WESTERN WATER ASSESSMENT

BUILDING CLIMATE RESILIENCE BY DESIGN

FINAL GRANT REPORT 2015 - 2022

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

TABLE OF CONTENTS

This report highlights activities supported by the National Oceanic and Atmospheric Administration (NOAA) Climate Program Office award number NA15OAR4310144.

Cover photo: Patsy Marley located in Utah's Wasatch-Cache National Forest. Credit: Seth Arens.

Photo to the left: Buckskin Gulch, southern Kane County, Utah. Credit: Seth Arens.

WESTERN WATER ASSESSMENT
https://wwa.colorado.edu

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

WWA TEAM MEMBERS

CURRENT TEAM

Principal Investigators

- Lisa Dilling
  Director and Lead PI, 2015-2021
- Ben Livneh
  Director and Co-lead PI, 2021-2022
- Benét Duncan
  Managing Director and Co-lead PI, 2021-2022
- Noah Molotch

Staff Team

- Benét Duncan
  Managing Director; Former Sustained Assessment Specialist
- Seth Arens
  Utah Research Integration Specialist
- Katie Clifford
  Lead Social Scientist
- Ethan Knight
  Associate Scientist
- Ami Nacu-Schmidt
  Graphic Designer
- Liz Payton
  Water Resources Specialist

Researchers

- Karen Bailey
- Joe Kasprzyk
- Corrie Knapp
- Leanne Lestak
- Intiaz Rangwala
- Andrea Ray
- Heather Yocum

Graduate Students

- Natalie Bennett
- Kaitlyn Bishay
- Nels Bjarke
- Carli Brucker
- Eric Kennedy
- Luca Palasti
- Emily Peters

FORMER TEAM MEMBERS ON THIS AWARD

Principal Investigators

- Joe Barsugli, 2015-2022
- Elizabeth McNie, 2015-2017
- Bill Travis, 2015-2022

Staff Team

- Ursula Rick, former Managing Director
- Jeff Lukas, former Colorado Research Integration Specialist
- Eric Gordon, former Managing Director
- Lineke Woelders, former Research Scientist
- Tim Bardsley, former Utah Research Integration Specialist

Researchers

- Jeff Deems
- Candida Dewes
- Corrie Knapp
- Keith Musselman

Undergraduate Students

- Phillip Kamps
- Ethan Knight*
- Angela Korneev
- Luke Nordgrenn
- Ethan Petersen

Graduate Students

- John Berggren
- Ethan Burns
- Katie Clifford*
- Samuel Ehret
- Keith Jennings
- Aislyn Keyes
- Adam McCurdy
- Keith Musselman
- Rebecca Page
- Dominik Schneider
- Rebecca Smith
- Christa Torrens
- Travis Williams

Postdoctoral Scholars

- Andrew Badger
- Jen Henderson
- Mark Raleigh
- Trisha Shrum

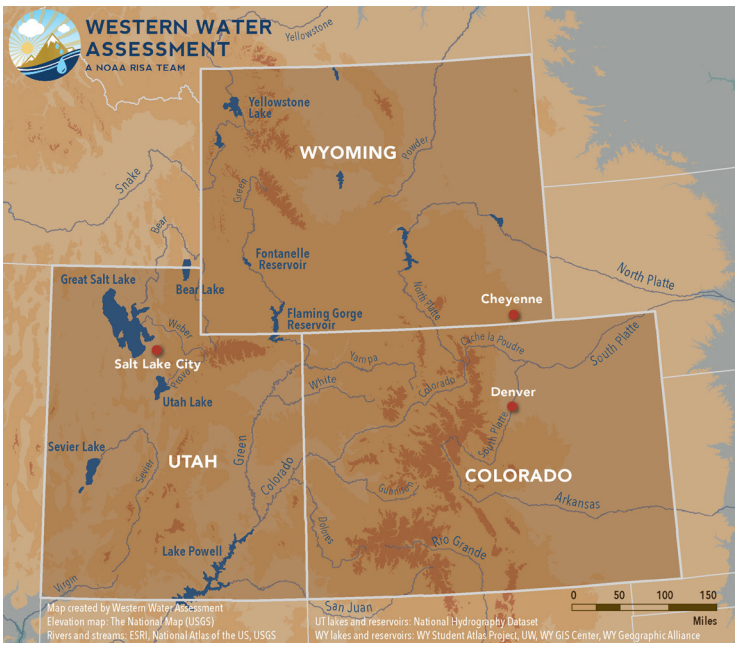
**means former student transitioned to current employee*

ABOUT WESTERN WATER ASSESSMENT

The Western Water Assessment (WWA) is a university-based applied research program that seeks to build societal resilience to climate variability and climate change. We work across the Intermountain West—Colorado, Utah, and Wyoming—and conduct innovative research in partnership with communities and decision makers in the region, helping them make the best use of science in planning and managing for climate impacts. Our interdisciplinary team brings together researchers and staff with expertise in social and physical sciences, enabling us to develop practical research programs and useful information products. We are one of 12 NOAA Climate Adaptation Partnerships (CAP; formerly Regional Integrated Sciences and Assessments, or RISA) teams across the country.

WWA is led by our Principal Investigator (PI) group; our full-time staff members focus on program management, research development and synthesis, and coordination of stakeholder interactions. Our broader network of investigators and partners comes from universities and government institutions across our region and provides a wide range of expertise. The

Photo above: Great Sand Dunes. Credit: Jeff Lukas.



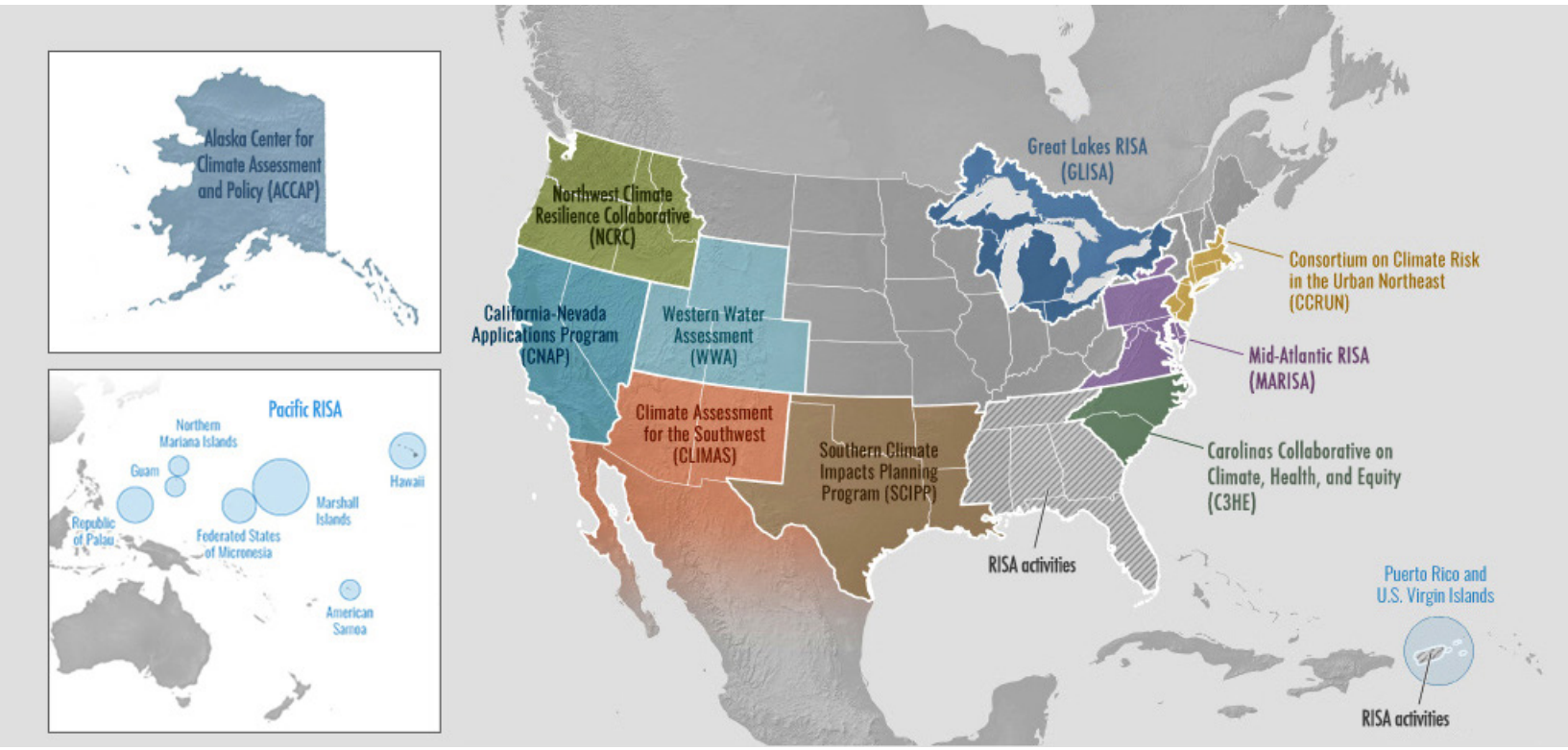
WWA's vision is to build regional resilience to compound hazards, with a particular focus on underserved Indigenous and small rural communities and utilities.

WWA External Advisory Board consists of national experts from across the science-policy landscape, and provides critical programmatic guidance to the core staff and PIs. Taken together, this network represents a broad base of expertise and relationships that enable WWA to meet stakeholder needs and advance scientific understanding.

WWA'S ROLE AND IMPACT

For over 20 years, WWA has been building relationships and advancing climate science to build resilience and meet information needs of communities, resource managers, and state and federal agencies. We also have made contributions that advance physical and social climate sciences, exploring research questions that are relevant and timely for partners. Throughout our research and engagement activities, we prioritize mentorship for students and early career professionals, through internships, research assistantships, fellowships, and staff positions. From 2015-2022, WWA leveraged NOAA CAP/RISA support, private donor funding, and other grants and programs to support and/or mentor 22 students. This provided critical exposure to best practices in conducting usable science in the Intermountain West region.

A program evaluation conducted in 2019-2020 tracked the impact of our research, integration, and outreach activities from 2015-2019. The evaluation included an analysis of website analytics, a survey of 128 stakeholders and partners, and interviews with five survey participants. Participants shared that engagement with WWA researchers and staff has helped to increase their scientific understanding of climate impacts, supported peer learning among decision makers, and provided information that has encouraged organizations and communities to take actions that build resilience. Respondents indicated that information and data from WWA have aided their planning, decision-making, and forecasting activities. They valued engaging with us through the VCAPS process, collaborating on projects, and working with WWA staff for support and expertise. Respondents largely reported greater awareness, knowledge, and understanding of climate vulnerability and felt that WWA resources have contributed to this, particularly by increasing awareness or understanding, and providing data or information.



ABOUT THIS REPORT

This report highlights the research contributions and societal impacts that WWA achieved with our 2015-2020 NOAA CAP/RISA award, which extended into 2022 with no-cost extensions. During that time, our work focused on: climate vulnerability and adaptive capacity in the Intermountain West; extremes and climate risk management; designing organizations and networks for usable science; and understanding and monitoring drought in the WWA region.

The following sections provide brief summaries of the projects and activities supported during our 2015-2022 NOAA CAP/RISA award. Each summary provides specific information about project partners, impacts, and leveraged funding. Activities are divided into the following six focal areas:

Analyzing and supporting adaptation in the Intermountain West

Fostering networks and communities of practice

Improving institutional design for usable science

Decision-making for extremes

Snow and water science for improved management

Assessing and moving cutting-edge climate science into practice

WWA BY THE NUMBERS

2015 - 2022

PARTNERS

Number of WWA Partners **86**

Number of students supported or partnered with **22**

TYPES AND NUMBER OF ORGANIZATIONS

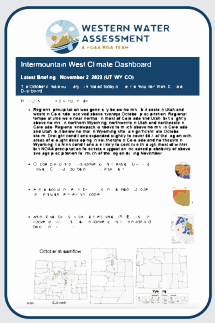
- Tribes 2
- NOAA-Affiliated Federal Partners 7
- Non-NOAA Federal Partners 8
- CAP/RISA Partners 6
- State Agency Partners 7
- Regional Water Providers & Managers 16
- Local Governments 12
- Academic Partners 14
- NGOs & Collaboratives Partners 7

RESEARCH AND COMMUNICATIONS

164 Research Publications

Number of News/Media Features **223**

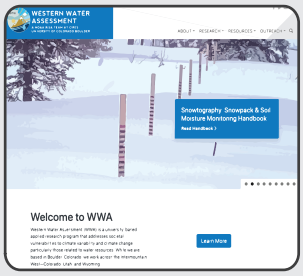
Number of (IWCD) Climate Briefings **84**



621 Number of Social Media Posts

18 Number of Recorded Webinars, Workshops, and Presentations

Number of Website Pageviews **289,493**



RESEARCH FINDINGS AND ACCOMPLISHMENTS: FOCAL AREA 1

ANALYZING AND SUPPORTING ADAPTATION IN THE INTERMOUNTAIN WEST

1.1 VCAPS PILOT PROJECT

In 2018-2019, WWA led the VCAPS (Vulnerability, Consequences, and Adaptation Planning Scenarios) pilot project in six communities in Colorado (Carbondale, Cortez, Durango, and Routt County) and Utah (Moab and Springdale). Originally developed by researchers in North Carolina, the VCAPS process centers community knowledge and experiences to identify climate vulnerabilities and actions communities can take to build resilience. Workshops focused on key climate hazards that WWA staff identified in partnership with community champions. Due to the historic drought in 2018, all of the communities chose to focus on drought, and two communities also focused on extreme precipitation.

Following completion of the pilot workshops, we conducted a project evaluation with participants from all six of the communities that participated in VCAPS. Katie Clifford conducted phone interviews with community champions from each VCAPS community, and collaborated with Lisa Dilling and Benét Duncan to conduct an online survey of all participants. Zoë McAlear, a graduate student at MIT who assisted with the Moab VCAPS workshop, evaluated the impacts of this pilot project for her Master's thesis. She found that the majority of workshop participants felt the workshops had supported adaptation planning in their community, and identified opportunities to increase the efficacy of future workshops. Clifford, McAlear, and co-authors have an accepted manuscript at the Bulletin of the American Meteorological Society (BAMS) synthesizing their findings and lessons learned to support similar co-production workshops. Lastly, Ethan Petersen, a Stanford undergraduate Cardinal Quarter Fellow, analyzed existing adaptation planning and conducted additional interviews in 2020 to identify Wyoming communities that might benefit from VCAPS workshops in the future.

Photo above: Great Salt Lake. Credit: Seth Arens.

IMPACT - The VCAPS workshops provided locally relevant climate information and convened conversations that have helped smaller municipalities to advance their own efforts to increase resilience to severe drought. WWA researchers have continued to engage with staff in the City of Cortez department of public works to help build water system resilience. This has included exploring opportunities for supplemental funding to support drought planning activities in Cortez and developing updated information about climate impacts to inform a drought contingency plan. Since the VCAPS workshop, the City of Cortez has pursued a number of actions to increase their adaptive capacity, including convening cross-departmental meetings to discuss drought and water supply, and launching the Water is Our Future conservation initiative in 2019. The City of Carbondale used strategies co-developed in the VCAPS workshop to inform municipal investments in new water treatment facilities and landscaping. The City of Durango has incorporated climate considerations into their evaluations of bids for water infrastructure projects.

WWA INVESTIGATORS - Lisa Dilling, Katie Clifford, Ursula Rick, Benét Duncan, Rebecca Page, Seth Arens, Imtiaz Rangwala, Samuel Ehret, Jeff Lukas

PARTNERS - Carolinas Integrated Sciences and Assessments (CISA); Carbondale, Cortez, Durango, and Routt County, CO; Moab and Springdale, UT

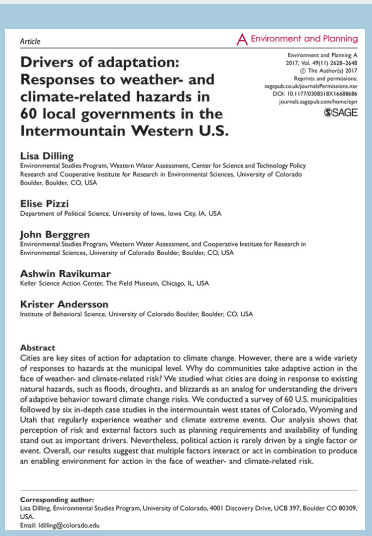
LEVERAGED FUNDING - Stanford Cardinal Quarter Fellowship Program

1.2 DRIVERS OF ADAPTATION IN LOCAL GOVERNMENTS

Cities, rather than state or federal governments, are often the first to take action to deal with natural hazards and climate change. WWA's Lisa Dilling and John Berggren published a paper entitled *Drivers of adaptation: Responses to weather- and climate-related hazards in 60 local governments in the Intermountain West U.S.* to explore the kinds of actions cities in the region are taking and why.

Over the course of two years, they interviewed city managers, emergency managers, and at least one elected official in each city to find out what drives municipalities to take action to adapt to existing weather and climate hazards. In six of the cities, the team dug deeper, talking in depth to as many as 10 additional municipal employees and managers involved in hazard planning and response.

KEY FINDINGS - The drivers of adaptation to hazards vary, and the researchers found several key elements that are influential in the development of hazard response plans, including whether a town or city had previously experienced a natural hazard event, whether a city thought they faced potential risk of experiencing an event, whether the city had a "champion" —an individual who pushed for hazard planning and response, and whether a city received external incentives such as funding or regulations. No single variable drove what cities did, but the combination of several different variables seemed to influence cities to take more action. Of those, the presence of external funding or external regulations stood out as the most significant variable in predicting whether a city would implement plans to deal with climate hazards.


Article — Environment and Planning

Drivers of adaptation: Responses to weather- and climate-related hazards in 60 local governments in the Intermountain Western U.S.

Environment and Planning A
2017, Vol. 49(11) 2628–2648
© The Author(s) 2017
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0308518X17688686
journals.sagepub.com/home/epn
SAGE

Lisa Dilling
Environmental Studies Program, Western Water Assessment, Center for Science and Technology Policy Research and Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA

Elise Pizzi
Department of Political Science, University of Iowa, Iowa City, IA, USA

John Berggren
Environmental Studies Program, Western Water Assessment, and Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA

Ashwin Ravikumar
Keller Science Action Center, The Field Museum, Chicago, IL, USA

Krister Andersson
Institute of Behavioral Science, University of Colorado Boulder, Boulder, CO, USA

Abstract
Cities are key sites of action for adaptation to climate change. However, there are a wide variety of responses to hazards at the municipal level. Why do communities take adaptive action in the face of weather- and climate-related risk? We studied what cities are doing in response to existing natural hazards, such as floods, droughts, and blizzards as an analog for understanding the drivers of adaptive behavior toward climate change risks. We conducted a survey of 60 U.S. municipalities followed by six in-depth case studies in the intermountain west states of Colorado, Wyoming and Utah that regularly experience weather and climate extreme events. Our analysis shows that perception of risk and external factors such as planning requirements and availability of funding stand out as important drivers. Nevertheless, political action is rarely driven by a single factor or event. Overall, our results suggest that multiple factors interact or act in combination to produce an enabling environment for action in the face of weather- and climate-related risk.

Corresponding author:
Lisa Dilling, Environmental Studies Program, University of Colorado, 4001 Discovery Drive, UCB 397, Boulder CO 80309, USA.
Email: ldilling@colorado.edu

Drivers of adaptation: Responses to weather- and climate-related hazards in 60 local governments in the Intermountain Western U.S. by L. Dilling et al.

WWA INVESTIGATORS - Lisa Dilling, John Berggren

PARTNERS - Elise Pizzi (University of Iowa), Ashwin Ravikumar (The Field Museum), Krister Andersson (CU Boulder)

1.3 DYNAMICS OF COMMUNITY VULNERABILITY IN DROUGHT PLANNING AND MITIGATION

As municipalities implement adaptation or mitigation plans based on past drought experience that improve their resilience to drought, they can cause unintended vulnerabilities for other communities. From 2017-2019, WWA/CIRES postdoctoral research fellow Jen Henderson, together with WWA researchers Lisa Dilling and Ursula Rick, and collaborators Rebecca Morss and Olga Wilhelmi (National Center for Atmospheric Research - NCAR), led a project to understand more about the dynamics of resilience and vulnerability as adaptation actions are undertaken. The project had three goals:

1. To understand the types of vulnerabilities to drought that water utilities, industries, agricultural producers, and municipal leaders are concerned about and plan for;
2. To trace the dynamic nature of vulnerabilities to drought that emerge between urban and adjacent rural communities as they implement drought plans;
3. To identify the triggers for emergent vulnerabilities that may be displaced across time and space in drought contexts.

Henderson interviewed representatives from stakeholders involved in the water issue in two locations: along the Arkansas River Basin in Colorado and the Weber River Basin in Utah. She also surveyed the agricultural community in the Arkansas River Basin, and reviewed relevant historical and policy documents.

KEY FINDINGS - While there had been some negative consequences of adaptive actions in the past, she and her collaborators found that social learning occurred after individuals experienced unanticipated impacts from others' decisions. They found four 'features' of social learning that helped people respond to unanticipated consequences: governance structures that support holistic river management; expanding relationship boundaries beyond small-scale decisions that capture interactions and emergent problems; knowledge of direct or indirect experiences of others; and creation of safe spaces to experiment with adaptation changes. Their examples of stakeholders who learned to adapt together can be of use to others navigating drought extremes.

WWA INVESTIGATORS - Jen Henderson, Lisa Dilling, Ursula Rick

PARTNERS - Olga Wilhelmi and Rebecca Morss (NCAR)

LEVERAGED FUNDING - CIRES Visiting Postdoctoral Fellow program

1.4 WILDFIRE PREPAREDNESS IN COLORADO

Beginning in 2020, WWA graduate student Natalie Bennett, under the supervision of Lisa Dilling, conducted research into how communities prepare for wildland fire in Colorado. Using a case study approach, she investigated how local public officials, non-governmental partners, and community members plan and implement actions to minimize the risks to their communities from wildfire. Bennett aimed to understand the role of stakeholder and community participation in wildfire mitigation planning and building community adaptive capacity. Through semi-structured interviews, she explored the participatory processes involved in the creation of Community Wildfire Protection Plans (CWPPs) in Colorado, their persistence in communities over time, and how they interact with other behavioral and social drivers of adaptive capacity.

KEY FINDINGS - Bennett found CWPPs had a limited role by themselves in promoting fire adaptation in communities. Rather, other factors in communities such as awareness of risk due to a past event, or the presence of an effective community champion may be more important in promoting actions that reduce vulnerability to wildfire, and can help to create an enabling environment for CWPPs to be more effective in supporting planning.

WWA INVESTIGATORS - Natalie Bennett, Lisa Dilling

PARTNERS - Karen Bailey, Amanda Carrico

1.5 CLIMATE-INFORMED WATER MANAGEMENT IN GOLDEN, COLORADO

Liz Payton worked with the City of Golden, Colorado in 2020 to explore the relationship between their water use and evapotranspiration (ET) in preparation for development of a water resources master plan for the city. WWA provided historical ET and other climate data and analysis, as well as projections of ET and water supply. Through this effort, she trained the city staff on how to access and use online climate data tools. She worked with the city to determine the appropriate time scales for water use prediction and explored historical trends in water use and potential drivers of water demand.

IMPACT - City water resources staff used this information in communications with city planners and decision makers. Since then, Payton has continued to engage with City of Golden staff to provide guidance and updated analysis to inform their assessment of water conservation measures and management decisions.

WWA INVESTIGATORS - Liz Payton

PARTNERS - City of Golden

1.6 WWA SUMMER GRADUATE FELLOWS & INTERNSHIPS

WWA was excited to launch our WWA Summer Graduate Fellowship program in 2020, with the generous support of a private donor. The fellowship supports CU Boulder graduate students to lead projects with WWA researchers, exposing them to usable science activities and principles. Our inaugural fellow, PhD student Christa Torrens, conducted interviews with climate service providers and other partners in Wyoming to explore the landscape of climate planning and opportunities. In 2021, we hosted two Summer Graduate Fellows: PhD student Aislyn Keyes worked with Liz Payton to evaluate flood risk and resilience in manufactured housing communities, and Master's student Ethan Burns worked with Benét Duncan to develop fact sheets about ecological drought and wildfire impacts on water systems and communities.

WWA is committed to supporting student learning beyond our Summer Graduate Fellowship program, through internships and other opportunities. In 2020, Ethan Petersen, a Stanford undergraduate Cardinal Quarter Fellow, analyzed existing adaptation planning and conducted additional interviews to identify Wyoming communities that might benefit from community adaptation workshops in the future. WWA's Ethan Knight, then-student intern in Spring 2020, conducted a survey of the *Colorado River Basin Climate and Hydrology: State of the Science report* sponsors to better understand how they expected to use the report. Nearly all of the respondents indicated that they had already used the report to broaden their understanding of the Colorado River Basin, to educate users and the public, develop research projects, educate their boards and other decision makers, and to get up-to-date information on climate and hydrology research in the basin. WWA also hosted a summer intern, Oliver Buckley, in 2020. Oliver conducted interviews and literature review to produce a report and presentation about current decision-science research in water resources. In 2018, Samuel Ehret, a Master's student at the University of Bern, completed an internship with WWA working with Lisa Dilling and Katie Clifford to support our VCAPS project, drafting reports and participating in partner interviews.

IMPACT - Graduate and undergraduate students gained exposure and understanding of core principles of conducting collaborative, usable science. Their projects have informed future WWA activities and helped to strengthen relationships in the region. For example, since publication of the fact sheets produced by Ethan Burns, WWA has received direct requests for information and engagement from communities in Wyoming and Colorado, including the Colorado Mountain Town 2030 initiative and the Wyoming Association of Rural Water Systems.

WWA INVESTIGATORS - Lisa Dilling, Katie Clifford, Benét Duncan, Liz Payton, Ethan Knight

PARTNERS - Ethan Petersen, Oliver Buckley, Samuel Ehret, Christa Torrens, Aislyn Keyes, Ethan Burns

LEVERAGED FUNDING - Private donor support; Stanford Cardinal Quarter Fellowship

RESEARCH FINDINGS AND ACCOMPLISHMENTS: FOCAL AREA 2

IMPROVING INSTITUTIONAL DESIGN FOR USABLE SCIENCE

Improving the public value of science: A typology to inform discussion, design and implementation of research by E. McNie et al.

2.1 RESEARCH DESIGN AND IMPLEMENTATION: BEYOND "BASIC" VS. "APPLIED"

WWA researcher Elizabeth McNie collaborated with former CAP/RISA Program Manager Adam Parris and researcher Dan Sarewitz (Arizona State University) to develop a multi-dimensional typology of research activities.

KEY FINDINGS - Their findings, published in a paper entitled *Improving the public value of science: A typology to inform discussion, design and implementation of research*, describe a more complete view of research activities and expectations of researchers about use of research. Attributes of research efforts can be evaluated on a spectrum from science-centric to user-oriented, and they include such concepts as disciplinary focus, knowledge exchange, social capital, flexibility, and boundary management. Using the typology can inform science-policy planning and decisions, and WWA team members tested the typology by evaluating their research projects.

WWA INVESTIGATORS - Elizabeth McNie

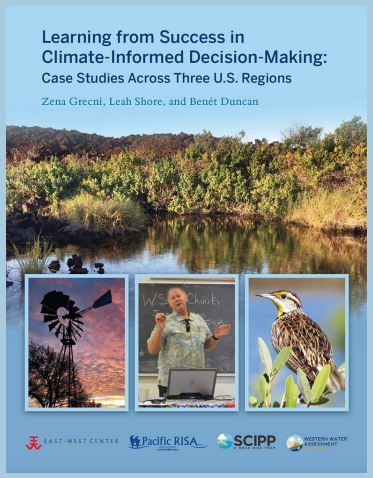
PARTNERS - Adam Parris (formerly NOAA CAP/RISA), Dan Sarewitz (Arizona State University)

Photo above: Snow stakes leaning on T-posts to check alignment with a snowtography camera. Credit: Seth Arens.

2.2 SUSTAINED CLIMATE ASSESSMENT FOR THE U.S. SOUTHWEST

WWA researcher Benét Duncan led the Sustained Climate Assessment in the Southwest project from 2017-2019, in collaboration with WWA's Elizabeth McNie, Lisa Dilling, and Ursula Rick, and with sustained assessment specialists and other researchers across the CAP/RISA network. In this project – a collaboration with Climate Assessment for the Southwest (CLIMAS) and the Colorado-Nevada Applications Program (CNAP) CAP/RISA teams – WWA investigated opportunities for sustained assessment in the U.S. Southwest National Climate Assessment (NCA) region, which includes Arizona, California, Colorado, Nevada, New Mexico, and Utah. The project explored the broad existing capacity for climate assessment in the region with the goal of identifying existing examples of sustained climate assessment, and connecting climate service providers and users to increase access to information and understanding of climate impacts in decision-making contexts.

As part of this project, Duncan had conversations and conducted informal interviews with producers of current and previous NCA reports to better understand the sustained climate assessment landscape and to create an initial vision. She also conducted a review of existing literature on climate service provision and developed a typology of the range of weather and climate information producers in the region. The typology informed the selection of case studies that have successfully produced usable climate and weather information on a sustained basis, including assessments at a range of scales. Duncan then collaborated with Leah Kos, then the sustained assessment specialist for the Southern U.S. CAP/RISA team, and Zena Grecni, the sustained assessment specialist for the Pacific Islands CAP/RISA team, to synthesize lessons from case studies across their respective regions.



Learning from Success in Climate-Informed Decision-Making: Case Studies Across Three U.S. Regions by Z. Grecni, L. Shore, and B. Duncan

KEY FINDINGS - *Learning from Success in Climate-Informed Decision-Making*, published in 2019, identifies five themes that provide practical lessons for others looking to integrate climate information into decision-making processes in a sustained way.

WWA INVESTIGATORS - Benét Duncan, Lisa Dilling, Elizabeth McNie, Ursula Rick

PARTNERS - Zena Grecni (Pacific RISA), Leah Kos (SCIPP), Dan Ferguson (CLIMAS), Tamara Wall (CNAP)

LEVERAGED FUNDING - CAP/RISA Sustained Assessment Support

2.3 EVALUATING USABLE SCIENCE PROGRAMS TO OPTIMIZE OUTCOMES

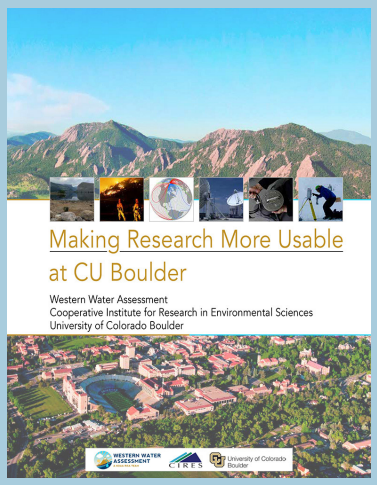
In 2014, WWA researcher Elizabeth McNie conducted an evaluation of the Upper Colorado River Basin (UCRB) Drought Early Warning System (DEWS). (The UCRB DEWS has since been reorganized into the Intermountain West DEWS.) At that time, the UCRB DEWS was part of the National Integrated Drought Information System (NIDIS) but was operated out of the Colorado Climate Center at Colorado State University, and activities centered on regular webinars and a website that shared information about drought conditions with water managers, agricultural producers, and other decision makers. WWA's evaluation assessed whether the UCRB DEWS was meeting NIDIS' goals and improving drought preparedness in the Upper Colorado River Basin. The evaluation report described several areas where the UCRB DEWS was succeeding and recommended steps that could be taken to improve its effectiveness.

IMPACT - To support implementation of the evaluation recommendations, McNie delivered presentations to NIDIS and Colorado Climate Center staff. She also provided support as the evaluation was used to inform NIDIS strategic planning for the next phase of the DEWS. In 2016-2017, she drafted a strategic plan for UCRB DEWS.

WWA INVESTIGATORS - Elizabeth McNie

PARTNERS - NIDIS, Colorado Climate Center

2.4 USABLE SCIENCE ACROSS CU BOULDER



Making Research More Usable at CU Boulder by L. Dilling, K. Clifford, and E. McNie

WWA is active within the University of Colorado Boulder community in promoting the production of usable science. In 2017-18, as part of a seed grant from the Office of Vice Chancellor for Research and Innovation, WWA researchers Lisa Dilling, Katie Clifford, Elizabeth McNie, and others wrote *Making Research More Usable at CU Boulder*. The guide describes a spectrum of ways to conduct research that will more directly benefit stakeholders outside of academia, and it includes example projects from across the university. The report received significant inter-campus media coverage and was shared across several departments throughout CU Boulder. Ursula Rick, Benét Duncan, and Dilling then used the guide to create the Usable Science Lecture and Workshop in 2019. The lecture convened a panel of CU Boulder researchers who are leading usable science efforts, and the workshop helped to train graduate students in best practices for making their research more usable.

In 2016, WWA was awarded a grant to work with a University of Colorado Grand Challenge program, Earth Lab, to ensure Earth Lab research connects to the needs of Colorado stakeholders and to train researchers across campus in the production of usable science. In August 2016, WWA held a Usable Science 101 workshop with the Earth Lab team. Led by Elizabeth McNie, Katie Clifford, and Ursula Rick, it covered definitions of usable science, how it differs from other modes of research, challenges to producing it, the importance of building relationships with stakeholders, and some key communication skills. McNie then administered her typology of science with the Earth Lab team to give them a diagnostic look at their specific research projects.

The team also developed a graduate student seminar which taught the theory and practice of producing usable science and was offered in spring of 2017 and 2018 for a total of 15 students. In June 2017, WWA held a workshop for wildfire practitioners and researchers to improve the usability of a wildfire database created by Earth Lab's Lise St. Denis.

IMPACT - WWA facilitated learning about the production of usable science across the CU Boulder campus, focusing on both student and faculty researchers.

WWA INVESTIGATORS - Lisa Dilling, Elizabeth McNie, Katie Clifford, Ursula Rick, Benét Duncan

PARTNERS - Earth Lab

LEVERAGED FUNDING - CU Boulder Research and Innovation Office

2.5 MAPPING CLIMATE SERVICES

Decision makers often have challenges getting the relevant, salient, timely information they need to help them adapt to climate change. Hundreds of organizations have been created or evolved to help create, translate and disseminate potentially useful climate information. Such climate service organizations exist in both public and private domains, at research universities and private organizations, and represent a wide variety of sectors. Unfortunately, potential users of climate information often do not know where to look for relevant information, nor are producers of climate information well-connected to potential users, resulting in a gap that separates the supply and demand of climate information.

This project, supported by the NOAA Western Regional Collaboration Team, represented a first attempt to reduce this gap by creating a comprehensive database of climate service providers in the western United States. This collaborative project was led by WWA researcher Elizabeth McNie and Climate Assessment for the Southwest (CLIMAS) researcher Allison

Meadow and then continued by CLIMAS researcher Ben McMahan and WWA researcher Benét Duncan. Organizations were assigned attributes based on the sector in which they work, the types of information they provide, the service area covered, the type of sponsoring organization, and many others.

IMPACT - The research team created a searchable database that is open and usable by the public to identify potential climate service providers and partners, and a report that provides preliminary analysis of findings from the database.

WWA INVESTIGATORS - Elizabeth McNie, John Berggren, Benét Duncan

PARTNERS - Allison Meadow, Ben McMahan, Gigi Owen, and Lynn Rae (CLIMAS, University of Arizona); Rachel Norton (University of Colorado, Denver)

LEVERAGED FUNDING - NOAA Western Region Collaboration Team

2.6 CLIMATE KNOWLEDGE AND PERCEPTIONS IN SOUTHWEST COLORADO

Climate perception can include interpretations of experienced climate, beliefs about how climate works or changes, attitudes about climate issues such as the human role in climate change, and even climate preferences. This study focused on how people come to "know" climate, not just climate change science, in a more fundamental way. WWA's Katie Clifford conducted semi-structured interviews of residents of the Gunnison Basin in Colorado whose livelihoods and activities bring them in routine contact with weather, climate, and landscape. She and WWA researcher Bill Travis found that:

1. People often focus on climate-related proxies that might be disregarded as tangential within narrow definitions of climate science.
2. People use rubrics to structure climate knowledge, they understand climate as relational and connected.
3. Climate knowledge does not isolate individual climate elements but accentuates the complex way that many processes together constitute climate. These findings reveal that, for the interviewees, climate is a social-ecological-atmospheric construct.

This project, supported by the NOAA Western Regional Collaboration Team, represented a first attempt to reduce this gap by creating a comprehensive database of climate service providers in the western United States. This collaborative project was led by WWA researcher Elizabeth McNie and Climate Assessment for the Southwest (CLIMAS) researcher Allison Meadow and then continued by CLIMAS researcher Ben McMahan and WWA researcher Benét Duncan. Organizations were assigned attributes based on the sector in which they work, the types of information they provide, the service area covered, the type of sponsoring organization, and many others.

KEY FINDINGS - This research provided new interpretations of results from previous research on attitudes about climate change, especially skepticism. A focus on climate skepticism assumes that climate change beliefs are based on ignorance, politics, and socio-economic motivations, when differences in climate experiences and climate knowledges could lead to some of these differences in attitude. A better understanding of climate knowledge can shape how we work to mitigate and adapt to climate change. By understanding more about how people know climate, we may be able to better interpret climate attitudes and beliefs, diagnose why past efforts to encourage climate adaptation and mitigation have been unsuccessful, and provide insights into limits on the effective application of climate information. Further, this improved understanding of how people perceive climate can help climate service providers make their services more useful. Clifford and Travis worked with undergraduate research assistant Luke Nordgrenn to apply climate perception findings to lessons for climate service providers.

WWA INVESTIGATORS - Katie Clifford, Bill Travis

2.7 CONTRIBUTING TO CAP/RISA USABLE SCIENCE SCHOLARSHIP

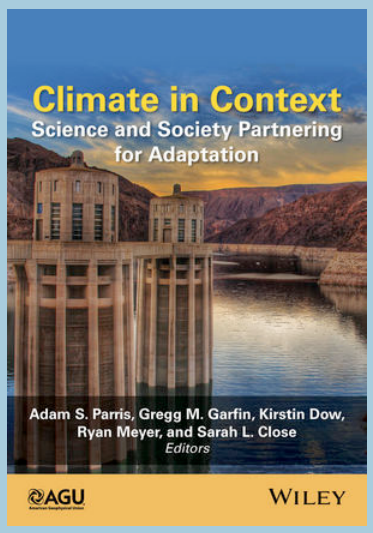
WWA researchers Eric Gordon, Lisa Dilling, Elizabeth McNie, and Andrea Ray contributed to the book *Climate in Context: Science and Society Partnering for Adaptation*, edited by Adam Parris (former CAP/RISA Program Manager) and Gregg Garfin (University of Arizona). Published in 2018, the book explores lessons learned from the CAP/RISA program. Gordon, Dilling, McNie, and Ray collaborated to write *Chapter 11: Navigating scales of knowledge and decision-making in the Intermountain West: Implications for science policy*. This chapter shares insights gained from WWA's years of working across multiple scales of research and decision-making and emphasizes the importance of working across scales to effectively support research, outreach, and engagement with decision makers.

Dilling also collaborated with researchers at other CAP/RISA programs to develop *Chapter 1: Assessing needs and decision contexts: RISA approaches to engagement research*. This chapter of the book emphasizes the importance of integrating physical, social, and behavioral sciences in the development of usable climate science. Social and behavioral sciences provide knowledge about behavior, policy, institutions, and decision contexts that is critical to increasing the usability of the physical sciences.

IMPACT - WWA researchers collaborated with other CAP/RISA researchers and program staff to advance scholarship of usable science.

WWA INVESTIGATORS - Lisa Dilling, Eric Gordon, Elizabeth McNie, Andrea Ray

PARTNERS - NOAA CAP/RISA Program Office



CHAPTER 1

Assessing needs and decision contexts: RISA approaches to engagement research

Caitlin F. Simpson[1], Lisa Dilling[2], Kirstin Dow[3], Kirsten J. Lackstrom[3], Maria Carmen Lemos[4] and Rachel E. Riley[5]

[1]U.S. Department of Commerce, NOAA Climate Program Office, 1315 East West Highway, Room 12212, Silver Spring, MD 20910, USA
[2]Western Water Assessment, Environmental Studies Program and Center for Science and Technology Policy Research, Cooperative Institute for Research in Environmental Sciences, University of Colorado, 4001 Discovery Drive, Boulder, CO 80309-0397, USA
[3]Carolinas Integrated Sciences and Assessments RISA and Department of Geography, University of South Carolina, 709 Bull Street, Columbia, SC 29208, USA
[4]Great Lakes Integrated Sciences and Assessments RISA and School of Natural Resources and Environment, University of Michigan, 430 E. University Ave, Ann Arbor, MI 48109-1115, USA
[5]Southern Climate Impacts Planning Program RISA, University of Oklahoma, 120 David L. Boren Blvd., Suite 2900, Norman, OK 73072, USA

1.1 Introduction

Research on how mankind will adapt to climate variability and change are undeniably important, and yet, traditionally, society tends to turn mainly to physical science for gaining expertise on climate. The Regional Integrated Sciences and Assessments (RISA) program has attempted to remedy this situation by assimilating and generating knowledge that supports the usability of the physical sciences by expanding social and behavioral science on climate and society. We simply cannot understand how best to adapt to climate without gaining knowledge about behavior, policy, institutions, and decision contexts because these aspects often affect the ability of society to respond to and incorporate climate knowledge. Climate research is not only a study of physical processes and impacts, but also a study of individuals, communities, and institutions.

From the beginning, the RISA program has included a human dimensions research element. The number of social scientists in the RISA teams has grown significantly over the course of the program as NOAA staff overseeing

Climate in Context: Science and Society Partnering for Adaptation, First Edition.
Edited by Adam S. Parris, Gregg M. Garfin, Kirstin Dow, Ryan Meyer, and Sarah L. Close.
© 2016 John Wiley & Sons, Ltd. Published 2016 by John Wiley & Sons, Ltd.

Chapter 1 by C. Simpson et al.

CHAPTER 11

Navigating scales of knowledge and decision-making in the Intermountain West: implications for science policy

Eric S. Gordon[1], Lisa Dilling[1,2], Elizabeth McNie[1] and Andrea J. Ray[1,3]

[1]Western Water Assessment, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, 216 UCB, Boulder, CO 80309, USA
[2]Environmental Studies Program and Center for Science and Technology Policy Research, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, 4001 Discovery Drive, Boulder, CO 80309-0397, USA
[3]Physical Sciences Division, NOAA Earth System Research Laboratory, 325 Broadway, R/PSD1, Boulder, CO 80305, USA

11.1 Introduction

Defined simply as the "spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon," [1] scale is a key analytical and explanatory attribute of the human–environment system [2]. Considerations of scale are fundamental to investigating and understanding how to support research, outreach, and engagement with decision-makers who need useful information to expand policy alternatives, clarify choices, and otherwise improve policy outcomes [3]. Unfortunately, navigating across multiple scales of research and decision-making is a difficult task for many traditional research entities, and failure to actively manage multiscalar challenges can lead to the production of information that is not useful for decision support.

In this chapter, we illustrate how the Western Water Assessment (WWA) has identified and addressed problems of scale in order to support climate-sensitive decision-making by water resource managers in the Intermountain West. One of the oldest Regional Integrated Sciences and Assessments (RISA) programs, WWA began in 1998 as an initiative among scientists

Climate in Context: Science and Society Partnering for Adaptation, First Edition.
Edited by Adam S. Parris, Gregg M. Garfin, Kirstin Dow, Ryan Meyer, and Sarah L. Close.
© 2016 John Wiley & Sons, Ltd. Published 2016 by John Wiley & Sons, Ltd.

Chapter 11 by E. Gordon et al.

RESEARCH FINDINGS AND ACCOMPLISHMENTS: FOCAL AREA 3

SNOW AND WATER SCIENCE FOR IMPROVED MANAGEMENT

3.1 SNOW PERSISTENCE AND STREAMFLOW PREDICTION

WWA researcher Ben Livneh has led ongoing research to advance our understanding of climate impacts on snowpack and subsequent impacts on streamflow and water supply prediction. Tools have included remote sensing, hydrologic modeling, and laboratory experiments to explore research questions that are grounded in the priorities and concerns of regional water managers. In 2020, Livneh and former WWA collaborator Andrew Badger (now at NOAA Climate Prediction Center) investigated how declines in future snowpack could impair water supply prediction capabilities in a warmer world. They used downscaled hydrologic simulations from 28 climate model projections to evaluate the predictability of drought in snowmelt dominated systems across the western U.S.. They found that snow will be less able to predict seasonal drought in 69% of these systems by mid-century, and in 83% of these systems by late century.

Livneh also helped lead a virtual workshop in June 2020 titled ***Projecting Rocky Mountain Snow Persistence and Depth Under Climate Change***. The workshop was designed to bring state, federal, and Tribal land and resource managers in Colorado, Wyoming, and Montana together with university researchers to identify snow modeling and snowpack tool needs to support habitat assessment and planning. Since then, he gave several talks to regional stakeholder audiences that facilitated a deeper understanding of regional water issues and needs.

IMPACT - This work is helping to change the culture of hydrologic research by centering stakeholder information needs and interests in designing research activities and sharing results.

Photo above: View of the Flatirons in Boulder, Colorado. Credit: Benét Duncan.

WWA INVESTIGATORS - Ben Livneh

PARTNERS - Andrew Badger (NOAA CPC)

LEVERAGED FUNDING - NOAA NIDIS

3.2 UNDERSTANDING REGIONAL WATER MANAGEMENT RELIANCE ON WATER SUPPLY FORECASTING

Ben Livneh is collaborating with Joseph Kasprzyk and Benét Duncan on an interdisciplinary, stakeholder-driven project that is developing and evaluating new techniques for anticipating and predicting drought that do not rely purely on snow-based methods–harnessing alternative techniques to improve capabilities to predict and respond to drought. This research builds on previous work showing that snowpack information will be less useful for predicting streamflow in the future. It is supported by an award from the NOAA Modeling, Analysis, Predictions and Projections (MAPP) program and leverages WWA stakeholder connections and expertise. Livneh, Kasprzyk, and graduate students Parthkumar Modi, Brooke Ely, Maddy Pernat, and Sydney Walker are using hydrologic modeling and machine learning techniques to identify new metrics and techniques that can improve predictability.

This work is being conducted with the needs of western U.S. water management entities in mind, considering regional characteristics and shifts to a warmer, less snow-dominated future climate. Duncan led the team in collecting direct input from a wide range of regional stakeholders through an online survey administered in the fall of 2021 to help shape the modeling and machine learning work and assess the feasibility of alternative strategies for seasonal water supply forecasting.

WWA INVESTIGATORS - Ben Livneh, Joseph Kasprzyk, Benét Duncan

PARTNERS - Colorado Basin River Forecast Center (CBRFC), Denver Water, Climate Impacts Group (University of Washington), Seattle Public Utilities

LEVERAGED FUNDING - NOAA MAPP

3.3 ADVANCING SNOWPACK MAPPING IN THE WEST

WWA has worked to promote the usability and effective application of snowpack monitoring information, including development of spatial snow data products that add appreciable value at low cost to users. In the spring of 2018, WWA pilot-tested a MODIS-based spatial snow water equivalent (SWE) product developed by WWA researchers Noah Molotch and Leanne Lestak for the WWA Intermountain West region (Utah, Colorado, and Wyoming). The product and an accompanying report were released five times from late March to late May 2018 to approximately 15 water managers, snow scientists, streamflow forecasters, and climate service providers.

WWA's Heather Yocum then conducted phone interviews as part of an evaluation of the MODIS-based spatial SWE product, and to identify general lessons learned about spatial snow products and their potential added value. This report was finalized and released in August 2018. It included identification of the most useful and/or compelling information in the product, particularly maps, report summary, and tabular information, and suggested improvements to data presentation, report frequency, creation of an online archive and interactive website, and inclusion of more analysis of lower elevation snowpack. WWA produced the MODIS-based SWE product for the spring 2019 season as well, with enhancements as indicated by the pilot-test feedback.

IMPACT - Since then, Molotch and Lestak have continued to produce the MODIS-based SWE product with support from WWA, NOAA Colorado Basin River Forecast Center (CBRFC), and other water providers. This SWE mapping has contributed significant adaptive capacity in the region for stakeholders evaluating real-time water supply conditions. The CBRFC is also exploring ways to integrate new SWE data into their seasonal runoff forecasts.

WWA INVESTIGATORS - Noah Molotch, Leanne Lestak, Heather Yocum

PARTNERS - CBRFC

LEVERAGED FUNDING - CBRFC, Denver Water

3.4 ESTIMATING SNOW-WATER EQUIVALENT AND SNOWMELT

WWA researcher Noah Molotch, CU Boulder research faculty Keith Musselman, and graduate students Aaron Heldmyer and Theodore Barnhart made three major research discoveries that advance understanding of the characteristics of snow and snowmelt in the region.

KEY FINDINGS - First, they analyzed Snowpack Telemetry (SNOTEL) data and discovered an increasing trend in mid-winter snowmelt over the past 3+ decades. Second, they used SNOTEL data to identify statistical relationships between snow cover duration and maximum snow-water equivalent which has important implications for future work to improve estimates of snow-water equivalent. Third, using a series of hypothetical snowmelt model experiments they disentangled the influence of snowmelt rate and snowmelt timing on the magnitude of runoff. This result has important implications for water availability as climate warming continues to cause snow to melt earlier in the spring.

WWA INVESTIGATORS - Noah Molotch, Keith Musselman, Ben Livneh, Aaron Heldmyer, Theodore Barnhart

3.5 USABILITY OF REMOTELY SENSED SNOWPACK DATA

A key indicator of water availability, and the primary input to streamflow forecast models, is April 1 snow water equivalent (SWE) in watersheds. April 1 SWE has historically been calculated from a network of in situ Snowpack Telemetry (SNOTEL) observing sites across the West, but two remote-sensing-based approaches have recently been developed to complement and extend the SNOTEL network. This project aimed to understand the usability of these spatial SWE products by water managers, and their potential to improve runoff forecasts. In the first approach, used by WWA researcher Noah Molotch and collaborators, MODIS satellite snow-cover measurements along with a regression from historic SNOTEL data were combined to reconstruct SWE. In the second, used by WWA researcher Jeff Deems and collaborators, airborne LIDAR measurements of snow depth were used to estimate SWE.

Researchers interviewed water managers in the Uncompahgre and Rio Grande River Basins in summer 2016 to better understand their needs and concerns with respect to snow data and runoff forecasting. Focusing on recent stressful events as identified by the water managers, they used the spatial SWE products and hydrologic models to simulate how the new SWE products could have provided better information to prepare for those events. Molotch and researcher Keith Jennings prepared MODIS data for the two basins to be used in hydrologic models. Deems prepared ASO data from the Uncompahgre Basin for use in the models. WWA researcher Mark Raleigh used the SNOW-17 model, which is currently used by the Colorado Basin River Forecast Center, while WWA researcher Ben Livneh used the DHSVM model to explore the impact of various snow regimes on streamflow. Jennings used high resolution snow depth observations and SWE estimates from ASO to quantify errors in the snow products.

KEY FINDINGS - Jennings found that NLDAS-2 was not useful in the Uncompahgre River Basin. Similarly, the SNODAS SWE product performed poorly relative to ASO data, as it overestimated subalpine SWE and underestimated alpine SWE.

WWA INVESTIGATORS - Jeff Lukas, Noah Molotch, Jeff Deems, Ben Livneh, Mark Raleigh, John Berggren, Keith Jennings

LEVERAGED FUNDING - $60,000 NASA Graduate Student Fellowship for Keith Jennings

3.6 GUIDANCE ON THE USE OF IN SITU SNOWPACK INFORMATION

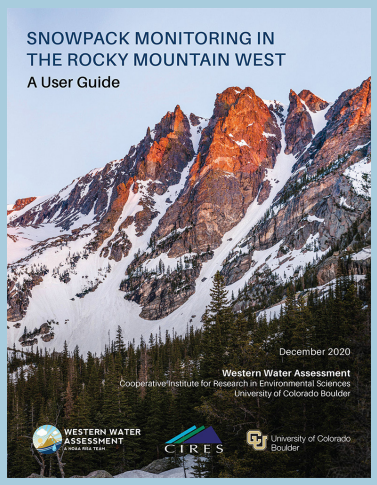
There has been widespread use of snow information from the network of >800 in situ snowpack telemetry (SNOTEL) observing sites across the West. Conditions at SNOTEL sites (e.g., percent of normal snow water equivalent, or SWE) may not be representative of conditions in the large areas between these point measurements, and at elevations above and below the range of the SNOTEL sites. WWA researchers Jeff Deems and Mark Raleigh worked to identify the most representative SNOTEL data in space and time, so that users can make more robust estimates of basin-wide SWE volumes given the limitations of the SNOTEL network. Airborne Snow Observatory (ASO) data collected from western Colorado was used to ground-truth inferences about the robustness of SNOTEL data, and leveraged analyses of SNOTEL and observed and modeled streamflow data by WWA researcher Ben Livneh and collaborator Andrew Badger from a related NOAA Sectoral Applications Research Program (SARP) project.

IMPACT - The findings of the analyses were distilled and presented at a half-day workshop for water managers and others in western Colorado in September 2018.

WWA INVESTIGATORS - Jeff Lukas, Jeff Deems, Mark Raleigh, Ben Livneh, Andrew Badger

LEVERAGED FUNDING - NOAA SARP

3.7 SNOWPACK MONITORING USER'S GUIDE



Snowpack Monitoring in the Rocky Mountain West: A User Guide by L. Woelders, J. Lukas, E. Payton, and B. Duncan

Monitoring the evolution of the snowpack over the course of the winter and spring is critical to forecasting streamflow and managing water supply. Snow monitoring is also vital to other river-based interests, such as fisheries management and guided rafting. WWA researcher Jeff Lukas worked with Lineke Woelders, Ethan Knight, and Liz Payton to develop *Snowpack Monitoring in the Rocky Mountain West: A User Guide* for water managers, decision makers, forecasters, researchers, and others who use, collect, and produce snow information.

The guide describes fundamental characteristics of snowpack, processes that drive its variability, and challenges in monitoring. It highlights the key role of snowpack in seasonal water supply forecasting and describes networks of point observations and products that provide spatial snowpack estimates. It also provides guidance on accessing, interpreting, and applying snow data.

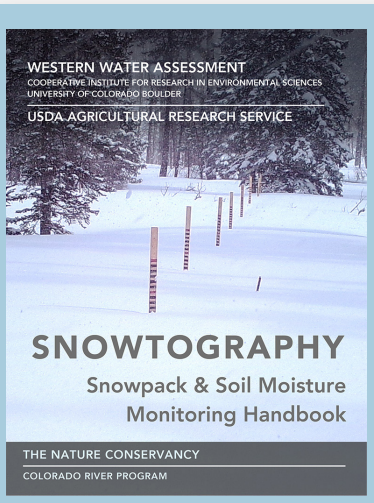
IMPACT - *Snowpack Monitoring in the Rocky Mountain West: A User Guide* highlighted the need for additional snow monitoring data across the Intermountain West, particularly in locations and at elevations where SNOTEL and snow course sites do not provide sufficient coverage. Following release of the guide, Payton and Knight engaged with stakeholders through a two-part webinar series featuring guest speakers Karl Wetlaufer (NRCS), Jeff Deems (CIRES), Gus Goodbody (NRCS), and Patrick Kormos (CBRFC).

WWA INVESTIGATORS - Jeff Lukas, Lineke Woelders, Liz Payton, Ethan Knight, Benét Duncan

LEVERAGED FUNDING - CBRFC, NRCS

3.8 SNOWTOGRAPHY HANDBOOK

WWA's *Snowpack Monitoring in the Rocky Mountain West: A User Guide* and *Colorado River Basin Climate and Hydrology: State of the Science*, both released in 2020, highlighted the need for additional snow monitoring data across the Intermountain West, particularly in locations and at elevations where the NRCS's SNOTEL and snow course sites are sparse. In 2021, WWA, in collaboration with The Nature Conservancy (TNC) and the USDA-Agricultural Research Service (ARS), produced a "snowtography" handbook to increase snow monitoring and data collection in forested settings. WWA researcher Liz Payton led development of *Snowtography: Snowpack and Soil Moisture Monitoring Handbook* in collaboration with Seth Arens and Benét Duncan. She worked closely with co-authors Marcos Robles (TNC) and Joel Biederman (USDA-ARS).



Snowtography: Snowpack and Soil Moisture Monitoring Handbook by E. Payton, J. Biederman, and M. Robles

The handbook supports resource managers, researchers, and practitioners working in forested headwater settings where the arrangement and density of trees, or the size and severity of disturbances, affect snowpack persistence and soil moisture availability. The handbook guides readers through the process of establishing their own snowtography and soil moisture monitoring stations. It offers guidance on site selection, snowtography options, equipment requirements, and installation. The instructions were beta-tested by stakeholders at sites in Arizona and in the San Juan National Forest in southwestern Colorado, and their feedback informed the final handbook.

IMPACT - The handbook has proved to be a valuable information asset for our partners and stakeholders as they pursue increased snowpack monitoring to help guide climate-informed water management decisions. With the help of the handbook, TNC established a project with ARS that will expand snowtography in the Dolores Watershed in 2022 and then in Wyoming in 2023.

WWA INVESTIGATORS - Liz Payton, Seth Arens, Benét Duncan

PARTNERS - The Nature Conservancy, USDA-Agricultural Research Service, Dolores Watershed Resilient Forest Collaborative

LEVERAGED FUNDING - TNC

3.9 NASA IMPACTS AND BENEFITS ASSESSMENT FROM IMPROVED STREAMFLOW FORECASTS

The value of forecast information not only comes from direct measures such as hydropower generation or storage volumes, but also in a range of social, environmental, and economic forms. The question is not about the quantitative 'value' of improving forecast information, but rather how users can benefit from improved forecasts. WWA Investigator Heather Yocum collaborated with the Research Triangle Institute (RTI) International to explore this question. They engaged with Denver Water and Dolores Water Conservancy District, and utilized a range of elicitation and modeling processes to understand how decisions are currently made and how those decisions may change when given forecasts of increased skill. They also investigated the economic, environmental, or social ramifications of these 'improved' decisions, and potential constraints from fully utilizing improved forecast information.

KEY FINDINGS - The research team found that the value of forecast information has different qualitative and quantitative interpretations, so it benefits from a multi-perspective, interdisciplinary approach. They also found that reservoir

operations tend to act conservatively, which can limit the value of improved information, as can legal or other parameters that constrain operations. Irrigators face reduced farm yields and lower economic returns with water supply forecast errors, while higher confidence in timing and size of excess reservoir inflows would benefit recreational rafting.

WWA INVESTIGATORS - Heather Yocum, Travis Williams, Luca Palasti

PARTNERS - RTI

LEVERAGED FUNDING - NASA ROSES

3.10 SNOW MONITORING WORKSHOPS WITH DATA USERS

Real-time monitoring of snowpack is essential to forecasting runoff amount and timing and preparing for both drought and flooding. WWA researchers Noah Molotch, Leanne Lestak, and Jeff Deems developed new spatially explicit snowpack monitoring data products based on remote sensing that could usefully complement the NRCS snowpack telemetry (SNOTEL) network and facilitate new streamflow forecasting approaches. To help identify how best to deploy these products and enhance their overall utility, WWA organized three one-day user workshops in late summer 2015 in Colorado, Utah, and Wyoming. The workshops brought together a total of 180 participants, mainly representing a core user community of local, state, and federal water managers, along with other stakeholders, researchers, and operational information providers. WWA and our partners provided a brief overview of snow hydrology informed by the latest science on snowpack processes, described the current status of snowpack monitoring capacity and products, and solicited feedback on how participants are using them. We then introduced the spatially-explicit snowpack monitoring products and solicited feedback on their present utility and potential future utility.

IMPACT - Post-workshop evaluations indicate that participants consistently reported gains in knowledge of snow hydrology and monitoring, and improved awareness of existing and emerging products. We summarized the workshop content and findings in a report to NIDIS and our other partners. The workshops also helped Molotch and Deems refine and deploy their respective snowpack-monitoring products, by informing them about user needs and capacities, and by connecting them with users and collaborators.

WWA INVESTIGATORS - Jeff Lukas, Noah Molotch, Jeffrey Deems, Tim Bardsley, Elizabeth McNie, D. Schneider, Leanne Lestak

PARTNERS - A. Marrs and C. McNutt (NIDIS), M. Hoobler (Wyoming State Engineer's Office), M. Stokes and S. Bender (Colorado River Basin Forecast Center), B. Domonkos and R. Julander (NRCS Snow Survey)

3.11 SNOWPACK, DROUGHT, AND WATER SUPPLY IN A WARMING MOUNTAIN WEST WORKSHOP

Lineke Woelders, Seth Arens, and Benét Duncan produced the ***Snowpack, Drought, and Water Supply in a Warming Mountain West*** workshop, which included a series of presentations, discussions, and a panel conversation about climate impacts on water supply over days in 2020. The workshop was sponsored by NOAA CPO in collaboration with the Water Research Foundation, and was part of a series of workshops across the country that helped connect water managers and other stakeholders with tools like the NOAA Water Resources Dashboard. The workshop was initially planned as an in-person event but transitioned to a virtual workshop due to the COVID-19 pandemic. Hosting it online allowed us to reach additional stakeholders from small-to-midsize communities across Colorado, Utah, and Wyoming.

IMPACT - Results from the workshop informed decisions about improvements in NOAA's Water Resources Dashboard, and helped WWA identify information needs among small-to-midsize communities and water providers across the region.

WWA INVESTIGATORS - Lineke Woelders, Seth Arens, Benét Duncan

PARTNERS - NOAA CPO, Water Research Foundation

RESEARCH FINDINGS AND ACCOMPLISHMENTS: FOCAL AREA 4

FOSTERING NETWORKS AND COMMUNITIES OF PRACTICE

4.1 THREE CENTERS RETREATS

WWA has a close relationship with the USDA Northern Plains Climate Hub (NPCH) and the USGS North Central Climate Adaptation Science Center (NC CASC), including 'Three Centers Retreats' held twice a year and ongoing collaborative research and engagement projects. The Three Centers Retreats provide an important opportunity to identify collaborative projects, avoid overlap, and to coordinate efforts in the region with our respective stakeholder and partner groups. This often includes presentations about existing research projects; discussions about how to leverage our ongoing work to meet stakeholder needs; and identification of opportunities to conduct new collaborative projects that help to advance scientific knowledge in stakeholder-relevant ways.

IMPACT - This is a critical example of cross-agency coordination and collaboration, and allows us to maximize our impact in the region with stakeholders, partners, and in academic scholarship. These retreats have sparked a range of collaborative efforts, including WWA researcher Bill Travis' ongoing research related to drought decision-making among farmers and ranchers; development of a peer-reviewed publication that describes our centers' collaborative relationship; and development of a series of fact sheets about ecological drought and community and water system resilience to wildfire. We have also disseminated the model and how this "collaboratory" has worked over the years in a publication in the Bulletin of the American Meteorological Soceity (BAMS) led by former WWA director Kristen Averyt and co-authored by members of all three centers.

Photo above: Research retreat rafting the Cataract Canyon of the Colorado River in October 2019.

WWA INVESTIGATORS - Bill Travis, Lisa Dilling, Kristen Averyt, Benét Duncan, Ursula Rick, Jeff Lukas, Seth Arens, Joe Barsugli, Liz Payton, Lineke Woelders, Ethan Knight, Katie Clifford

PARTNERS - USGS NC CASC, USDA NPCH

4.2 COMMUNITIES OF PRACTICE AND THE USE OF HYDROCLIMATE INFORMATION

WWA graduate student Rebecca Page, together with WWA researchers Ben Livneh, Lisa Dilling, and Jeff Lukas, leveraged WWA relationships and expertise to strengthen a NOAA Sectoral Applications Research Program (SARP)-funded project that focused on four key scientific questions:

1. How vulnerable are snowmelt dominated systems to warming and associated changes in snowpack/streamflow predictability?
2. Are higher elevation snow measurements more resilient to warming?
3. How do water managers currently use information?
4. Why do managers use and trust new information?

As part of this effort, Page conducted interviews with Western Slope water managers regarding their use of hydroclimate information.

KEY FINDINGS - Page and Dilling found that communities of practice that bind water managers together are critical for advancing usable science efforts. Larger, well-resourced water systems are often able to serve as early adopters of new information, and can share their experiences among the broader community of water managers. Information could be more effectively and broadly shared by increasing the capacity of these larger water systems to engage with rural and smaller water systems. Page also found that, while experiences of climate extremes like drought can motivate organizational change in small water systems and lead to increased adaptation, they did not always do so. Organizational worldviews and cultures as well as community feedback were important mediators of institutional readiness for adaptive change. Livneh, Dilling, and Page co-organized a stakeholder workshop in Glenwood Springs, Colorado in 2018 in order to connect physical and social science findings with regional water managers. A focus of the workshop was on decisions surrounding drought management and the implications of changing snowpack for water supply forecasting.

WWA INVESTIGATORS - Rebecca Page, Lisa Dilling, Ben Livneh, Jeff Lukas

PARTNERS - Colorado Climate Center, Colorado River District

LEVERAGED FUNDING - NOAA SARP

4.3 UNDERSTANDING AND BUILDING WATER SYSTEM RESILIENCE IN UTAH

WWA researcher Seth Arens has worked extensively to build and strengthen relationships with water managers in Utah. Through these relationships, he advanced a range of research, data analysis, synthesis, and outreach activities with water managers to increase understanding of climate impacts and adaptation opportunities, and to use the latest climate information to help inform decision-making.

Arens and colleagues at WWA worked with the Weber Basin Water Conservancy District (WBWCD) on several projects. In 2015, he engaged in a partnership with WBWCD and Utah Division of Water Resources (UTDWR) on a project to evaluate the impacts of climate change on future water supply and paleohydrology scenarios for the reliability of water deliveries in the Weber Basin. In 2016, he developed projections of future Weber River streamflow to assist with WBWCD's drought contingency planning process, which was supported in part by the Bureau of Reclamation. From 2019-2021, Arens led development of the *Weber Basin Climate Vulnerability Assessment*, which brought together an interdisciplinary group of scientists in Utah to synthesize climate information and develop new projections to inform future water management

planning. WBWCD was the first water provider in Utah to develop a comprehensive climate change vulnerability assessment.

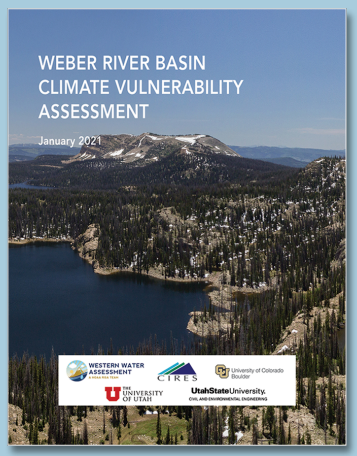
Arens also worked with the Jordan Valley Water Conservancy District (JVWCD) in 2015-17 to develop downscaled projections of future potential evapotranspiration (PET) and future outdoor water demand. Arens provided a presentation to the JVWCD Board of Directors and a written report summarizing his findings.

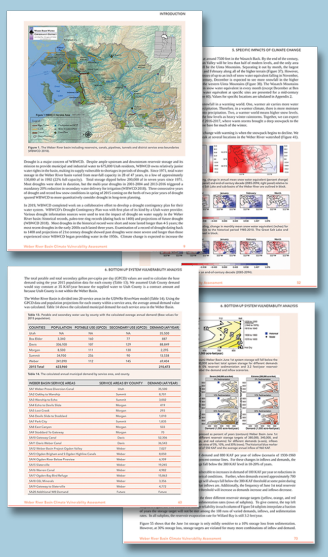
IMPACT - Water providers along the Wasatch Front have explicitly incorporated climate information into their water management planning efforts.

WWA INVESTIGATORS - Seth Arens, Candida Dewes

PARTNERS - WBWCD, JVWCD, UTDWR

LEVERAGED FUNDING - Bureau of Reclamation, WBWCD





Weber Basin Climate Vulnerability Assessment by S. Arens et al.

4.4 NETWORK-BASED LEARNING FOR WATER SECTOR PREPAREDNESS

WWA researcher Benét Duncan collaborated with partners at Aspen Global Change Institute (AGCI) and the National Center for Atmospheric Research (NCAR) on a project to expand water sector climate preparedness in small-to-midsize communities in the Intermountain West region through network-based learning. The project, which was funded through a NOAA SARP grant, sought to leverage partnerships and strengthen networks to expand access and reduce the cost to co-produce climate services for the water sector in this region.

As part of this project, Duncan convened and moderated a session at the Colorado Municipal League's Annual Conference in June 2019. The season focused on connecting Colorado's communities with weather and climate information, and it featured talks by key community partners from our VCAPS workshops in Cortez and Carbondale, CO. She also co-organized a virtual workshop in March 2020 with communities in the broader Intermountain West region to explore how they use and access information, and how networks can support those activities in the future.

The project grew from the Mountain West Climate Service Providers Partnership, a network of researchers and local champions working to increase access to information, tools, and other resources to help small and medium-sized communities throughout the Mountain West region prepare for climate change. Duncan and Seth Arens are members of the Partnership.

IMPACT - WWA and partners helped to strengthen connections between small-to-midsize communities to expand access to climate services and peer learning.

WWA INVESTIGATORS - Benét Duncan, Seth Arens

PARTNERS - James Arnott (AGCI), Julie Vano (AGCI, formerly NCAR)

LEVERAGED FUNDING - NOAA SARP

4.5 LONG-TERM DROUGHT IMPACTS IN THE LAKE POWELL REGION

Beginning in 2019, WWA research scientist Seth Arens led an effort to develop a collaborative network of researchers and resource managers to study the impacts of drought-induced drying of Lake Powell on the Colorado River in Cataract and Glen Canyons. Regional drought since 2001 has caused systematic reductions to annual streamflow in the Upper Colorado River Basin and one important consequence of the drought is a dramatic reduction in the amount of water stored in Lake Powell. The filling of Lake Powell in the 1960s transformed the landscapes of the Colorado River through Glen and Cataract Canyons; today, the drying of Lake Powell is changing the hydrology, geomorphology and ecology of once-inundated landscapes.

As of 2018, no one was investigating the dramatic changes to riverine and terrestrial landscapes caused by a drying Lake Powell. In October 2019, Arens organized and led a science-focused, week-long river trip down Cataract Canyon with researchers from the University of Utah and other organizations including the U.S. Geological Survey, Utah Water Science Center, Utah Geological Survey, Canyonlands National Park, Utah State University, American Rivers and the Returning Rapids Project. Supported by the University of Utah Global Change and Sustainability Center, the goals of the trip included: collecting preliminary data to support future research, fostering a stronger connection between WWA and the University of Utah, connecting the nascent Returning Rapids Project with regional researchers, and developing a network of researchers and organizations interested in studying changes to the Colorado River due to a drying Lake Powell. The trip was successful in all of its goals.

IMPACT - Researchers have published work describing some of the changes in Cataract Canyon and Arens has nearly completed a manuscript describing ecological changes to terrestrial landscapes. The network of researchers collaborating with the Returning Rapids Project continues to grow and issues related to a drying Lake Powell have gained attention in regional media.

WWA INVESTIGATORS - Seth Arens

PARTNERS - University of Utah, USGS, Utah Water Science Center, Utah Geological Survey, Canyonlands National Park, Utah State University, American Rivers, Returning Rapids Project

LEVERAGED FUNDING - University of Utah Global Change and Sustainability Center

Photo below: Aerial view of Lake Powell near Navajo Mountain in Glen Canyon. Credit: Adobe Stock.

RESEARCH FINDINGS AND ACCOMPLISHMENTS: FOCAL AREA 5

DECISION-MAKING FOR EXTREMES

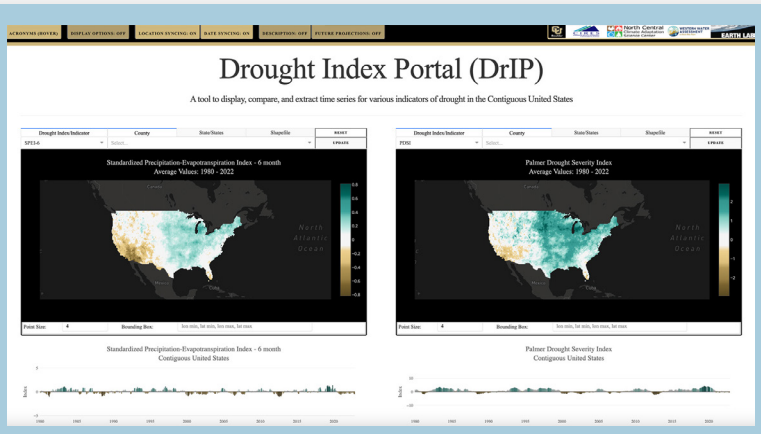
5.1 CLIMATE, DROUGHT, AND DECISION-MAKING IN RANCHING

WWA researcher Bill Travis, together with WWA-supported graduate students Adam McCurdy, Trisha Shrum, Travis Williams, and Luca Palasti, led development of simulation models and decision tools for drought and hydro-climatic uncertainty in climate adaptation, with a particular focus on dryland agriculture and ranching sectors. This research aimed to analyze decision processes in climate-sensitive sectors, and to build decision models that act as both research tools and decision aids.

In 2015-16, Travis and McCurdy developed the "Crop Switch" model that assessed the benefits of changing crops in the Northern Great Plains with warming temperatures and included calculation of the role of crop insurance in making the switch. From 2016-18, Travis, McCurdy, and Shrum modeled rancher adaptation to drought in collaboration with the USDA Northern Plains Climate Hub (NPCH) and the North Central Climate Adaptation Science Center (NC CASC). They built the Drought Ranch Insurance Response (DRIR) model. Online experiments with the model indicated that ranchers with insurance did not increase grazing intensity compared to those without insurance, but that insured individuals purchased more supplemental hay as their incomes rose relative to uninsured individuals. Through a literature review, Shrum, Travis, and collaborators also found that a large gap remains between the information needs of ranchers seeking to adapt dynamically to drought and the information that is available.

From 2017-2020, Travis, Shrum, and Williams continued this work by analyzing a wide range of drought indices in comparison to insurance triggers. Williams and Travis created the Drought Index Portal (DrIP), available at **https://droughtindexportal.colorado.edu**. DrIP is a web analytic resource that allows users to display, compare, and extract time series for various

Photo above: View of the Marshall Fire in Louisville, Colorado on December 30, 2021. Credit: Ami Nacu-Schmidt.



Drought Index Portal website: **https://droughtindexportal.colorado.edu**

indicators of drought in the contiguous United States. They published an analysis comparing alternative drought indices as a basis for the USDA's range insurance program.

Travis extended this work with WWA graduate student Luca Palasti, who developed a decision model for livestock ranching using bi-weekly "Grass-Cast" forage forecasts, to test whether these forecasts provide added economic value to range livestock operations in the Great Plains and Rocky Mountains at their current skill level. Initial results indicate key factors governing forecast value for producers are: skill, timing of decisions, risk aversion, and adaptation costs. But they also found that value is especially derived when Grass-Cast information reduces the likelihood of a producer taking an unnecessary adaptation, suggesting a high nominal value for operational forecast systems.

WWA INVESTIGATORS - Bill Travis, Adam McCurdy, Trisha Shrum, Travis Williams, Luca Palasti

PARTNERS - NC CASC, USDA NPCH

LEVERAGED FUNDING - CU Boulder Earth Lab, NC CASC, National Drought Mitigation Center (University of Nebraska-Lincoln), and the USDA NPCH

5.2 ADAPTING STORMWATER INFRASTRUCTURE TO EXTREME PRECIPITATION

Increases in precipitation intensity raise questions about how to best adapt stormwater infrastructure. WWA researcher Bill Travis and graduate student Adam McCurdy developed a model to simulate the effects of increasing flows on roadway culverts, which are typically constructed to convey certain flow volumes. Key model inputs include when and how to modify stormwater infrastructure as culvert failures become more likely. McCurdy applied the model to a testbed of selected culvert emplacements in Colorado, and calculated the costs of different adaptation pathways or strategies.

KEY FINDINGS - They found that aggressive anticipatory replacement of culverts is economically inefficient even under rather large climate change scenarios, due to the sunk investment of culverts and the traffic disruption caused by construction. The most efficient adaptation pathway under climate uncertainty appears to be investing in evaluation of the vulnerability of each culvert, no matter its life-cycle status, and adapting only those likely to fail in the near future.

WWA INVESTIGATORS - Bill Travis, Adam McCurdy

5.3 UTILITY ADAPTATION DECISION-MAKING UNDER DEEP UNCERTAINTY

Changing extremes have added to an already challenging decision environment for water managers. Traditional methods of identifying alternatives for water supply management may not fully capture the range of existing preferred alternatives, meaning that utilities may miss some solutions that appropriately balance tradeoffs.

In this project, WWA graduate student Rebecca Smith, together with researchers Lisa Dilling, Joseph Kasprzyk, Kristen Averyt, and Imtiaz Rangwala, co-produced and tested a newly developed multi-objective decision tool, balancing conflicting management objectives under climate extremes and determining how policy alternatives perform under

severe climate uncertainty. The MOEA tool includes a complete model of the hypothetical Front Range water management context, including decision levers. They developed downscaled climate scenarios and led a series of workshops in 2015 and 2016 with Front Range water utilities to test the utility of the tool.

IMPACT - The research team gained understanding of how water managers relate tradeoff information to their current needs and practices, got feedback about potential uses and barriers to use, provided exposure for the emerging tool, and learned about the general process of utilities adopting a new tool. The managers valued the opportunity to understand how performance in some objectives affected performance in others. They shared that the workshop was a more effective way to learn about complex research tools than reading reports, and that, along with workshops, consultants, case studies, and innovative neighboring utilities were all factors that could lead to the adoption of new tools.

WWA INVESTIGATORS - Lisa Dilling, Joseph Kasprzyk, Rebecca Smith, Kristen Averyt, Imtiaz Rangwala

PARTNERS - Laurna Kaatz (Denver Water), Leon Basdekas (Colorado Springs Utilities), Northern Water Conservancy District, Aurora Water, City of Boulder Utilities, City of Fort Collins Utilities

LEVERAGED FUNDING - NOAA SARP

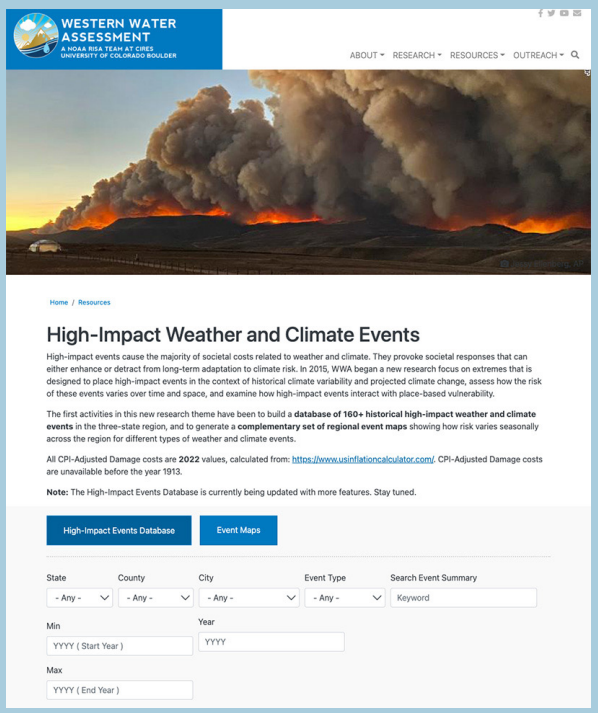
5.4 REGIONAL EXTREMES DATABASE AND EVENT MAPS

WWA researchers Bill Travis and Jeff Lukas and WWA graduate student Adam McCurdy developed a **database of historical high-impact weather and climate events that occurred in Colorado, Wyoming, and Utah from 1862–2017**. The database includes avalanches, cold waves, dam failures, droughts, floods, hail, high winds, landslides, tornadoes, wildfires, and winter storms. McCurdy, Travis, and Lukas also created and published a set of monthly maps on the WWA website using NOAA's National Center for Environmental Information (NCEI) Storm Events Database to better understand the spatial and seasonal patterns in event occurrence for six event types. These event maps show the average number of events for each month of the year, by county, for the period of record available for that event type.

After the launch of WWA's new website in September 2021, Ethan Knight, Lineke Woelders, and Liz Payton updated the contents and increased the utility of the database. They added recent and missing historical high-impact weather and climate events in the region. They created an online calendar listing all events in the database and used the calendar to produce "On This Day in History" event posts on Twitter. This has proven to be an effective form of communication, creating public interest and engaging people and stakeholders with the database.

IMPACT - On July 22, 2021, the database was used by the local CBS station in Denver, CO to explore the impacts of major flooding events in Colorado. Since then, the database has been used by other reporters to place recent events in historical context. The event maps have also proven to be effective in connecting stakeholders with our database, and have been used in stakeholder reports like the Wyoming State Hazard Mitigation Plan (2021–2026).

WWA INVESTIGATORS - Ethan Knight, Adam McCurdy, Bill Travis, Jeff Lukas, Liz Payton, Lineke Woelders



https://wwa.colorado.edu/resources/high-impact-weather-and-climate-events

5.5 FLASH DROUGHTS AND EDDI

WWA researchers including Imtiaz Rangwala, Candida Dewes, Joe Barsugli, and Jeff Lukas, along with partners at NOAA Physical Science Laboratory (PSL), National Integrated Drought Information System (NIDIS), North Central Climate Adaptation Science Center (NC CASC), Desert Research Institute (DRI), and the Western Regional Climate Center (WRCC), advanced the application of a new tool for drought early warning - the Evaporative Demand Drought Index (EDDI), both regionally and nationally. EDDI, developed by Mike Hobbins at the NOAA PSL, exploits the strong physical relationship between evaporative demand of the atmosphere and actual loss of water from the land surface through evapotranspiration. It can serve as an indicator of both rapidly evolving "flash" droughts (those that develop over a few weeks) and sustained droughts (developing over months but lasting up to years). The team worked with Dr. Hobbins in the development and refining of the **interactive EDDI website**, created a stakeholder-centered User's Guide and other interpretive materials, and developed products catering to different regions and stakeholders, including EDDI products on the WWA Intermountain West and Rocky Mountain-High Plains Climate Dashboards and continental US-wide EDDI maps to inform the U.S. Drought Monitor. The team also introduced EDDI to stakeholders at the Wind River Indian Reservation for their drought planning project workshops and in a webinar. Discussion at the workshops suggested that EDDI effectively captured the rapidly changing conditions in 2015, which the U.S. Drought Monitor was unable to capture.

WWA researchers continued outreach and research on EDDI. Rangwala and Lukas led a webinar in Spring 2017, focused on the physical basis behind EDDI, how it compares to other drought indices, and potential uses of EDDI, including flash drought.

IMPACT - EDDI is hosted on the NOAA PSL website and is used to complement older drought indices to identify, track, and study drought.

WWA INVESTIGATORS - Imtiaz Rangwala, Joe Barsugli, Candida Dewes, Jeff Lukas

PARTNERS - Mike Hobbins, NOAA PSL, NC CASC, NIDIS, DRI, WRCC

Photo below: Fish Springs, Utah. Credit: Adobe Stock.

RESEARCH FINDINGS AND ACCOMPLISHMENTS: FOCAL AREA 6

ASSESSING AND MOVING CUTTING-EDGE CLIMATE SCIENCE INTO PRACTICE

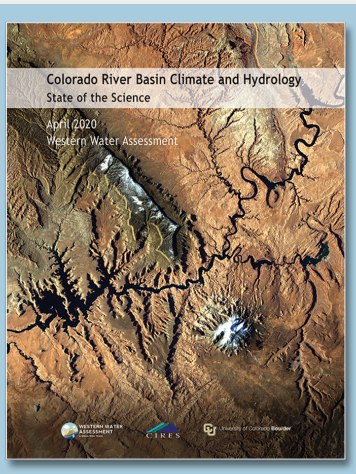
6.1 COLORADO RIVER BASIN CLIMATE AND HYDROLOGY: STATE OF THE SCIENCE REPORT

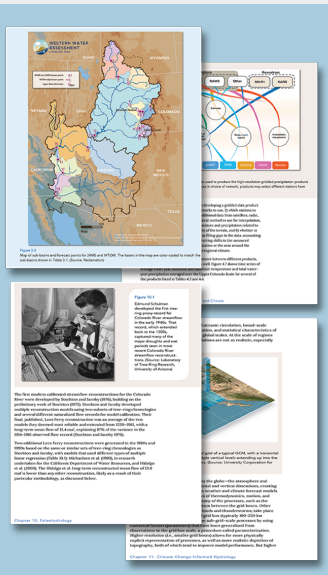
In recent decades, increasing water demand, dry conditions, and warming temperatures have impacted the Colorado River, creating greater uncertainty about the future of the basin's water supply. With support and guidance from over a dozen federal, state, and local water agencies, WWA researchers teamed up with leading experts to synthesize nearly 800 peer-reviewed studies, agency reports, and other sources to assess the state of the science and technical practice relevant to water resources in the Colorado River Basin.

Released in April 2020, *Colorado River Basin Climate and Hydrology: State of the Science* creates a shared understanding of the physical setting and the latest data, tools, and research underpinning the management of Colorado River water resources. In identifying both challenges and opportunities, the report guides water resource managers and researchers in efforts to improve the short-term and mid-term forecasts and long-term projections for the basin's water system. WWA's Jeff Lukas and Liz Payton served as co-lead authors and co-editors of the report, while Lineke Woelders, Ethan Knight, and Benét Duncan contributed to the text and provided support and coordination. An additional 13 subject matter experts contributed content as co-authors.

IMPACT - Since its release, the report has guided water resource managers and researchers in efforts to improve forecasts and projections for the basin's water supplies. This is articulated best by Southern Nevada Water Authority's

Photo above: CU Boulder's Niwot Ridge Long Term Ecological Research program Tundra Lab on Niwot Ridge. Credit: Jeremy Papasso.





Colorado River Basin Climate and Hydrology: State of the Science by J. Lukas and E. Payton (Eds.)

Seth Shanahan, who coordinates the Colorado River Climate and Hydrology Workgroup that sponsored the report: "The State of the Science report continues to serve as a blueprint for our multi-agency basinwide (aka, Colorado River Climate and Hydrology Work Group) research to operations agenda. Specifically in 2021, the Work Group met to consider new project implementation priorities. We amended our procedures to specifically consider the opportunities described in the SOS report and 4 of 6 projects that we agreed to pursue were SOS opportunities. The SOS continues to serve as our chief tool for engaging with the research community and educating our constituencies… The SOS continues to be unparalleled in its breadth and depth and is often cited in agency reports, presentations, interviews, etc. for numerous purposes. Simply put, the SOS report continues to be profoundly impactful."

WWA INVESTIGATORS - Liz Payton, Jeff Lukas, Ethan Knight, Lineke Woelders, Benét Duncan, Joseph Barsugli, Imtiaz Rangwala, Jeff Deems

OTHER COLLABORATORS (CO-AUTHORS) - Stephanie McAfee, University of Nevada, Reno; Andy Wood, National Center for Atmospheric Research (NCAR) Research Applications Lab (RAL); Connie Woodhouse, University of Arizona, Climate Assessment for the Southwest (CLIMAS); Ben Harding, Lynker; Rebecca Smith, Bureau of Reclamation, Lower Colorado Basin Region; Ethan Gutmann, NCAR RAL; Flavio Lehner, NCAR Climate & Global Dynamics Lab, and ETH Zürich; Klaus Wolter, CU Boulder, CIRES; Carly Jerla, Bureau of Reclamation, Lower Colorado Basin Region; James Prairie, Bureau of Reclamation, Upper Colorado Basin Region

PARTNERS - Arizona Department of Water Resources, Bureau of Reclamation, California's Six Agency Committee, Central Arizona Water Conservation District, Colorado River Water Conservation District, Colorado Water Conservation Board, Denver Water, Metropolitan Water District of Southern California, New Mexico Interstate Stream Commission, Southern Nevada Water Authority, Utah Division of Water Resources, and the Wyoming State Engineer's Office

LEVERAGED FUNDING - Bureau of Reclamation, Colorado River Climate and Hydrology Workgroup, Colorado Water Conservation Board

6.2 NATIONAL CLIMATE ASSESSMENTS

The National Climate Assessment (NCA) is a critical, congressionally mandated resource that summarizes the current and future impacts of climate change in the United States. WWA staff member Liz Payton was appointed the Water Chapter Lead and researcher Corrie Knapp was appointed the Northern Great Plains Chapter Lead for the Fifth National Climate Assessment (NCA5). Imtiaz Rangwala is a Technical Contributor for the Water chapter. As Water Chapter Lead, Payton has selected a team of authors with expertise in assessing climate impacts to the nation's surface and groundwater resources and the consequences of those impacts to human and natural systems, with an emphasis on the authors' ability to bring diverse perspectives to the team. She is responsible for chapter development and writing, ensuring that the chapter tells a clear and compelling narrative. Payton led a virtual, national, public engagement workshop to introduce the proposed chapter outline and solicit comments from the public. The NCA5 is expected to be released in late 2023.

WWA staff also participated in satellite stakeholder meetings for the Fourth National Climate Assessment (NCA4) for the Southwest and Northern Great Plains regions in 2018, and WWA researcher Ben Livneh coauthored the Northern Great Plains chapter of the report. WWA also coordinated with the USGS North Central Climate Adaptation Science Center and the USDA Northern Plains Climate Hub to support outreach related to the release of NCA4.

IMPACT - The NCA5 will provide critical climate information for managers, decision makers, NGOs, and the public.

WWA INVESTIGATORS - Liz Payton, Corrie Knapp, Imtiaz Rangwala, Ben Livneh

PARTNERS - USGCRP

6.3 CLIMATE PLANNING IN UTAH

WWA research scientist Seth Arens has deepened relationships with managers and decision makers in Utah, particularly the Utah Division of Water Resources (UDWRe) and the Utah Division of Emergency Management (DEM). In July 2018, Arens and the National Integrated Drought Information System (NIDIS) regional coordinator convened a drought stakeholder meeting in collaboration with the UDWRe. At the meeting, drought coordinators from Colorado, Arizona, and New Mexico shared their experiences with stakeholders in Utah. This meeting built on a workshop planned and facilitated in November 2017 by Arens and NIDIS to introduce the IMW DEWS and to begin a conversation about drought planning in Utah. Following the July 2018 workshop, the state of Utah activated its Drought Response Plan and formally began drought planning efforts.

In early 2019, Seth Arens worked with the Utah Division of Emergency Management to provide content and input for the 2019 revision of the Utah State Hazard Mitigation Plan. The 2019 Utah Hazard Mitigation Plan was one of the first state planning documents that explicitly acknowledged the future risks of climate change.

IMPACT - This ongoing interest in climate change planning represents a shift in climate planning in the state. It also led to development of a new Utah Hazard Planning Tool and Dashboard, supported by more recent CAP/RISA program funding.

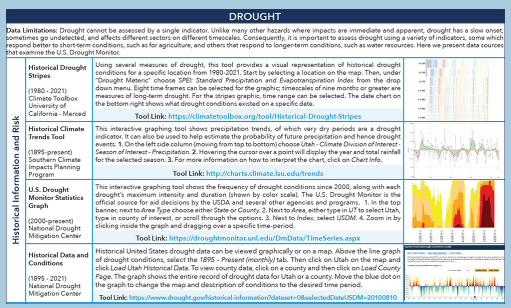
WWA INVESTIGATORS - Seth Arens

PARTNERS - NIDIS, Utah Division of Water Resources, Utah Division of Emergency Management

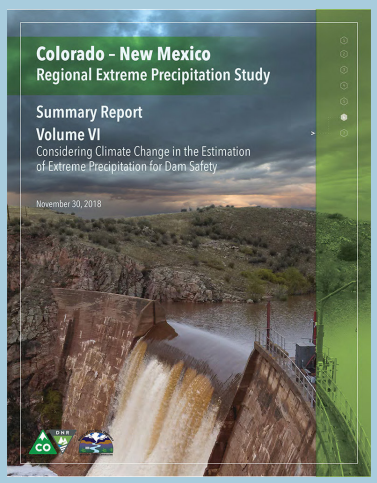
LEVERAGED FUNDING - NIDIS

The UHP Tool is a climate information resource designed specifically for Utah hazard planners to get information about the past incidence, current risk, and future projections of natural hazards in Utah.

The UHP Tool contains a section for each hazard that provides information sources about historical hazard incidence or current risks and any available projections of future hazard occurrence.



6.4 CONSIDERING CLIMATE IMPACTS IN DAM SAFETY



Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety by K. Mahoney, J. Lukas, and M. Mueller

WWA initiated an effort to provide a roadmap for incorporating climate change influences into Probable Maximum Precipitation (PMP) estimates used in the evaluation of spillway adequacy for dams in Colorado and New Mexico. This effort was part of a larger project sponsored by the Colorado Division of Water Resources and the New Mexico Office of the State Engineer to update decades-old PMP estimates in these states using modern technical methods and current scientific understanding. WWA's Jeff Lukas collaborated with NOAA ESRL physical scientist Kelly Mahoney and CIRES Research Scientist Michael Mueller, to take stock of the state of the science and practice in PMP estimation with respect to climate change. The resulting synthesis report, *Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety*, was released in December 2018 and is included as Volume VI of the final *Colorado-New Mexico Regional Extreme Precipitation Study report*.

The report recommended that updated PMP values in dam-safety rules account for the increase in precipitable water with warming temperatures, which is the climate-change risk for which there is the most confidence. In early 2019, The Colorado Dam Safety Office proposed Rule 7.2.4, which would apply an atmospheric moisture factor (multiplier) of 1.07 to PMP values to account for the expected future warming and associated increases in atmospheric moisture availability from 2020 to 2070. The rule was officially adopted in November 2019.

IMPACT - The results of this work were used to develop Colorado Dam Safety Office Rule 7.2.4 to consider future warming in PMP values for dam safety. In recognition of the importance of this work, Lukas and collaborators Eric James (CIRES), Kelly Mahoney (NOAA), Rob Cifelli (NOAA), Trevor Alcott (NOAA), and Bill McCormick (Colorado Dam Safety Office), were awarded a 2019 COLABS Governor's Award for High-Impact Research under the category of "Pathfinding Partnerships." The award noted that the project will enhance safety and community resilience efforts and inform the Colorado State Engineer and Army Corp of Engineers' priorities and urgent projects.

WWA INVESTIGATORS - Jeff Lukas

PARTNERS - Eric James (CIRES), Kelly Mahoney (NOAA), Rob Cifelli (NOAA), Trevor Alcott (NOAA), and Bill McCormick (Colorado Dam Safety Office)

6.5 DROUGHT PLANNING AT THE WIND RIVER INDIAN RESERVATION

In collaboration with the Eastern Shoshone and Northern Arapaho tribes, in 2015-2016 WWA partners at the North Central Climate Adaptation Science Center (NC CASC) and the National Drought Mitigation Center (NDMC) helped to develop a comprehensive drought plan for the Wind River Indian Reservation in Wyoming. The research team developed analytical tools and provided analysis to inform the drought plan. WWA investigator Elizabeth McNie provided evaluation support and helped to inform the research design. She used a typology of research approaches to guide the design and analysis of research goals, objectives, and processes to help ensure that the project met its goals of producing useful drought information to inform future policy decisions. She also delivered her findings to a joint meeting of the research team.

WWA INVESTIGATORS - Elizabeth McNie

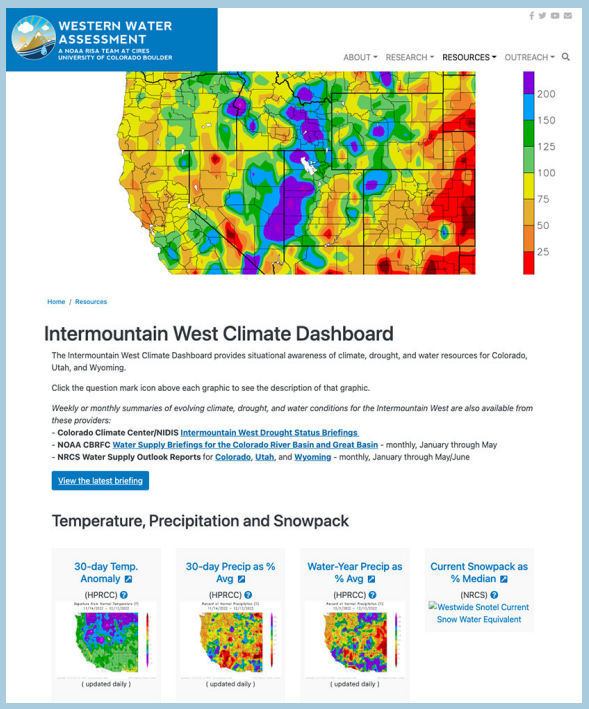
PARTNERS - S. McNeeley (NC CASC), C. Knutson (NDMC), Wind River Reservation

6.6 REGIONAL CLIMATE DASHBOARDS

The **Intermountain West Climate Dashboard**, which debuted in October 2012, is an internet resource that provides information and graphics about current and forecasted regional weather, climate and water information. Feedback from WWA stakeholders through multiple program evaluations and analyses of website traffic indicate that the dashboard is a very useful 'one-stop shop' for up-to-date climate and water information for WWA's three-state region.

In 2015, WWA built on this success by implementing a second, similar dashboard covering the combined eight-state region of WWA, the North Central Climate Adaptation Science Center (NC CASC), and the USDA Northern Plains Climate Hub (NPCH), in collaboration with those two entities. The Rocky Mountains and High Plains Climate Dashboard has proven to be useful to stakeholders of our three centers. In September 2021, we released updated dashboards that use the most up-to-date web design technology on our new program website.

We have also continued to release monthly **Intermountain West Climate Briefings**, which are posted on our website and emailed to our broad stakeholder mailing list. The monthly climate and weather summaries have proven to be very popular, with a high open and click-through rate, and requests from stakeholders to continue to produce them.



https://wwa.colorado.edu/resources/intermountain-west-climate-dashboard

IMPACT - In WWA's 2020 program evaluation survey, over 88% of respondents reported having used and/or recommended the dashboard to others. One noted, "I visit and use [the dashboard] at least monthly if not more frequently. I highlight [it] as a resource to colleagues and stakeholders at least a dozen times a year at various meetings/conferences/etc.!" Another respondent shared, "We are pushing for contractors working on studies to access and utilize these resources [in the dashboard] in their evaluation of water supply and demand modeling moving forward to begin to move our plans forward with potential changes of climate change."

WWA INVESTIGATORS - Jeff Lukas, Seth Arens, Ethan Knight

PARTNERS - NC CASC, NPCH

6.7 WE ARE WATER

Led by the CIRES Education and Outreach Team, the NSF-supported We are Water project is an exciting collaboration between scientists, Indigenous science educators, learning researchers, informal educators, and library staff. The project engages with water-stressed communities in the Four Corners region, particularly Indigenous and Latinx communities, through a co-developed library exhibit and other programs, including educational videos and recordings. Benét Duncan is a Science Advisor, and Seth Arens, Ethan Knight, Ami Nacu-Schmidt, and Lineke Woelders also developed learning materials, a social media campaign, and event outreach. Knight traveled to Aztec, New Mexico in June 2022 to host We are Water's Mini Film Festival focusing on water quality, access, and scarcity challenges in the region.

WWA INVESTIGATORS - Benét Duncan, Ethan Knight, Lineke Woelders, Seth Arens

PARTNERS - Anne Gold, Brigitta Rongstad (CIRES Education and Outreach)

LEVERAGED FUNDING - NSF

We are Water Exhibit at Aztec Public Library, NM.

We are Water Take and Make Kits.

APPENDIX

WESTERN WATER ASSESSMENT PUBLICATIONS

2015-2016

Averyt, K., 2016. Energy-Water Nexus: Head-on Collision or Near-Miss? American Scientist, May/June, pp. 158–165. https://www.americanscientist.org/article/energy-water-nexus-head-on-collision-or-near-miss.

Brugger, J., A. Meadow, A. Horangic, 2016. Lessons from First-Generation Climate Science Integrators. Bulletin of the American Meteorological Society 97, pp. 355-365. https://doi.org/10.1175/BAMS-D-14-00289.1.

Dickerson-Lange, S.E., J. A. Lutz., K. A. Martin, M. S. Raleigh, R. Gersonde and J.D. Lundquist, 2015. Evaluating observational methods to quantify snow duration under diverse forest canopies. Water Resources Research, 51. https://doi.org/10.1002/2014WR015744.

Dilling, L., 2015. Adaptation. Research Handbook on Climate Governance, Ed. K. Bäckstrand and E. Lövbrand, 470-479, Edward Elgar Publishing.

Dilling, L. and J. Berggren, 2015. What do stakeholders need to manage for climate change and variability? A document-based analysis from three mountain states in the Western U.S. Regional Environmental Change, 15(4), pp. 657-667. https://doi.org/10.1007/s10113-014-0668-y.

Goharian, E., S. J. Burian, T. Bardsley and C. Strong, 2015. Incorporating Potential Severity into Vulnerability Assessment of Water Supply Systems under Climate Change Conditions. Journal of Water Resources Planning and Management. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000579.

Gordon, E., L. Dilling, E. McNie, A.J. Ray, 2016. Navigating Scales of Knowledge and Decision Making in the Intermountain West: Implications for Science Policy. In: Climate in Context: Lessons learned from the RISA Program, Parris, A, et al, eds. Wiley & Sons.

Kasprzyk, J., P. Reed, D. Hadka, 2016. Battling Arrow's Paradox for Discovering Robust Water Management Alternatives. Journal of Water Resources Planning and Management, 142(2), 04015053. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000572.

Kirchhoff, C. and L. Dilling, 2016. The role of U.S. states in facilitating effective water governance under stress and change. Water Resources Research, April 17. https://doi.org/10.1002/2015WR018431.

Klein, R. and L. Dilling, 2015. The Colorado Basin River Forecast Center and the Decision Making Process. Western Water Assessment White Paper, October, 2015. http://hermes.cde.state.co.us/drupal/islandora/object/co:33184/datastream/OBJ/view.

Lapo, K., L. Hinkelman, M. S. Raleigh and J.D. Lundquist, 2015. Impact of errors in the surface radiation balance on simulations of snow water equivalent and snow surface temperature. Water Resources Research, 51. https://doi.org/10.1002/2014WR016259.

Mahoney, K., F.M. Ralph, K. Wolter, N. Doesken, M. Dettinger, D. Gottas, T. Coleman and A. White, 2015. Climatology of extreme daily precipitation in Colorado and its diverse spatial and seasonal variability. Journal of Hydrometeorology, 16, pp. 781-792. https://doi.org/10.1175/JHM-D-14-0112.1.

McNie, E.C., A. Parris and D. Sarewitz. 2016. Improving the public value of science: A typology to inform discussion, design and implementation of research. Research Policy, 45(4) pp. 884-895, May. https://doi.org/10.1016/j.respol.2016.01.004.

Mountain Research Initiative Working Group, 2015. Elevation-Dependent Warming in Mountain Regions of the World. Nature Climate Change, 5: 424-430. https://doi.org/10.1038/nclimate2563.

Raleigh, M.S., J. D. Lundquist and M.P. Clark, 2015. Exploring the impact of forcing error characteristics on physically based snow simulations within a global sensitivity analysis framework. Hydrology and Earth Systems Sciences, 19, pp. 3153-3179. https://doi.org/10.5194/hess-19-3153-2015.

Raleigh, M.S., B. Livneh, K. Lapo and J.D. Lundquist, 2016. How does availability of meteorological forcing data impact physically-based snowpack simulations? Journal of Hydrometeorology, 17, pp. 99-120. https://doi.org/10.1175/JHM-D-14-0235.1.

Rangwala, I., T. Bardsley, M. Pescinski, and J. Miller, 2015. SNOTEL sensor upgrade has caused temperature record inhomogeneities for the Intermountain West: Implications for climate change impact assessments. Western Water Assessment Climate Research Briefing. https://wwa.colorado.edu/sites/default/files/2021-08/Rangwalaetal2015.pdf.

Rangwala I., N. Pepin, M. Vuille and J. Miller, 2015. Influence of Climate Variability and Large-Scale Circulation on Mountain Cryosphere. In The High-Mountain Cryosphere: Environmental Changes and Human Risks, edited by C. Huggel, J Clague, A. Kääb and M. Carey. Chapter 2. Cambridge University Press.

Rangwala, I., M. Hobbins, J. Barsugli, and C. Dewes, 2015. EDDI: A Powerful Tool For Early Drought Warning. WWA 2-pager document. http://wwa.colorado.edu/publications/reports/EDDI_2-pager.pdf.

Rangwala, I., C. Dewes and J. Barsugli, 2016. High Resolution Climate Modeling for Regional Adaptation. EOS, 97, March 25. https://doi.org/10.1029/2016EO048615.

Ray, A.J., 2016. Providing climate science to real-world policy decisions: a scientist's view from the trenches. pp.141-160 in: Water Policy and Planning in a Variable and Changing Climate. Eds: Kathleen Miller, Alan Hamlet, Douglas Kenney, Kelly T. Redmond, CRC Press.

Smith, R., J. Kasprzyk and E. Zagona, 2016. Many-Objective Analysis to Optimize Pumping and Releases in Multireservoir Supply Network. Journal of Water Resources Planning and Management, 142(2), 04015049. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000576.

2016-2017

Barnhart, T., N.P. Molotch, B. Livneh, A. Harpold, J. Knowles, D. Schneider, 2016. Snowmelt rate dictates streamflow. Geophysical Research Letters, 43(15): 8006-8016. https://doi.org/10.1002/2016GL069690.

Burnham, M., Z. Ma., J. Endter-Wada and T. Bardsley, 2016. Water Management Decision Making in the Face of Multiple Forms of Uncertainty and Risk. Journal of the American Water Resources Association. https://doi.org/10.1111/1752-1688.12459.

Dewes C.F., I. Rangwala, J. J. Barsugli, M.T. Hobbins and S. Kumar, 2017. Drought risk assessment under climate change is sensitive to methodological choices for the estimation of evaporative demand. PLoS ONE, 12(3): e0174045. https://doi.org/10.1371/journal.pone.0174045.

Dilling, L., E. Pizzi, J. Berggren, A. Ravikumar and K. Andersson, 2017. Drivers of adaptation: Responses to weather- and climate-related hazards in 60 local governments in the Intermountain Western U.S., Environment and Planning A, 1-21. https://doi.org/0.1177/0308518X16688686.

Dilling, L., K. C. Kelsey, D. P. Fernandez, Y. D. Huang, J. B. Milford and J. C. Neff, 2016. Managing Carbon on Federal Public Lands: Opportunities and Challenges in Southwestern Colorado. Environmental Management. https://doi.org/10.1007/s00267-016-0714-2.

Eden, J.M., K. Wolter, F.E.L. Otto and G.J. van Oldenborgh, 2016. Multi-method attribution analysis of extreme precipitation in Boulder, Colorado. Environmental Research Letters, 11, 124009. https://doi.org/10.1088/1748-9326/11/12/124009.

Finnessey, T., M. Hayes, J. Lukas and M. Svaboda, 2016. Using climate information for drought planning. Climate Research, 70, p. 251-263. https://doi.org/10.3354/cr01406.

Hoerling, M. J. Eischeid, J. Perlwitz, X. Quan and K. Wolter, 2016. Characterizing Recent Trends in U.S. Heavy Precipitation. J. Climate, 29, 2313-2332. http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-15-0441.1.

Houle, E.S., B. Livneh and J.R. Kasprzyk, 2017. Exploring Snow Model Parameter Sensitivity Using Sobol' Variance Decomposition. Environmental Model and Software, 89, 144–158. https://doi.org/10.1016/j.envsoft.2016.11.024.

Klein, R. and E. McNie, 2017. Research Transitions in the NOAA RISA Program. Western Water Assessment Report.

Livneh B. and M.P. Hoerling, 2016. The Physics of Drought in the U.S. Central Great Plains. Journal of Climate, 29, 6783-6804. https://doi.org/10.1175/JCLI-D-15-0697.1.

Lukas, J., E. McNie, T. Bardsley, J. Deems and N. Molotch, 2016. Snowpack Monitoring for Streamflow Forecasting and Drought Planning. Western Water Assessment report to NIDIS. https://wwa.colorado.edu/sites/default/files/2022-08/Snowpack_Monitoring_for_Streamflow_Forecasting_and_Drought_Planning.pdf.

McCurdy, A.D. and W.R. Travis, 2017. Simulated climate adaptation in stormwater systems: Evaluating the efficiency of adaptation strategies. Environment Systems and Decisions, 1-16, February 13. https://doi.org/10.1007/s10669-017-9631-z.

Meadow, A., E. McNie, J. Berggren, R. Norton, B. McMahan, G. Owen and L. Rae, 2016. NOAA Western Region: Climate Service Providers Database Development and Preliminary Analysis. Western Water Assessment, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, 18 pages.

Raseman, W. J., J.R. Kasprzyk, F.L. Rosario-Ortiz, J.R. Stewart and B. Livneh, 2017. Emerging investigators series: a critical review of decision support systems for water treatment: making the case for incorporating climate change and climate extremes. Environmental Science: Water Research & Technology. https://doi.org/10.1039/C6EW00121A.

Rice, J., T. Bardsley, P. Gomben, D. Bambrough, S. Weems, S. Leahy, C. Plunkett, C. Condrat, L.A. Joyce, 2017. Assessment of watershed vulnerability to climate change for the Uinta-Wasatch-Cache and Ashley National Forests, Utah. Gen. Tech. Rep. RMRS-GTR-362. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 111 p.

Rondeau, R., B. Neely, M. Bidwell, I. Rangwala, L. Yung, K. Clifford and T. Schulz, 2017. Sagebrush Landscape: Upper Gunnison River Basin, Colorado: Social-Ecological Climate Resilience Project. North Central Climate Science Center, Ft. Collins, Colorado. https://mountainscholar.org/handle/10217/180878.

Rondeau, R., B. Neely, M. Bidwell, I. Rangwala, L. Yung, K. Clifford, and T. Schulz, 2017. Spruce-Fir Landscape: Upper Gunnison River Basin, Colorado. Social-Ecological Climate Resilience Project. North Central Climate Science Center, Ft. Collins, Colorado. https://mountainscholar.org/bitstream/handle/10217/180879/CNRWCNHP_2017_SECR_Spruce-Fir_Landscape_Report.pdf.

Schneider, D. and N.P. Molotch, 2016. Real-time estimation of snow water equivalent in the Upper Colorado River Basin using MODIS-based SWE reconstructions and SNOTEL data. Water Resources Research, 52(10): 7892-7910. https://doi.org/10.1002/2016WR019067.

Simpson, C., L. Dilling, K. Dow, K. Lackstrom, M.C. Lemos and R. Riley, 2016. Assessing needs and decision contexts: RISA approaches to engagement research. Climate in Context: Science and Society Partnering for Adaptation, Ed. A. Parris and G. Garfin3-26, Wiley and Sons.

Wolter, K., M. Hoerling, J.K. Eischeid and L. Cheng, 2016. What History Tells us about 2015 US Daily Rainfall Extremes [in "Explaining Extremes of 2015 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 97, S9-13. https://www.jstor.org/stable/26265418.

Woodhouse, C. A., J. J. Lukas, K. Morino, D. M. Meko and K. K. Hirschboeck, 2016. Using the past to plan for the future – The value of paleoclimate reconstructions for water resource planning. In Water Policy and Planning in a Variable and Changing Climate, edited by K. Miller, A. Hamlet, D. Kenney, and K. Redmond. CRC Press.

2017-2018

Averyt, K., J.D. Derner, L. Dilling, R. Guerrero, L. Joyce, S. McNeeley, E. McNie, J. Morisette, D. Ojima, R. O'Malley, D. Peck, A.J. Ray, M. Reeves and W. Travis, 2018. Regional Climate Response Collaboratives: Multi-Institutional Support for Climate Resilience. Bulletin of the American Meteorological Society, 891-898. https://doi.org/10.1175/BAMS-D-17-0183.1.

Baker, E., T. H. Painter, D. Schneider, A. Meddens, J. A. Hicke and N. P. Molotch, 2017. Quantifying insect-related forest mortality with the remote sensing of snow. Remote Sensing of Environment, 188: 26-36. https://doi.org/10.1016/j.rse.2016.11.001.

Berggren, J., 2018. Utilizing sustainability criteria to evaluate river basin decision-making. J. Reg. Environ. Change. https://doi.org/10.1007/s10113-018-1354-2.

Clifford, K.R. and W.R. Travis, 2018. Knowing climate as a social-ecological-atmospheric construct. Global Environmental Change, Volume 49, pp. 1–9. https://doi.org/10.1016/j.gloenvcha.2017.12.007.

Derner, J., D. Briske, M. Reeves, T. Brown-Brandl, M. Meehan, D. Blumenthal, W. Travis, D. Augustine, H. Wilmer, D. Scasta, J. Hendrickson, J. Volesky, L. Edwards and D. Peck, 2017. Vulnerability of grazing and confined livestock in the Northern Great Plains to projected mid- and late-twenty-first century climate. Climatic Change. https://doi.org/10.1007/s10584-017-2029-6.

Dilling, L., K. Clifford, E. McNie, J. Lukas and U. Rick, 2018. Making Research More Usable at CU Boulder. Western Water Assessment Report, 26 pp. https://wwa.colorado.edu/sites/default/files/2021-07/Making%20Research%20More%20Usable%20at%20CU%20Boulder.pdf.

Dilling, L., R. Morss and O. Wilhelmi, 2018. Learning to Expect Surprise: Hurricanes Harvey, Irma, Maria, and Beyond. Journal of Extreme Events, Vol. 4, No. 3. https://doi.org/10.1142/S2345737617710014.

Friedrich, K., R. Grossman, J. Huntington, P. Blanken, J. Lenters, K. Holman, D. Gochis, B. Livneh, J. Prairie, E. Skeie, N. Healey, K. Dahm, C. Pearson, T. Finnessey, S. Hook and T. Kowalski, 2018. Reservoir Evaporation in the Western United States: Current Science, Challenges, and Future Needs, Bulletin of the American Meteorological Society. https://doi.org/10.1175/BAMS-D-15-00224.1.

Jennings, K.S., T. Winchell, B. Livneh and N.P. Molotch, 2018. Spatial variation of the rain-snow temperature threshold across the Northern Hemisphere, Nature Communications, 9, 1148. https://www.nature.com/articles/s41467-018-03629-7.

Jennings, K.S., T. Kittel and N. P. Molotch, 2018. Observations and simulations of the seasonal evolution of snowpack cold content and its relation to snowmelt and the snowpack energy budget. Cryosphere, 12(5): 1595-1614. https://doi.org/10.5194/tc-12-1595-2018.

Henderson, J., 2018. Unintended Consequences of Drought Planning Along the Arkansas River in Colorado. Colorado Water, 35 (2) 10-14.

Livneh, B., A.M. Badger and J.J. Lukas, 2017. Assessing the robustness of snow-based drought indicators in the Upper Colorado River Basin under future climate change, World Environmental and Water Resources Congress, May 2017-03, p 15. https://doi.org/10.1061/9780784480618.051.

Lukas, J., 2018. A Brief Overview of Drought Monitoring Indicators and Resources for Colorado. Colorado Water, 35 (2) 22-25.

Lukas, J., M. Hobbins, I. Rangwala and the EDDI team, 2017. The EDDI User Guide v1.0. https://esrl.noaa.gov/psd/eddi/pdf/EDDI_UserGuide_v1.0.pdf.

McCurdy, A.D. and W.R. Travis, 2017. Simulated climate adaptation in storm-water systems: Evaluating the efficiency of within-system flexibility. Climate Risk Management. https://doi.org/10.1016/j.crm.2017.12.002.

McNeeley S.M., C. Dewes, C. J. Stiles, T. Beeton, I. Rangwala, M. Hobbins and C. Knutson, 2017. Anatomy of an interrupted irrigation season: Micro-drought at the Wind River Indian Reservation. Climate Risk Management. https://doi.org/10.1016/j.crm.2017.09.004.

Painter, T.H., S.M. Skiles, J.S. Deems, W.T. Brandt and J. Dozier, 2018. Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow. Geophysical Research Letters. https://doi.org/10.1002/2017GL075826.

Rangwala I. and C. F. Dewes, 2018. Downscaled climate projections at 800m spatial resolution for the north central United States based on the Multivariate Adaptive Constructed Analog (MACA) method from selective CMIP5 models. ScienceBase. https://doi.org/10.21429/C9704J.

Rondeau, R., B. Neely, M. Bidwell, I. Rangwala, L. Yung, K. Clifford and T. Schultz, 2017. Spruce-Fir Landscape: Upper Gunnison River Basin, Colorado. Social-Ecological Climate Resilience Project. Report prepared for the North Central Climate Science Center, Ft. Collins, Colorado, pp. 55. http://www.cnhp.colostate.edu/download/documents/2017/SECR_Spruce-Fir_Landscape_Report_4-30-2017_Final_with_Appendices.pdf.

Rondeau, R., B. Neely, M. Bidwell, I. Rangwala, L. Yung, K. Clifford and T. Schultz, 2017. Sagebrush Landscape: Upper Gunnison River Basin, Colorado: Social-Ecological Climate Resilience Project. Report prepared for the North Central Climate Science Center, Ft. Collins, Colorado, pp. 56. http://www.cnhp.colostate.edu/download/documents/2017/SECR_Sagebrush_Landscape_Report_4-30-2017_Final_and_Appendices.pdf.

Shrum, T. R., W. R., Travis, T. M. Williams and E. Lih, 2018. Managing climate risks on the ranch with limited drought information. Climate Risk Management, February 22. https://doi.org/10.1016/j.crm.2018.01.002.

Smith, R, J.R. Kasprzyk and L. Dilling, 2017. Participatory Framework for Assessment and Improvement of Tools (ParFAIT): Increasing the impact and relevance of water management decision support research. Environmental Modelling and Software, Volume 95, September, pp. 432-446. https://doi.org/10.1016/j.envsoft.2017.05.004.

Smith, R, J.R. Kasprzyk and L. Basdekas, 2018. Experimenting with water supply planning objectives using the Eldorado Utility Planning Model multireservoir testbed. Journal of Water Resources Planning and Management. vol. 144, no. 8. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000962.

Wall, T.U., E. McNie and G.M. Garfin, 2017. Use-inspired science: Making science usable by and useful to decision makers. Frontiers in Ecology and the Environment, Special Issue: Translational ecology, Vol. 15, Issue 10, pp. 551-559. https://doi.org/10.1002/fee.1735.

2018-2019

Arens, S., K. Clifford and D. Rumore, 2018. Final Workshop Report for Vulnerability Consequences and Adaptation Planning Scenarios (VCAPS) for the Cities of Springdale, Rockville and Hurricane. Western Water Assessment: Salt Lake City, UT.

Clifford, K., J. Henderson, S. Arens, S. Ehret, L. Dilling and B. Duncan, 2018. Final Workshop Report for Vulnerability Consequences and Adaptation Planning Scenarios (VCAPS) for the City of Cortez. Western Water Assessment: Boulder CO. https://www.cityofcortez.com/DocumentCenter/View/1418/VCAPS-FINAL-REPORT-MARCH-2019.

Dilling, L., J. Berggren, J. Henderson and D. Kenney, 2019. Savior of rural landscapes or Solomon's Choice? Colorado's experiment with Alternative Transfer Methods for water (ATMs). Water Security 6. https://doi.10.1016/j.wasec.2019.100027.

Dilling, L., M.E. Daly, D.A. Kenney, R. Klein, K. Miller, A.J. Ray, W.R. Travis and O. Wilhelmi, 2018. Drought in urban water systems: Learning lessons for climate adaptive capacity. Climate Risk Management. https://doi.org/10.1016/j.crm.2018.11.001.

Ehret, S., J. Lukas, S. Arens, K. Clifford and L. Dilling, 2018. Final Workshop Report for Vulnerability Consequences and Adaptation Planning Scenarios (VCAPS) for the Town of Carbondale. Western Water Assessment: Boulder CO. https://www.carbondalegov.org/Carbondale_VCAPS_Final_Draft_2019_21_01.pdf.

Jennings, K.S., T.G.F. Kittel and N.P. Molotch, 2018. Observations and simulations of the seasonal evolution of snowpack cold content and its relation to snowmelt and the snowpack energy budget. The Cryosphere, 12, 1595-1614. https://doi.org/10.5194/tc-12-1595-2018.

Jennings K.S., T.S. Winchell, B. Livneh and N.P. Molotch, 2018. Spatial variation of the rain-snow temperature threshold across the Northern Hemisphere, Nature Communications, 9, Article number: 1148. https://doi.org/10.1038/s41467-018-03629-7.

Jepsen, S.A., T.C Harmon; D.L Ficklin, N.P. Molotch and B. Guan, 2018. Evapotranspiration sensitivity to air temperature across a snow-influenced watershed: space-for-time substitution versus integrated watershed modeling, Journal of Hydrology, 556, Pgs 645-659. https://doi.org/10.1016/j.jhydrol.2017.11.042.

Kirchhoff, C. J., J. J. Barsugli, G. L. Galford, A. V. Karmalkar, K. Lombardo, S. Stephenson, M. Barlow, A. Seth, G. Wang and A. Frank, 2019. Climate assessments for local action. Bull. Amer. Meteorol. Soc. https://doi.org/10.1175/BAMS-D-18-0138.1.

Knowles, J.K., N.P. Molotch, E. Trujillo and M. Litvak, 2018. Snowmelt-driven trade-offs between early and late season productivity negatively impact forest carbon uptake during drought, Geophysical Research Letters, 45(7), Pgs 3087-3096. https://doi.org/10.1002/2017GL076504.

Lemos, M.C., H. Eakin, L. Dilling and J. Worl, 2019. Ch. 26. Social Sciences, Weather, and Climatic Change. Invited contribution to American Meteorological Society 100-year Anniversary Monograph. https://doi.10.1175/amsmonographs-d-18-0011.1.

Mahoney, J., J. Lukas and M. Mueller, 2018. Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety. VI of the Colorado – New Mexico Regional Extreme Precipitation Study, November, 57 pp. https://wwa.colorado.edu/publications/reports/co-nm-reps_summary.pdf.

Molotch, N., D. Schneider, L. Lestak, U. Rick and J. Lukas, 2019a. Spatial Estimates of Snow-Water Equivalent (SWE), Intermountain West Region, March 16, 2019. Western Water Assessment Intermountain West SWE Series. 24 pp. https://wwa.colorado.edu/publications/reports/0RockyMtn_SWE_Report_20190316.pdf.

Molotch, N., D. Schneider, L. Lestak, U. Rick and J. Lukas, 2019b. Spatial Estimates of Snow-Water Equivalent (SWE), Intermountain West Region, April 1, 2019. Western Water Assessment Intermountain West SWE Series. 24 pp. https://wwa.colorado.edu/publications/swe_reports/20190401_RockyMtn_SWE_Report.pdf.

Molotch, N., D. Schneider, L. Lestak, U. Rick and J. Lukas, 2019c. Spatial Estimates of Snow-Water Equivalent (SWE), Intermountain West Region, April 19, 2019. Western Water Assessment Intermountain West SWE Series. 24 pp. https://wwa.colorado.edu/publications/swe_reports/20190419_RockyMtn_SWE_Report.pdf.

Molotch, N., D. Schneider, L. Lestak, U. Rick and J. Lukas, 2019d. Spatial Estimates of Snow-Water Equivalent (SWE), Intermountain West Region, May 3, 2019. Western Water Assessment Intermountain West SWE Series. 24 pp. https://wwa.colorado.edu/publications/swe_reports/20190503_RockyMtn_SWE_Report.pdf.

Page, R., L. Dilling, U. Rick, B. Duncan, I. Rangwala and J. Lukas, 2018. Final Workshop Report for Vulnerability Consequences and Adaptation Planning Scenarios (VCAPS) for the City of Durango. Western Water Assessment: Boulder CO. https://co-durango.civicplus.com/DocumentCenter/View/14429/WWA-VCAPS-in-Durango-Final-Report.

Rangwala, I. and M. Hobbins, 2019. Flash Droughts in the Mountain West: Emerging Risks under a Warmer Climate. Mountain Views: Chronicles of the Consortium for Integrated Climate Research in Western Mountains, May, 34-37. https://www.fs.fed.us/psw/cirmount/publications/pdf/Mtn_Views_may_19.pdf.

Rick, U., B. Duncan, K. Clifford and L. Dilling, 2018. Final Workshop Report for Vulnerability Consequences and Adaptation Planning Scenarios (VCAPS) for Routt County. Western Water Assessment: Boulder CO.

Smith, R., J. Kasprzyk and L. Dilling, 2019. Testing the potential of Multiobjective Evolutionary Algorithms (MOEAs) with Colorado water managers. Environmental Modelling & Software, Vol. 117, 149-163. https://doi.org/10.1016/j.envsoft.2019.03.011.

Williams, T.M. and W.R. Travis, 2019. Evaluating alternative drought indicators in a weather index insurance instrument. Wea. Climate Soc., 0. https://doi.org/10.1175/WCAS-D-18-0107.1.

Yocum, H., J. Lukas and U. Rick, 2018. Spring 2018 MODIS-Based Spatial SWE Product for the Intermountain West Region: Feedback from Beta Testers. Western Water Assessment Report, August, 53 pp. https://wwa.colorado.edu/publications/reports/MODIS_based_SWE_product.pdf.

Zheng, Z., N.P. Molotch, C.A. Oroza, M. Conklin and R.C. Bales, 2018. Spatial snow estimation for mountainous areas using wireless-sensor networks and remote-sensing products, Remote Sensing of Environment, 215, Pgs 44–56. https://doi.org/10.1016/j.rse.2018.05.029.

2019-2020

Clifford, K.R., W.R. Travis and L.T. Nordgren, 2020. A Climate Knowledges Approach to Climate Services. Climate Services 18 (April): 100155. https://doi.org/10.1016/j.cliser.2020.100155.

Dilling, L., A. Prakash, Z. Zommers, F. Ahmad, N. Singh, S. de Wit, J. Nalau, M. Daly and K. Bowman, 2019. Is Adaptation Success a Flawed Concept? Nature Climate Change 9 (8): 572–74. https://doi.org/10.1038/s41558-019-0539-0.

Grecni, Z., L. Shore and B. Duncan, 2019. Learning from Success in Climate-Informed Decision-Making: Case Studies Across Three U.S. Regions. Honolulu: East-West Center. 34pp. https://www.eastwestcenter.org/climate-casestudies.

Hobbins, M. and J. Barsugli, 2020. Threatening the Vigor of the Colorado River. Science 367 (6483): 1192–93. https://doi.org/10.1126/science.abb3624.

Hoerling, M., J. Barsugli, B. Livneh, J. Eischeid, X. Quan and A. Badger, 2019. Causes for the Century-Long Decline in Colorado River Flow. Journal of Climate 32 (23): 8181–8203. https://doi.org/10.1175/JCLI-D-19-0207.1.

Kirchhoff, C.J., J.J. Barsugli, G.L. Galford, A.V. Karmalkar, K. Lombardo, S. R. Stephenson, M. Barlow, A. Seth, G. Wang and A. Frank, 2019. Climate Assessments for Local Action. Bulletin of the American Meteorological Society 100 (11): 2147–52. https://doi.org/10.1175/BAMS-D-18-0138.1.

Livneh, B. and A.M. Badger, 2020. Drought less predictable under declining future snowpack. Nature Climate Change 10, 452–458. https://doi.org/10.1038/s41558-020-0754-8.

Lukas, J. and E. Payton, eds., 2020. Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment, University of Colorado Boulder. https://doi.org/10.25810/3hcv-w477.

Page, R. and L. Dilling, 2019. The Critical Role of Communities of Practice and Peer Learning in Scaling Hydroclimatic Information Adoption. Weather, Climate, and Society 11 (4): 851–62. https://doi.org/10.1175/WCAS-D-18-0130.1.

Page, R. and L. Dilling, 2020. How Experiences of Climate Extremes Motivate Adaptation among Water Managers. Climatic Change 161 (3): 499–516. https://doi.org/10.1007/s10584-020-02712-7.

Raseman, W.J., J. Jacobson and J.R. Kasprzyk, 2019. Parasol: An open source, interactive parallel coordinates library for multi-objective decision making. Environmental Modelling and Software, vol 116: 153-163. https://doi.org/10.1016/j.envsoft.2019.03.005.

Smith, R.M., J.R. Kasprzyk and R. Balaji, 2019. Using multivariate regression trees and multiobjective tradeoff sets to reveal fundamental insights about water resources systems. Environmental Modelling and Software, Vol 120: 104498. https://doi.org/10.1016/j.envsoft.2019.104498.

Smith, R., J. Kasprzyk and L. Dilling, 2019. Testing the Potential of Multiobjective Evolutionary Algorithms (MOEAs) with Colorado Water Managers. Environmental Modelling & Software 117 (July): 149–63. https://doi.org/10.1016/j.envsoft.2019.03.011.

Steinberg, D., B.K. Mignone, J. Macknick, Y. Sun, K. Eurek, Badger, A.M., B. Livneh and K.B. Averyt, 2020. Decomposing supply-side and demand-side impacts of climate change on the U.S. electricity system through 2050. Climatic Change. https://doi.org/10.1007/s10584-019-02506-6.

Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, R. Seager, J.T. Abatzoglou, K. Bolles, S.H. Baek, A. Badger and B. Livneh, 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science, 368(6488), 314-318. https://doi.org/10.1126/science.aaz9600.

Williams, T.M. and W.R. Travis, 2019. Evaluating Alternative Drought Indicators in a Weather Index Insurance Instrument. Weather, Climate, and Society 11 (3): 629–49. https://doi.org/10.1175/WCAS-D-18-0107.1.

2020-2021

Abolafia-Rosenzweig, R., A. M. Badger, E. E. Small and B. Livneh, 2020. A continental-scale soil evaporation dataset derived from soil moisture active passive satellite drying rates. Scientific Data 7 (1): 406. https://doi.org/10.1038/s41597-020-00748-z.

Abolafia-Rosenzweig, R., M. Pan, J.L. Zeng and B. Livneh, 2021. A remotely sensed ensemble to observe the terrestrial water budget over major global river basins. Remote Sensing of Environment 252, 112191. https://doi.org/10.1016/j.rse.2020.112191.

Arens, S., L. Jamieson, P. Brooks, A. Weech, C. Strong, J. Everitt and D.E. Rosenbergs, 2021. Weber River Basin Climate Vulnerability Assessment. Western Water Assessment. https://wwa.colorado.edu/publications/reports/weber_basin_report.pdf.

Barsugli, J. J., A. J. Ray, B. Livneh, C. F. Dewes, A. Heldmyer, I. Rangwala, J. M. Guinotte and S. Torbit, 2020. Projections of mountain snowpack loss for wolverine denning elevations in the Rocky Mountains. Earth's Future 8 (10). https://doi.org/10.1029/2020EF001537.

Bjarke, N., B. Livneh, S. Elmendorf, N. Molotch, E. L. Hinckley, N. Emery, P. Johnson and K. Suding, 2020. Catchment scale observations at the Niwot Ridge long-term ecological research site. Hydrological Processes, July 21. https://doi.org/10.1002/hyp.14320.

Clifford, K. R., 2020. Problematic exclusions: Analysis of the Clean Air Act's exceptional event rule revisions. Society & Natural Resources 34 (2), 135-148. https://doi.org/10.1080/08941920.2020.1780358.

Clifford, K., L. Yung, W. R. Travis, R. Rondeau, I. Rangwala, C. Wyborn, N. Burkhardt and E. Neeley, 2020. Navigating climate adaptation on public lands: How views on ecosystem change and scale interact with management approaches. Environmental Management 66, 614–628. https://doi.org/10.1007/s00267-020-01336-y.

Clifford, K. and W. R. Travis, 2021. The new (ab)normal: Outliers, everyday exceptionality, and the politics of data management in the anthropocene. Annals of the American Association of Geographers 111(3), 932-943. https://doi.org/10.1080/24694452.2020.1785836.

Crausbay, S., A. Ramirez, J. Betancourt, J. B. Bradford, J. Cartwright, J. B. Dunham, C. Enquist, A. Frazier, K. Hall, J. S. Littell, C. H. Luce, R. Palmer, I. Rangwala, L. Thompson and S. Carter, 2020. Unfamiliar territory: Emerging themes for ecological drought research and management. One Earth 3(3), 337-353. https://doi.org/10.1016/j.oneear.2020.08.019.

Culler, E., A. Badger, J. Minear, K. Tiampo, S. Zeigler and B. Livneh, 2020. A multi-sensor evaluation of precipitation uncertainty for landslide-triggering storm events. Hydrological Processes. https://doi.org/10.22541/au.160619798.86581537/v1.

Culler, E. S., B. Livneh, B. Rajagopalan and K. F. Tiampo, 2021. A data-driven evaluation of post-fire landslide susceptibility. Landslides and Debris Flows Hazards. https://doi.org/10.5194/nhess-2021-111.

Deschamps-Berger, C., S. Gascoin, E. Berthier, J. Deems, E. Gutmann, A. Dehecq, D. Shean and M. Dumont, 2020. Snow Depth Mapping from Stereo Satellite Imagery in Mountainous Terrain: Evaluation Using Airborne Laser-Scanning Data. The Cryosphere 14 (9): 2925–40. https://doi.org/10.5194/tc-14-2925-2020.

DeRousseau, M. A., J. H. Arehart, J. R. Kasprzyk and W. V. Srubar, III, 2020. Statistical variation in the embodied carbon of carbon mixtures. Journal of Cleaner Production 275(123088). https://doi.org/10.1016/j.jclepro.2020.123088.

Esit, M., S. Kumar, A. Pandey, D. Lawrence, I. Rangwala and S. Yeager, 2021. Seasonal to multi-year soil moisture drought forecasting. npj Climate and Atmospheric Science 4(16). https://doi.org/10.1038/s41612-021-00172-z.

Henn, B., K. N. Musselman, L. Lestak, F. M. Ralph and N. P. Molotch, 2020. Extreme runoff generation from atmospheric river driven snowmelt during the 2017 Oroville Dam spillways incident. Geophysical Research Letters 47 (14). https://doi.org/10.1029/2020GL088189.

Hermes, A. L., H. M. Wainwright, O. Wigmore, N. Falco, N. P. Molotch and E-L. S. Hinckley, 2020. From patch to catchment: A statistical framework to identify and map soil moisture patterns across complex alpine terrain. Frontiers in Water 2 (November): 578602. https://doi.org/10.3389/frwa.2020.578602.

Hoerling, M., L. Smith, X-W. Quan, J. Eischeid, J. Barsugli and H. F. Diaz, 2021. Explaining the spatial pattern of U.S. extreme daily precipitation change. Journal of Climate 34(7), 2759–2775. https://doi.org/10.1175/JCLI-D-20-0666.1.

Jennings, K. S. and N. P. Molotch, 2020. Snowfall fraction, cold content, and energy balance changes drive differential response to simulated warming in an alpine and subalpine snowpack. Frontiers in Earth Science 8 (June): 186. https://doi.org/10.3389/feart.2020.00186.

Kampf, S. K., B. M. Gannon, C. Wilson, F. Saavedra, M. Ellen Miller, A. Heldmyer, B. Livneh, P. Nelson, and L. MacDonald, 2020. PEMIP: Post-fire erosion model inter-comparison project. Journal of Environmental Management 268 (August): 110704. https://doi.org/10.1016/j.jenvman.2020.110704.

Kumar, S., M. Newman, D. M. Lawrence, M-H. Lo, S. Akula, C-W. Lan, B. Livneh and D. Lombardozzi, 2020. The GLACEhydrology experiment: Effects of land–atmosphere coupling on soil moisture variability and predictability. Journal of Climate 33 (15): 6511–29. https://doi.org/10.1175/JCLI-D-19-0598.1.

Livneh, B. and A. M. Badger, 2020. Drought less predictable under declining future snowpack. Nature Climate Change 10 (5): 452–58. https://doi.org/10.1038/s41558-020-0754-8.

Lukas, J. and E. Payton, eds., 2020. Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment, University of Colorado Boulder. https://doi.org/10.25810/3hcv-w477.

Murray, D., A. Hoell, M. Hoerling, J. Perlwitz, X. Quan, D. Allured, T. Zhang, J. Eischeid, C. A. Smith, J. Barsugli, J. McWhirter, C. Kreutzer and R. S. Webb, 2020. Facility for weather and climate assessments (FACTS): A community resource for assessing weather and climate variability, Bulletin of the American Meteorological Society 101(7), E1214-E1224. https://doi.org/10.1175/BAMS-D-19-0224.1.

Musselman, K. N., N. Addor, J. A. Vano and N. P. Molotch, 2021. Winter melt trends portend widespread declines in snow water resources. Nature Climate Change 11 (5): 418–24. https://doi.org/10.1038/s41558-021-01014-9.

Pan, J., M. T. Durand, Z. Courville, B. J. Vander Jagt, N. P. Molotch, S. A. Margulis, E. J. Kim, M. Schneebeli and C. Mätzler, 2021. Evaluation of stereology for snow microstructure measurement and microwave emission modeling: A case study. International Journal of Digital Earth March, 1–21. https://doi.org/10.1080/17538947.2021.1902006.

Quebbeman, J., G. Van Houtven, H. Yocum, T. Williams and N. Flores, 2020. NASA Impacts and Benefits Assessment from Improved Streamflow Forecasts. RTI International, Western Water Assessment, University of Colorado Boulder, June 16. https://www.rti.org/publication/nasa-impacts-and-benefits-assessment-improved-streamflow-forecasts/fulltext.pdf.

Rosenberg, D. E., Y. Filion, R. Teasley, S. Sandoval-Solis, J. S. Hecht, J. E. van Zyl, G. F. McMahon, J. S. Horsburgh, J. R. Kasprzyk and D. G. Tarboton, 2020. The next frontier: Making research more reproducible. Journal of Water Resources Planning and Management 146(6): 01820002. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001215.

Schneider, D., N. P. Molotch, J. S. Deems and T. H. Painter, 2021. Analysis of topographic controls on depletion curves derived from airborne lidar snow depth data. Hydrology Research 52 (1): 253–65. https://doi.org/10.2166/nh.2020.267.

Schulz T., H. Wilmer, H. M. Yocum, E. Winford, D. Peck, A. C. Monlezun, H. Schmalz, T. Klemm, K. Epstein, V. Jansen, W. Kelley, R. Bruegger, S. Fick, J. Gazing Wolf, J. Grace, R. Mann and J. Derner, 2021. Campfire conversations at the 2020 annual meeting: Insights & lessons learned from "cuss-and-discuss" rather than "chalk-and-talk." Rangelands 43(4), 166- 172. https://doi.org/10.1016/j.rala.2021.04.003.

Switanek, M. B., J. J. Barsugli, M. Scheuerer and T. M. Hamill, 2020. Present and past sea surface temperatures: A recipe for better seasonal climate forecasts. Weather and Forecasting 35(4): 1221–34. https://doi.org/10.1175/WAF-D-19-0241.1.

Webb, R. W., M. S. Raleigh, D. McGrath, N. P. Molotch, K. Elder, C. Hiemstra, L. Brucker and H. P. Marshall, 2020. Within stand boundary effects on snow water equivalent distribution in forested areas. Water Resources Research 56(10). https://doi.org/10.1029/2019WR024905.

Woelders, L., J. Lukas, E. Payton and B. Duncan, 2020. Snowpack Monitoring in the Rocky Mountain West: A User Guide. Western Water Assessment. https://wwa.colorado.edu/publications/reports/Snowpack_User_Guide_February_2021.pdf.

2021-2022

Badger, Andrew M., Nels Bjarke, Noah P. Molotch and Ben Livneh, 2021. The Sensitivity of Runoff Generation to Spatial Snowpack Uniformity in an Alpine Watershed: Green Lakes Valley, Niwot Ridge Long-Term Ecological Research Station. Hydrological Processes 35 (9). https://doi.org/10.1002/hyp.14331.

Bailey, K. M., K. R. Hooker, A. A. Loggins, A. D. Potash, D. W. Hardeman and R. A. McCleery, 2022. It Pays to Get Paid: Factors Influencing Wildlife-Related Employment Success. Wildlife Society Bulletin 46 (1). https://doi.org/10.1002/wsb.1252.

Barnhart, T. B., J. Vukomanovic, P. Bourgeron and N. P. Molotch, 2021. Future Land Cover and Climate May Drive Decreases in Snow Wind-Scour and Transpiration, Increasing Streamflow at a Colorado, USA Headwater Catchment. Hydrological Processes 35 (11). https://doi.org/10.1002/hyp.14416.

Bjarke, N. R., B. Livneh, S. C. Elmendorf, N. P. Molotch, E. S. Hinckley, N. C. Emery, P. T. J. Johnson, J. F. Morse and K. N. Suding, 2021. Catchment-Scale Observations at the Niwot Ridge LongTerm Ecological Research Site. Hydrological Processes 35 (9). https://doi.org/10.1002/hyp.14320.

Brooks, P. D., A. Gelderloos, M. A. Wolf, L. R. Jamison, C. Strong, D. K. Solomon, G. J. Bowen, et al., 2021. Groundwater-Mediated Memory of Past Climate Controls Water Yield in Snowmelt-Dominated Catchments. Water Resources Research 57 (10). https://doi.org/10.1029/2021WR030605.

Burns, E., 2021a. Ecological Drought in the Intermountain West. Western Water Assessment. https://wwa.colorado.edu/sites/default/files/2022-01/ecological_drought_fact_sheet_2021.pdf.

Burns, E., 2021b. The Impacts of Wildland Fire on Municipal Water Supply. Western Water Assessment. https://wwa.colorado.edu/sites/default/files/2022-02/wildfire_fact_sheet_2021.pdf.

Clifford, K. R., A. E. Cravens and C. N. Knapp, 2022. Responding to Ecological Transformation: Mental Models, External Constraints, and Manager Decision-Making. BioScience 72 (1): 57–70. https://doi.org/10.1093/biosci/biab086.

Crausbay, S. D., H. R. Sofaer, A. E. Cravens, B. C. Chaffin, K. R. Clifford, J. E. Gross, C. N. Knapp, et al., 2022. A Science Agenda to Inform Natural Resource Management Decisions in an Era of Ecological Transformation. BioScience 72 (1): 71–90. https://doi.org/10.1093/biosci/biab102.

Dilling, L., M. C. Lemos and N. Singh, 2021. Commentary: First, Do No Harm: Scaling Usable Knowledge for Just and Equitable Outcomes. Global Environmental Change 71 (November): 102404. https://doi.org/10.1016/j.gloenvcha.2021.102404.

Gaughan, A. E., N. E. Kolarik, F. R. Stevens, N. G. Pricope, L. Cassidy, J. Salerno, K. M. Bailey, M. Drake, K. Woodward and J. Hartter, 2022. Using Very-High-Resolution Multispectral Classification to Estimate Savanna Fractional Vegetation Components. Remote Sensing 14 (3): 551. https://doi.org/10.3390/rs14030551.

Hale, K. E., A. N. Wlostowski, A. M. Badger, K. N. Musselman, B. Livneh and N. P. Molotch, 2022. Modeling Streamflow Sensitivity to Climate Warming and Surface Water Inputs in a Montane Catchment. Journal of Hydrology: Regional Studies 39 (February): 100976. https://doi.org/10.1016/j.ejrh.2021.100976.

Henderson, J., L. Dilling, R. Morss, O. Wilhelmi and U. Rick, 2021. 'We Got in the Pilot Program to Learn from It:' Features of Social Learning in Drought Contexts Along the Arkansas River in Colorado. Weather, Climate, and Society, June. https://doi.org/10.1175/WCAS-D-20-0120.1.

Keyes, A., 2021. Mobile Homes and Flood Risk: An Analysis of Flood Risk and Historical Flooding in the Intermountain West and Michigan. Western Water Assessment. https://wwa.colorado.edu/sites/default/files/2021-11/Final_Report_Keyes_2021.pdf.

Kroepsch, A. C. and K. R. Clifford, 2022. On Environments of Not Knowing: How Some Environmental Spaces and Circulations Are Made Inscrutable. Geoforum 132 (June): 171–81. https://doi.org/10.1016/j.geoforum.2021.05.009.

Lukas, J. and E. Payton, eds., 2020. Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment, University of Colorado Boulder. https://doi.org/10.25810/3hcv-w477.

Magness, D. R., L. Hoang, R. T. Belote, J. Brennan, W. Carr, F. S. Chapin, K. Clifford, W. Morrison, J. M. Morton and H. R. Sofaer, 2022. Management Foundations for Navigating Ecological Transformation by Resisting, Accepting, or Directing Social–Ecological Change. BioScience 72 (1): 30–44. https://doi.org/10.1093/biosci/biab083.

Payton, E., J. Biederman and M. Robles, 2021. Snowtography: Snowpack & Soil Moisture Monitoring Handbook. November. https://doi.org/10.25810/R9S7-4T28.

Pierce, D. W., L. Su, D. R. Cayan, M. D. Risser, B. Livneh and D. P. Lettenmaier, 2021. An Extreme-Preserving Long-Term Gridded Daily Precipitation Data Set for the Conterminous United States. Journal of Hydrometeorology, May. https://doi.org/10.1175/JHM-D-20-0212.1.

Rangwala, I., W. Moss, J. Wolken, R. Rondeau, K. Newlon, J. Guinotte and W. R. Travis, 2021. Uncertainty, Complexity and Constraints: How Do We Robustly Assess Biological Responses under a Rapidly Changing Climate? Climate 9 (12): 177. https://doi.org/10.3390/cli9120177.

Shrum, T. R. and W. R. Travis, 2022. Experiments in ranching: Rain-index insurance and investment in production and drought risk management. Applied Economics Perspectives & Policy 44: 1513–1533. https://doi.org/10.1002/aepp.13304.

Su, J., R. Goel, S. Burian, S. J. Hinners, A. Kochanski, C. Strong and M. E. Barber, 2021. Water Quality Trading Framework with Uncertainty for River Systems Due to Climate and Population Characteristics. Water 13 (13): 1738. https://doi.org/10.3390/w13131738.

Western Water Assessment, 2022. Utah Hazard Planning Tool. Edited by S. Arens. Western Water Assessment. https://wwa.colorado.edu/sites/default/files/2022-04/Utah%20Hazard%20Planning%20Tool%20011422.pdf.

Williams, A. Park, Ben Livneh, Karen A. McKinnon, Winslow D. Hansen, Justin S. Mankin, Benjamin I. Cook, Jason E. Smerdon, et al., 2022. Growing Impact of Wildfire on Western US Water Supply. Proceedings of the National Academy of Sciences 119 (10): e2114069119. https://doi.org/10.1073/pnas.2114069119.

Yang, K., K. N. Musselman, K. Rittger, S. A. Margulis, T. H. Painter and N. P. Molotch, 2022. Combining Ground-Based and Remotely Sensed Snow Data in a Linear Regression Model for Real-Time Estimation of Snow Water Equivalent. Advances in Water Resources 160 (February): 104075. https://doi.org/10.1016/j.advwatres.2021.104075.

WESTERN WATER ASSESSMENT

A NOAA RISA TEAM

Western Water Assessment
Cooperative Institute for Research in Environmental Sciences
University of Colorado Boulder

http://wwa.colorado.edu