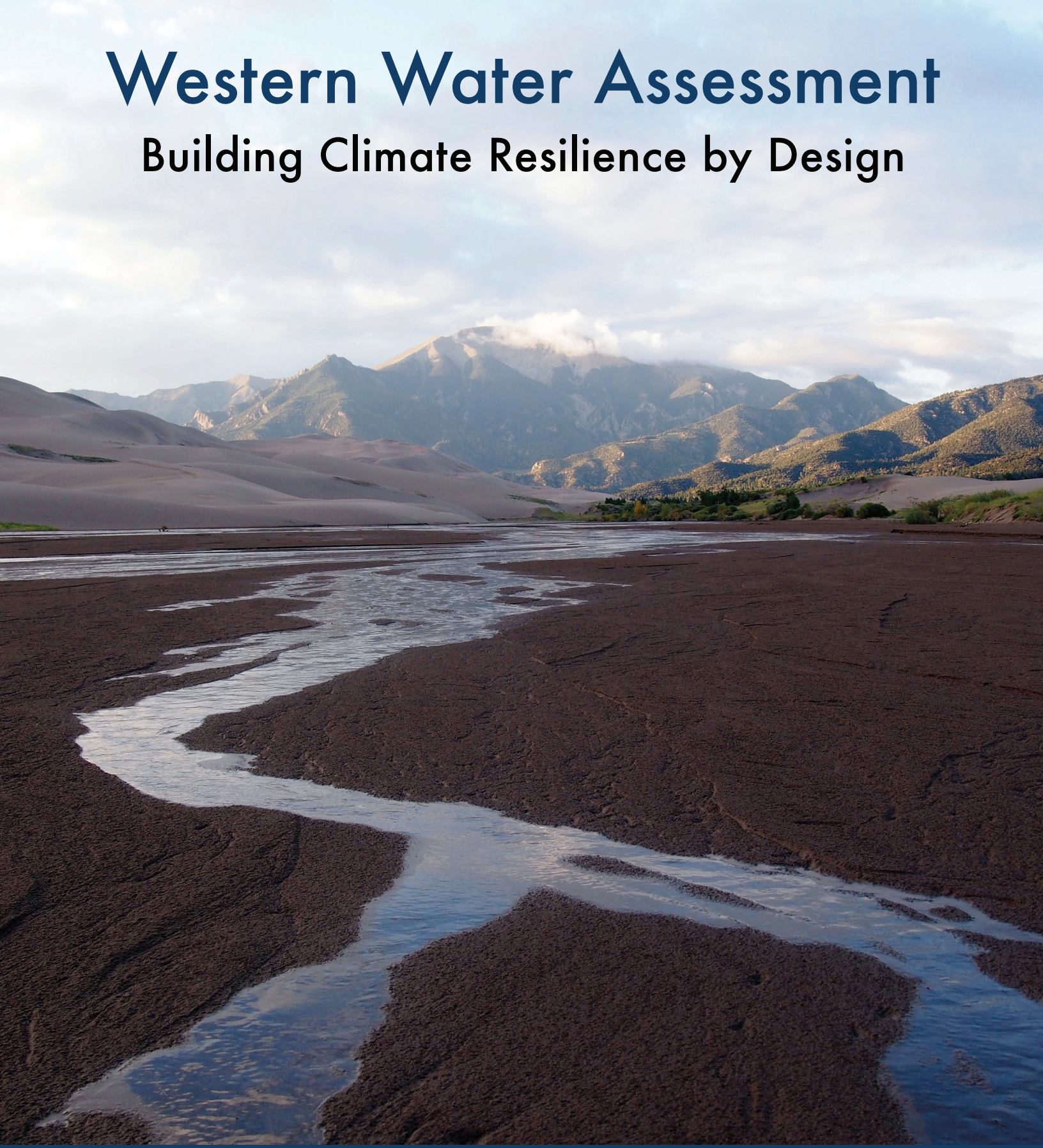
Western Water Assessment

Building Climate Resilience by Design



2016 - 2017 ANNUAL REPORT

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

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Principal Investigator	**Co-Investigators**
Lisa Dilling, University of Colorado Boulder	Joseph Barsugli, University of Colorado Boulder Elizabeth McNie, University of Colorado Boulder Noah Molotch, University of Colorado Boulder William Travis, University of Colorado Boulder

Performance period covered in this report: June 1, 2016–May 31, 2017.

Cover photograph: Jeff Lukas, Medano Creek at Great Sand Dunes National Park

Introduction

The mission of Western Water Assessment (WWA) is to conduct innovative research in partnership with decision makers in the Rocky Mountain West, helping them make the best use of science to manage for climate impacts. Using multidisciplinary teams of experts in climate, hydrology, ecology and policy, WWA works with decision makers across Colorado, Utah and Wyoming to produce policy-relevant information about climate variability and change. By building relationships with and networks of decision makers, our team is able to develop practical research programs and useful information products. WWA focuses its work on four overarching themes.

1. Climate Vulnerability and Adaptive Capacity in the WWA Region
2. Extremes and Climate Risk Management
3. Designing Organizations and Networks for Usable Science
4. Understanding and Monitoring Drought in the WWA Region

WWA is formally part of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder (CU Boulder), and our researchers and partners come from universities and government institutions across our region.

WWA Staff and Research Team

WWA is comprised of a core staff of six (Table 1) who focus on program management, research development and synthesis, and coordination of stakeholder interactions. During this past year, WWA hired a climate assessment specialist, Benét Duncan to work on the sustained assessment project. In addition to the core staff shown below, WWA's graphic design/outreach specialist (Ami Nacu-Schmidt) is shared with the Center for Science and Technology Policy Research (CSTPR) at CU Boulder in order to increase efficiency and leverage resources.

Table 1. Western Water Assessment Core Staff

Staff	Title	Email Address	Expertise
Lisa Dilling	Director	ldilling@colorado.edu	Climate information, decision making
Ursula Rick	Program Manager	ursula.rick@colorado.edu	Science policy, glacial hydrology
Elizabeth McNie	Research Scientist	mcnie@colorado.edu	Science policy, program evaluation
Jeff Lukas	Research Integration Specialist, Colorado and Wyoming	lukas@colorado.edu	Climate variability and climate change, paleoclimatology
Seth Arens	Research Integration Specialist, Utah	www.arens@gmail.com	Eco-hydrology, air quality
Benét Duncan	Climate Assessment Specialist	mailto:Benet.duncan@colorado.edu	Climate indicators, oceanography

WWA's research team (Table 2) includes physical scientists and social scientists at the University of Colorado, NOAA and the National Center for Atmospheric Research (NCAR).

Table 2. Western Water Assessment Research Team

Team Member	Title	Expertise
Averyt, Kristen	Associate Director for Science, CIRES, Univ. of Colorado	Climatology, energy-water, assessment processes
Barsugli, Joseph	Lead Researcher, Western Water Assessment Research Scientist, CIRES, Univ. of Colorado	Climate dynamics
Berggren, John	Graduate Research Assistant, Univ. of Colorado	Climate adaptation, water policy
Clifford, Katie	Graduate Research Assistant, Univ. of Colorado	Conservation decision making
Deems, Jeff	Research Scientist, CIRES, Univ. of Colorado	Climate and snow modeling
Henderson, Jen	CIRES Postdoctoral Fellow	Weather and society
Jennings, Keith	Graduate Research Assistant, Univ. of Colorado	Snowpack remote sensing
Kaspryzk, Joseph	Assistant Professor, Civil Engineering, Univ. of Colorado	Multi-objective analysis for water management
Klein, Roberta	Managing Director, Center for Science and Technology Policy Research, Univ. of Colorado	Environmental policy
Livneh, Ben	Assistant Professor, Civil Engineering, Univ. of Colorado	Hydrologic modeling
Mahoney, Kelly	Research Scientist, NOAA ESRL Physical Sciences Division	Hydrometeorology, extreme precipitation
McCurdy, Adam	Graduate Research Assistant, Univ. of Colorado	Climate risk assessment
Molotch, Noah	Lead Researcher, Western Water Assessment Assistant Professor, Dept. of Geography, Univ. of Colorado	Snow hydrology
Morss, Rebecca	Scientist III, National Center for Atmospheric Research	Socioeconomic and policy impacts of weather
Page, Rebecca	Graduate Research Assistant, Univ. of Colorado	Decisions in natural resources
Rangwala, Imtiaz	Research Scientist, CIRES, Univ. of Colorado and NOAA ESRL	Regional climate change, high elevation climate
Ray, Andrea	Scientist, NOAA ESRL Physical Sciences Division	Climate-society interactions, water management
Shrum, Trisha	WWA and Earth Lab Post-Doctoral Fellow	Natural resource economics
Smith, Rebecca	Graduate Research Assistant, Univ. of Colorado	Multi-objective analysis for water management
Travis, William	Interim Director, Lead Researcher, Western Water Assessment Associate Professor, Geography, Univ. of Colorado	Natural hazards, climate impacts and adaptation
Wessman, Carol	Professor, Ecology and Evolutionary Biology, Univ. of Colorado	Landscape ecology, remote sensing
Wilhelmi, Olga	Project Scientist III, National Center for Atmospheric Research	Vulnerability and adaptation to weather and climate
Wolter, Klaus	Research Scientist, CIRES, Univ. of Colorado and NOAA ESRL	Climatology and meteorology
Yocum, Heather	Research Scientist, CIRES, NOAA ESRL	Climate & social systems

New Areas of Focus

WWA was awarded a Sustained Assessment Project by the NOAA Climate Program and Assessment Program Offices to supplement our main grant to work on sustained climate assessment for the U.S. Southwest. This will be a new focus for WWA and required us to shape a position to best contribute to a national sustained climate assessment over the two years of this project. We will focus on making connections between existing assessment activities and compiling lessons learned from case studies of successful climate assessments. We are also expanding geographically and moving to more rural work. One project in Pueblo, CO looks at drought impacts across the rural/urban interface, and in southwest Utah, we are introducing climate information to a rural planning group. Finally, we are pursuing new partnerships with those interested in usable science across CU Boulder.

Table 3. New partnerships and areas of focus developed in 2016-2017.

New Area of Focus	**Relevant Projects (see pp. 6 and XX)**
Sustained Climate Assessment in the Southwest Drought at the Rural/Urban Interface	• Sustained Climate Assessment Summary (cross-RISA) • Drought Experience in Pueblo, CO • Ranching Drought Insurance Project
New Partnerships	**Relevant Projects (see pp. XX-XX)**
Earth Lab, University of Colorado West Zion Corridor Regional Planning Partnership	• Usable Science at the University of Colorado Boulder • Climate Information for a Rural National Park Gateway Community

New Climate Services and Stakeholder Products

Forest Resilience and Climate Change for the Colorado State Forest Service: In October 2016, the Colorado State Forest Service (CSFS) made live a new webpage, titled "Colorado's Forests in a Changing Climate", to communicate to their stakeholders--mainly forest landowners in Colorado--about the risks posed by climate change and steps they can take to promote forest resilience to climate change. The technical background on climate change came mainly from the 2014 WWA report, "Climate Change in Colorado", and WWA's **Jeff Lukas** reviewed the draft page content for accuracy. Jeff was then invited to the CSFS annual conference in February 2017, to brief CSFS staff on recent climate and ecological trends, the latest research on the projected impacts of climate change to Colorado's forests, and climate adaptation strategies for forest managers.

Future Outdoor Water Use in Jordan Valley, Utah: The Jordan Valley Water Conservancy District (JVWCD) is concerned about future outdoor water use in a changing climate. WWA's **Seth Arens** provided projections of potential evapotranspiration (PET), past trends in PET, and a model of observed PET and current outdoor water use to help JVWCD understand how water demand may change in the future. This model was then used to predict future outdoor water use in Jordan Valley's service area based on projections of future PET with changing climate.

Climate Service Providers Database: In partnership with CLIMAS and the NOAA Western Regional Climate Center, WWA's **Elizabeth McNie** and **John Berggren** did an assessment of more than 130 public sector and nonprofit organizations that provide climate services to eleven western states. The NOAA Western Region Climate Service Providers Database is a searchable directory of climate service providers in the west that makes climate services easier to find. A preliminary analysis report classifies the service providers, gives the sectors and regions served, and identifies topical and geographic gaps.

Sustained Climate Assessment for the U.S. Southwest

In January 2017, WWA launched a new project: Sustained Climate Assessment in the Southwest. This project is led by **Benét Duncan**, WWA's new Climate Assessment Specialist. WWA is collaborating with CLIMAS and CNAP to investigate opportunities for sustained assessment in the US Southwest National Climate Assessment (NCA) region – an area that includes Arizona, California, Colorado, Nevada, New Mexico, and Utah – and to develop a process for sustained assessment in the region. The project is drawing on broad existing capacity for climate assessment in the southwest with the goal of connecting climate service providers and users to increase access to information and understanding of climate impacts in decision-making contexts. It stems from recommendations made in the Third NCA report. WWA is focusing on four key sectors: water, oceans and coasts, agriculture, and transportation. These sectors were chosen because they represent a range of existing assessment capacity in the region and because of their relatively large footprint in the region. Recommendations for an ongoing assessment process may vary by sector – a reflection of the capacity and opportunity associated with each.

During this reporting period, WWA established an informal advisory group that includes core partners at CLIMAS and CNAP, members of the Federal Advisory Committee on sustained climate assessment and leading thinkers in sustained assessment, connected with leaders and authors for the Fourth NCA (currently in development), and built new relationships with experts in climate assessment from each of the focal sectors. Benét traveled throughout the Southwest region to the following meetings and conferences to learn about current assessment activities, and she was an organizer for the sustained assessment pre-meeting forum at the 2017 National Adaptation Forum.

- February 2017: Tucson, AZ for National Climate Assessment (NCA) Southwest (SW) Town Hall and NCA SW Author Meeting
- March 2017: Tucson, AZ for Water Resources Research Center (WRRC) Annual Conference: Irrigated Agriculture in Arizona and Colorado Water Institute Workshop: Alternatives to Permanent Fallowing of Agricultural Land
- April 2017: Palo Alto, Davis, and Sacramento, CA for meetings and Reno, NV for Great Basin Climate Forum
- May 2017: St. Paul, MN for National Adaptation Forum

In the coming months, WWA will collaborate with climate service providers and users to identify key elements of an ongoing climate assessment process for the region. This will include development of case studies that highlight particularly useful/successful assessment activities.

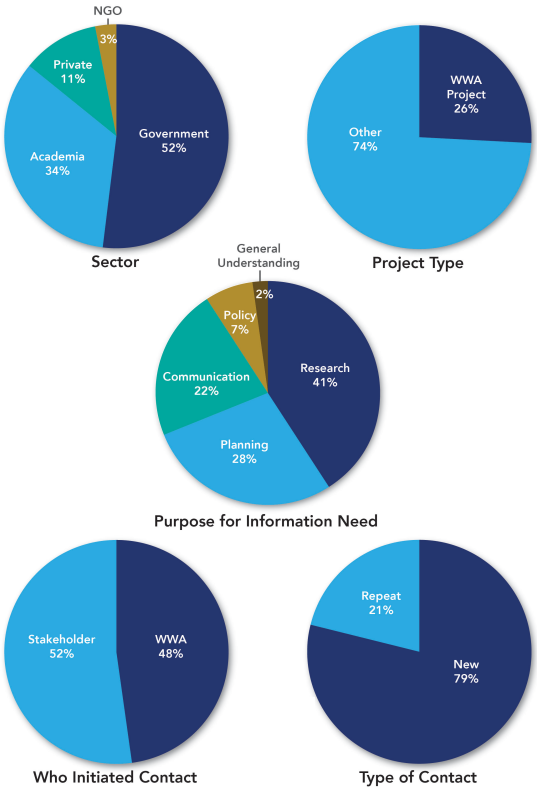
WWA staff also participated in the 4th National Climate Assessment satellite stakeholder meetings for the Southwest Region in Boulder, CO on February 21st and for the North Central Region in Ft. Collins, CO on February 2nd.

WWA Evaluation

WWA is continuing to combine what it is calling the Meadow-Wall Framework, which gives project-level evaluation of co-production, and the WWA framework that uses customized metrics to evaluate WWA. Much of WWA's work consists of ongoing activities, relationship building and maintenance, education, and outreach, in addition to discrete research projects. While focused on outputs and outcomes, the Meadow-Wall and WWA frameworks are also well-suited for evaluating the building and maintaining of social capital, the quality of stakeholder and researcher relationships, and network participation. WWA also administered to the research team a 'Typology of Research'. This assessment served to identify and characterize the overall profile of various research projects and to inform discussion and deliberation about the research in order to evaluate how each project was or was not meeting its stated goals.

This year, WWA developed a stakeholder tracking form that tracked our interaction with stakeholders for a six-month period in order to understand how we interact with our partners and users, whether we are forming new relationships, how often we are asked for information vs. reaching out to our stakeholders, etc. This initial six-month period of data will be used as a baseline from which to measure changes at the end of this rebid period, and is experimental in that our analysis of the tracking data will show what key information may have been missed and what information about our stakeholder interaction is not needed. The stakeholder tracking form was filled out by six WWA team members who were asked to track all interactions they had with stakeholders, including other researchers, potential users of WWA information, other collaborators as well as the general public. The form tracked:

- Who initiated contact
- Mode of contact (email, in person, phone)
- Affiliation of stakeholder
- Sector (government, academia, public)
- Purpose of contact (planning, policy development, general understanding, education/communication/outreach, operations, research
- Duration of contact
- Whether the subject related to an official WWA project



WWA tracked 243 contacts and 282 hours of contact time. The most frequently cited purposes for engagement included meeting/training/class planning, project meetings, workshops, and conversations about collaboration or potential collaboration. 79% of contacts were repeats and 21% were new contacts. WWA and our stakeholders initiated contact at an almost equal pace. The most common sector represented was government with 52%, followed by academia (34%), private (11%), and NGO (3%). 41% of the contacts were for research purposes, 28% planning purposes, 22% communication and outreach, 7% policy and 2% was for general understanding.

WWA Impact Across the Region

WWA has had broad impact across Colorado, Wyoming and Utah through various efforts such as workshops, webinars, decision tools and our climate dashboard. We convened a day-long symposium for our partners, stakeholders and other CU Boulder researchers, which drew over 50 attendees from across our region and throughout CU Boulder. From the symposium, we learned how the incorporation of climate information is changing within our stakeholders' organizations and how we might better partners with them to produce useful information. We also learned about ongoing research within CU Boulder that might be useful to our stakeholders and the research groups with which we can collaborate.

One example of WWA's efforts to build expertise in climate adaptation was in a project, supported partially by the NOAA Sectoral Applications Research Program, on the use of Multi-Objective Evolutionary Algorithm (MOEA)-assisted optimizations for decision-making under severe climate uncertainty. We held a workshop on June 30, 2016 for nine Colorado water utilities to give them hands-on experience with use of a MOEA tool customized for the Colorado Front Range water system. This effort allowed researchers to understand how water managers relate tradeoff information to their current needs and practices, get feedback about potential uses and barriers to use, provide exposure for the emerging tool, and learn about the general process of utilities adopting a new tool. The managers valued the ability to understand how performance in some objectives affected performance in others, and even though some objectives were prioritized, the relationships between them provided valuable insight. They cited relevant uses, such as demonstrating to customers how much service they would have to forego in order to avoid unpopular infrastructure. The desire to understand how one or more decisions mapped to overall system performance was a prevalent theme. While enthusiastic about the potential for MOEA-assisted optimization on a technical level, managers noted that transmitting the technical findings to a non-technical board of directors or city council would be a significant challenge. Finally, they reported that the workshop was a more effective way to learn about complex research tools than reading reports or articles, 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 researchers continue to interpret ongoing weather events and climate conditions through our website, dashboards, and many individual requests. Examples include updating our Intermountain West Climate Dashboard to better integrate into the NIDIS Intermountain West Drought Early Warning System (IMW DEWS), providing historic MODIS satellite snowpack data to the State of Wyoming, and we continue to produce bimonthly briefings for the Colorado Water Availability Task Force meetings about the state of the climate system and moisture anomalies anticipated for the upcoming season.

Contributions to the NIDIS Intermountain West DEWS

During this reporting period, WWA contributed to the Intermountain West Drought Early Warning System (IMW DEWS) through several activities. WWA's **Jeff Lukas**, **Elizabeth McNie** and **Seth Arens** helped plan and facilitate two meetings of the newly expanded IMW DEWS that now includes Arizona and western New Mexico, one in Tucson, AZ in September 2016 and one in Denver, CO in October 2016. These Drought and Climate Outlooks provided an opportunity for NIDIS to introduce the new IMW DEWS and to hear from stakeholders about their needs for drought information. In November 2016,

WWA also helped convene a meeting of strategic partners in the IMW DEWS to begin the process of integrating the many sources of drought information already available across the IMW DEWS region.

In partnership with CLIMAS, WWA's **Jeff Lukas** updated the WWA Intermountain West Climate Dashboard to better integrate it into the IMW DEWS system. With the addition of AZ and western NM to the Upper Colorado River Basin DEWS to form the IMW DEWS, we added AZ and NM to the dashboard data previously provided for CO, UT and WY. We also incorporate information from CLIMAS in our monthly written summary and added CLIMAS' reservoir maps for the Colorado River Basin. Finally, the dashboard now includes more prominent links and connections to the Colorado Climate Center, NIDIS and CLIMAS resources.

Seth Arens continued to work with the Jordan Valley Water Conservancy District (JVWCD) in Utah on future outdoor water use. This project provided projections of potential evapotranspiration (PET), and past trends in PET and its components to help JVWCD understand how water demand may change in the future. Using downscaled climate data, past trends in PET, and projections of future outdoor watering season length, a model of observed PET and outdoor water use was developed. This model was then used to predict future outdoor water use based on projections of future PET. A report on this project was presented to JVWCD in April 2017.

As part of WWA's research on the impacts of changing snowpack on streamflow, **John Berggren** interviewed several water managers in the Uncompahgre Basin in western Colorado to understand their key concerns and past events as they relate to information about snowpack. In general, dry years are of more concern than wet years to the water managers interviewed, and timing of snowmelt and runoff are critical in very dry years. **Keith Jennings** focused on comparing existing snow products in the Uncompahgre Basin. The large spatial scale of NLDAS-2 grid cells made the snow product unsuitable for use. Only 8 grid cells completely or partially overlapped the Uncompahgre River Basin and they often showed snow-free conditions when snow was still reported at two SNOTEL sites. Similarly, the SNODAS SWE product performed poorly relative to ASO data, typically overestimating subalpine SWE while significantly underestimating alpine SWE. We have also taken initial steps towards modeling SWE in the Uncompahgre using the Distributed Hydrology Vegetation Soil Model. The two goals of this modeling effort are to reproduce SWE volumes and distributions relative to ASO data and to simulate difficult water resource management scenarios as reported in the user surveys performed by John Berggren.

In Spring of 2017, WWA held two webinars on drought, one on the use of EDDI, *Evaporative Demand Drought Index (EDDI): Tracking the "Atmospheric Demand" Side of Drought for Monitoring and Early Warning*, and one on a new ranching drought insurance tool, *Decision Making in the Face of Drought by Western Range Livestock Producers*. **Imtiaz Rangwala** and **Jeff Lukas** presented to ~50 parricipants on the physical basis behind EDDI, how it compares to other drought indices and possible uses of EDDI, including an emphasis on flash drought. In the second, **William Travis** and **Trisha Shrum** presented to ~20 participants on their new ranching insurance tool, which allows users to experiment with the economics of purchasing the relatively new USDA Pasture, Forage and Rangeland Insurance product, which pays out based on NOAA's gridded precipitation. They presented an online experiment of five years of rainfall and insurance purchases with various options for adapting to drought.

WWA 2016-2017 Program Highlights

Major Research Findings and Publications

Local Climate Adaptation in Colorado, Utah and Wyoming

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 Western U.S." to explore the kinds of actions these cities are taking and why. Over the course of two years, they talked to city managers, emergency managers and at least one elected official in each city to find out what each place is doing to handle 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. Responses 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 was really pushing for hazard planning and response, and
- whether a city received external incentives, such as funding or regulations.

No one variable drives what cities do, but the combination of a few different variables seems to get 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.

❖ 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, doi: 10.1177/0308518X16688686.

Stormwater Infrastructure Upgrades in a Changing Climate

WWA researchers **William Travis** and **Adam McCurdy** explored how and when stormwater infrastructure should be replaced given projected changes in flooding and extreme precipitation events. Four adaptation strategies, nominal (no change), anticipatory (replace and increase capacity of all culverts before end of life), concurrent (increase capacity at end of life replacement) and reactive (replace and increase capacity after damage), were modeled for actual culvert emplacements in Colorado to examine the effect of adaptation strategy and culvert characteristics on cost efficiency and service level under varying rates of climate change. For a distributed system of infrastructure units like culverts, knowing more about existing characteristics can improve the efficacy of adaptation strategies more than better projections of climate change. Transportation departments choosing climate adaptation strategies often lack detailed data on culverts, and gathering that data could improve the efficiency of adaptation despite climate uncertainty. In particular, anticipatory adaptation performed poorly as evaluated by both cost and level of service. This was caused by the increased number of replacements that sacrificed the value of the structures prior to the end of their useful life. Many

transportation agencies would need additional data collection to learn the specific characteristics of their culverts; however, the additional cost of getting such information may eliminate benefits gained by using it to choose appropriate adaptation strategies.

- 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, doi:10.1007/s10669-017-9631-z.

Improved Spatial Snowpack Data for Streamflow Forecasting

Accurate measurement of springtime snow-water equivalent (SWE) is critical for water managers and water users, including agricultural producers, in Colorado, Utah and Wyoming. Current water supply forecasting techniques commonly use a regression between historical runoff and SWE measured at NRCS SNOTEL sites and snow courses, but increasing streamflow variability has reduced the ability of common regression analyses based on such point measurements of SWE to forecast runoff. The addition of spatially-explicit estimates of SWE using remotely-sensed data can improve these forecasts. **Noah Molotch** and **Dominick Schnieider** estimated the historic spatial distribution of weekly SWE for the Upper Colorado River basin from January to June, from 2001–2012, using both the in-situ SNOTEL data and MODIS satellite measurements of snow extent. Notable improvements were observed in alpine terrain with the inclusion of spatial snow measurements. On average, they found 31% greater SWE depth in areas above 3000 m elevation; these high-elevation areas contribute up to 66% of the total annual SWE volume in the driest year. They also found that observations of snow-cover depletion from previous years provide important information for estimating SWE in real time. This research extends SWE reconstructions to real-time applications and illustrates that doing so significantly improves the accuracy of SWE estimates.

- 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. DOI: 10.1002/2016WR019067 - 9916

Climate Information Use in Drought Planning

Historically, drought has been responded to rather than prepared for, yet studies have illustrated that proactive investment in drought risk management reduces impacts and overall response costs. One key element of preparedness is the use of sufficient climate information for monitoring, forecasting, and tracking long-term trends. In the face of a changing climate and increasing variability, these types of data are even more critical for planning and overall resiliency. The systematic use of these data to inform the drought planning component of drought risk management is a relatively recent development. Actionable science has direct applicability for planning and decision-making, and allows for an iterative process between scientists and end users that can build long-term drought resiliency.

WWA researcher **Jeff Lukas** worked with partners at the Colorado Water Conservation Board and Department of Natural Resources to understand how planners are increasingly relying on climate data, ranging from paleoclimatological records to experimental seasonal forecasts, to guide their long-term drought preparedness and climate change adaptation efforts. This information can then be used to inform broader policy and planning efforts, unifying the scientific basis across multiple processes. Data-

driven decision-making using climate information can help depoliticize actions and increase overall resiliency and response in times of drought, which will be increasingly important as the world warms.

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

R2X in the RISA Network

The transition of research to operations (R2O), applications (R2A) or commercialization (R2C), known collectively as R2X, is a key goal across NOAA. In 2017, WWA surveyed the RISA network to learn more about the factors that help or hinder the process of R2X within both the research and recipient organizations. According to the survey, most RISA programs explicitly encourage research transitions and dedicate resources in support of those transitions. The most successful R2X transitions were for planning, improve warnings (tornado, drought, fire, flood), forecast or tool development, improved drought/flood monitoring, data input for models, improving decision making, informing water and resource managers, and informing the broader operational system. Projects tended to be successful when there was buy-in from the recipient organization, a need was filled, there was engagement with users or it significantly advanced understanding. R2X transitions tend to be unsuccessful when there is a lack of manpower and monetary resources, a lack of planning, and a lack of social capital with the recipient organization.

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

Select Outreach Activities

Usable Science Across CU Boulder

WWA was awarded a grant to work with a University of Colorado Grand Challenge program, Earth Lab, to ensure their research is connected to Colorado stakeholders and to train people across campus in the production of usable science. In August 2016, WWA held a Usable Science 101 workshop on 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 doing research, challenges to producing it, the importance of building relationships with stakeholders, and some key communication skills. Elizabeth then administered her typology of science with the Earth Lab team to give them a thumbprint of their specific research project. The team developed a graduate student seminar for Spring 2017, which taught the theory and practice of producing usable science to eight graduate students. WWA will convene a second workshop in June 2017 with Earth Lab's wildfire team and potential users of physical and socioeconomic fire data.

Earth Lab
UNIVERSITY OF COLORADO **BOULDER**

Climate Change and Drought Planning for the US Forest Service

Jeff Lukas and **Seth Arens** have been asked to participate in several US Forest Service (USFS) workshops on climate change and drought. Seth presented future climate projections at two Wasatch Front workshops for the Intermountain Adaptation Partnership, one focused on the Wasatch and Uinta sub-region and the other on the Plateaus region of central Utah. The goal of each meeting was to introduce information about climate change in the region and to gather USFS resource managers to brainstorm about potential climate adaptation strategies. In March 2017, Seth gave a presentation for the USFS at a drought workshop in March 2017 in Ogden, UT. In April 2017, Jeff Lukas participated in a USFS workshop in Salida, CO, entitled "Climate Change and Drought: Adaptation in the Rocky Mountain Region," which aimed to provide information and tools about drought to several national forests in Colorado undergoing Forest Plan revisions. Jeff presented on future climate and drought risks, and contributed to discussions and small-group breakouts.

Drought Webinars

In Spring of 2017, WWA held two webinars on drought, one on the use of EDDI (evaporative demand drought index) and one on a new ranching drought insurance tool. Both were sponsored by our partners at NIDIS. **Imtiaz Rangwala** and **Jeff Lukas** presented on the physical basis behind EDDI, how it compares to other drought indices and possible uses of EDDI, including an emphasis on flash drought. About 50 people attended the EDDI webinar. In the second, **William Travis** and **Trisha Shrum** presented their new ranching insurance tool, which allows users to experiment with the economics of purchasing the relatively new USDA Pasture, Forage and Rangeland Insurance product, which pays out based on NOAA's gridded precipitation. They presented an online experiment of five years of rainfall and insurance purchases with various options for adapting to drought. About 20 people attended this webinar.

Mountain Research Station Retreat with USDA Northern Plains Hub and NC CSC

WWA hosted a retreat at the University of Colorado's Mountain Research Station for the USDA Northern Plains Climate Hub and the USGS North Central Climate Science Center. Colleagues from the National Park Service and NIDIS were also in attendance at this day and a half event. The sessions focused on drought and the various projects in progress across the three centers. Climate assessment activities were also a key focus with discussion of the upcoming 4th National Climate Assessment and the role each center would play in that process.

WWA 2016-2017 Project Reports

Balancing Severe Decision Conflicts under Climate Extremes in Water Resource Management

Primary Investigator(s): L. Dilling, J. Kasprzyk, L. Kaatz (Denver Water)

Other Investigator(s): R. Smith, K. Averyt, I. Rangwala, L. Basdekas (Colorado Springs Utilities)

Stakeholders: Denver Water, Colorado Springs Utilities, Northern Water Conservancy District, Aurora Water, City of Boulder Utilities, City of Fort Collins Utilities (collectively known as the Front Range Climate Change Group)

Exploring the utility of multi-objective evolutionary algorithms (MOEAs) for improving the ability of water utilities to identify viable adaptation strategies under climate extremes.

Over the past several years there have been increasing calls for decision support tools in the area of climate, and acknowledgement that changing extremes add to an already challenging decision environment for water managers. Recurring droughts, floods, and concerns over extreme events in the future have created a strong interest among water managers in the Front Range of Colorado in how to plan for these extremes. 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 of the solutions that appropriately balance among tradeoffs. In this project, we have co-produced and are testing a newly developed multi-objective decision tool, balancing conflicting management objectives for water planning under climate extremes and determining how policy alternatives perform under severe climate uncertainty. In the past year, we have completed optimization runs with a complete model of the hypothetical Front Range water management context. We have developed performance objectives for the model and used CMIP3 and CMIP5 Bureau of Reclamation downscaled climate projections to develop climate scenarios to test the utility of the MOEA tool. We conducted a workshop to evaluate how water managers interacted with the tool and understand its use in potential future decisions. WWA collaborators contributed significant expertise in the design and conduct of the workshop. A dissertation project is being completed summarizing the results of these experiments and tool testing.

Deliverables: Second workshop held on June 30, 2016. Four conference presentations and one publication (Smith et al. in press)

Leveraged Funding: $261,000 from NOAA SARP competitive grant (L. Dilling, PI)

Regional Extremes Database and Event Maps

Primary Investigator(s): W. Travis, J. Lukas, K. Wolter

Other Investigators(s): A. McCurdy

Stakeholders: Hazard mitigation planners, emergency managers, water resource managers

Developing a database and visualizations of extreme events to assist hazard planners and emergency managers.

Extreme events cause the majority of societal costs related to weather and climate and can provoke adaptive responses. This project is designed to place extreme events in the context of historical climate variability and projected climate change, assess how risk varies over time and space, and examine how extreme events interact with place-based vulnerability. To this end, WWA built two databases of historical extreme weather and climate events in the WWA three-state region (Colorado, Utah and Wyoming), both available on our website. The first is a selective roster of ~160 of the highest-impact weather and climate events in the three-state region back to the mid-1800s, and the second is a more comprehensive dataset culled from the NOAA NCEI Storm Events Database focused on the post-1950 period that includes over 20,000 weather events. The roster of high-impact events has been reviewed by all three of the state climate offices in our region. From the larger dataset of storm events, we generated a set of monthly occurrence maps, by county, for ten different event types. These databases are intended to be useful to hazard planners and emergency managers trying to identify where and when the risk for different types of extreme events is greatest. It will also serve as a foundation for further research on what leads to the variation in risk over time and space. We are currently reaching out to stakeholders to solicit suggestions to refine these products and apply the data.

Deliverables: Web-based searchable database of high-impact historical events and set of event maps for 10 different event types.

Drought planning on the Wasatch Front using paleo-drought information and future climate projections

Primary Investigator(s): S. Arens

Stakeholders: Weber Basin Water Conservancy District, Utah Division of Water Resources and Utah State University

Partners: D. Johnson and D. Hess (Weber Basin Water Conservancy District), D. Rosenberg and J. Stagge (Utah State University), S. McGettigan, C. Hasenyager and A. Nay (Utah Division of Water Resources)

Drought contingency plan development for Weber Basin Water Conservancy District

Weber Basin Water Conservancy District (WBWCD) was awarded a grant in June 2016 from the US Bureau of Reclamation to develop a drought contingency plan. Arens received one month of salary from the grant award to develop future projections of Weber River streamflow.

The project uses a RiverWare systems model of the Weber River Basin to explore how past and future droughts may impact water availability and reservoir storage in the Weber River Basin. WBWCD is a relatively junior water rights holder, despite providing water to several hundred thousand residents of the northern Wasatch Front. The project will use information derived from paleo-reconstructions of Weber River streamflow using tree rings to understand how droughts of the past could impact water availability in the Weber River Basin. Future Weber River streamflows were projected using the NOAA Colorado Basin River Forecast Center operational models. Information about past and future drought conditions in the Weber River Basin will be used to develop a drought contingency plan to help WBWCD prepare for future variability in Weber River water availability.

Deliverables: Future projections of Weber River streamflow based on projected changes in temperature and precipitation derived from Global Climate Models. A report on this project will be completed by WBWCD in Fall 2017.

Leveraged funding: $150,000 each from US Bureau of Reclamation and WBWCD

Use of Potential Evapotranspiration to Predict Future Water Use

Primary Investigator: S. Arens

Stakeholders: Jordan Valley Water Conservancy District (JVWCD)

Partners: B. Forsythe, T. Schultz (JVWCD), C. Dewes

Using downscaled projections of future potential evapotranspiration to predict future water demand

This project will provide projections of potential evapotranspiration (PET), past trends in PET and its components to help JVWCD understand how water demand may change in the future. The Multivariate Adaptive Constructive Analog (MACA) downscaled climate dataset will be used to calculate PET for three future time periods. An analysis of past trends in PET, evaporation and the physical drivers of both processes will be conducted. A key component of future water demand is also the length of the outdoor watering season; projections of future temperatures and the growing degree day index will be used to characterize future changes in the length of the outdoor watering season. A model between observed PET and outdoor water use was developed. This model was then used to predict future outdoor water use based on projections of future PET. This study aims to inform long-term planning for JVWCD by giving estimates of how much outdoor water use may change due to changes in PET.

Deliverables: A final report on this project was prepared for JVWCD in April 2017. The project report will be adapted to a WWA white paper in summer 2017.

Dynamics of Vulnerability Between Urban and Rural Communities in Drought Planning and Mitigation

Primary Investigator: Jennifer Henderson, Lisa Dilling, Ursula Rick, Rebecca Morss (NCAR) and Olga Wilhelmi (NCAR)

Stakeholders: Water utilities, municipalities, and agricultural community along Arkansas River Basin

Using remotely sensed snowpack data to reduce negative impacts in water management

As municipalities implement adaptation or mitigation plans based on past drought experience that improve their resilience, emergent and unexpected vulnerabilities can arise in response to these changes. They can happen immediately in response to water strategies or may be displaced in time or space (e.g. in rural communities months later). The goals of this project are threefold: 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 the implement drought plans; 3) To identify the triggers for emergent vulnerabilities that may be displaced across time and space in drought contexts. To meet these goals, the PI is interviewing representatives from each stakeholder group in sites along the Arkansas River Basin. Initial results suggest that stakeholders are well versed in the common vulnerabilities their sector faces, and even new resilient strategies that have emerged based on experiences with recent droughts (e.g. 2002 and 2012). However, many expressed surprise at some of the unanticipated outcomes in adjacent communities. This project will be extended to two other sites, in Utah and Wyoming, to better understand the range of stakeholder needs for better information about drought and climate information, new strategies for thinking about the interrelatedness between urban and rural communities, and tools that may help them better understand their own sector's or community's unique vulnerabilities and resilience strategies based on past experiences with drought.

Deliverables: Peer reviewed papers, drought experience scale

Leveraged funding: $100,000, 2-year CIRES Visiting Fellowship

Usability of Remotely Sensed Snowpack Data for Streamflow Forecasting and Water System Management

Primary Investigator(s): J. Lukas, N. Molotch, J. Deems

Other Investigator(s): B. Livneh, M. Raleigh, J. Berggren, K. Jennings

Stakeholders: National Integrated Drought Information System (NIDIS), Uncompahgre Basin water managers, Rio Grande Basin water managers, Colorado Basin River Forecast Center

Using remotely sensed snowpack data to reduce negative impacts in water management

A key indicator of water availability, and the primary input to streamflow models, is April 1 snow water equivalent (SWE), which has historically been monitored from a network of in-situ SNOTEL observing sites across the West, but two remote-sensing-based approaches have recently been developed to complement and extend the SNOTEL network. In the first approach, used by Molotch and group, MODIS satellite snow-cover measurements along with a regression from historic SNOTEL data are combined to reconstruct SWE. In the second, used by Deems and group, airborne LIDAR measurements of snow depth are used to estimate SWE. This project will assess the usability of these spatial SWE products by water managers, and their potential to improve runoff forecasts. In summer 2016, phone interviews were conducted with water managers in the Uncompahgre River and Rio Grande basins to better understand how they have used snowpack data and runoff forecasts in their decision-making, especially managing for drought years and very wet years. Focusing on those recent years in which there were unusual snowpack and runoff conditions that were difficult to monitor, forecast, and prepare for, we will use the spatial SWE products and hydrologic model simulations to assess whether the new SWE products could have provided better information to prepare for those events. PI Molotch and K. Jennings have prepared MODIS data for the two basins to be used in hydrologic models. PI Deems has prepared ASO data from the Uncompahgre Basin for use in the models. K. Jennings leveraged high-resolution snow depth observations and snow water equivalent (SWE) estimates from NASA's Airborne Snow Observatory (ASO) in order to quantify errors in current snow products. He found the large spatial scale of NLDAS-2 grid cells made the snow product unsuitable for use. Only 8 grid cells completely or partially overlapped the Uncompahgre River Basin and they often showed snow-free conditions when snow was still reported at the two aforementioned SNOTEL sites. Similarly, the SNODAS SWE product performed poorly relative to ASO data (Fig. 1). SNODAS typically overestimated subalpine SWE while significantly underestimating alpine SWE. We have also taken initial steps towards modeling SWE in the Uncompahgre using the Distributed Hydrology Vegetation Soil Model (DHSVM).

Deliverables: Report on the impact of snowpack data on the stressful events and decisions related to those events.

Leveraged funding: $60,000, NASA Graduate Student Fellowship for K. Jennings

Mapping Climate Services

Primary Investigator(s): E. McNie, A. Meadow (CLIMAS, University of Arizona)

Stakeholders: NOAA Western Regional Collboration Team

Toward closing the gap between climate service providers and users.

Adapting to climate change requires decision makers to have information in hand that is relevant to solve their problems, information that is salient, credible and legitimate. Decision makers, however, do not often have the information they need; perhaps they are unaware of existing useful information, get too much of the wrong kind of information, or have information needs that go unmet, leaving them to muddle through important decisions that could help people adapt to climate variability and 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 developed a database of climate-service organizations in the NOAA West region as a first attempt to bridge the gap between producers and users. 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. The finished product is a searchable database that is open and usable by the public as well as a report that provides preliminary analysis of the findings from the database.

Deliverables: Searchable database, Climate Service Providers Database Development and Preliminary Analysis report

Evaluation of Drought Planning Research on the Wind River Reservation

Primary Investigator(s): E. McNie

Stakeholders: S. McNeeley (North Central Climate Science Center), C. Knutson (National Drought Mitigation Center), Wind River Reservation

Providing support for tribal drought planning efforts on the Wind River Reservation.

In collaboration with the Eastern Shoshone and Northern Arapahoe tribes, WWA partners at the DoI NC CSC and the NDMC are developing a comprehensive drought plan for the Wind River Indian Reservation in Wyoming. The research team is developing analytical tools and provides analysis to inform the drought plan. WWA investigator McNie's role is providing evaluation support and helping to inform the research design. She used a typology of research approaches to guide the design and analysis of research goals, objectives and processes in order to 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.

Deliverables: Typology survey results, evaluation of drought planning research

Evaporation, Drought, and the Water Cycle Across Timescales: Climate Foundational Sciences for the North Central Climate Science Center

Primary Investigator(s): I. Rangwala, J. Barsugli, B. Livneh, M. Hobbins (NIDIS)

Other Investigator(s): J. Lukas, A. Ray, K. Clifford

Stakeholders: The Nature Conservancy, US Forest Service, other conservation agencies

Partners: J. Morisette, D. Ojima, and S. McNeeley (NCCSC); R. Rondeau, CO Natural Heritage Program; J. Rice (Southern Rockies LCC); L. Joyce (USFS Rocky Mountain Research Station); D. Llewellyn (Bureau of Reclamation); M. Friggens (US Forest Service)

Providing climate science support for the DOI North Central Climate Science Center, particularly for water cycle issues.

The *Climate* Foundational Science Area (FSA) identifies and addresses the physical climate science challenges that are important for ecologists and natural resource managers in the NCCSC domain, as well as meet their climate information and data requirements. In order to understand how climate change will affect the ecosystems in this region, we conduct research to improve our ability to understand, measure and model the surface water balance, and how that balance might change during the 21st century. A critical research, tool development and outreach effort of Climate FSA is focused on drought, which is a dominant driver of ecological, economic, and social stress in the region, and is also an important integrating theme across the different NCCSC's FSAs. Project engagements more specifically include: (a) research into the examination of physical mechanisms (e.g., extended surface heating and/or periods of low precipitation, snow and soil moisture processes, and anomalies and trends in the evaporative demand), for both historical and 21st century time periods in different regions of the NCCSC domain, that modulate drought evolution, persistence and dissipation, as well as their relationship with the synoptic-scale climate features, (b) evaluation and development of climate products that are relevant to the surface water balance and drought (e.g., drought indices such as EDDI), (c) climate research support to NCCSC funded projects (e.g., WRIR Drought Preparedness Project), (d) synthesis and assessment of existing information on drought research relevant to the NCCSC domain for use in adaptation, and (e) a continuing stakeholder outreach and engagement to enhance usability of this research and information that's developed.

Leveraged Funding: $450,777 from the NCCSC.

Communicating Climate Change for the U.S. Forest Service Intermountain Adaptation Partnership

Primary Investigator(s): D. Peterson and J. Halofsky (USFS/University of Washington), L. Joyce (USFS) and S. Arens

Stakeholder: U.S. Forest Service

Partners: L. Joyce (USFS), M. Talbert and J. Morisette (USGS North Central Climate Science Center)

Providing climate change and drought assessment to the USFS in Utah

The Intermountain region of the U.S. Forest Service began a formal planning process to consider the impacts of climate change on forest resource management called the Intermountain Adaptation Partnership. S. Arens was asked by the U.S. Forest Service to present information about future climate projections at two Wasatch Front workshops about the Intermountain Adaptation Partnership. One meeting focused on the Wasatch and Uinta sub-region of the Intermountain West and the other workshop focused on the Plateuas region of central Utah. The goal of each meeting was to introduce information about climate change in the Intermountain West and to gather USFS resource managers to brainstorm about potential climate adaptation strategies. S. Arens was also asked to participate in reviewing the final Intermountain Adaptation Partnership report. S. Arens was also asked by the USFS to give a presentation at an Intermountain West drought workshop in March 2017 in Ogden, UT.

Deliverables: Present information about future climate in the Intermountain West region for two workshops in June 2016. Present information about drought and climate change in the Intermountain West at a USFS drought workshop in March 2017.

Decision Analysis for Climate Adaptation

Primary Investigator(s): W. Travis

Other Investigator(s): A. McCurdy, T. Shrum

Stakeholders: Ranchers and others associated with the range livestock industry (e.g., ag extension specialists)

Development of simulation models and decision tools for drought adaptation

The adaptation decision analysis project seeks to analyze decision processes in climate-sensitive sectors and to build decision models that act as both research tools and decision aids. In this year, we put all of our focus on the western range livestock industry, aka ranching, the most extensive agricultural system in the American West. With assistance from the USDA Northern Plains Climate Hub, the WWA team finished building, and distributed two versions of the Drought Ranch Insurance Response (DRIR) model. Both include modules that calculate ranch outcomes with and without the USDA's forage and range insurance, an index insurance product linked to NOAA's gridded precipitation product. The spreadsheet version, which is easiest for producers to use, can be downloaded, along with instructions, from the WWA's "Understanding and Monitoring Drought" webpages. An on-line version, written in the R coding language, was demonstrated on a NIDIS-sponsored webinar in May which also provided the URL for running it online. Next steps are to invite producers and others to test the drought response model via agricultural conferences and publications. The next research steps are to submit a paper describing the model for peer-reviewed publication and to set-up experimental trials to gather sufficient run samples to test hypotheses about the role of drought forecasts, insurance, and market conditions in rancher decision-making in the face of drought.

Deliverables: Working spreadsheet version of the drought decision model (DRIR) demonstrated in webinar and published in downloadable from on the WWA website. Test verison of the online "R" verison (DRIR-R) demonstrated in a NIDIS webinar and URL published for testing.

Intermountain West Climate Dashboards

Primary Investigator(s): J. Lukas

Partners: NIDIS, CLIMAS

Stakeholders: Water resources managers; anyone needing to monitor evolving weather, climate, and hydrologic conditions

Expansion of the scope of widely used climate information web resource to match the Intermountain West Drought Early Warning System.

The WWA Intermountain West Climate Dashboard, is a web resource with a grid of 30 weather, climate and water information graphics that are automatically updated on the Dashboard as their providers update them. The graphics are supplemented by monthly text briefing highlighting the most important conditions and trends. Feedback from WWA stakeholders has indicated that this Dashboard is a very useful 'one-stop shop' for up-to-date climate and water information for WWA's three-state region. The creation of similar dashboards by other climate-service entities (e.g., the Great Basin Climate Dashboard by WRCC and DRI/CNAP) is confirmation of the effectiveness of this format. Since the initiation of the Dashboard, its spatial scope has been focused on Colorado, Utah, and Wyoming. The creation of the Intermountain West Drought Early Warning System (IMW DEWS) by NIDIS in 2016 created an incentive to expand the Climate Dashboard to cover the other states in the IMW DEWS: Arizona and New Mexico. In May 2017 the graphics displayed on the Dashboard were updated and expanded so those two states were included for all climate and water variables. A second monthly text briefing focused on Arizona and New Mexico was also initiated, using the highlights from the latest CLIMAS Southwest Climate Outlook.

Deliverables: The Intermountain West Climate Dashboard web resource

Research to Operations in the RISA Network

Primary Investigator(s): E. McNie, R. Klein

Stakeholders: RISA Programs, NOAA Climate Program Office

Research in the usability of climate and weather research has suggested that there is a 'valley of death' that separates the production and development of research outputs and tools with their use by practitioners, resulting in the production of potentially useful weather and climate information that goes unused. WWA sought to investigate this valley of death in the context of how well climate-service related research becomes operational in the context of the RISA program. Research to operations, applications or other use (R2X) should, hypothetically, be a more robust practice in organizations such as the RISAs. This year Roberta Klein and Elizabeth McNie developed a research project to examine R2X in the RISA program. A survey was sent to all investigators in the RISA programs (except the most recently developed RISA) and were asked a variety of questions to ascertain the effectiveness of R2X, support for or barriers against R2X, and how might the RISA program better support R2X efforts within individual RISA programs. Findings from the research which were included in a report indicate that many of the challenges and opportunities identified in previous National Research Council reports exist within the RISA program. However, there are also opportunities for the RISA program to provide better support, including financial and programmatic, for individual RISA programs to enhance their effectiveness of R2X.

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

Extremes: Adapting stormwater infrastructure to extreme precipitation

Primary Investigator(s): W. Travis, A. McCurdy, I. Rangwala

Stakeholders: Stormwater managers.

Developing models of stormwater infrastructure replacement

In this second year of work on this extreme events theme, focused on how to adapt stormwater infrastructure, we finalized the "Culvert" model, placed the R code on our webpage under "Stormwater Management," for download, and published a peer-reviewed article on the model and its results. The model simulates the effects of increasing flows on roadway culverts, which are typically constructed to convey certain flow volumes. Key model outputs include when and how to modify stormwater infrastructure as climate changes and culvert failures become more likely. The key finding, conveyed in our previous annual report (and now in formal publication) was that aggressive anticipatory replacement of culverts is economically inefficient even under rather large climate change scenarios. This is 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 to invest more effort to evaluate the vulnerability of each culvert no matter what its life-cycle status, and adapt only those likely to failure in the near term. So, this year we also created a second version of the model to test how information about vulnerability of each structure installation site can improve prescriptions for planned adaptation. A paper from the new approach is currently in revise-and-resubmit.

Deliverables: McCurdy, A.D. & Travis, W.R. (2017) *Environmental Systems and Decisions* 37: 214. doi:10.1007/s10669-017-9631-z

Model description and code published on WWA website. A. McCurdy and W. Travis, "Simulated Climate Adaptation in Stormwater Conveyance Structures". Culvert model 2.0 developed to test alternative outcomes, and paper in revise-and-resubmit at *Climate Risk Management*

Extreme Precipitation Estimation Under Climate Change for Dam Safety

Primary Investigator(s): K. Mahoney, J. Lukas

Stakeholders: Colorado Division of Water Resources Dam Safety Program; New Mexico Office of the State Engineer, CO-NM REPS technical advisory board members and other stakeholders

Assessing the state of the science and practice in extreme precipitation estimation under climate change

The Colorado Division of Water Resources and the New Mexico Office of the State Engineer have identified and set as a priority the need to update their extreme precipitation estimates for use in the evaluation of spillway adequacy for dams in these states, based on the most modern methods and scientific understanding available. Due to similarities in geography and meteorology between Colorado and New Mexico, a cooperative, regional study (Colorado-New Mexico Regional Extreme Precipitation Study; CO-NM REPS) has been undertaken, the first instance of states combining resources and working collaboratively toward a solution to the problem. The project began in June 2016 and is scheduled to be completed in June 2018. Of particular concern in both states are questions about the physical limits on high-elevation rainfall amounts and the annual exceedance probability (AEP) of the extreme rainfall amounts used for spillway design. This has led to an innovative ensemble approach deploying three different methods to update extreme precipitation estimates. The CO-NM REPS does not seek to explicitly incorporate climate change influences in Probable Maximum Precipitation (PMP) estimates through any three approaches. Recognizing that the approaches may have limitations in characterizing future risk in a changing climate, the study's sponsors have asked WWA to take stock of the state of the science and practice in PMP estimation and climate change in a white paper that will become an appendix of the study final report. An initial literature search and review was completed in spring 2017, and is currently being supplemented by a survey of the experts comprising the CO-NM REPS Technical Advisory Board.

Deliverables: White paper to be published as appendix of the CO-NM REPS final report in 2018; potential for peer-reviewed paper

APPENDIX A: List of 2016-2017 WWA Publications

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. DOI: 10.1002/2016GL069690 - 9723

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*, DOI: 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. doi: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, doi: 10.1177/0308518X16688686.

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*, doi: 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**,** 9pp. http://iopscience.iop.org/article/10.1088/1748-9326/11/12/124009/meta

Finnessey, T., M. Hayes, J. Lukas and M. Svaboda (2016). Using climate information for drought planning. *Climate Research,* 70, p. 251-263, doi: 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.

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.

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.

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, doi: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*.

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.

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.

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. DOI: 10.1002/2016WR019067 - 9916

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.

Smith, R, J.R. Kasprzyk, and L. Dilling. "Participatory Framework for Assessment and Improvement of Tools (ParFAIT): Increasing the impact and relevance of water management decision support research" *Environmental Modelling and Software*. In Press.

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.

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.

APPENDIX B: WWA Appearances in Media

2017

May 31, 2017
"Strengthening the Voice for Sustainability"
American Libraries Magazine

May 26, 2017
"Crowley County: A 'Poster Child' for Less Water?"
NPR's KRCC

May 24, 2017
"A Future With Less Water: Climate Change Along the Arkansas River"
NPR's KRCC

April 21, 2017
"What to expect in our mountain forests as the climate warms"
Mountain Town News

April 11, 2017
"THE BUZZ: Sliding into the Future"
Planet Jackson Hole

April 6, 2017
"How Will Climate Change Transform Colorado Springs Over The Next 100 Years?"
KRCC, NPR

February 25, 2017
"Gardner could lead on climate change"
Daily Camera

February 15, 2017
"Is the valley destined for more wild, destructive storms as climate change tightens its grip around Jackson?"
Planet Jackson Hole

January 2017
"Noah Molotch interview on snowpack in the Sierras"
KCBS Radio, San Francisco

January 18, 2017
"It's getting hotter, but experts hesitant to blame Colorado Springs' wild weather on climate change"
The Gazette

2016

December 2, 2016
"Ursula Rick - The Science Informant"
The Nerd Heard By Ryan Vachon

November 20, 2016
"Existential threats in the Colorado River Basin"
Mountain Town News

October 24, 2016
"Colorado's Rapid Population Growth Causes Traffic Problems, Environmental Concerns"
CPR Here and Now

September 16, 2016
"Colorado River faces flood of challenges"
Post Independent

September 5, 2016
"Colorado River seminar takes place on Sept. 16"
Post Independent

August 11, 2016
"Slower Snowmelt Affects Downstream Water Availability in Western Mountains"
Nevada Today

July 20, 2016
"As Climate Change Pushes Runoff Earlier, Water And Colorado Ag No Longer Cleanly Overlap"
KUNC

July 18, 2016
"Climate and Water: The Shifting Hydrograph"
Colorado Foundation for Water Education