and watersheds; 3) integrated modeling systems that address social and ecological change over appropriate spatial and temporal scales; 4) climate adaptive agriculture and food security; and 5) social and environmental justice to create thriving, inclusive communities in the face of the impacts of climate and demographic change.

Our founding CAP team members, all at CSU (see research.colostate.edu/cip/cap/ for a complete list), approach climate adaptation through their diverse

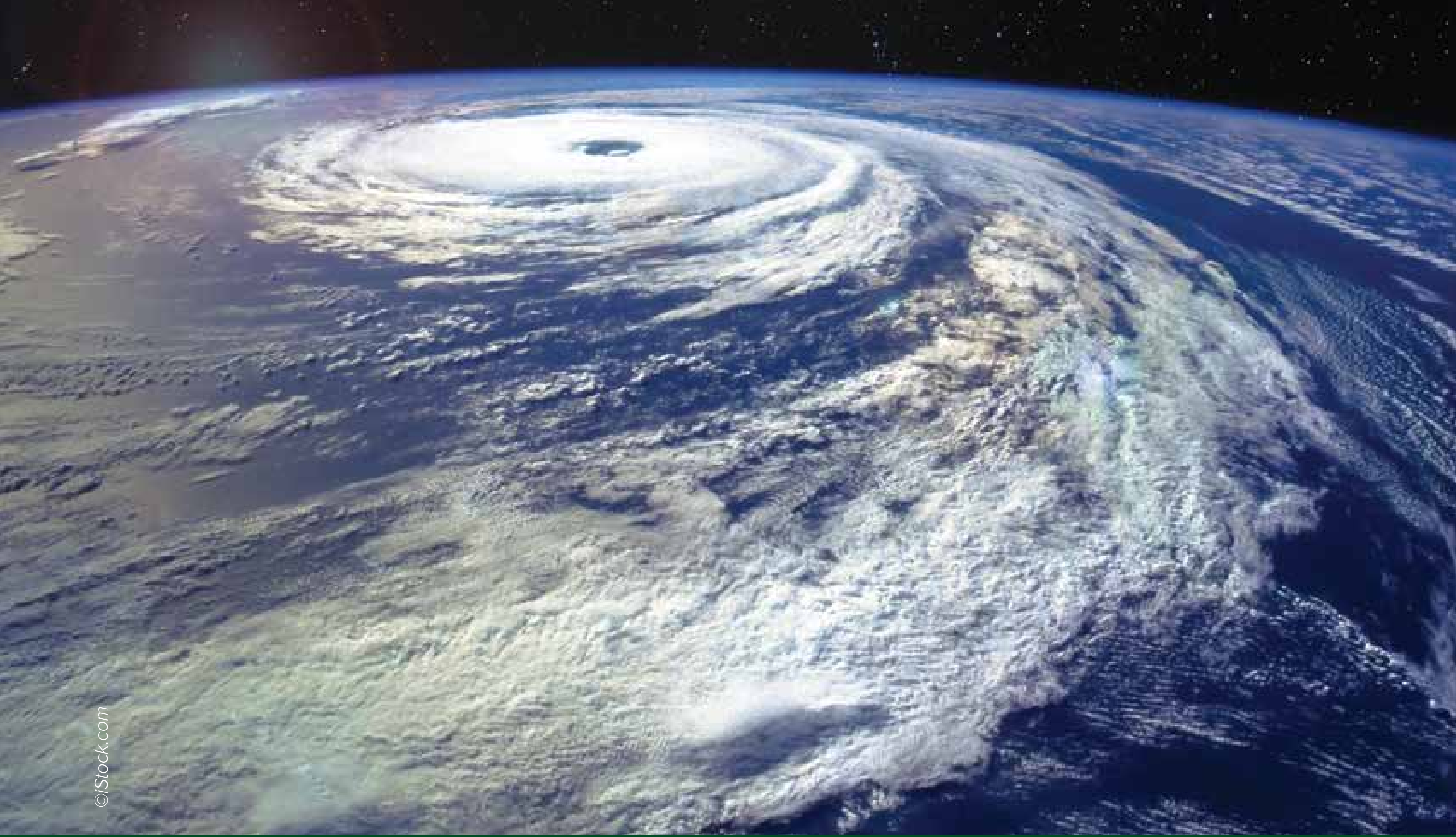
We envision strengthening and sustaining CSU's ability to reach out to policymakers, to inform research priorities, respond to their needs, and inform policy development.

disciplinary training and a wide range of experience working in policy and outreach. For instance, social scientists on our team bring important perspectives on social systems, history, and policy aspects of adaptation challenges. Courtney Schultz, team lead from the Department of Forest and Rangeland Stewardship, researches policy approaches for living with more wildfire, and Leisl Carr-Childers, co-lead from the History Department, brings expertise that is critical for working with communities affected by climate change in a way that is sensitive to historical relationships to places, landscapes, and natural resources. Lindsey Schneider in the Ethnic Studies Department brings a critical perspective to examining the challenges Tribal Nations and other Indigenous communities encounter to sustain their relationships with the land in the face of a changing climate and persistent legal and political barriers. Our team is also strong in biophysical science to allow us to coordinate research at the nexus of the human-environment relationship. For instance, Camille Stevens-Rumann is a fire ecologist in the Department of Forest and Rangeland Stewardship who looks at how climate change is altering fire behavior and post-fire forest ecosystem recovery, while Brad Udall at the CoWC examines climate impacts on future Colorado River flows and opportunities and challenges for water users to adapt to reduced water availability. Nathan Mueller from the Departments of Soil and Crop Sciences and Ecosystem Science and Sustainability examines how agriculture can adapt to climate change, exploring the effectiveness of adaptation actions such as crop migration. Jim Hurrell, from the Department of Atmospheric Science, analyzes the processes and mechanisms responsible for climate variability and change and uses Earth system models to predict future climatic changes to understand the impacts of proposed climate intervention (or geoengineering) techniques. Hussam Mahmoud, from the Department of Civil and Environmental Engineering, examines the impact to the built infrastructure in areas vulnerable to climate-driven disasters. Our team also includes center leaders with expertise in stakeholder and policymaker engagement, including Beth Conover, Director of the Salazar Center for North American Conservation, which convenes stakeholders to share diverse perspectives on how to address climate impacts on species migration, biodiversity loss, and community health and equity. Peter Backlund, Associate Director of the School of Global Environmental Sustainability, brings years of experience as a climate scientist and working in policy at the national level, including at the White House's Office of Science and Technology Policy. Postdoctoral scholar Niki vonHedemann, a geographer who studies climate adaptation in forest ecosystems, and program manager Tamera Breidenbach, a graduate student studying state-level climate adaptation planning also are key personnel on our team. Together, and in partnership with existing centers on campus, we will work together to build a strong foundation for the CAP to facilitate research collaboration and strengthen our ability to engage in policy outreach with state and federal governments.

Our Next Steps and Long-Term Goals

Our work will occur across three areas: building out a vision and structure for our partnership, developing new research collaborations, and working to strengthen our connection to policymakers. We are getting started this spring by forming our team, developing our vision, and strengthening partnerships. Our early activities will include a training for faculty members eager to engage in federal policy outreach, with an eye towards organizing a CSU "Week in Washington" in 2022 to connect researchers and policymakers more directly. We are also aiming to co-host with the Salazar Center in 2021 a symposium focused on climate adaptation. We are working towards an inaugural CAP conference in 2023 at CSU focused on research, policy, and management to address climate change adaptation and a future regional conference on climate change in the West. Another goal is to develop our expertise in convening "think-tank" type conversations with a broad range of partners to identify policy solutions and partnerships to address climate adaptation challenges. Our first policy workshops in this arena will focus on the challenge of increasing the application of prescribed fire to support more resilient forest landscapes. On the research front, some of our early activities will include fundraising for interdisciplinary research around topics such as recovering from natural disasters and beginning a speaker series with socials (hopefully with more in-person socializing soon!) to connect researchers, identify synergies, and pursue novel ideas together.

In the long run, our goal is for the CAP to serve as a vibrant hub for research and policy outreach around climate adaptation. We envision strengthening and sustaining CSU's ability to reach out to policymakers, to inform research priorities, respond to their needs, and inform policy development. Eventually, with stable funding and a leadership and advisory board, we will work in partnership with others on campus and in the region to become a center of excellence in this arena. If you are interested in learning more or partnering with us, please contact one of us, and keep an eye out for more information a research.colostate.edu/cip/cap/.

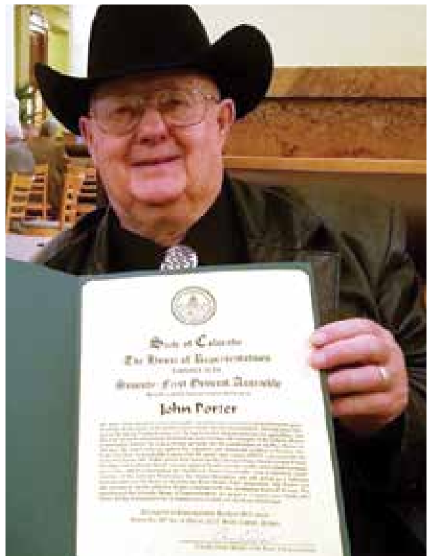


Climate-driven disturbances and their interactive effects are increasingly disruptive to global social and ecological systems, with disproportionate impacts falling on economically disadvantaged and socially marginalized people.

In Memory of John Porter

Dr. Melissa Mokry, Editor, Colorado Water Center

John Porter, an inspiring and dedicated advocate and leader within the Colorado water resources community, passed away on December 28, 2020. His passion and expertise in water resources originated from his farming and water management experience early on in his career. He was a Colorado State University Alumni where he graduated with a degree in agriculture business. John was a life-long learner, mentor, and leader across local, state, and federal agencies. He was fascinated to learn about other individuals' perspectives concerning water resource issues and management. He would approach complex topics head-on, encouraging compromise, and partnership to progress the water resources arena.



John Porter was honored by the Colorado State House of Representatives. Photo courtesy of the Porter Family.

John served as a valued member of several boards, including: the Montezuma Valley Irrigation Company, Southwestern Water Conservation District, Colorado Water and Power Authority, Colorado Water Congress, Water Education Colorado, Colorado Water Trust, and the seven-state Colorado River Water Users Association. He also served on the Colorado Water Center's External Advisory Board and negotiated for the Colorado Ute Indian Water Rights Settlement Act of 1988.

Moreover, his dedication to water resources was profound and influential. Amongst his impressive array of accomplishments, he helped bring water to the communities of Cortez, Towaoc, Dover Creek, to farmers within Montezuma and Dolores counties, and the Ute Mountain Ute Indian Tribe. In honor of his crucial work, he was awarded the Wayne N. Aspinall "Water Leader of the Year" award by the Colorado Water Congress, Water Leader of the Year in 2000, and the Citizen Award from the U.S. Bureau of Reclamation.

His dedication and passion for water resources live on in the Water Oral Histories Collection at the Colorado State University Water Resources Archive (lib.colostate.edu/find/archives-special-collections/collections/water-resources-archive/). Coloradoans will benefit from his hard work and dedication to water resources management and policy for years to come.

Chimney Rock is located on the Ute Mountain Ute Reservation, not far from Cortez, Colorado. ©iStock.com

Dr. Jeremy Rugenstein

Assistant Professor, Geosciences, Colorado State University

Jeremy Rugenstein started in August 2020 as an Assistant Professor in the Department of Geosciences within the Warner College of Natural Resources at Colorado State University (CSU). Originally from Albuquerque, New Mexico, Jeremy developed an interest in understanding modern climate change while working as an interpretive ranger for the U.S. Forest Service at the crest of the Sandia Mountains outside Albuquerque. He completed a Bachelors in Earth Science at Rice University in Houston, Texas, where he gained an interest in how the geologic record can be used to understand the long-term response of climate and the carbon cycle to continued emissions of CO_2. Following his Bachelors, Jeremy worked several years in science policy-related positions, including at the U.S. Institute for Environmental Conflict Resolution and within the American Geophysical Union's Public Affairs Office in Washington, D.C., before going on to complete a Ph.D. in Earth System Science at Stanford University, studying the impact of mountain uplift on long-term climate change in Asia. Most recently, Jeremy spent several years in Europe as a Postdoctoral Fellow, first at the ETH Zürich in the Institute of Geology and then as an Alexander von Humboldt Fellow at the Max Planck Institute for Meteorology in Hamburg, Germany.

Dr. Jeremy Rugenstein. Photo courtesy of Max Planck Institute for Meteorology.

Jeremy's research focuses on leveraging the geologic record of past warm, high CO_2 climates to understand how anthropogenic emissions of CO_2 today will impact terrestrial ecosystems and the hydrological cycle. Over the past 50 million years, Earth's climate has cooled substantially, from the warm, largely ice-free climate of the early Eocene with atmospheric CO_2 of 1,000–2,000 ppm (3–5 times higher than today's level) to the low CO_2 climate with a bipolar glaciation that characterizes the Quaternary Earth (i.e., the past 2.6 million years ago). To reconstruct past terrestrial climates and ecosystems, Jeremy's research group uses the stable isotopes of oxygen and carbon as embedded in minerals that form in soils and lakes—carbon isotopes reflect the type and productivity of vegetation on the landscape and oxygen isotopes record both the source of precipitation and the interaction between precipitation and evaporation over land. Combined with sedimentological observations, these isotopes provide a picture of how vegetation, precipitation, and evaporation changed in response to higher CO_2 in the past.

Though the reason behind the current rise in atmospheric CO_2 is well-understood, the long-term decline of atmospheric CO_2 prior to the advent of modern civilization remains controversial. Much of Jeremy's research also examines the mechanisms that can cause long-term, geologic changes in CO_2 and, in particular, how changes in climate are affected by long-term changes in CO_2 and also feedback and modify the geologic carbon cycle. This work utilizes simple models of climate coupled to models of the geologic carbon cycle to probe interactions and feedback between these two critical components of the Earth system.

At CSU, Jeremy is installing several new geochemical instruments in the Natural Resource Ecology Laboratory (NREL) EcoCore Facility, including a device to measure oxygen and carbon stable isotopes in carbonate rock and CO_2 and a laser water-isotope analyzer that will be able to rapidly measure the isotopes of water. He is currently teaching Historical Geology and developing classes in Paleoclimate, Earth System History, and Stable Isotope Geochemistry. His current projects include understanding: how the hydrology of the Southwest changed when CO_2 was much higher (~600–1,000 ppm) during the middle Miocene (15 million years ago); when the Altai Mountains in Mongolia became high enough to dramatically alter the climate in Asia, and; how precipitation and evaporation across Europe and Eurasia varied during past warm, high CO_2 climates.

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Congratulations to the 2021-2022 **CSU Competitive Grant Program Awardees**

Driving solutions to seemingly impossible water resource problems, the Colorado Water Center supports the launch of important projects with seed grants for CSU faculty and staff. Our five funded projects for next year feature collaborative, interdisciplinary research projects targeting the impacts of fire and educating diverse communities about our watersheds and the issues we face.

Camille Stevens-Rumann and her team study impacts and recovery of Colorado's forests after the 2020 fires. Photo courtesy of Camille Stevens-Rumman.

Water Research Teams

Effects of the Cameron Peak Fire on Stream-Riparian Food Webs Along an Elevational Gradient

Team Investigators

PI: Dan Preston, Assistant Professor, Department of Fish, Wildlife and Conservation Biology

Dan Preston. Photo by Michael P. King.

Co-PIs:

1. Yoichiro Kanno, Assistant Professor, Department of Fish, Wildlife, and Conservation Biology
2. Ryan Morrison, Assistant Professor, Department of Civil and Environmental Engineering
3. Kurt Fausch, Professor Emeritus, Department of Fish, Wildlife, and Conservation Biology
4. Johanna Kraus, Research Ecologist, USGS, Columbia Environmental Research Center
5. James Roberts, Research Ecologist, USGS, Great Lakes Science Center
6. Chris Kennedy, Fish Biologist, US Fish and Wildlife Service, Colorado Fish and Wildlife Conservation Office
7. Matt Fairchild, Forest Fisheries Biologist, US Forest Service, Arapaho and Roosevelt National Forests
8. Dick Jefferies, Conservation Chair, Trout Unlimited, Rocky Mountain Flycasters Chapter
9. Jennifer Kovecses, Executive Director, Coalition for the Poudre River Watershed

Fire, Fungi, and Flora: How Plant and Soil Microbial Succession Drive Hydrologic Processes Post-Fire

Team Investigators

PI: Camille Stevens-Rumann, Assistant Professor, Department of Forest and Rangeland Stewardship

Co-PIs:

1. Michael McNorvell, M.S. Student, Department of Forest and Rangeland Stewardship
2. Charles Rhoades, Research Biogeochemist, Rocky Mountain Research Station
3. Michael Remke, Research Associate, Mountain Studies Institute

Water Fellow

Knowing Rivers for Life: Toward an Ethic for Flowing Waters

Team Investigators

PI: Kurt Fausch, Professor Emeritus, Department of Fish, Wildlife, and Conservation Biology

Kurt Fausch

Co-PIs:

1. Audrey Harris, M.S. Student, Department of Fish, Wildlife, and Conservation Biology
2. George Valentine, M.S. Student, Department of Fish, Wildlife, and Conservation Biology
3. Sam Lewis, M.S. Student, Department of Fish, Wildlife, and Conservation Biology
4. Kristine Mackessy, Illustrator
5. Jeremy Monroe, Director, Freshwaters Illustrated
6. Erin Greb, Cartographer, Erin Greb Cartography

Water Education & Engagement Projects

Writing Water: Engaging Underserved Youth and Adults Through Critical Literacy and Water Education

Team Investigators

PI: Tobi Jacobi, Director, Community Literacy Center, Department of English

Co-PIs:

1. Mary Ellen Sanger, Associate Director, Community Literacy Center, Department of English

The Community Literacy Center's SpeakOut! Writing Workshop educates and empowers underserved and incarcerated populations. Photo courtesy of Tobi Jacobi.

Tobi Jacobi

2. Lisa Schlueter, Programs and Volunteer Coordinator, Larimer County Jail
3. Lori Whitson, Programs and Volunteer Coordinator, Larimer County Community Corrections

River Investigators: Connecting Youth and Families to the Cache la Poudre River

Team Investigators

PI: Nicole Stafford, Director, Colorado State University Environmental Learning Center

Co-PIs:

1. Kira Puntenney-Desmond, Research Associate, Ecosystem Science and Sustainability; Project Manager, Stream Tracker
2. Stephanie Kampf, Professor, Ecosystem Science and Sustainability

Nicole Stafford

3. Aditi Bhaskar, Assistant Professor, Civil and Environmental Engineering
4. Steven Fassnacht, Professor, Ecosystem Science and Sustainability
5. Randall Boone, Professor, Ecosystem Science and Sustainability
6. John Moore, Professor, Ecosystem Science and Sustainability, Director of the Natural Resource Ecology Laboratory
7. Julia Klein, Associate Professor, Ecosystem Science and Sustainability
8. Andrew Warnock, Director, Natural Sciences Education and Outreach Center
9. Linden Pearsall, Project Coordinator, Poudre Heritage Alliance
10. Jennifer Kovecses, Executive Director, Coalition for the Poudre River Watershed

Water Research Awards 11/16/2020-2/22/2021

Andales, Allan A., Soil and Crop Sciences, Foundation for Food and Agriculture Research, ICC: Irrigation Innovation Consortium, $1,720,000

Arabi, Mazdak, Civil and Environmental Engineering, National Science Foundation, SRN: Urban Water Innovation Network (U-WIN): Transitioning Toward Sustainable Urban Water Systems, $43,549

Arabi, Mazdak, Civil and Environmental Engineering, Colorado Department of Public Health and Environment, E.Coli Sampling in the Cache la Poudre River, $115,445

Arabi, Mazdak, Civil and Environmental Engineering, Colorado Department of Public Health and Environment, eRAMS Tools for CDPHE-WQCD, $90,000

Bhaskar, Aditi, Civil and Environmental Engineering, National Science Foundation, CAREER: Science and Education for Connecting Urban Irrigation Efficiency to Streamflow in Semi-Arid Cities, $286,307

Borch, Thomas, Soil and Crop Sciences, U.S. Department of Agriculture-National Institute of Food and Agriculture, Oilfield-Produced Water as Alternative Source for Agricultural Irrigation: Impact on Soil and Crop Health, $499,989

David, Olaf, Civil and Environmental Engineering, U.S. Department of Agriculture-Agricultural Research Service, WEPP Watershed Web-Based GIS Interface, $73,000

Kampf, Stephanie K., Natural Resource Ecology Laboratory, Department of the Interior-U.S. Geological Survey, CESU-RM: Are Mountain Lakes on a Trajectory of Rapid Eutrophication Toward Harmful Algal Blooms, $38,400

Kanno, Yoichiro, Fish, Wildlife, and Conservation Biology, Colorado Water Conservation Board, Sustaining Plains Aquatic Ecosystems Using an Integrated Ecological and Social Approach, $134,015

Koons, David N., Fish, Wildlife, and Conservation Biology, Ducks Unlimited, Productivity of Breeding Waterfowl on Working Lands in a Flood Irrigated System, $3,900

Kummerow, Christian D., Atmospheric Science, University of Washington, Snow: Learning How to Scale Success from the Field Experiment to the Earth System, $42,882

Myrick, Christopher A., Fish, Wildlife, and Conservation Biology, Department of the Interior, U.S. Fish and Wildlife Services, Effects of Light Level and Surface Roughness on the Passage Success of Plains Fishes in Rock Ramp Fishways, $27,065

Myrik, Christopher A., Fish, Wildlife, and Conservation Biology, Colorado Division of Parks and Wildlife, Triploid Walleye: A New Frontier for Managing Cool Water Predators in the West, $85,614

Parton, William J., Natural Resource Ecology Laboratory, University of Nebraska, USDA Support for the United States Drought Monitor and Climate Hub Activities for 2020-2023, $74,250

Water Research Awards 11/16/2020-2/22/2021

Quinn, Jason C., Mechanical Engineering, Department of Energy-Advanced Research Projects Agency-Energy, UNrealized Critical Lanthanide Extraction via Sea Algae Mining (UNCLE-SAM): Domestic Production of Critical Materials from Seawater, $139,600

Quinn, Jason C., Mechanical Engineering, Department of Energy-Advanced Research Projects Agency-Energy, TT&O-UNrealized Critical Lanthanide Extraction via Sea Algae Mining (UNCLE-SAM): Domestic Production of Critical Materials from Seawater, $30,400

Sara L. Rathburn, Geosciences, City of Fort Collins, Assessing Drainage Basin History Using Delta Stratigraphy at Halligan Reservoir, North Fork Cache la Poudre River, Colorado, $39,836

Ross, Matthew R.V., Ecosystem Science and Sustainability, City of Fort Collins, Distributed Sensor Networks and Data Fusion to Improve Watershed Resilience in the Cache la Poudre Watershed, $11,999

Sanderson, John S., Dean of Natural Resources, City of Fort Collins, Halligan Water Supply Project, Development of Adaptive Management Plan, Phase 1: Internal Alignment, $27,280

Schumacher, Russ S., Atmospheric Science, Oklahoma State University, Enhancing the Capacity for Rural Libraries to Engage the Public in Drought Sciences, Monitoring, and Adaptation, $4,610

Simpson, Rodney T., Natural Resource Ecology Laboratory, Battelle Memorial Institute, Water Chemistry, $137,996

Suter, Jordan, Agricultural and Resource Economics, University of Rhode Island, Does Mental Stress Affect Preferences for Groundwater Management?, $15,497

Wilusz, Carol J., Microbiology, Immunology, and Pathology, Colorado Department of Public Health and Environment, COVID-19: Wastewater Testing for State of Colorado, $234,000

Wilusz, Carol J., Microbiology, Immunology, and Pathology, Colorado Department of Public Health and Environment, COVID-19: Wastewater Testing for State of Colorado, $256,000

Wolk, Brett H., Forest and Rangeland Stewardship, U.S. Department of Agriculture, U.S. Forest Service-Forest Research, Developing and Applying Outcome Based Measures with U.S. Forest Service Region 2 Watershed Partnerships, $180,000

Wrighton, Kelly C., Soil and Crop Sciences, Department of Energy-Pacific Northwest National Laboratory, River Corridor Hydrobiogeochemistry from Reaction to Basin Scale Subsurface Biogeochemical Research Scientific Focus Area, $102,425

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Originally named Boulder Dam, Hoover Dam on the Colorado River River near Boulder City, Nevada impounds water to create Lake Mead, the largest reservoir by volume in United States. ©iStock.com

Water Calendar

July 2021

19-21 **2021 CUAHSI Biennial Colloquium**
Virtual
The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) will host this virtual symposium. Diverse fields of water science come together to discuss developments in the hydrology sector of the Earth Sciences. Researchers present their latest findings and developments, propose community workshops, and interact with colleagues from all over the country. Participants will have a unique opportunity to discuss ideas, network with colleagues, and build new relationships in a casual environment. Students are especially encouraged to attend.
cuahsi.org

19-21 **2021 AWRA Virtual Summer Conference: Connecting Land and Water for Healthy Communities**
Virtual
The American Water Resources Association brings together organizations and professionals across disciplines to address the design, integration, and implementation of programs and research to improve the connection of land and water planning and policy.
awra.org/Members/Events_and_Education/Events/2021_Summer_Conference

26-28 **One World, Connected Through Conservation: 76th SWCS International Annual Conference**
Virtual
Attendees around the world will share their conservation stories and bring natural resource management solutions from far and wide into their homes and offices.
swcs.org/Events/Conferences/2021-Annual-Conference

August 2021

24-26 **Colorado Water Congress Summer Conference**
Steamboat Springs, CO
Stay informed about water issues in Colorado including land use planning, growth, and climate while engaging in professional development activities.
cowatercongress.org/summer-conference.html

September 2021

21-23 **Colorado Wildland Fire Conference**
Grand Junction, CO
Experts from national, state, and local levels of government, academic, and community organizations will present on the theme of "Resilient Colorado: Moving Forward in Evolving Wildfire Landscapes."
wildfire-colorado.com/

Nebraska National Guard crew members dump water onto the High Park Fire near Fort Collins in 2012. Photo by Staff Sergeant Tate Petersen.

USGS Recent Publications

Data Releases

Cross-section geometry and sediment-size data from Muddy Creek and North Fork Gunnison River below Paonia Reservoir, western Colorado, 2019; 2020, U.S. Geological Survey Data Release; R.J. Richards, M.F. Henneberg
doi.org/10.5066/P9LU3AOR

Drone- and ground-based measurements of velocity, depth, and discharge collected during 2017-18 at the Arkansas and South Platte Rivers in Colorado and the Salcha and Tanana Rivers in Alaska, USA; 2020, U.S. Geological Survey Data Release; W.R. McDermott, J.W. Fulton
doi.org/10.5066/P9TJ7S4O

Elevation data from Fountain Creek between Colorado Springs and the Confluence of Fountain Creek at the Arkansas River, Colorado, 2020; 2020, U.S. Geological Survey Data Release; L.A. Hempel, A.L. Creighton, Z.D. Kisfalusi
doi.org/10.5066/P98J7DRO

Geospatial datasets developed for a groundwater-flow model of the Denver Basin Aquifer System, Colorado; 2020, U.S. Geological Survey Data Release; S.S Paschke, N.B. Oliver
doi.org/10.5066/P9CHGG0V

Invertebrate community data from native trout lakes and streams in the Southern Rocky Mountains; 2020, U.S. Geological Survey Data Release; J.L. Miller, J.J. Roberts, T.S. Schmidt, D.M. Walters
doi.org/10.5066/P9OBCCXQ

Near-surface geophysical data collected in the Sunflower Drain study area near Delta, Colorado, March 2018; 2020, U.S. Geological Survey Data Release; M.A. Mast
doi.org/10.5066/P9LKYX9H

Quality-control data for volatile organic compounds and environmental sulfur-hexafluoride data for groundwater samples from the Williston Basin, USA; 2020, U.S. Geological Survey Data Release; P.B. McMahon
doi.org/10.5066/P98H46DG

Water-quality and discharge data from draining mine tunnels near Silverton, Colorado 1988-2015; 2020, U.S. Geological Survey Data Release; K. Walton-Day, R.L. Runkel, M.A. Mast, S.L. Qi
doi.org/10.5066/P9FE667O

Water-quality data for stream and hyporheic zone samples altered by injection of sodium bromide tracer during a synoptic-sampling study, Leavenworth Creek, Clear Creek County, Colorado, 2012; 2019, U.S. Geological Survey Data Release; K. Walton-Day, R.L. Runkel, B.A. Kimball
doi.org/10.5066/P9P311YV

Journal Articles

Critical shifts in trace metal transport and remediation performance under future low river flows; 2020, Environmental Science and Technology (54)24, 15742-15750; P. Byrne, P. Onnis, R.L. Runkel, I. Frau, S.F.L. Lynch, P. Edwards
doi.org/10.1021/acs.est.0c04016

Geochemistry and age of groundwater in the Williston Basin, USA: assessing potential effects of shale-oil production on groundwater quality; 2020, Applied Geochemistry; P.B. McMahon, J.M. Galloway, A.G. Hunt, K. Belitz, B.C. Jurgens, T.D. Johnson
doi.org/10.1016/j.apgeochem.2020.104833

Transport and speciation of uranium in groundwater-surface water systems impacted by legacy milling operations; 2021, Science of the Total Environment (761), 143314; P. Byrne, C.C. Fuller, D.L. Naftz, R.L. Runkel, N.J. Lehto, W.L. Dam
doi.org/10.1016/j.scitotenv.2020.143314

U.S. Geological Survey Scientific Investigations Reports, and Maps

Bathymetry of Deadmans Lake, Golf Course Reservoir 9, Ice Lake, Kettle Lakes 1–3, and Non-Potable Reservoirs 1–4 at the U.S. Air Force Academy, Colorado, 2019; 2020, U.S. Geological Survey Scientific Investigations Map 3463, Pamphlet, 12; M.S. Kohn, L.A. Hempel
doi.org/10.3133/sim3463

Characterization of groundwater quality and discharge with emphasis on selenium in an irrigated agricultural drainage near Delta, Colorado, 2017–19; 2020, U.S. Geological Survey Scientific Investigations Report 2020-5132,34; M.A. Mast
doi.org/10.3133/sir20205132

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This publication is financed in part by the U.S. Department of the Interior Geological Survey, through the Colorado Water Center and CSU's College of Agriculture, Warner College of Natural Resources, Agricultural Experiment Station, and Extension.

Water diverted from the Colorado River near Palisade is used to irrigate orchards, vineyards, and farms. Variability in quantity and timing of water availability has significant impacts on agriculture. ©iStock.com

References

Climate Change and Forest Regeneration: What to Expect and Where to Go

Dr. Ethan Bucholz, Academic Liaison and Experiential Learning Specialist, Colorado State Forest Service, Warner College of Natural Resources, Colorado State University; Dr. Amanda West Fordham, Associate Director, Science, and Data Division, Colorado State Forest Service, Warner College of Natural Resources, Colorado State University

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., & Curtis-Mclane, S. (2008). Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications*, *1*, 95–111. doi.org/10.1111/j.1752-4571.2007.00013.x

Aitken, S.N., & Whitlock, M.C. (2013). Assisted gene flow to facilitate local adaptation to climate change. *Annual Review of Ecology, Evolution, and Systematics*, *44*, 367–388. doi.org/10.1146/annurev-ecolsys-110512-135747

Bentz, B.J., Régnière, J., Fettig, C.J., Hansen, E.M., Jane, L., Hicke, J.A., Kelsey, R.G., Negrón, J.F., & Seybold, S.J. (2010). Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *BioScience*, *60*(8), 602–613. doi.org/10.1525/bio.2010.60.8.6

Briggs, J.S., Hawbaker, T.J., & Vandendriesche, D. (2015). Resilience of ponderosa and lodgepole pine forests to mountain pine beetle disturbance and limited regeneration. *Forest Science*, *61*, 689–702.

Carlson, A.R., Sibold, J.S., & Negrón, J.F. (2020). Canopy structure and below-canopy temperatures interact to shape seedling response to disturbance in a Rocky Mountain subalpine forest. *Forest Ecology and Management*, *472*, 118234. doi.org/10.1016/j.foreco.2020.118234

Chambers, M.E., Fornwalt, P.J., Malone, S.L., & Battaglia, M.A. (2016). Patterns of conifer regeneration following high severity wildfire in ponderosa pine – dominated forests of the Colorado Front Range. *Forest Ecology and Management*, *378*, 57–67. doi.org/10.1016/j.foreco.2016.07.001

Collins, B.J., Rhoades, C.C., Hubbard, R.M., & Battaglia, M.A. (2011). Tree regeneration and future stand development after bark beetle infestation and harvesting in Colorado lodgepole pine stands. *Forest Ecology and Management*, *261*(11), 2168–2175. doi.org/10.1016/j.foreco.2011.03.016

Coop, J.D., Parks, S.A., Stevens-Rumann, C.S., Crausbay, S.D., Higuera, P.E., Hurteau, M.D., Tepley, A., Whitman, E., Assal, T., Collins, B.M., Davis, K.T., Dobrowski, S., Falk, D.A., Fornwalt, P.J., Fulé, P.Z., Harvey, B.J., Kane, V.R., Littlefield, C.E., Margolis, E.Q., & Rodman, K.C. (2020). Wildfire-driven forest conversion in western North American landscapes. *BioScience*, *70*(8), 659–673. doi.org/10.1093/biosci/biaa061

Davis, K.T., Dobrowski, S.Z., Higuera, P.E., Holden, Z.A., Veblen, T.T., Rother, M.T., Parks, S.A., Sala, A., & Maneta, M.P. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(13), 6193–6198. doi.org/10.1073/pnas.1815107116.

Kayes, L.J., & Tinker, D.B. (2012). Forest structure and regeneration following a mountain pine beetle epidemic in southeastern Wyoming. *Forest Ecology and Management*, *263*, 57–66. doi.org/10.1016/j.foreco.2011.09.035

Nagel, L.M., Palik, B.J., Battaglia, M.A., Amato, A.W.D., Guldin, J.M., Swanston, C.W., Janowiak, M.K., Powers, M.P., Joyce, L.A., Millar, C.I., Peterson, D.L., Ganio, L.M., Kirschbaum, C., & Roske, M.R. (2017). Adaptive silviculture for climate change: a national experiment in manager-scientist partnerships to apply an adaptation framework. *Journal of Forestry*, *115*.

Pettit, J.M., Burton, J.I., Derose, R.J., Long, J.N., & Voelker, S.L. (2019). Epidemic spruce beetle outbreak changes drivers of engelmann spruce regeneration. *Ecosphere*, *10*. doi.org/10.1002/ecs2.2912

Stevens-Rumann, C.S., Kemp, K.B., Higuera, P.E., Harvey, B.J., Rother, M.T., Donato, D.C., Morgan, P., & Veblen, T.T. (2018). Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, *21*(2), 243–252. doi.org/10.1111/ele.12889

Westerling, A., Hidalgo, H., Cayan, D.R., & Swetnam, T.W. (2006). Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, *313*, 940–943. doi.org/10.1126/science.1128834

Windmuller-Campione, M.A., & Long, J.N. (2015). If long-term resistance to a spruce beetle epidemic is futile, can silvicultural treatments increase resilience in spruce-fir forests in the central Rocky Mountains? *Forests*, *6*, 1157–1178. doi.org/10.3390/f6041157

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References

How is Climate Change Impacting Colorado River Flow?

Brad Udall, Senior Water, and Climate Scientist and Scholar, Colorado Water Center

Dr. Jonathan Overpeck, Samuel A. Graham Dean and Collegiate Professor, School of Environment and Sustainability, University of Michigan

Das, T., Pierce, D.W., Cayan, D.R., Vano, J.A., & Lettenmaier, D.P. (2011). The importance of warm season warming to western U.S. streamflow changes. *Geophysical Research Letters*, *38*(23), L23403. doi.org/10.1029/2011GL049660

Hoerling, M., Barsugli, J., Livneh, B., Eischeid, J., Quan, X., & Badger, A. (2019). Causes for the century-long decline in Colorado River flow. *Journal of Climate*. doi.org/10.1175/JCLI-D-19-0207.1

Milly, P.C.D., & Dunne, K.A. (2020). Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, *367*(6483), 1252–1255. doi.org/10.1126/science.aay9187

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*(3), 2404–2418. doi.org/10.1002/2016WR019638

Woodhouse, C.A., Pederson, G.T., Morino, K., McAfee, S.A., & McCabe, G.J. (2016). Increasing influence of air temperature on upper Colorado River streamflow: temperature and Colorado streamflow. *Geophysical Research Letters*, *43*(5), 2174–2181.

doi.org/10.1002/2015GL067613

Xiao, M., Udall, B., & Lettenmaier, D.P. (2018). On the causes of declining Colorado River streamflows. *Water Resources Research*, *54*(9), 6739–6756.

How Has Precipitation Changed Over Time Across Colorado?

Dr. Becky Bolinger, Assistant State Climatologist, Colorado Climate Center

Barnett, T.P., Adam, J.C. & Lettenmaier, D.P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature,* 438, 303-309.

Doesken, N.J., Pielke Sr., R.A., & Bliss, O.A.P. (2003). *Climatography of the United States. No. 60.* climate.colostate.edu/climate_long.html.

Frankson, R., Kunkel, K., Stevens, L., & Easterling, D. (2017). Colorado state climate summary. *NOAA Technical Report NESDIS 149-CO,* 4. statesummaries.ncics.org/chapter/co/.

Lukas, J., Barsugli, J., Doesken, N., Rangwala, I., & Wolter, K. (2014). Climate change in Colorado. *A Report for the Colorado Water Conservation Board,* wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf

Julander, R.P., & Clayton, J.A. (2018). Determining the proportion of streamflow that is generated by cold season processes versus summer rainfall in Utah, USA. *Journal of Hydrology: Regional Studies,* 17, 36-46, doi.org/10.1016/j.ejrh.2018.04.005

NOAA, National Centers for Environmental Information, *Climate at a Glance.* Data downloaded in March 2021: ncdc.noaa.gov/cag/statewide/time-series.

Udall, B. & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research.* doi.org/10.1002/2016WR019638

Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K., Baek, S.H., Badger, A.M., & Livneh, B. (2020). Large contribution from anthropogenic warming to an emerging North American megadrought. *Science, 368* (6488), 314-318.

The CSU Climate Adaptation Partnership: Connecting Research and Policy to Address the Challenges of Living with Climate Change

Dr. Courtney Schultz, Dr. Leisl Carr Childers, Dr. Niki vonHedemann, and Tamera Breidenbach, Colorado State University; Climate Adaptation Partnership for Policy Innovation and Research Coordination

Buma, B., & Schultz, C. (2020). Disturbances as opportunities: learning from disturbance-response parallels in social and ecological systems to better adapt to climate change. *Journal of Applied Ecology*, *57*(6), 1113–1123. doi.org/10.1111/1365- 2664.13606

Davies, I.P., Haugo, R.D., Robertson, J.C., & Levin, P.S. (2018). The unequal vulnerability of communities of color to wildfire. *PLOS ONE*, *13*(11). doi.org/10.1371/journal.pone.0205825

Gonzalez, P., Garfin, G.M., Breshears, D.D., Brooks, K.M., Brown, H.E., Elias, E.H., Gunasekara, A., Huntly, N., Maldonado, J.K., Mantua, N.J., Margolis, H.G., McAfee, S., Middleton, B.R., Udall, B.H. (2018). Southwest. In. Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., & Steward, B.C. (Eds.), *Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II.* (pp. 1101-1184). U.S. Global Change Research Program, Washington, D.C., USA. doi.10.7930/NCA4.2018.CH25

Hassan, E., & Mahmoud, H.N. (2020). An integrated socio-technical approach for post earthquake recovery of interdependent healthcare systems. *Reliability Engineering*, *201*(106953), 1-15. doi.org/10.1016/j.ress.2020.106953

IPCC (2014). Annex II: Glossary. Mach, K.J., Planton, S., & von Stechow, C. (Eds.). *IPCC: Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 117-130). Geneva, Switzerland. ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_Annexes.pdf

Masson-Delmotte, V., Zhai, P., Portner, H.O., Roverts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Pean, C., Pidcok, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (2018). Summary for policymakers. *Global warming of 1.5℃. An IPCC Special Report on the impacts of global warming of 1.5℃ above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* archive.ipcc.ch/report/sr15/pdf/sr15_citation.pdf

McWethy, D.B., Schoennagel, T., Higuera, P.E., Krawchuk, M., Harvey, B.J., Metcalf, E.C., Buma, B., Virapongse, A., Kulig, J.C., Stedman, R.C., Ratajczak, Z., Nelson, C.R., & Kolden, Cr. (2019). Rethinking resilience to wildfire. *Nature Sustainability*, *2*(9), 797–804. doi.org/10.1038/s41893-019-0353-8

Millar, C.I., & Stephenson, N.L. (2015). Temperate forest health in an era of emerging megadisturbance. *Science*, *349*(6250), 823–826. doi.org/10.1126/science.aaa9933

Schultz, C. A., & Moseley, C. (2019). Collaborations and capacities to transform U.S. fire management. *Science*, *366*(6461), 38-40. doi.org/10.1126/science.aay3727