

# Colorado Water

March/April 2018

A photograph of a tan military-style truck driving through a muddy, debris-filled road. The truck is moving towards the viewer, splashing through the mud. In the back of the truck, several people wearing yellow rain gear and hard hats are visible. The road is flanked by steep, rocky embankments and dense evergreen trees. The scene suggests a natural hazard, such as a landslide or flood, in a forested area.

## NATURAL HAZARDS



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# COLORADO WATER

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## Director's LETTER




Floods, wildfires, drought, and violent storms producing hail and tornadoes are all too frequent visitors to Colorado. Given the hurricanes and resulting billions of dollars in damage that Texas and Puerto Rico experienced in 2017, we can just be grateful Colorado does not experience this particular type of natural hazard. It is certain that extreme hydrologic events and other natural hazards will eventually occur in a neighborhood near you, we just cannot not know exactly when, where, and how severe they might be. The cost and impact of these natural hazards continues to underscore the need for natural hazards research and risk communication.

2018 is shaping up to be another serious drought year in Colorado and across the Southern High Plains. Drought tends to be a slow-motion disaster, but resulting wildfires move at deadly speeds. The 2018 forecast for the Colorado River indicates unregulated inflows to an already low Lake Powell stand at just 43% of average at the time of this writing. So we must continue to plan for hydrologic extremes, monitor conditions, and employ a variety of incentives and regulations to protect the built and natural environment from natural hazards. Humans seem to naturally want to live and build their homes and businesses near water, but given the magnitude, cost and increasing frequency of extreme events, we need to change the way we think about development near coastlines, forests, and flood prone areas.

Risk communication, more specifically, risk messaging is critical to help the lay public, local planners, and decision makers understand the consequences of their building decisions, improve upon mitigation, as well as preparedness measures. Risk, probability, and the notion of vulnerability related to natural hazards are tricky in some instances to convey, let alone communicate. The term “100-year flood” is often a source of confusion because it leads some people to believe that a given flood will only occur once every 100 years. The United States government decided in the 1960s to use the 1% annual exceedance probability flood as the basis for the National Flood Insurance Program. This level was chosen as a balance between protecting the public and not overly restricting property rights. The fact is that a significant flood can happen any year, and can happen in successive years.

Clearly, we cannot afford to build our infrastructure to withstand every conceivable risk, so we need to plan for resiliency – the ability to bounce back after a natural hazard. While a great deal of uncertainty surrounds the occurrence of natural hazards, the recovery and rebuilding process is well documented, and tends to be methodical and slow. The 2013 Front Range flood, which occurred almost 5 years ago this coming fall, still has lasting impacts and the road to recovery is progressing, but will take time. It goes without saying that the ten lives lost in the 2013 flood can never be restored and in all of these events, the financial and emotional costs on survivors living with the loss of homes, possessions, pets, and livestock take their toll. On the positive side, the 2013 flood resulted in a number of new watershed coalitions that are still actively working to restore floodplains and river reaches.

This issue of *Colorado Water* focuses on natural hazards. There is cutting-edge natural hazards research at CSU and within the community of water research professionals including research devoted to: hurricane forecasting, wildfires, drought, and flooding. Climate change adds an additional wrinkle if we cannot rely on the historical record to predict extreme event frequency and intensity. The uncertainty around how climate change will alter local hydrologic conditions only intensifies the need for research focused on improving forecasting tools, better planning, and infrastructure.

It is certain that natural hazards will continue to have lasting impacts on the individuals, infrastructure, and ecosystems in Colorado. These natural hazards change us and the way we view our rivers, oceans, and forests. New lessons learned from the recent droughts, wildfires, and floods inform our hazard planning, monitoring, risk communication, and decision-based support services for decision makers and the lay public. Right now, the Governor's Drought Task Force is closely monitoring current drought conditions and the State is in the process of updating the Drought Plan. Are we prepared if the summer of 2018 brings the next severe drought and wildfire season to Colorado? 

*Reagan Waskom*

Director, Colorado Water Institute

# High-Impact

## Rainfall and Floods in Colorado

Russ Schumacher,  
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Colorado Climate Center,  
Associate Professor,  
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### SYNOPSIS

Colorado has been the location of many major floods over the years, but these disasters have provided researchers with opportunities to better understand the multi-faceted processes that lead to a flood. This research—which is increasingly interdisciplinary—has also offered insights into how to better predict rainfall and flooding, and how to mitigate floods' devastation.

**Y**ou do not need to live in Colorado for long, before you notice the wide variety of interesting weather that occurs here. There are many different phenomena across our state that can be disruptive. Some of them might be a cause for celebration for some people—snow days—but others are a serious threat to property, the state's economy, and even people's lives. Because of dedicated research and technological advances, great strides have been made in recent years to improve weather forecasts and how they are communicated. Even so, understanding and predicting high-impact weather is still a major challenge, particularly in Colorado, where we have sharp changes in the topog-



*Russ Schumacher*





*Just one of hundreds of buildings damaged or destroyed during the Big Thompson flood. Photo courtesy of the Water Resources Archive.*

raphy and weather, from the mountains to plains warm to cold temperatures, wet to dry, sprinkles to golf ball-sized hail, and so on.

In October 2017, I was named the Colorado State Climatologist, and the Director of the Colorado Climate Center, following Nolan Doesken's retirement after four decades (!) of serving the state and the country with his climatological expertise, first as the Assistant and then State Climatologist. The Colorado Climate Center leads numerous projects related to the weather and climate of our state, but one important role that we play is to collect and analyze data on the high-impact weather systems that affect Colorado, and to put those events into historical context. In particular, analysis of rainfall and floods has been a large component of the CCC's activities in the past,

including Nolan Doesken's launch of the CoCoRaHS network after recognizing the dearth of rainfall observations in the 1997 Fort Collins flash flood. In this article, I will focus specifically on the hazards from heavy rainfall and flooding in Colorado, including research activities that are leading to improvements in how we understand, forecast, and communicate about these hazards.

Although we live in a semi-arid climate, Colorado has a history of major floods. The "where and when" of heavy precipitation varies widely across the state, with extreme amounts of precipitation occurring during all seasons of the year, at both

low and high elevations (e.g., Mahoney et al., 2015). Some of the worst floods occur when sufficient moisture moves into Colorado, often—but not always—during the "monsoon season" in late July and early August, which brings the threat of slow-moving, heavily raining storms. But rainfall is only the first ingredient for floods. We need to know what will happen once that rain hits the ground, which is affected by how much rain has fallen recently, the characteristics of that ground (urban or rural locations? flood-control measures? what type of soil?) and also which individuals, structures, ecosystems, or industries are likely to be in the path.

We are now nearing the five-year anniversary of one of the most significant disasters in recent memory: the Great Colorado Flood of September 2013. That flood highlighted all of these facets of the flood hazard: record rainfalls

Because of dedicated research and technological advances, great strides have been made in recent years to improve weather forecasts and how they are communicated”



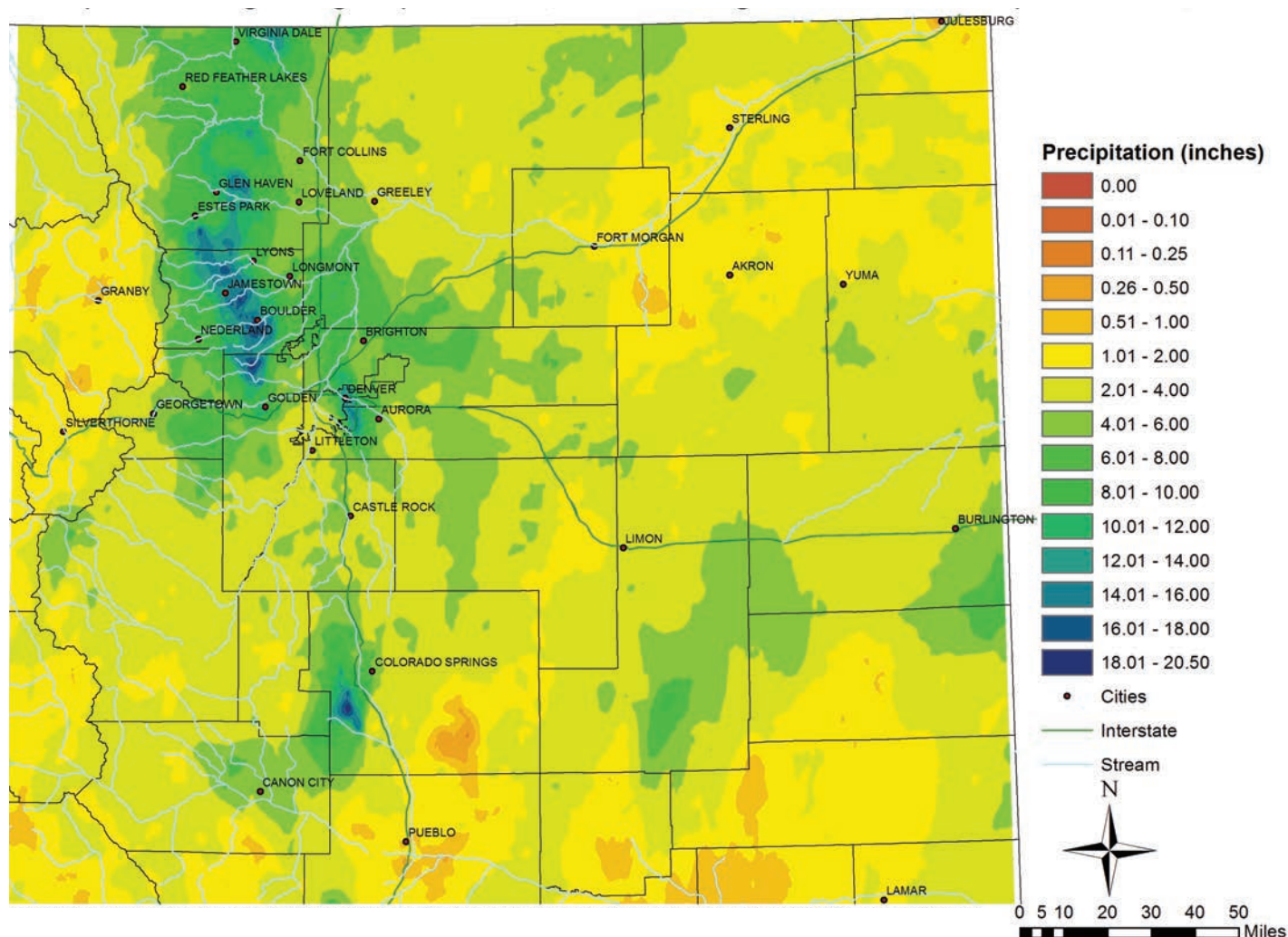


Figure 1. Total precipitation (inches) over eastern Colorado from September 8-17, 2013. Map created with the Storm Precipitation Analysis System (SPAS) through a collaborative effort by Applied Weather Associates, LLC., MetStat, Inc., and the Colorado Climate Center. Radar data supplied by Weather Decision Technologies, Inc. Image courtesy of Zach Schwalbe, Colorado Climate Center.

(Figure 1) occurred across a broad swath of the Front Range and adjacent plains, which then led to devastating flooding, landslides, complicated evacuations, and long-lasting recovery efforts. Unfortunately, ten lives were lost during the 2013 flood (NWS, 2014), but in comparison to other major floods in Colorado like the 1976 Big Thompson flood (143 fatalities) or the 1965 Denver flood (21 fatalities), the loss of life was comparatively low, especially considering the widespread destruction of property and infrastructure that occurred.

Prior to September 2013, meteorologists and climatologists worried most about flooding in the summer, when moisture can be pinned up against the mountains by upslope winds, and the winds aloft are fairly weak, resulting in slow-moving storms. These were the ingredients for the 1976 Big Thompson flood and 1997 Fort Collins flash floods, among others. Extreme rainfall can also occur in May and June, when thunderstorms are at their strongest in

Colorado. The June 16-17, 1965 flood in Denver and on the South Platte River is one prominent example. And even the September 2013 event was not entirely without precedent, as a flood with some similarities occurred in September of 1938. In both 1938 and 2013, the pattern in the atmosphere allowed for a circulation to become “cut off” from the larger-scale flow over Nevada and Utah for several days. To the east of this low-pressure center, very moist air (setting records for September; see Figure 2 from Huelsing et al., 2017) moved northward into Colorado, and persistent easterly (upslope) winds drove the moist air into the mountains for nearly a week, producing extreme rainfall across a broad swath of northern Colorado, including elevations as high as 10,000 ft (see Gochis et al., 2015, BAMS for a more detailed meteorological analysis).

The 2013 flood has been the focus of numerous interdisciplinary research studies, many of them led by CSU faculty, staff, and students. As one example, in work led by



former atmospheric science graduate student Annareli Morales, we showed that the development of a circulation in the lower levels of the atmosphere—a “mesovortex”—between Denver and Boulder on the evening of September 11<sup>th</sup> was responsible for the especially large rain rates and accumulations that occurred that night in the foothills of Larimer and Boulder counties (Morales et al., 2015). Other research groups have studied aspects of the meteorology, hydrology, geomorphology, public response, and other related topics.

The 2013 flood also happened to occur as I was leading a workshop on floods for graduate students from a broad range of disciplines: not only meteorologists and hydrologists, but also psychologists and historians and economists and sociologists and more (see Schumacher, 2016, BAMS). Scientists from different areas of expertise, even when studying the same phenomenon, often speak different technical languages, and this workshop was an effort to develop early-career researchers who could be “multilingual.” The workshop was in two parts, the main portion in 2013 occurred to hear from relevant speakers and devise interdisciplinary research projects, which the group would then report back on in 2014. Part of the 2013 workshop (held in Fort Collins, Colorado) was a tour of important flood sites along the Front Range, led by Matt Kelsch from the University Cooperation for Atmospheric Research (UCAR). We visited Creekside Park in Fort Collins, the epicenter of damage from the 1997 flood, which

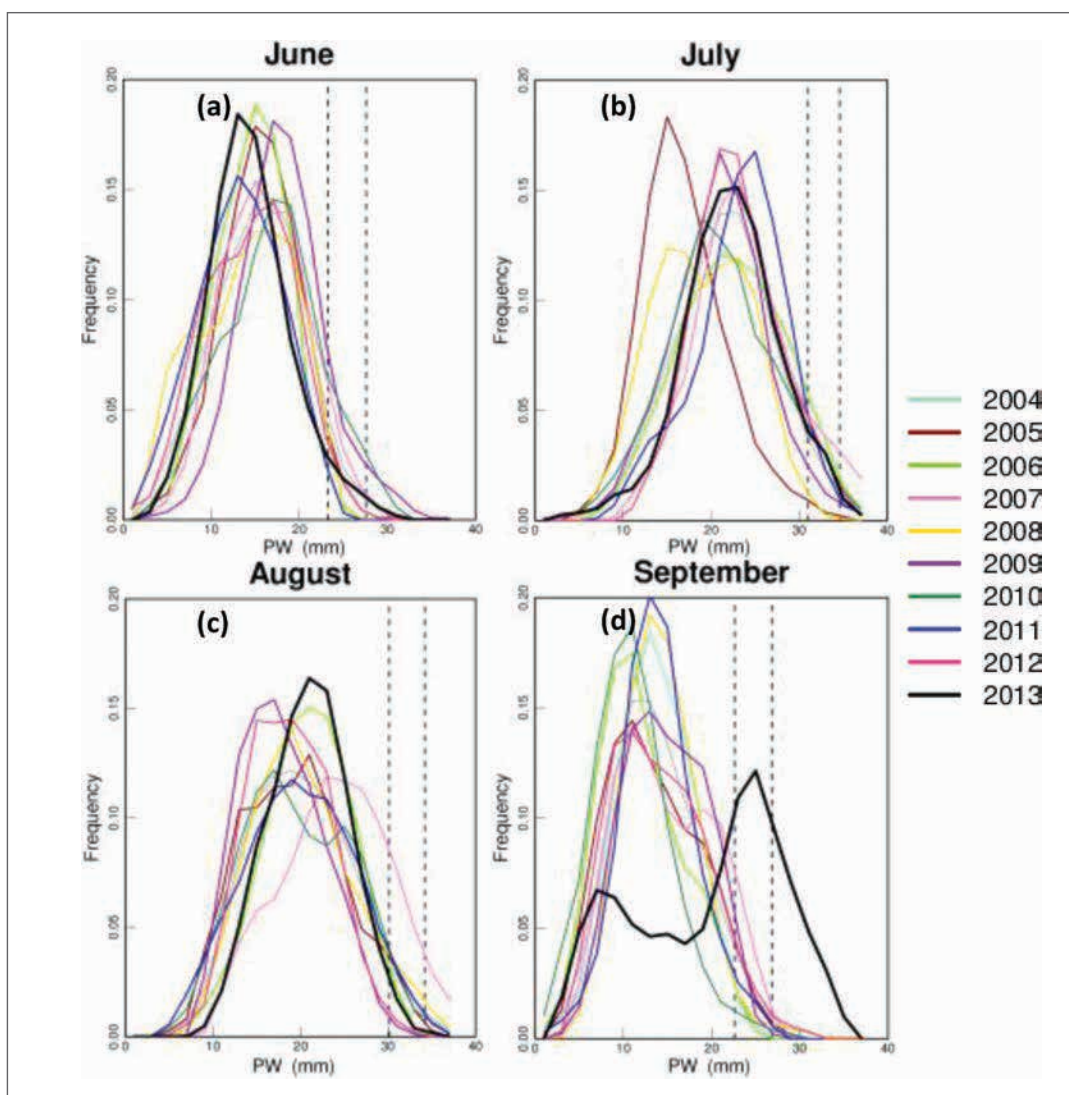


Figure 2. Illustration of how unusual the atmospheric moisture was during September 2013. Shown are distributions of precipitable water (PW; the total water vapor integrated through the atmosphere) at Boulder for June–September of 2004–2013. The dashed lines show the 95th and 99th percentile for each month over the 10-year record. Source: Huelsing et al. (2017).

includes a monument with illustrations of what the 25-, 50-, and 100-year floods would look like, and a high-water marker from 1997 way above all of those. We proceeded up Big Thompson Canyon to Viestenz-Smith park, which held remembrances (both natural and human-made) of the 1976 flood. Finally, we visited Rocky Mountain National Park (RMNP), where the Lawn Lake dam broke in 1982 and inundated Estes Park (but also left behind a beautiful and educational example of an alluvial fan in the park).

The plan was then to hold year two of the workshop in another location that had experienced a recent flood. And it turned out to be the same locations we had just visited. After floods devastated northern Colorado in September 2013, it was clear that the group needed to return to Colorado in the summer of 2014. We heard from local emergency managers about the impacts of the flood, and Matt Kelsch led us on an-



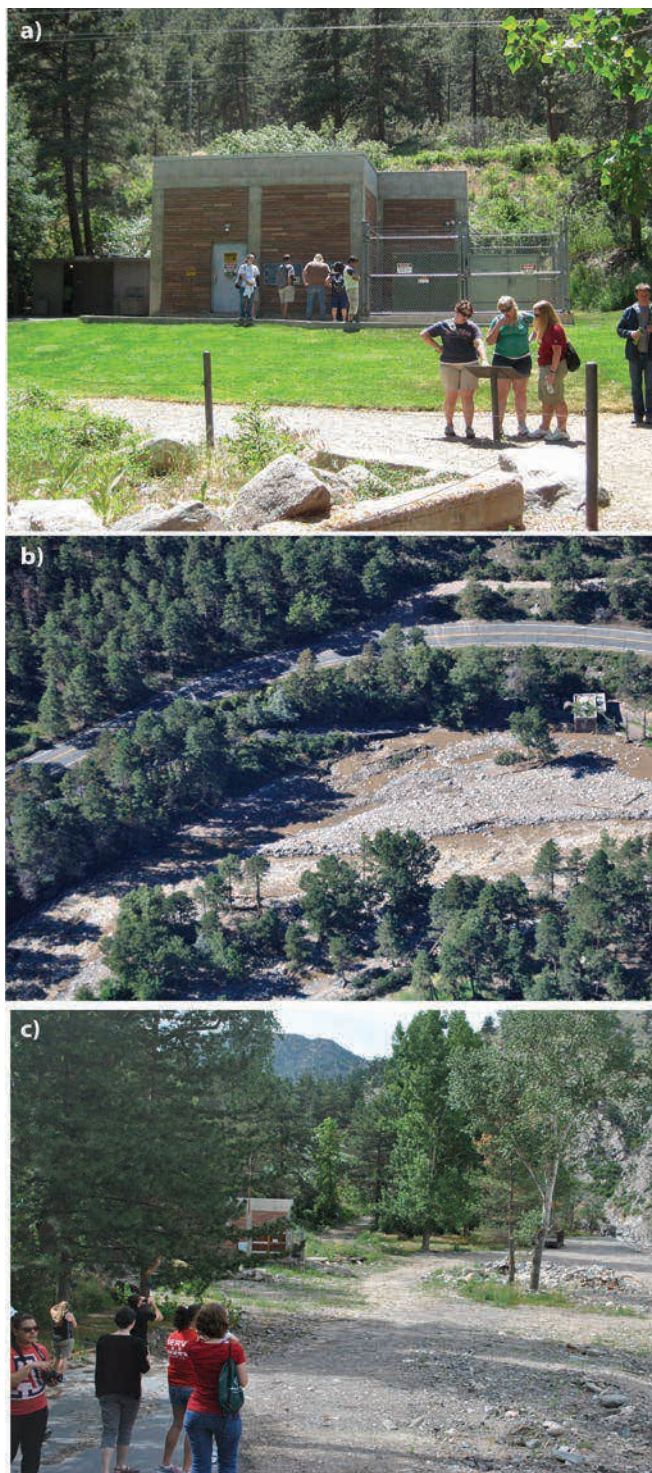


Figure 3. Photos of Viestenz-Smith Mountain Park, in the Big Thompson Canyon between Loveland and Estes Park, Colorado. (a) SPREAD workshop participants in June 2013, inspecting the ruins of a hydroelectric plant destroyed in the 1976 Big Thompson flood, with the building housing the current hydroelectric plant in the background (Photo courtesy of Jen Henderson) (b) Aerial photo in September 2013. The building seen in the top photo is in the upper right of this photo, with trees strewn atop it (Photo courtesy of the Civil Air Patrol) (c) SPREAD participants in July 2014, with the park under repair (Photo by Russ Schumacher) Compilation of images from Schumacher (2016), 2016 American Meteorological Society.

other tour, including locations like Lyons that saw some of the worst damage, as well as the newly rearranged alluvial fan in RMNP and the edge of Viestenz-Smith Park, which was completely inundated and remains closed as of this writing. This provided a unique education to all of us about the wide-ranging impacts of flooding: how it affects people, infrastructure, and the landscape.

The 2013 Colorado flood, in addition to more recent high-profile events like the West Virginia floods of 2016 and Hurricane Harvey in 2017 in Texas, has sparked renewed attention to the prediction, preparedness, and response to extreme rainfall and flooding. Fortunately, the research described above is beginning to make important strides. Large improvements have been made to weather-prediction and hydrologic models in recent years, and even more importantly, those models are now being coupled together in meaningful ways in the National Water Model and other similar tools. The variety of impacts that floods can have on urban areas and regions of complex terrain are becoming clearer, and how people respond to flood hazards is starting to be better understood, all of which can inform future planning and decision making.

Yet there is still a long way to go. Rainfall is one of the most difficult aspects of weather prediction. And it remains challenging to translate even highly accurate forecasts of unprecedented rainfall, like those during Harvey, into a “picture” of what the outcomes might look like for local officials. And as a result, devising a coordinated, meaningful public response to that forecast is elusive.

In Colorado, we are accustomed to a wide variety of natural hazards, with flooding being just one on a list that also includes severe hail, tornadoes, snowstorms, wildfires, and drought. But floods have represented some of the deadliest disasters in our state’s history. They remain very difficult to predict, and adequately preparing for them can be a challenge, as well as considering the broad range of factors that influence the likelihood and severity of flooding. Yet it is critical that we do prepare for them, through improved understanding that comes from interdisciplinary research, and through thoughtful action from the local to state to national scales.

## Acknowledgments

The SPREAD workshop and associated research was supported by a CAREER award from the National Science Foundation, grant number AGS-1157425.

References cited within the article are available in the online PDF version of *Colorado Water* located here:

<http://cwi.colostate.edu/newsletters.asp> 





# A Personal Perspective

on the Recovery From the 2013 Flood

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Colorado Water Conservation Board

Jamestown, Colorado Photo by Steve Fumwalt,  
Federal Emergency Management Agency

## SYNOPSIS

Floods can happen anytime and anywhere, and one of the most difficult aspects of a career in floodplain management is working in recovery activities following a major flood. It can be heart-wrenching to witness how a flood disaster affects the lives of everyday people, but it can be rewarding to help them get back on their feet. It is never too late to build back better, and opportunities to learn from disasters should never be ignored. Here is one professional's story.

## Flood recovery is not an easy business. At all.

The four-year anniversary of the costliest natural disaster in Colorado's history as a state quietly came and went with little fanfare in September. Many people not directly affected by the flood have understandably moved on and many have forgotten the event that took ten lives and resulted in approximately \$3-3.5 billion in damages. However, those affected by the flood often have daily reminders that flood recovery can be a slow, painful process that takes years to complete. It can often take that long to accept the realization that one can never be made whole following an event of this magnitude.

As a brief history reminder, the 2013 flood began on September 11, 2013 from a widespread, extended rainfall event that lasted several days and covered almost all of the northern Front Range and foothills as well as El Paso County. Some notable elements of this flood have changed the way we approach Colorado flood planning and mitigation and serve as a reminder of concepts easily forgotten:





Before



After

*The North St. Vrain upstream of Lyons and Apple Valley along Highway 36. The twin stem tree on river right (upper left of both photos) is a good guide to see how the channel width was reduced and the floodplain was accessed. There was also a lot of debris removal from pre to post. Photos by Kevin Houck*

- September is a target flood month. Even when experts think of Colorado flooding, the periods around Memorial Day and late July/early August often come to mind. The former is often associated with widespread regional rain events (similar to what was seen in September 2013) often combined with streams already swollen with runoff. The latter is often associated with isolated, but sometimes incredibly intense thunderstorms. September is often forgotten, but this event served as a reminder that tropically based events (such as this one) can enter Colorado under the right conditions. It is a rare occurrence, but when it does happen, it can be extremely dangerous and one that needs to be planned for.
- Even as high as 9,000 or 10,000 feet in elevation, the true design floods (i.e. 100-year, 500-year, or even

greater) are often still produced by rain events. This is easy to forget as the vast majority of high elevation annual streamflow peaks are produced by snowmelt runoff. But the rare events caused by heavy rainfall (perhaps only two or three out of every 100 years) often greatly eclipse the others. This is true for most of Colorado, with the only notable exception being higher elevation areas of north-western Colorado.

- The September 2013 event featured no snowfall, even in the highest elevations, and almost no convection. Both of these were unusual, and serve as an example of what other future devastating floods may look like.

All told, the elements of the event resulted in a “perfect storm” for a disaster. Up to 19 inches of rain fell around Boulder and the peak of the rainfall event happened overnight. The ten fatalities were the most for a Colorado flood since 143 people lost their lives in Colorado’s deadliest flood, the Big Thompson flood of 1976. In total, 20 Colorado counties were impacted and declared disasters. Over 16,000 homes were damaged with almost 1,900 completely destroyed. Almost 1,000 businesses were damaged or destroyed. 200 miles of state highways and numerous bridges were destroyed.

During the damage assessment phase immediately following the end of the flood event, I was assigned to Larimer County to assess damages. It was surreal attending a kickoff meeting at the County, where my team was told that it was impossible to get up into the canyons to assess damages on the ground. All that was available at the time was aerial video footage. My team was, however, able to get to Estes Park, but it was not easy. The roads of every major canyon going up into the foothills were impassable due to flood damages. At first, the only known road to Estes Park involved the Peak to Peak Highway beginning in Black Hawk. Normally a quiet, twisty highway that even during the best of times takes two hours to drive, this route became a major highway for disaster support services, debris removal vehicles (i.e. large garbage trucks), and heavy traffic that reduced the drive to 20 mph and increased the drive time to 3-4 hours one way. And that was from Black Hawk. For a government



official in the Larimer county seat of Fort Collins, they first had to drive through Denver to Black Hawk, making it up to a six hour, one-way trip to provide services to their constituents 40 miles away.

Witnessing the damage first hand is an element of my job I just will not ever get used to. It is sometimes too easy to look at the numbers and pass over them without giving much thought. But when you see it first hand, it can be difficult and shocking to see the impacts to the lives of the affected families. Standing alongside property owners, whose homes have been substantially destroyed or damaged has been one of the most professionally challenging situations I have ever encountered. They are often overcome with grief and sadness, and while it is crushingly easy to feel sorry for them, I have never experienced a flood firsthand before, and about all I can often muster is “I can’t imagine how you feel”. It is honest, but it is frustratingly inadequate to say to those in desperate need.

It also was not the first time. I have experienced other much smaller floods throughout Colorado. But the size of the flood does not matter at all when you are interacting with people that have lost everything. I also remember assisting with damage assessment during some of the recent large wildfires in the state, most notably the Waldo Canyon and Black Forest fires. The disaster is initiated by a different mechanism, but the grief experienced by those affected remains the same. As a father myself, it can hit close to home to encounter children crying while looking at their destroyed home or seeing seemingly day-to-day items like sports trophies, stuffed animals, or family pictures littered among the debris. Every one of these has a personal tale to tell.

Which brings us to the recovery effort. By definition, recovery involves the reestablishment of infrastructure as well as societal and community processes to a functioning state following a disaster. To say that this has been a long, slow process following the 2013 flood would be an understatement. Numerous efforts will still be ongoing when the (as I anticipate) much publicized five-year anniversary approaches next September. It could still be another couple of years beyond that before everything is as finished as it is going to be. For those that live in the area, and for those helping in the effort, it sometimes seems to never end.


My agency, the Colorado Water Conservation Board (CWCB), has been involved in a number of recovery efforts associated with this event. We have issued zero-interest emergency loans to water providers to repair infrastructure. We assisted with the post-event damage assessment and plans for mitigation efforts to coincide with the recovery. Through legislation associated with the 2015 Colorado General Assembly, we are fully reevaluating flood risk and floodplains throughout the flood affected area. We are developing a methodology to evaluate erosion hazards, something we saw in this flood like never before on the Front Range. But perhaps the biggest effort we are conducting involves a partnership with the Natu-

ral Resources Conservation Service (NRCS) to restore streams and watersheds in a resilient manner in an effort to prevent damages like this from happening in a future event.

Resiliency is a buzzword that has been inserted into numerous government processes, not just disaster recovery. The Colorado Resiliency and Recovery Office (CRRO) defines this term as “the ability of communities to rebound, positively adapt to, or thrive amidst changing conditions or challenges – including disasters and climate change – and maintain quality of life, healthy growth, durable systems, and conservation of resources for present and future generations”. Put another way in my own words – we are not just building back, we are building better. While some things may never be the same in some locations, we want to improve on certain elements and make this a better place to live and work. Incidentally, the CRRO has an excellent website on resiliency worth checking out at [www.coresiliency.com](http://www.coresiliency.com).

Some of the actions we have undertaken include the following:

- Creation of eight watershed coalitions, bringing together stakeholders of various background and interests to augment two that already existed prior to the flood,
- Preparation of eleven watershed master plans to guide the recovery process, prioritize projects, and seek funding sources to implement resilient processes,
- Implementation of the Emergency Watershed Protection Program (EWP) in partnership with the NRCS. This will involve approximately \$60 million of projects restoring watersheds and implementing resilient processes mentioned earlier. Some of these projects involve restoration to private property, one of the few government-funded programs that will do so,
- Partnership with the Colorado Department of Local Affairs in the implementation of the Colorado Watershed Resiliency Pilot Program, and
- Participation in the funding of these projects. Affected landowners and local governments are stretched thin with funds during the recovery efforts. The State of Colorado followed through with a promise to provide half of the statutory non-federal match of 25%. What this means is that local governments and private property owners are only charged with paying 12.5% of project costs (or one dollar out of eight). All told the State is actively managing over \$100 million of recovery funds dedicated to stream restoration. Approximately 15-20% of this funding is derived from State sources.

I cannot emphasize enough how difficult this event was for those impacted by it. Ten lives were lost and countless others changed forever. The impacts will be felt for generations. However, citizens and government leaders at all levels are committed to improving the situation for now and future generations. And we will not stop until we are done. 





# Unintended Consequences

## of Drought Planning Along the Arkansas River in Colorado

Jennifer Henderson, Postdoctoral Fellow, Western Water Assessment, CIRES, University of Colorado, Boulder

### SYNOPSIS

Drought, and concerns about of water scarcity, create a flurry of ever-changing activity across states like Colorado, which influences how people plan for the next one. Learning more about the actions different groups take and the policies they enact helps social scientists understand how modifications to strategies for water storage and water supply create a variety of unintended consequences.

*Names used in this article have been changed to protect the identity of participants because of Institutional Board of Review requirements for Human Subjects research in the social sciences at University of Colorado, Boulder.*

**G**reg works for the local water utility in Pueblo, Colorado and his job is to know water well. He pulled out photo-

**“I could step over the Arkansas River,” Greg said.\***

graphs of the summer in 2002, when one of the most severe droughts to hit Colorado forced many entities across the state to later reevaluate their drought plans. His photographs of the Arkansas River showed a largely empty river bed, muddy with damp dirt, dry grasses on its bank, and a few spotty puddles where the water once flowed.

I tried to imagine the river I had passed on my way into Pueblo, Colorado, a ribbon of green and brown, diminished to a trickle.

On ranches and farms nearby, wells would dry up, and small towns like Beulah would pay to have water trucked into their community. Along the waterway, rafting and fishing businesses would struggle to remain open, and businesses dependent on river flows would dip into their water shares housed in Pueblo Reservoir. The year 2002, and later, 2012, would reshape how people along the Arkansas River in Colorado planned for the next drought—much like the droughts of previous decades had. Drought, and concerns about of water scarcity, creates a flurry of ever-changing activity across states





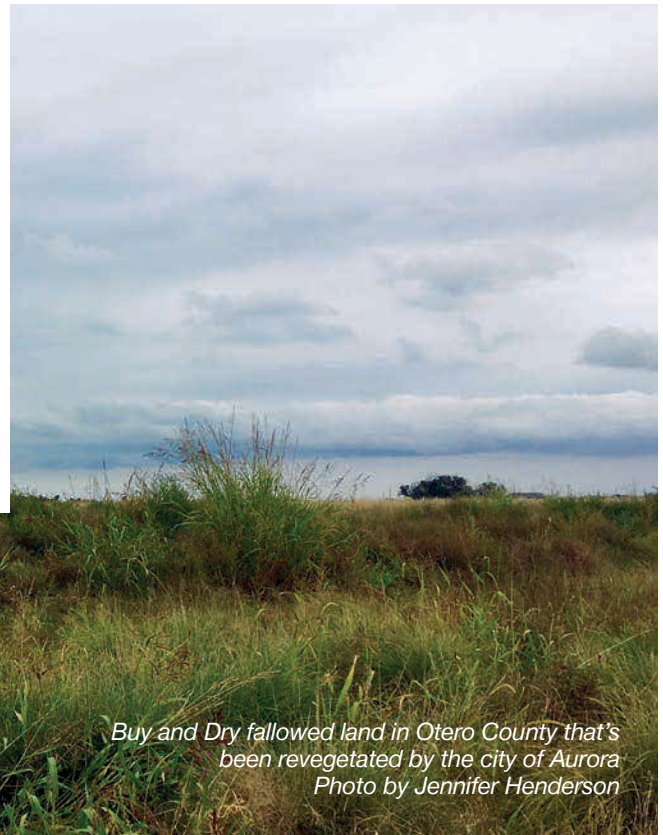
*Arkansas River, Pueblo Colorado  
Photo by Ken Lund*

like Colorado, which influences how people adapt. Learning more about the actions different groups take and the policies they enact helps social scientists like myself discover how modifications to strategies for water storage and water supply create a plethora of unintended consequences. This is the central issue of this article—and my research.

### **The Problem of Unintended Consequences**

Those of us who study the human dimensions of climate impacts and hazards planning know that water use in one area can affect in unknown ways elements of the system in another. Such “cascading effects” are difficult to anticipate and nearly impossible to trace because they can emerge in different timescales and places. Yet they are the invisible lines that tie all of us to water.

One of the more familiar examples of this phenomenon occurred as part of the well-known story of Crowley Coun-



*Buy and Dry fallowed land in Otero County that's  
been revegetated by the city of Aurora  
Photo by Jennifer Henderson*



*An example of a continued farm in Otero County  
Photo by Jennifer Henderson*



ty's struggle to stay a viable community. Beginning in 1955, during a decades long drought, farmers in Crowley County began to sell water rights to nearby towns—all told nearly 80,000 acre feet of water over 40 years (Sanchez, 2015). Called “buy-and-dry,” the process sent water to municipalities for lawns and household use, while the ground it used to irrigate dried up. Farms that were once productive became little more than “blank spaces” of weeds and dirt, as one farmer told me. As agriculture disappeared, adjacent populations diminished. The process took years, though similar tactics spread across Colorado as speculators bought more water rights.

We are still feeling the effects of this legacy today as beneficiaries of that buy-and-dry water, like Aurora, now find themselves responsible for revegetating former farmland with native prairie grasses (Goodland, 2015). Recently, some of these plots have been sold to developers and connected to city water—at least if they are close enough to access it—potentially perpetuating a need for more water. And municipalities who bought agricultural water rights in Otero County are conducting experiments, such as the Continued Farming Program, which irrigates formerly fallow fields with high efficiency technologies and diverts a small part of that water





back to the municipality. Farmers in Rocky Ford are likewise influenced by the haunting realities of Crowley County and some have elected to be part of Alternative Transfer Methods, in which they voluntarily fallow part of their farms three of ten dry years and lease unused water to municipalities. Memory, it seems, can be another unintended consequence.

As this example illustrates, in Colorado, a central tension arises around the pressures between two important groups: growing populations along the urban areas of the Front Range and the resulting pressure water utilities feel to secure enough water for the 10 million people estimated by state officials to

live in Colorado by 2050; and farmers and ranchers, who produce food resources for the region and whose crops continue to account for approximately 86% of the state's consumptive water use, according to the Colorado Water Conservation Board (CWCB). Add to this the stress that drought will place on local water supplies over the coming decades, and the complexity of the problem becomes clear.

### **Dynamics of Vulnerability**

To better identify how elements of drought planning interact among multiple groups, an interdisciplinary group of

*Browns Canyon National Monument  
Photo by Bureau of Land Management*





researchers in Boulder has developed a project to explore the unforeseen effects of climate adaptation and mitigation. Analysis of the problem in their paper, “The Dynamics of Vulnerability,” (Dilling et al., 2015) suggests that many who make decisions in the water sector about how to be more resilient to future droughts often do so through what are called “no or low regret” options. While there is no uniform definition, “no or low regret” decisions can be those that help improve other goals, such as biodiversity conservation, or that generate short-term and long-term benefits, such as reducing poverty rates.

However, the authors argue that all such options involve tradeoffs that may have surprising effects on others in the system that create new vulnerabilities. “This is not to say that such measures do not have value,” the authors conclude, “but rather that we need to think of adapting as a dynamic, iterative process” (p. 418). One way forward is to continually communicate across communities, take into consideration a variety of stressors on the water supply, and identify and trace how different elements of the system interact and affect one another.

Since January 2017, I have been developing case studies to pilot such methods. I work as a postdoctoral fellow at the Cooperative Institute for Research in Environmental Research (CIRES) at the University of Colorado, Boulder, and, to date, have interviewed thirty individuals in Colorado and Utah. My collaborators include researchers at the National Center for Atmospheric Research (NCAR) and at Western Water Assessment, a CIRES-based applied research program that collaborates with stakeholders on issues related to climate variability and climate change, particularly water resources. Based on results from this study and input from stakeholders, we aim to develop usable knowledge of evolving and emergent water use issues at the nexus of urban and rural development.

### **Spatiotemporal Issues & Problems of Definition**

In Colorado, we selected the Arkansas River as the first case study site, in part, because of the tension between rural and urban water use along its banks and chronic drought in the area. Interviews were conducted with individuals from various sectors, including water utilities, power companies, recreational businesses, farmers and ranchers, as well as regional and state government officials. Analysis of this work is just beginning but one important insight reveals that notions of vulnerability and resilience are not static, nor are they homogenous across sectors. This is not a novel insight as scholars have begun to critique the ubiquity with which these terms are used across contexts (Brown, 2013; Faas, 2016). Perhaps more interesting is how a vulnerability in one sector can be an unexpected resilience in another.

For instance, during the 2002 drought, rafting companies along the Arkansas River were forced to be creative for those clients who agreed to navigate a river that was so low in some areas that they had to carry their rafts to other sections downstream. Since recreation companies do not usually own water rights, they are dependent on water releases negotiated through relationships with others. As an industry, then, recreation is exposed to drought more easily than those who have water rights and they are sensitive to drought in that they cannot store water or replace rafting activities to buffer their economic losses.


**“Perhaps more interesting is how a vulnerability in one sector can be an unexpected resilience in another.”**

The same drought, however, provided what one recreation expert called a “scientific experiment you could never replicate” for fish, especially brown trout. Low flows on the river, which harmed recreational companies, actually became a boon to fisheries. “What we have found,” the recreational expert noted, “is that on average, a flow of 250 to 400 cfs is the optimal flow range for brown trout.” This is significantly lower than what is ideal for recreation, some 1,200 cfs.

After the 2002 drought revealed new knowledge of the river ecology, a Voluntary Flows Management Program in existence since the droughts in the 1980s, revised its policies to facilitate fish health. The program has updated its collaborative efforts along the Upper Arkansas River as new issues arise. It is an example that illustrates how what counts as resilience or vulnerability can involve the same stressor, and how water rights governed by static rules put in place more than a century before can accommodate new values for water use.

### **Useful Outcomes**

Scientists believe that as climates change, extremes in weather will become more common. Droughts may become more frequent and perhaps more severe, which requires an effort devoted to understanding systems under continual transformation across multiple scales, temporalities, and communities. Through this research, we aim to develop mechanisms to trace evolving adjustments to policies and practices. Our hope is that such insights might be useful to decision makers in municipalities, agricultural sectors, businesses, and communities across Colorado, as well as other Western states.

*This work is funded by a Postdoctoral Fellowship from the Cooperative Institute for Research in Environmental Sciences and in collaboration with Lisa Dilling, Rebecca Morss, Olga Wilhelmi, and Ursula Rick.* 



# Looking Backwards: Flood and Drought Documentation

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

## SYNOPSIS

Historical documentation of floods and droughts is not all that common or consistent. In Colorado State University's Water Resources Archive, flood documentation can be found in a number of collections, with two entire sets of documents focused solely on particular events. Drought documentation surfaces more as results from these disasters.

**"Looking backwards, of course, most anyone  
can see things after they happen."**

— Frank Milenski, "I'll Be Damned If I Know,"  
<https://hdl.handle.net/10217/89715>

**A**n Arkansas Valley farmer and irrigator, Frank Milenski contemplated life, water, and other subjects amidst his daily work and his service on boards for several water organizations. His creative writings, which survive in Colorado State University's Water Resources Archive, offer insights on his perspectives and his times.

In his free verse poem "I'll Be Damned If I

Know," Milenski contemplates weather extremes and disasters. He begins:

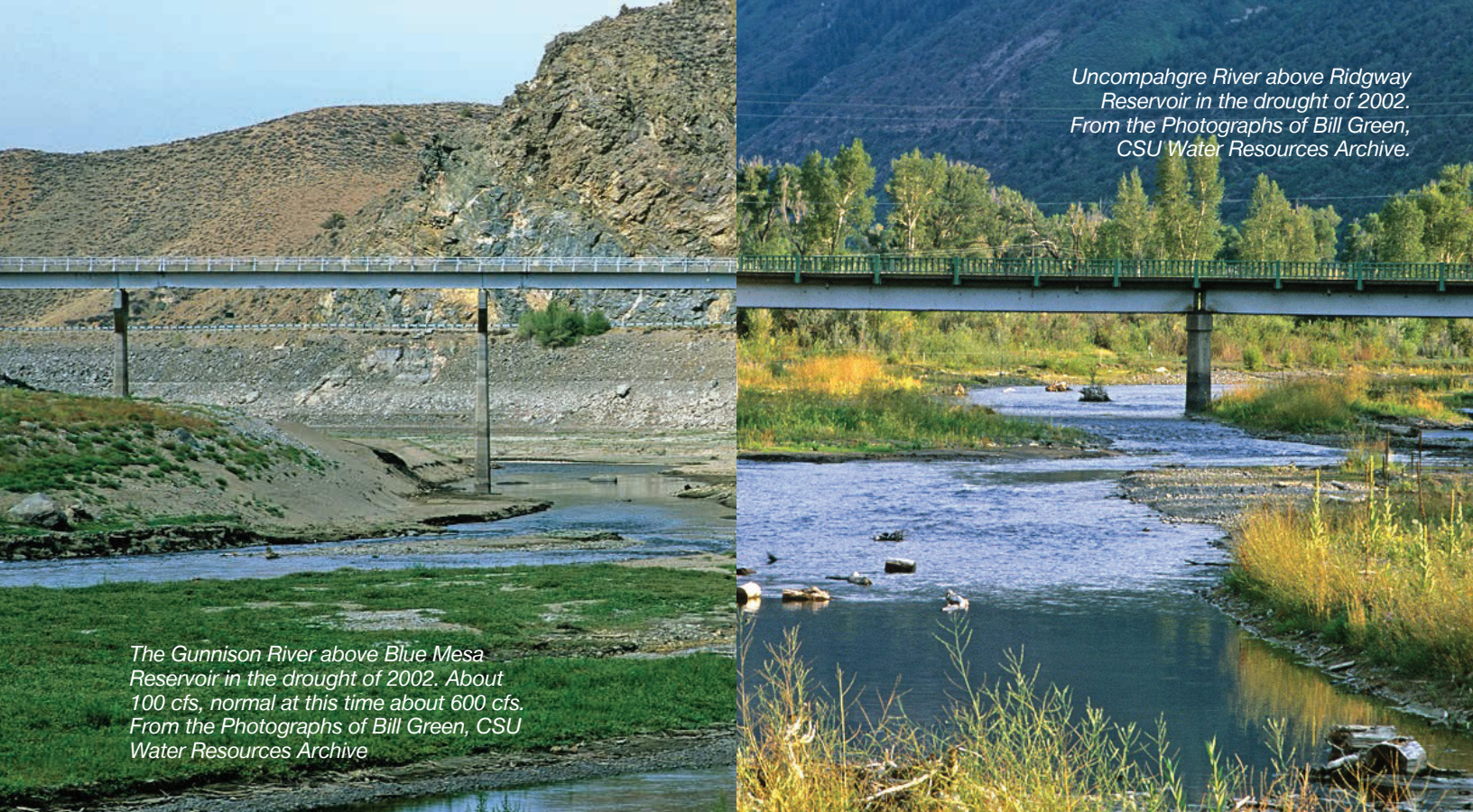
"Nineteen hundred ninety-five will go down in the farmer's history book as a strange year."

The "strange" weather that year caused Milenski to look back at other standout weather events, mainly floods, droughts, and blizzards. He expresses a common perspective on extreme weather and resulting disasters: we only recognize them after they have begun, and they cause a great deal of frustration.

Because disasters such as floods and droughts are rarely predicted, documentation of them varies widely and often only occurs after the worst of the event is over. As a result, historical documentation of floods and droughts is not all that common or consistent. For Colorado, the deadliest flood and the state's worst natural disaster, the 1976 deluge in Big Thompson Canyon, is best documented. Other floods, both before and since, are captured more randomly. Droughts, being slower, less dramatic events, are documented even less well.

*Looking northeast over flood debris toward downtown Pueblo after 1921 flood on Arkansas River. From the Irrigation Research Papers, CSU Water Resources Archive.*





*Uncompahgre River above Ridgway Reservoir in the drought of 2002. From the Photographs of Bill Green, CSU Water Resources Archive.*

*The Gunnison River above Blue Mesa Reservoir in the drought of 2002. About 100 cfs, normal at this time about 600 cfs. From the Photographs of Bill Green, CSU Water Resources Archive*

In the Water Resources Archive, flood documentation can be found in a number of collections, with two entire sets of documents focused solely on particular events. Drought documentation surfaces more as results from these disasters.

Part of the abundance of documentation about the 1976 Big Thompson flood, the **David McComb Big Thompson Flood Collection** contains six linear feet of materials collected for or created in the study of the disaster. Dr. McComb, a CSU history professor, conducted his study during Fall 1976, collecting flood photographs, newspaper clippings, and radio broadcast recordings. The core of his research involved interviewing more than 40 survivors, first responders, and elected officials about their experiences. These recordings and transcripts give an intimate view on the flood experience.

Other collections also document the Big Thompson flood from a civil engineering perspective. The most substantial of these is the **Records of Wright Water Engineers**, which contains 5.5 linear feet of Ken Wright's work as special consultant to Governor Lamm for the Big Thompson flood. These materials include not only meeting minutes, background documents, and newspaper clippings, but also reports, maps, and aerial photographs, providing a much more technical view of the event.

The other collection in the Water Resources Archive focused on a particular flood is the **Northern Colorado Flood Oral History Collection**. Documenting the 2013 Front Range flooding, the collection was created by history professor Ruth Alexander leading a team of graduate students, following Dr.

McComb's example of conducting oral histories. The focus in this case, however, was on officials and professionals with direct responsibility for flood management and recovery. In addition to these digital materials, newspaper coverage of the flood can also be found in the collection.

When it comes to drought, most of the documentation in the Water Resources Archive demonstrates the effect of the disaster, not the event itself. This is true for two collections, in perhaps unexpected ways. One is the **Papers of W.D. Farr**. The severe drought of the early 1930s motivated Farr (who was born in Greeley in 1910) to work for a new reliable water supply for northern Colorado. His efforts alongside his father and many others turned into the Colorado-Big Thompson transmountain diversion project. He then served on the board of the project's overseers, the Northern Colorado Water Conservancy District, for more than forty years. This and Farr's other service to water organizations is documented in his collection.

In the **Papers of Gregory J. Hobbs, Jr.**, there exist papers from the now-retired Colorado Supreme Court justice documenting the start of the Colorado Foundation for Water Education, in which he had involvement. As arranged by Justice Hobbs, these materials are followed immediately by drought files, as the 2002 Colorado drought had impact on the Foundation's beginning.

An exception to collections documenting the aftereffects of drought is the **Photographs of Bill Green**. His initial donation to the Water Resources Archive was 25 digital photographs depicting the severity of 2002 drought. The images largely





*House sliding down river bank into Arkansas River, probably after 1921 flood. From the Irrigation Research Papers, CSU Water Resources Archive.*

show low streamflows and reservoirs in danger of drying up.

Perhaps the most important activity that comes after floods and droughts pass and recovery is well underway is planning for the next disaster. Figuring out what happened and how to prepare for it if not prevent it becomes job number one. Collections in the Water Resources Archive that document this aspect of disasters include the **Records of the Colorado Water Resources Research Institute** and the **Papers of William P. Stanton**. The CWRRI (now the Colorado Water Institute) funded or participated in several drought studies and conferences over the years. The 2002 drought conference is particularly well documented here. Stanton worked for the Colorado Water Conservation Board on floodplain management for more than 20 years, and his files reflect that expertise.

Archival collections on floods and droughts can be used not only to study particular events, but also to determine lessons leading to planning and prevention. As Milenski did, people will continue to feel the frustrations of disasters, but can learn from the past while they wait “to see what will be in store in the whims of Mother Nature.”

Additional collections in the Water Resources Archive have more limited, though not necessarily less important, documentation on floods and droughts. All are available for research, and much of the Big Thompson flood documentation has been digitized. To discover these materials, conduct your own online search (<https://lib.colostate.edu/water/>) or contact the archivist at any time (970-491-1939;

[Patricia.Rettig@ColoState.edu](mailto:Patricia.Rettig@ColoState.edu)). 



*Damage from the Big Thompson flood in 1976. From the Maurice L. Albertson Papers, CSU Water Resources Archive.*



# The Significance of Snowpack in Defining Drought in Colorado

Becky Bolinger, Assistant State Climatologist, Colorado Climate Center

## SYNOPSIS

Drought is known to be the most commonly occurring natural hazard within Colorado. Because snowpack has major implications on the state's water supply, it is important to regularly monitor for indications of an emerging drought.

## Introduction

Drought is one of the most insidious natural hazards because there is no clear starting or ending point, and events can last for years. Impacts from drought are widespread and cross many sectors. In the U.S., agricultural losses from drought translate to billions of dollars in damage (NOAA-NCEI, 2017). In addition to the ag industry, municipal energy, and water, the recreation industry is also vulnerable to drought. The 2002 drought, for example, resulted in \$9 Billion worth of damages; its impacts on the western state's water supplies (in Lakes Powell and Mead) is still being observed to this day.

Most often, people associate drought with a deficit in precipitation. While this is the most obvious indicator of a meteorological drought, there are numerous other components that can contribute to a drought event. In an agricultural drought, increased temperatures and evaporative loss combined

with precipitation deficits can result in dry soils and vegetative stress. In a hydrologic drought, reduced runoff and low water supplies may be the dominant drivers. These conditions can develop over a relatively short time period (on the order of weeks to a month) and/or last for extended lengths of time (seasons to years).

In Colorado, drought is not uncommon. Although an extreme event (i.e. statistically rare), drought has been observed in some portion of the state for every year since the inception of the U.S. Drought Monitor (<http://droughtmonitor.unl.edu>) in 2000. Severe drought impacted the entire state in 2002 and 2012, both events contributing to widespread and devastating wildfires, amongst many other impacts. Studies have shown that drought duration and severity has increased in the U.S. southwest and are projected to increase throughout the 21<sup>st</sup> century (Andreadis and Lettenmaier, 2006; Sheffield and Wood, 2008).

## Importance of Snowpack

When considering a Colorado

Photo by Nicholas Kimball





drought, the impacts are far-reaching. Colorado is a head-water state, with four major rivers sending water to eighteen other states and Mexico (Water Education Colorado, 2017), and the majority of that water originates as mountain snowpack. The highly variable climate of Colorado not only means a greater frequency of drought, it also translates to high variability in snowpack from year-to-year. The important implication here is that there is a strong relationship between low snowpack and drought.

## Snowpack and Water Supplies

The evolution of the western states' water supply is simple – during the winter, snow accumulates in the mountains and is “stored” on the ground in a frozen state. As spring warms the temperatures and lengthens the day, that frozen storage melts, some of it infiltrating the soils and the rest running off into the rivers. It travels down the rivers until it's diverted to reservoirs, collected for future consumption. Figure 1 summarizes the variability of this process over a 30-year period. Typically, we observe that when snowpack is greater (less) than average, run-

off and reservoir storage are also greater (less) than average.

## Precipitation vs. Snowpack

One of the big questions surrounding how climate change will impact our future water supplies is – if there is less snowpack (because of warmer temperatures), but there is no trend in total precipitation, won't runoff remain the same? Research is ongoing to adequately answer this question, but initial results show that the answer can vary based on location.

As an example, consider two mountain regions in the western U.S. Using the Natural Resource Conservation Service's Snow Telemetry data (SNOTEL), we define two distinct regions, by averaging the snow water equivalent (or snowpack) throughout the regions. The Divide Rockies represents the river basins of western Colorado, and the Northern Pacific Coast contains the river basins along the Pacific coastline from northern California through Washington. Figure 2 examines the relationship between snowpack, precipitation, and runoff for these two regions. The scatter plot shows how runoff and precipitation are related

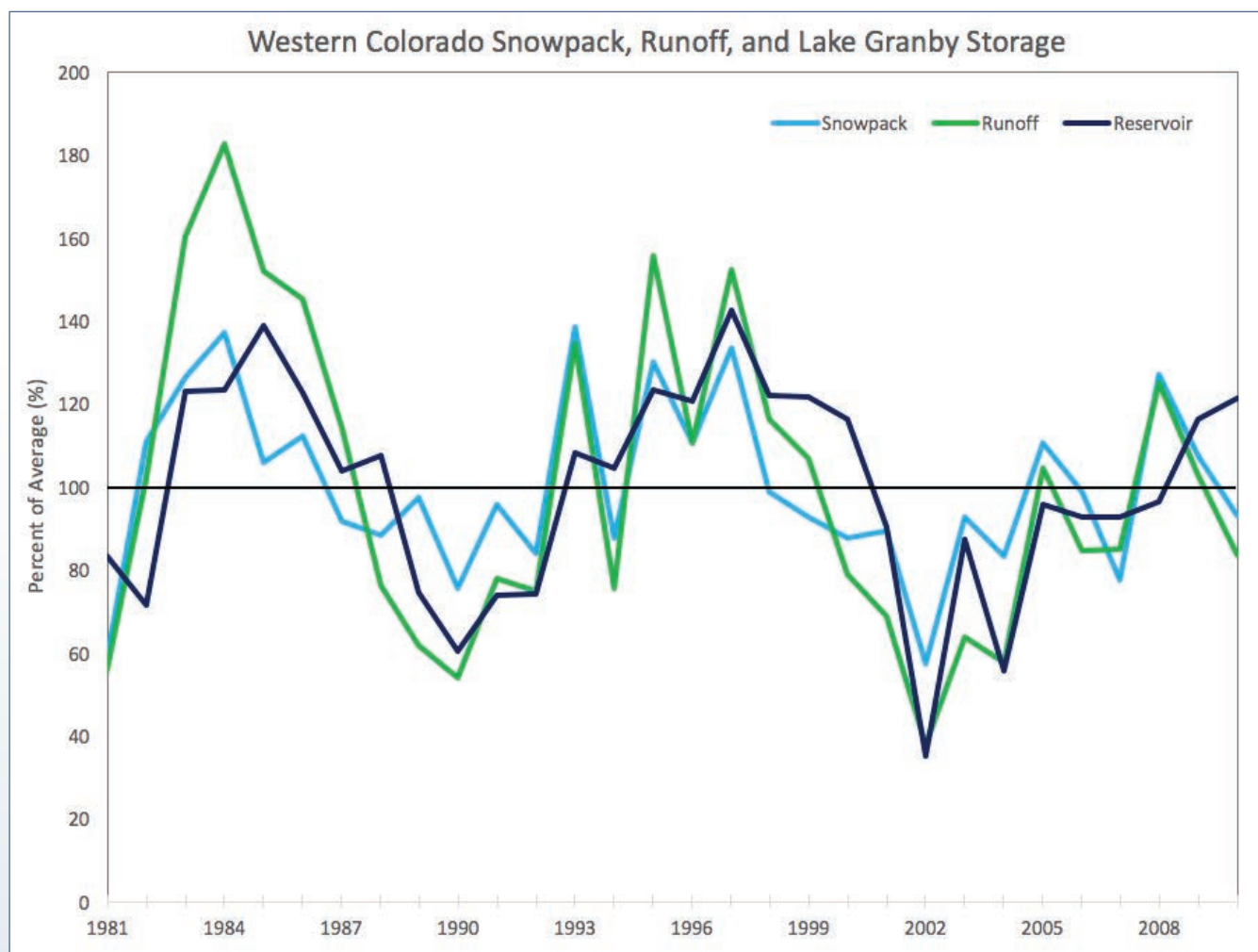


Figure 1. Time series of peak snowpack and runoff from western Colorado and end of season storage in Lake Granby, as a percent of average for 1981–2010.



Table 1. Correlation coefficients between monthly snow water equivalent and June Palmer Drought Severity Index.

January Snowpack	February Snowpack	March Snowpack	April Snowpack
0.45	0.47	0.52	0.59

(a perfect relationship would follow the black line). The color of each square represents snowpack – lower (higher) snowpack values are red (blue).

Focusing in on the left side of Figure 2 (the Divide Rockies), there are a few key points to highlight. There is a positive correlation between runoff and precipitation (although the scatter around the black line indicates that the relationship is not perfect). There are more red squares to the left and more blue squares to the right, showing that there is a relationship between snowpack and precipitation (e.g., it is more likely that a high snowpack year will be associated with higher precipitation). But note how there are more red squares below the black line and more blue squares above the black line. What this is showing is that it is common for years with lower snowpack and higher precipitation to coincide with years of lower runoff. In fact, the correlation between snowpack and runoff (0.87) is higher than the correlation between precipitation and runoff (0.81).

Now let us look at the right side (the Northern Pacific Coast). We observe a much stronger relationship between precipitation and runoff (the points are more concentrated around the black line). The relationship between snowpack and precipitation is not as obvious in this region. The most notable difference in this location, is that precipitation is much more highly correlated with runoff (0.96), and snowpack is less highly correlated with runoff (0.54).

So, what does this mean for the Colorado Rocky Mountains? First, Colorado’s runoff and water supply are highly sensitive to changes in snowpack. Second, a year with higher precipitation and lower snowpack is more likely to result in lower runoff and less water supply. Considering these points, we can see how important snowpack variability is for western water supply. And we can assume that as the climate warms and possibly reduces the length of the snow season, this could impact future water supplies, regardless of precipitation trends.

Variability in Snowpack

Previous research has suggested that observed trends in snowpack associated with climate change are not detectable in the interior Rocky Mountains (Regonda et al., 2005). The assumption is that prevalent temperatures are so much below freezing that the much higher elevations have not been vulnerable to a couple of degrees warming (conversely, the Pacific Northwest is experiencing more trends due to warming because tempera-

tures there are much closer to freezing/melting points). At present, climate change may not be a concern. So, a more important question to ask is–what drives interannual variability in snowpack? Bolinger et al. (2014) found that the difference between a “wet” and “dry” winter is the occurrence of a few large accumulating events. Figure 3 shows that the majority of snowfall days in a winter result in small accumulations (< 2.5 mm). In the dry winter of 2002, there was a much greater percentage of days with small accumulations. And in the wet winter of 1997, there is a larger frequency of occurrence of large accumulating events (> 10 mm). Bolinger et al. (2014) found one common key ingredient with large accumulating events: strong, low-level westerly winds.

Early Indication of Drought

One of the reasons drought is insidious in nature is that we often cannot pinpoint when it starts until well after the fact. Identifying early indicators of the onset of drought is essential. So, can snowpack be an early indicator?

Table 1 shows how snowpack might relate to drought during the subsequent demand season. For the 1981–2010 period statewide snowpack (as a percent of average) throughout the winter are compared to the statewide estimate of the Palmer Drought Severity Index (or PDSI) for the following June. The PDSI is a simplified index that uses temperature and precipitation to calculate relative drought stress. In Table 1, we find that there is a positive correlation between snowpack and drought severity in June. That correlation increases as June gets closer so that the strongest correlation occurs for April snowpack and June PDSI. If we narrow the scope, we can look at the peak snowpack values from western Colorado (from Figure 1) and compare that to June PDSI for the Colorado Headwaters area. This geographically narrowed analysis yields a strong correlation of 0.85.

These results suggest that monitoring of Colorado’s winter snowpack conditions could give scientists an “early warning” indicator of drought conditions in the following summer. More research should focus on basin-specific relationships and analyze other drought indices, including soil moisture, vegetative stress, and the U.S. Drought Monitor.

References cited within the article are available in the online PDF version of Colorado Water located here: <http://cwi.colostate.edu/newsletters.asp>



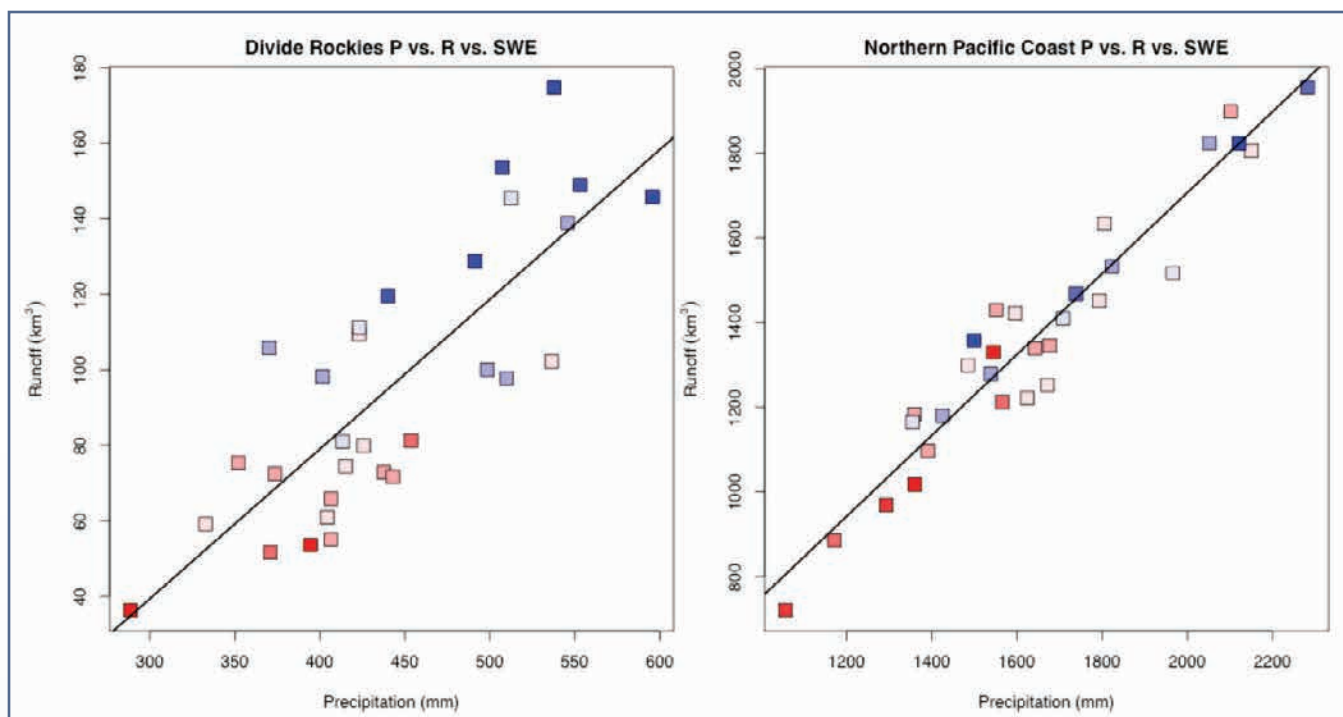


Figure 2. Plots of annual precipitation vs. annual runoff for the Divide Rockies (left) and the Northern Pacific Coast (right). Colors represent magnitude of peak SWE for that year, with reds indicating low SWE and blues showing higher SWE.

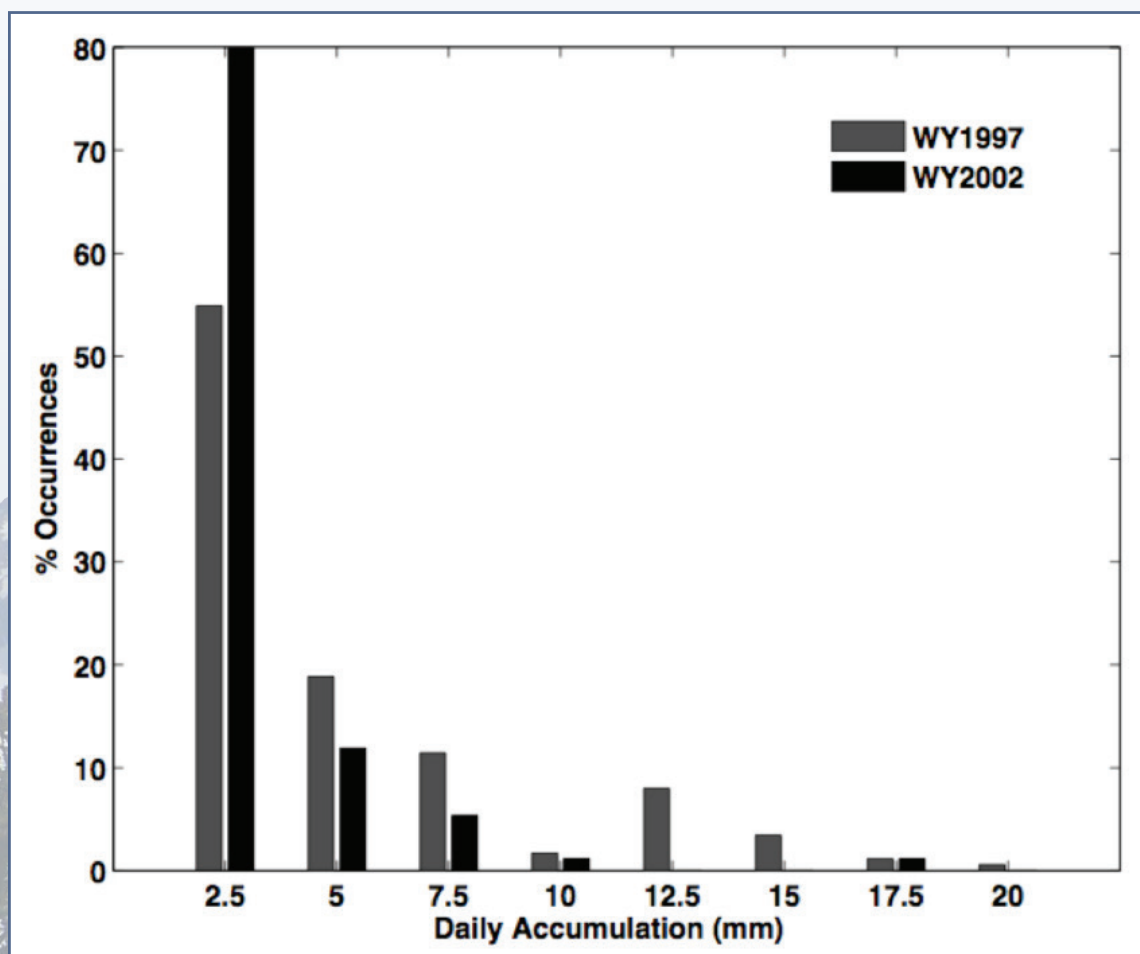



Figure 3. Frequency distribution of basin-averaged daily snow water equivalent accumulations during the winter years of 1997 (gray bars) and 2002 (black bars) from Bolinger et al. (2014).





# A Brief Overview of Drought Monitoring Indicators and Resources for Colorado

Jeff Lukas, Associate Scientist,  
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## SYNOPSIS

Drought indicators widely used by water interests in Colorado—precipitation, snowpack, soil moisture, streamflow, and more specialized drought indices—are accessible through a growing number of online tools and portals. This article identifies key indicators and resources for drought monitoring, including newer ones that may be less familiar, and provides general guidance about the use of drought indicators.

Whether one is a municipal water manager on the Front Range, or an onion grower in the Uncompahgre Valley, or a whitewater rafting outfitter on the Arkansas River, preparing for drought is a serious and necessary business. What these different sectors have in common is the need for drought monitoring information, in order to track current and emerging drought conditions.

The internet has greatly facilitated the development of new tools and the dissemination of drought information. But just because information is available online does not mean that potential users are aware of it or able to make good use of it. The plethora of different information providers and their respective products, tools, and portals can be overwhelming.

The objectives in this article are to identify key information resources for drought monitoring in Colorado, especially newer resources that may be less familiar, and share some general principles about the use of drought indicators.

## Real-Time Drought Monitoring

Monitoring is the most obvious element of drought preparation. There

are dozens of drought *indicators* used in monitoring to characterize the severity, duration, and spatial extent of different aspects of drought. Let us consider these indicators in light of how droughts initiate and progress (Figure 1). (Note: Indicators used here include both drought *indices* that are calculated specifically for drought monitoring and the variables such as precipitation and streamflow whose values may enter into indices or be monitored as-is.)

Droughts arise when atmospheric patterns that bring dry weather—such as high-pressure ridges—persist longer or are more frequent than normal so that a precipitation deficiency accumulates over weeks or months. Typically, the patterns that lead to below-normal precipitation also bring above-average temperatures, higher solar radiation, and lower humidity, and possibly higher winds. These conditions drive higher evaporative demand; i.e., the atmosphere becomes “thirstier” than normal. Sometimes, unusually high evaporative demand can trigger surface drying even when precipitation is near normal. But drought is primarily caused by reduced precipitation, and exacerbated by increased atmospheric loss of surface moisture, relative to average

conditions. This combination is referred to as *meteorological drought*.

During the growing season, reduced rainfall and increased evaporation can lead—sometimes in only a few weeks—to lower soil moisture and stress on crops and other vegetation. This is referred to as *soil moisture drought* or *agricultural drought*. If the meteorological drought lasts for several months, *hydrological drought* will often manifest in reduced streamflows and reservoir levels, with the familiar precursor of below-normal snowpack when the drought initiates in the winter season. These drought types are not exclusive; all may be occurring simultaneously. Drought impacts manifest over multiple timescales and spatial scales.

Most drought indicators (Table 1) capture a specific aspect of drought. Other indicators reflect multiple aspects of drought, providing a broader synthesis of drought conditions but giving up the specificity of other indicators. The most widely used drought indicators in Colorado include:

- Standardized Precipitation Index (SPI) or Percent of Normal Precipitation
- Snow-Water Equivalent (SWE) – throughout the snow season,

Drought affected farmlands east of Denver, Colorado. Photo by Lance Cheung, USDA



but especially April 1<sup>st</sup>

- Forecasted seasonal runoff - typically April-July
- Palmer Drought Severity Index (PDSI)
- Soil moisture- modeled or observed
- Streamflow
- Reservoir storage
- Surface Water Supply Index (SWSI)
- U.S. Drought Monitor (USDM)

These indicators collectively form the backbone of drought monitoring in our state and region, with different interests preferring certain indicators. In general, water managers follow SWE, seasonal runoff forecasts, and streamflows most closely; agricultural producers tend to focus on recent precipitation and soil moisture. Colorado's State Drought Mitigation and Response Plan uses a multiple indicators—SPI, PDSI, SWSI, and the USDM—as triggers for drought response. Compared with a decade ago, nearly all of the above indicators are available at finer spatial resolutions and/or with more frequent updates.

For example, the National Oceanic and Atmospheric Administration (NOAA) Colorado Basin River Forecast Center (CBRFC) produces daily-updated seasonal streamflow forecasts, in addition to the official monthly forecasts.

Looking beyond the “backbone” indicators can provide additional angles on drought. The new Evaporative Demand Drought Index (EDDI) focuses on the underappreciated evaporative-demand component of drought, as does the growing-season Reference Evapotranspiration (ET) from the CoAgMet network. The Standardized Precipitation-Evapotranspiration Index (SPEI) is effectively SPI plus evaporative demand. Other indicators incorporate satellite measurements of vegetation along with meteorological variables to depict land-surface and plant stress during the growing season: VegDRI, QuickDRI, and the Evaporative Stress Index (ESI).

Some drought indicators respond more quickly to changing conditions

than others. In general, indicators that track meteorological drought will signal the onset of dryness prior to those that track the agricultural and hydrological consequences. But it depends also on the *time window* of the indicator: the length of the period over which prior conditions are reflected in that indicator, either due to its calculation or the physical nature of what it measures. Table 1 shows the time windows of the different indicators. For example, PDSI incorporates precipitation and temperature over a roughly 9-month period, so it will clearly show a sustained drought but respond slowly to a rapidly emerging drought. Many indicators, such as SPI, SPEI, and EDDI, have flexible, user-selectable time-windows; using a 1-month time window for these indices will allow better detection of “flash” drought and other rapid changes, while a longer window will better show the severity of sustained conditions, like PDSI.

Regardless of the indicator and the time window, it is critical to know how severe and unusual the current drought

conditions are, and be able to compare severity across indicators. Table 2 shows how the increasingly familiar USDM categories of drought severity (D0, D1, D2, D3, and D4) correspond to percentiles, SPI/SPEI values, and PDSI values. Indicators that are based on percentiles (USDM, EDDI) or are standardized (SPI, SPEI) inherently tell you where the current value falls in the distribution of historic values, and thus how often that value would be expected. For example, conditions at or worse than the 15<sup>th</sup> percentile would be expected 15% of the time, or about every seven years for a drought indicator with an annual window like water-year streamflow or 12-month SPI. Expressing indicators like SWE and streamflow as percentiles instead of percent of normal can give you a clearer picture of drought severity that is consistent across basins.

So which drought indicators are the most “useful”? It really depends on the sector and system of interest, its drought vulnerabilities, the impacts that need to be avoided, and the timing

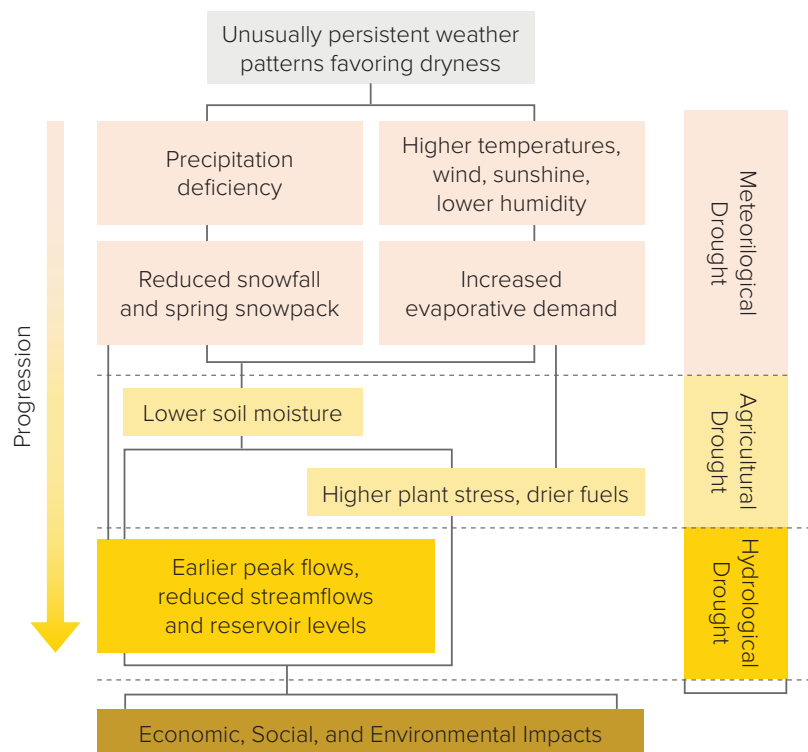


Figure 1. The typical sequence for the progression of drought through different drought types. Modified from the National Drought Mitigation Center, University of Nebraska



	Indicator; primary web resource	Based on these indicators or variables	Time window
Meteorological Drought	Standardized Precipitation Index (SPI)	Precipitation	User-selectable; 1-72 months
	Snow-water Equivalent (SWE) <a href="https://www.cbrfc.noaa.gov/">https://www.cbrfc.noaa.gov/</a>	n/a	From start of water year to date
	Standardized Precipitation-Evapotranspiration Index (SPEI)	Precipitation, Temperature	User-selectable; 1-72 months
	Palmer Drought Severity Index (PDSI)	Precipitation, Temperature	~9 months
	Evaporative Demand Drought Index (EDDI) <a href="https://www.esrl.noaa.gov/psd/eddi/">https://www.esrl.noaa.gov/psd/eddi/</a>	Temperature, Humidity, Wind speed, Solar Radiation	User-selectable; 1 week-12 months
	Reference Evapotranspiration (ET) <a href="https://coagmet.colostate.edu/">https://coagmet.colostate.edu/</a>	Temperature, Humidity, Wind speed, Solar Radiation	User-selectable; 1 day to growing season
Agricultural Drought	Soil Moisture (modeled; e.g., CPC, VIC) <a href="http://www.hydro.washington.edu/forecast/monitor/">http://www.hydro.washington.edu/forecast/monitor/</a>	Precipitation, Temperature, others	Several months
	Soil moisture (observed) <a href="https://www.drought.gov/drought/soil-moisture-map">https://www.drought.gov/drought/soil-moisture-map</a>	n/a	Several months
	VegDRI <a href="https://vegdr1.cr.usgs.gov/">https://vegdr1.cr.usgs.gov/</a>	SPI, PDSI, vegetation greenness	~3-8 months
	QuickDRI <a href="https://vegdr1.cr.usgs.gov/">https://vegdr1.cr.usgs.gov/</a>	SPI, ESI, VIC soil moisture, vegetation greenness	~1 month
	Evaporative Stress Index (ESI) <a href="https://hrsl.ba.ars.usda.gov/drought/">https://hrsl.ba.ars.usda.gov/drought/</a>	Satellite-derived actual ET; ratio with Reference ET	User-selectable; 1-3 months
Hydrological Drought	Forecasted Seasonal Streamflow <a href="https://www.wcc.nrcs.usda.gov/webmap/">https://www.wcc.nrcs.usda.gov/webmap/</a>	SWE, Water-year Precipitation, others	From start of water year to forecast date
	Current Streamflow <a href="https://waterwatch.usgs.gov/">https://waterwatch.usgs.gov/</a>	n/a	Weeks to months
	Current Reservoir Storage <a href="https://www.wcc.nrcs.usda.gov/basin.html">https://www.wcc.nrcs.usda.gov/basin.html</a>	n/a	Months to years
	Surface Water Supply Index (SWSI) <a href="http://water.state.co.us/DWRDocs/Reports/Pages/SWSIReport.aspx">http://water.state.co.us/DWRDocs/Reports/Pages/SWSIReport.aspx</a>	Precipitation, SWE, Streamflow, Reservoir Storage	Several months to years
	US Drought Monitor <a href="http://droughtmonitor.unl.edu/">http://droughtmonitor.unl.edu/</a>	SPI, PSDI, SWE, Soil Moisture, Streamflow, others	1-12+ months

*Table 1. Selected drought indicators, with their primary web resources (see Table 3 for additional resources), relationship with other indicators, and time windows.*

*Table 2. U.S. Drought Monitor (USDM) drought severity categories, potential impacts, and their relation to indicators expressed as percentiles, standardized indices, and the Palmer Drought Severity Index. The scale bar at bottom shows how the categories and percentiles relate to the expected frequency of occurrence. Modified from the National Drought Mitigation Center, University of Nebraska*

US Drought Monitor (USDM) Category	Description	Possible Impacts	Any indicator expressed in Percentiles	Standardized Precipitation Index (SPI) or SPEI	Palmer Drought Severity Index (PDSI)
D0	Abnormally Dry	Going into drought: • Short-term dryness slows planting, growth of crops or pastures Coming out of drought: • Some lingering water deficits • Pastures or crops not fully recovered	21 <sup>st</sup> to 30 <sup>th</sup>	-0.5 to -0.7	-1.0 to -1.9
D1	Moderate Drought	• Some damage to crops, pastures • Streams, reservoirs, or wells low, water shortages developing • Voluntary water-use restrictions requested	11 <sup>th</sup> to 20 <sup>th</sup>	-0.8 to -1.2	-2.0 to -2.9
D2	Severe Drought	• Crop or pasture losses likely • Water shortages common • Water restrictions imposed	6 <sup>th</sup> to 10 <sup>th</sup>	-1.3 to -1.5	-3.0 to -3.9
D3	Extreme Drought	• Major crop/pasture losses • Widespread water shortages or restrictions	3 <sup>rd</sup> to 5 <sup>th</sup>	-1.6 to -1.9	-4.0 to -4.9
D4	Exceptional Drought	• Exceptional and widespread crop/pasture losses • Shortages of water in reservoirs, streams, and wells	1 <sup>st</sup> to 2 <sup>nd</sup>	-2.0 or less	-5.0 or less

2 <sup>nd</sup>	5 <sup>th</sup>	10 <sup>th</sup>	20 <sup>th</sup>	30 <sup>th</sup>	50 <sup>th</sup> Percentile (Median)	100 <sup>th</sup>
D4	D3	D2	D1	D0		
2%	5%	10%	20%	30%		

Percent of the time that this drought condition or worse would be expected, based on the historical record



Table 3. Drought-monitoring resources that provide access to multiple drought indicators for Colorado. USDM = U.S. Drought Monitor; Precip = recent Precipitation; SPI = Standardized Precipitation Index; Snow = Snow-water equivalent; Flow = current Streamflow; Res = Reservoir storage; FlowCast = Seasonal Runoff Forecasts ; SWSI = Surface Water Supply Index; Temp = recent Temperatures; EDDI = Evaporative Demand Drought Index; ET = Reference Evapotranspiration; Soil = soil moisture; Veg = VegDRI; Outlooks = Seasonal Climate Outlooks.

Resource	Updated	Drought indicators shown	Real-time	Historical	Interactive tool	Comments
CCC-NIDIS IMW DEWS Drought Summary <a href="http://climate.colostate.edu/~drought/">http://climate.colostate.edu/~drought/</a>	Weekly	USDM, Precip, SPI, Snow, Flow, Res, Temp, EDDI, ET, Soil, Veg, Outlooks	✓			Most comprehensive one-stop shop for drought monitoring for CO.
WWA Intermtn. West Climate Dashboard <a href="http://www.colorado.edu/climate/dashboard.html">http://www.colorado.edu/climate/dashboard.html</a>	Daily	USDM, Precip, SPI, Snow, Flow, Res, Temp, EDDI, FlowCast, Outlooks	✓			Provides a quick visual overview of conditions across many indicators.
NRCS NWCC Interactive Map <a href="https://www.wcc.nrcs.usda.gov/webmap/">https://www.wcc.nrcs.usda.gov/webmap/</a>	Daily	Snow, Precip, Flow, FlowCast	✓	✓	✓	Versatile tool for exploring snow and precipitation at SNOTEL sites, and streamflow. Zoomable map.
NOAA CBRFC Conditions Map <a href="https://www.cbrfc.noaa.gov/">https://www.cbrfc.noaa.gov/</a>	Daily	Snow, Precip, Flow, FlowCast, Res, Soil	✓	✓	✓	Zoomable map with multiple overlays, to compare indicators. Most datasets don't cover eastern CO.
WRCC Westwide Drought Tracker <a href="https://wrcc.dri.edu/wwdt/">https://wrcc.dri.edu/wwdt/</a>	Monthly	PDSI, SPI, SPEI, Temp, Precip	✓	✓	✓	High-resolution (4-km) maps of indicators based on PRISM climate data.
CWCB WATF Drought Update <a href="http://owcb.state.co.us/public-information/flood-water-availability-task-forces/Pages/main.aspx">http://owcb.state.co.us/public-information/flood-water-availability-task-forces/Pages/main.aspx</a>	Monthly	Snow, Res, USDM, SWSI	✓			Two-page summary for CO, plus basin SWSI reports and additional resources.
NDMC Drought Risk Atlas <a href="http://droughtatlas.unl.edu/">http://droughtatlas.unl.edu/</a>	n/a	USDM, PDSI, SPI, SPEI, Temp, Precip		✓	✓	Many options for analysis but steeper learning curve than other tools.

of critical management decisions. Tracking multiple indicators is better; a single indicator may not capture a critical aspect of a particular drought. It takes time and some trial and error to determine the added value of new indicators, but they can help round out one's drought-monitoring "portfolio" and avoid future drought surprises.

Tracking and comparing multiple indicators has become much easier in the past several years with the advent of web "dashboards" and versatile map-based tools that show several or even dozens of different drought indicators (Table 3). These have been developed by the Colorado Climate Center (CCC) and the National Integrated Drought Information Center (NIDIS), the Western Water Assessment, the Natural Resources Conservation Service (NRCS), and the NOAA Colorado Basin River Forecast Center (CBRFC). All of the data on these sites are updated frequently—either daily or weekly—which complements the more detailed interpretation in the monthly reports and webinars by these same information providers and by the Colorado Water Availability Task Force.

## The Importance of Historical Context

Effective drought monitoring and re-

sponse requires context: understanding the history of drought for a particular location and system. What has been the frequency, intensity, duration, and spatial extent of past droughts? What impacts occurred during those droughts?

Through examining the historical record of one or more of the indicators used in real-time monitoring, current and emerging drought conditions can be more directly compared to past conditions and impacts. A long-term historical perspective also facilitates the use of drought indicators as triggers for response actions, by identifying thresholds in that indicator beyond which different types of impacts are likely to occur, given past experience. Note that newer indicators may have short periods of record that preclude long-term analysis.

Of the tools listed in Table 3, some allow exploration of historical data alongside tracking of real-time drought indicators. Other interactive web tools have been developed specifically to provide access to historical records of drought indicators, such as the West Wide Drought Tracker's time-series tool and the Drought Risk Atlas.

## The Bigger Picture: Drought Risk Management

Monitoring is a key element of the

broader task of *drought risk management*. This term refers to the coordinated monitoring, mitigation, and response mechanisms that enable decision-makers to go beyond simply reacting to drought impacts as they occur, by the following:

- anticipating the spectrum of drought events that could occur;
- identifying vulnerabilities to those drought events;
- detecting a drought early in its development (monitoring);
- responding in a timely manner; and
- implementing measures to reduce vulnerabilities and impacts (mitigation) while not in active response mode.

Ideally, these coordinated elements are encoded in a formal drought plan, such as the statewide Colorado Drought Mitigation and Response Plan and similar drought plans that have been developed for many water agencies around the state. The drought risk management framework is applicable to all sectors and entities of different sizes.

Further reading and additional resources are available in the online PDF version of Colorado Water located here:

<http://cwi.colostate.edu/newsletters.asp> 





# Flooding and Sedimentation

## Following the 2012 High Park Fire

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### SYNOPSIS

Over the past five years, researchers at Colorado State University have been using field observations and remote-sensing data to understand flooding and sedimentation after the 2012 High Park Fire.

**T**he recent fires and ensuing deadly mudslides in Southern California have once again brought public attention to wildfires and their effects on society and the environment. Over the past several decades, the area and severity of wildfires have increased due to climate change, earlier snowmelt, and historic wildfire suppression (e.g., Westerling et al., 2006), and with population expanding in the urban-wildland interface, improving our understanding of how fires impact flooding and sedimentation at the watershed scale is increasingly important.

When a forested area is burned, its hydrologic response is fundamentally changed such that runoff and hillslope erosion for a given storm are greatly increased. High-severity fires consume the surface organic layer in the soil, and they can induce the development of a water-repellent layer at or near the soil surface (DeBano, 2000). Wildfire consumption of litter on the ground surface exposes bare mineral soil and decreases surface roughness, and when rain falls on the newly exposed, burned, soil, particles can become dislodged and the surface can become sealed (e.g., Larsen et al., 2009). The loss of surface cover and organic matter, increase in soil hydrophobicity, reduction in surface roughness, and surface sealing combine to cause a dramatic decline in the soil infiltration rate, which





*Feature image. Deposition in Skin Gulch following the July 2012 flood. Lee MacDonald shown in the photo; photo taken by Peter Nelson.*

increases the likelihood that a given storm will produce infiltration-excess overland flow. This transition from subsurface to surface runoff, along with increased flow velocities due to loss of roughness, increases surface erosion by sheetwash, rilling, and gullying, leading to orders-of-magnitude increases in hillslope erosion rates compared to pre-fire conditions.

Over the past five years, researchers across Colorado State University (CSU) have been studying the effects of wildfire in our own backyard. The High Park Fire (HPF) was ignited by a lightning strike on June 9, 2012, and over the next three weeks it burned 353 km<sup>2</sup> and nearly 260 homes in the northcentral Colorado Front Range, making it the third largest wildfire in Colorado's recorded history. The proximity of this fire to Fort

Collins and CSU spurred research investigating the physical and biological response to the fire, which has been supported with funds from the National Science Foundation, U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture via the Colorado Agricultural Experiment Station, and USDA Forest Service. Most of our understanding of how fires affect runoff and erosion has come from studies conducted at the plot to small hillslope scale, while flooding, water quality, and sedimentation at larger watershed scales are of primary concern to resource managers and the public. To this end, a major objective of the physical science portion of research on the HPF has been to use field and remote-sensing data to understand spatial and temporal patterns of post-fire erosion and deposition at the watershed scale.

### Five Years of Data

We have been documenting changes to the channel network in two ~15 km<sup>2</sup> watersheds that drain to the Cache la Poudre River, Skin Gulch (SG), and Hill Gulch (HG) (Figure 1). Both watersheds burned at approximately 65% moderate to high severity, with the highest severity burning occurring in the upper portions of SG and the lower portions of HG. Since the fire, we have installed 10 monumented cross sections in SG and 11 in HG. Each cross-section has been surveyed 16 to 23 times, generally between seasons and after summer thunderstorms, and with each cross-sectional survey a longitudinal profile survey was also collected. This dataset is rich with information and without equal in post-fire geomorphic research. We have devised methods to normalize cross section and longitudinal profile data from different surveys, which allows us to compute local changes in elevation and cross-sectional area from survey-to-survey.

We also have been using remotely sensed airborne laser scanning (ALS) topographic data to investigate geomorphic changes at a larger spatial scale than is possible with traditional surveying methods. These datasets are 1-meter resolution digital elevation models, derived from point clouds collected from a laser scanner mounted to an airplane, and at this resolution the topographic data capture features relevant to important geomorphic processes. These datasets were collected in Fall 2012, Summer 2013, Fall 2013, Summer 2014, and Summer 2015. We developed techniques to co-register all of these datasets together, and once registered we differed consecutive datasets to determine spatial patterns and overall volumes of erosion and deposition.

### A Tale of Two Floods

In the western United States, the largest and most destructive floods after wildfires are caused by localized, short-duration summer convective thunderstorms. On July 6, 2012, just a few days after the HPF was fully contained, a thunderstorm occurred in the upper portion of SG which burned primarily at high severity (Figure 1). This storm was very localized,



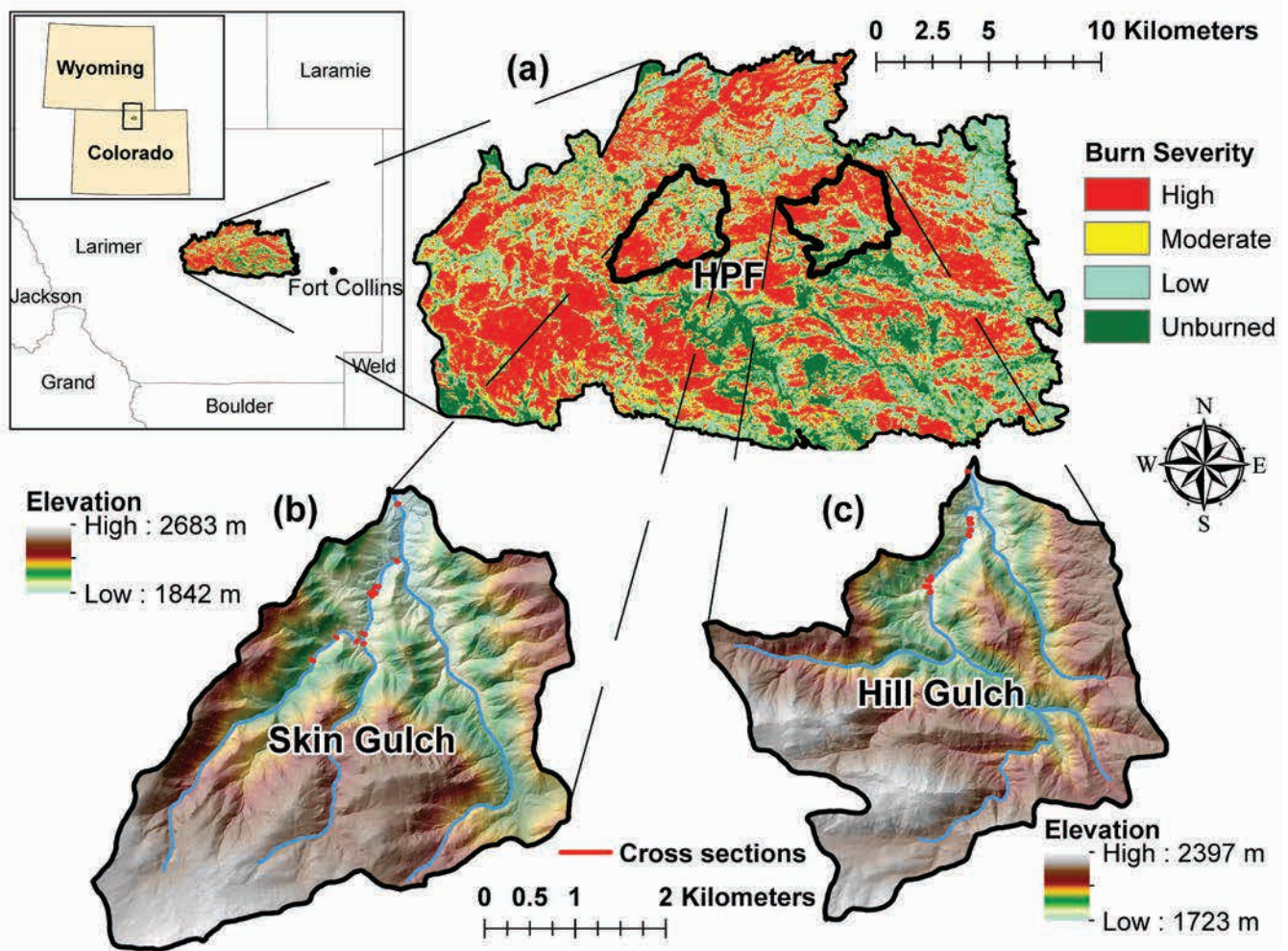


Figure 1. Location of the High Park Fire (HPF) and study watersheds. Graphic created by Dan Brogan.

with rainfall coming in two short bursts with peak 15-minute intensities on the order of 50 mm/h, which for this part of the country tends to happen about every other year. Although this was a fairly “typical” storm, thanks to the co-location of the peak rainfall rates with the highest burn severity, the resulting flood was anything but typical. The flood caused a tremendous amount of deposition, filling the valley bottom with sediment in places, transporting and imbricating boulders, and depositing piles of woody debris several meters high against standing trees (feature image). Because this flood occurred so soon after the fire, we were not able to make any measurements at the time, but we did survey high-water mark locations to constrain the inundated area at peak flow, and we used these data with the ALS topography in a two-dimensional hydraulic model to estimate the magnitude of the peak flow for this flood. Our model estimate of the peak discharge of 90-210 m<sup>3</sup>/s (or 20-46 m<sup>3</sup>/s/km<sup>2</sup>) is a striking result, as it indicates that, when normalized by watershed area, this was one of the largest rainfall-runoff floods ever measured in the United States and Puerto Rico (Brogan et al., 2017).

The following year, in September 2013, the entire Colorado

Front Range experienced a very different type of storm. An unusually large, long-duration, and generally lower intensity storm resulting from monsoonal moisture being directed to the central and northern Colorado Front Range (Gochis et al., 2014) triggered flooding and landslides from Boulder to the Wyoming border, including at our HPF field sites. In SG, this storm lasted roughly seven days and dropped about five times the maximum total rainfall from the July 2012 storm, although the maximum 15-minute intensities were only 25-31 mm/h. This was a truly historic storm, as recurrence intervals for this storm have been estimated to be several hundred to 1,000 years. This storm also produced very significant changes to the geomorphology of the channel network, as it flushed most of the fire-generated sediment from the watersheds and in places it caused several meters of channel incision and tens of meters of channel widening (Figure 3). Our best estimate of the peak flow in SG for this storm, however, is 20 to 50 m<sup>3</sup>/s (2.3 to 5.7 m<sup>3</sup>/s/km<sup>2</sup>) – still a large flood, but smaller than the July 2012 flood, illustrating the profound effect of brief but intense precipitation over areas recently burned at high severity and providing a compelling example of the flooding dangers posed by wildfire.



## Connecting Watershed Characteristics and Sediment Dynamics

Although the September 2013 flood had a lower peak discharge than the July 2012 flood, our survey and ALS data indicate that the 2013 flood was much more geomorphically effective, primarily because of its exceptionally long duration. The 2013 flood caused such a dramatic change in the channel network that in our analyses we have split the time since the fire into two periods: before the 2013 Front Range floods and after them. Before the floods, our study watersheds had very active geomorphic changes occurring from storm to storm and from season to season, with significant variability within cross sections and longitudinal profiles. After the 2013 flood this variability declined dramatically, and ALS differencing indicates that both watersheds are essentially in equilibrium, with similar volumes of erosion and deposition.

We are still working to use our data to better understand how watershed characteristics affect sedimentation patterns after wildfire. We are relating local estimates of erosion and deposition, computed from ALS differencing, to local topographic metrics such as valley width, slope, and confinement, as well as precipitation and burn severity. Our initial results have found slope and valley width to have the strongest correlation with sedimentation patterns, which is encouraging as they suggest that topography itself can provide some information on expected patterns of erosion and deposition. Ultimately, our hope is that this work will help post-fire management more effective, and improve our understanding of the relative importance of fires and floods on the landscape.

*References cited within the article are available in the online PDF version of Colorado Water located here:*

<http://cwi.colostate.edu/newsletters.asp> 



*Figure 3. RTK-GNSS surveying in Skin Gulch after the 2013 flood. This location experienced several meters of incision during the 2013 flood. Andy Brew shown in the photo, photo taken by Dan Brogan.*





# Integrating Risk Information Seeking Behavior and Risk Perception of Wildfires and Floods

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## A Theoretical Approach

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### SYNOPSIS

Understanding risk-related information seeking and risk perception is imperative to better prepare individuals and decision makers for natural hazards such as wildfires and floods. This article provides a general overview of these theories and future application related to the High Park Fire Burn Area.



## Introduction

It is evident that Colorado experiences a vast array of natural hazards such as wildfires and floods. As a result, these natural hazards place individuals and property at risk for catastrophe in some instances. Communication of such risks is key to understanding how to better prepare individuals and ensure effective, best management practices for decision makers and the lay public. Additionally, it is important to incorporate multidisciplinary research when assessing natural hazards and suggest a set of frameworks that can assist decision makers and researchers to better understand risk perception,

improve upon risk communication, and more specifically understand risk-related information seeking behavior. Furthermore, it is also crucial to further bridge the gap between applied and theoretical natural hazard research. This will ensure that decision makers can more efficiently help the public with natural hazards, ensure communication is effective and efficient, and provides the opportunity to potentially reduce risk and vulnerability.

This article provides a general, brief overview of risk perception, risk-related information seeking constructs, the importance of this type of research, and suggests the application for this research within the High Park Fire burn area. Research focused on risk perception and risk-related information seeking is timely and imperative, since it has the potential to influence educational outreach, mitigation, as well as future communication strategies within the wildland urban interface (WUI) and floodplains not only within the High Park Fire burn area, but also across Colorado.

and communication research, providing critical awareness about judgement of risk (Wachinger et al., 2013) and insight into what may influence successful risk communication (Kellens et al., 2011). It has been assessed through different viewpoints over the years including the cultural, sociological, and psychometric paradigms. The cultural paradigm proposes that risk perception is socially constructed, whereas a sociological approach is based upon the influences of institutions related to risk. More commonly discussed and researched is the psychometric paradigm, suggesting “risk as feelings” (Slovic et al., 2004). This particular approach towards risk perception is most commonly found within risk-related information seeking studies and an important factor for researchers and decision makers to assess.

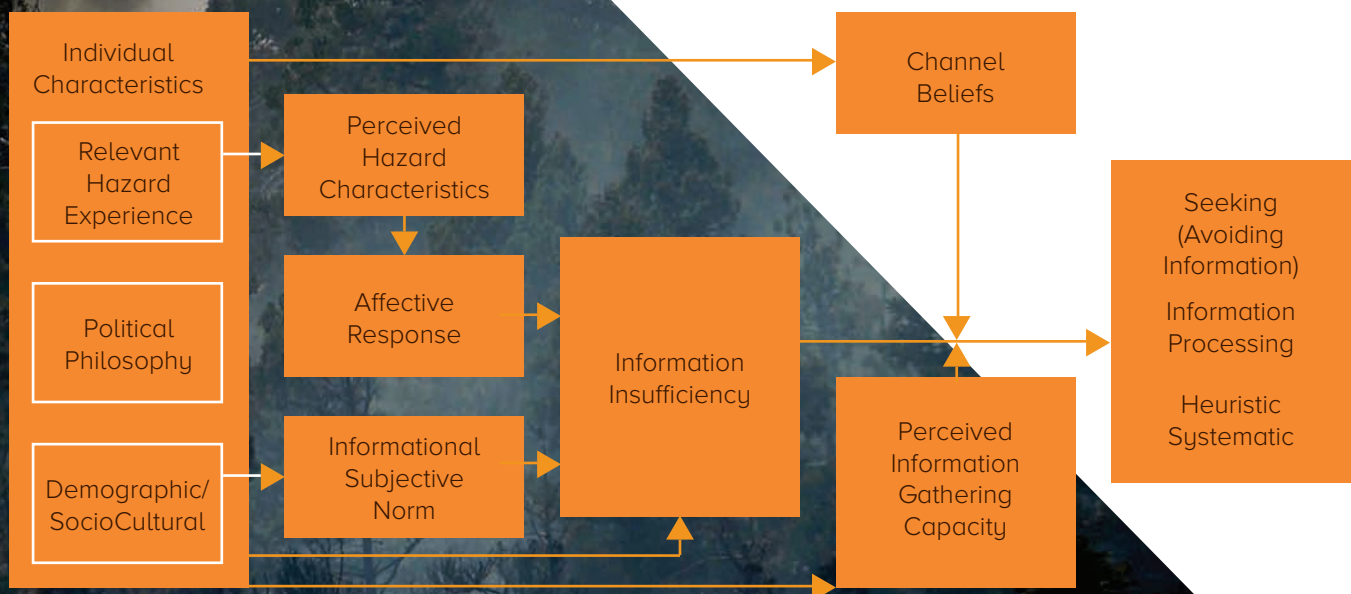
## Risk-Related Information Seeking Constructs

Like risk perception, risk-related information seeking is also commonly found within communication studies and social science research. It has predominantly been linked to public health research, but more recently gained traction within natural hazards research over the past two decades, filling a gap in the literature (Griffin et al., 1999; Griffin

Figure 1. The risk information seeking and processing (RISP) model. (Griffin et al. 1999; Griffin et al. 2006).

## Risk Perception

Risk perception has been a central concept within social science



The Waldo Canyon Fire photo by Master Sgt. Jeremy Lock , U.S. Air Force



et al., 2008; Kievik & Gutteling, 2011). The lay public often relies on risk-related information before, during, and after a natural hazard. Additionally, decision makers often heavily rely on risk-related information about a given natural hazard in order to make important preparedness, response, mitigation, as well as recovery decisions for a given community in hopes of reducing risk and vulnerability (Steelman et al., 2015). Without risk-related information, decision makers are unable to effectively mitigate risk and individuals have the potential to continue to be vulnerable (Steelman et al., 2015). However, it is

Over the years, there have been three dominant frameworks that have the potential to aid researchers and decision makers in assessing risk-related information seeking behavior including: the risk information seeking and processing model (RISP), the framework for risk information seeking (FRIS), as well as the planned risk information seeking model (PRISM) (Afifi & Weiner, 2006; Griffin et al., 1999; Griffin et al., 2008; Kahlor, 2010; Li et al., 2017; Ter Huurne, 2008; Zeng et al., 2017), as seen in Figures 1-3. The RISP model has been the most widely applied, not only providing insight into risk-related information

tion, social psychology, and primarily public health. It focuses on understanding motivation, capacity, behavioral intentions, information seeking, information processing, as well as attitude towards risk. As seen in Figure 1, the RISP model includes eleven relationships amongst varying determinants including: 1) relevant hazard experience, 2) political philosophy, 3) demographic/sociocultural, 4) perceived hazard characteristics, 5) affective response, 6) informational subjective norms, 7) information insufficiency, 8) channel beliefs, 9) perceived information gathering capacity, 10) seeking information, and 11) information processing (Griffin et al., 1999; Kahlor et al., 2003). Each of these provides unique insight into the potential influences of risk-related information seeking.

Over time, researchers have attempted to further understand risk-related information seeking beyond the RISP model given it appears more theoretical than practical in some instances. Here is where the FRIS and PRISM model can be just as useful, if not more.

The FRIS model, as seen in Figure 2, provides insight into the social-psychological determinants that influence how individuals will seek risk-related information. This construct includes six different determinants including: (1) risk perception, (2) self-efficacy, (3) involvement, (4) affective response, (5) information sufficiency, and (6) subjective norms (Ter Huurne, 2008). Information processing is not included in this construct; however, it does focus on evaluating informational subjective norms as well as affective responses. This construct varies from the RISP and PRISM since it provides further insight into the psychological components than the others.

Lastly, the PRISM model, as seen in Figure 3, includes elements from a variety of theoretical constructs, including determinants such as (1) attitude toward seeking, (2) risk perception, (3) affective risk response,

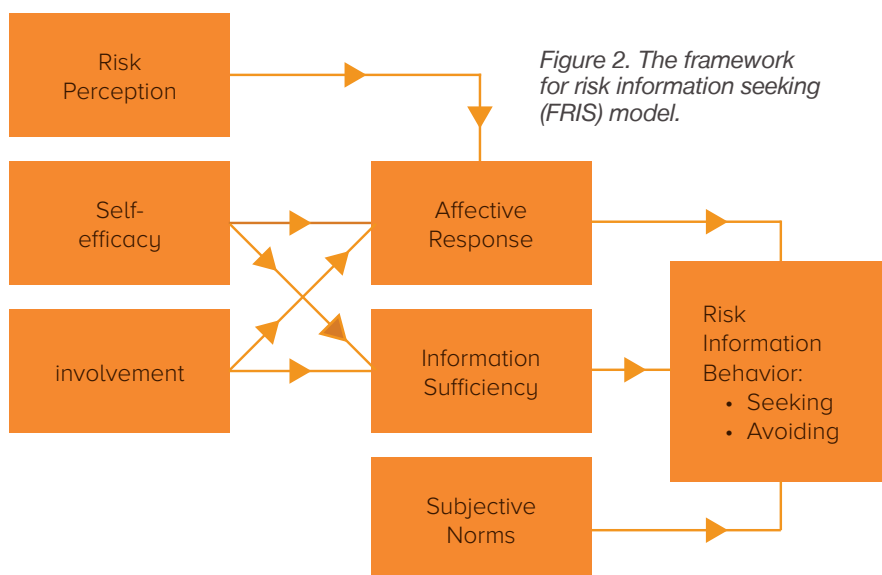


Figure 2. The framework for risk information seeking (FRIS) model.

important to note that even though there may be risk-related information, not all individuals will seek that information or that it will result in better decision-making (Rose et al., 2017). However, it does provide a preliminary evaluation of protective behavior and suggests that decision makers could be more cognizant of what factors may influence risk-related information seeking behavior such as information needs, past hazard experience, as well as response efficacy, which come from the different risk-related information seeking constructs, and are rooted in risk communication, social psychology, as well as public health (Kellens et al., 2012; Zeng et al., 2017).

seeking but also information processing. Also, portions of the PRISM and FRIS models come from the RISP model, suggesting they are all connected in one way or another. It is important to briefly highlight the difference of each model, providing insight into what determinants may be critical for decision makers and researchers to assess to better understand the lay public and their risk-related information seeking behavior related to wildfires and floods.

The RISP model is built upon constructs from the Heuristics Systematic Model (HSM) and the Theory of Planned Behavior (TPB), drawing upon research focused on risk communica-



(4) perceived knowledge insufficiency, (5) seeking-related subjective norms, (6) perceived current knowledge, and (7) perceived seeking control. This approach towards understanding risk-related information seeking focuses on it as a planned behavior and intention (Eastin et al., 2015; Kahlor, 2010). It particularly differs from the RISP model since it predicts information seeking intentions, whereas the RISP model evaluates an individual's actual risk-related information seeking behavior. Overall, all three constructs have the potential to assess an individual's risk-related information seeking behavior and risk perception. Given its multidisciplinary nature, strong theoretical foundation in communication studies, and ease of applicability and application in an applied setting, risk-related information seeking and risk perception research help fill a gap within the risk communication literature focused on natural hazards. Furthermore, it is important to provide an example of a community that could

benefit from this type of research for best management practices and improve upon risk communication.

### Suggestions for Application of Risk-Related Information Seeking Behavior and Risk Perception Research

Risk-related information seeking behavior and risk perception research is particularly timely and important given the increase in frequency and severity of natural hazards such as wildfires and floods and recent occurrence of these hazards the past two decades within Colorado. The High Park Fire burn area, as seen in figure 4, is of particular interest given the 2012 wildfire that occurred within this geographic region followed by two flood events within the area in 2012 and 2013, as further discussed in the Nelson article featured in this issue of *Colorado Water*.

Even though this area has already burned relatively recently and experienced some flooding, individuals

within the area may be at risk for experiencing future wildfires and floods in nearby locations and eventually relying upon critical risk-related information from decision makers. As a result, my dissertation research will focus on better understanding how certain determinants from the risk-related information seeking theories such as past hazard knowledge, information need, as well as risk perception, to name a few, can provide insight into risk-related information seeking behavior through a survey. Stay tuned to find out more and better understand the implications this research may have on future risk messaging, risk perception, educational outreach, as well as hazard management within the area as it relates to wildfires and floods.

References cited within the article are available in the online PDF version of *Colorado Water* located here:

<http://cwi.colostate.edu/newsletters.asp>

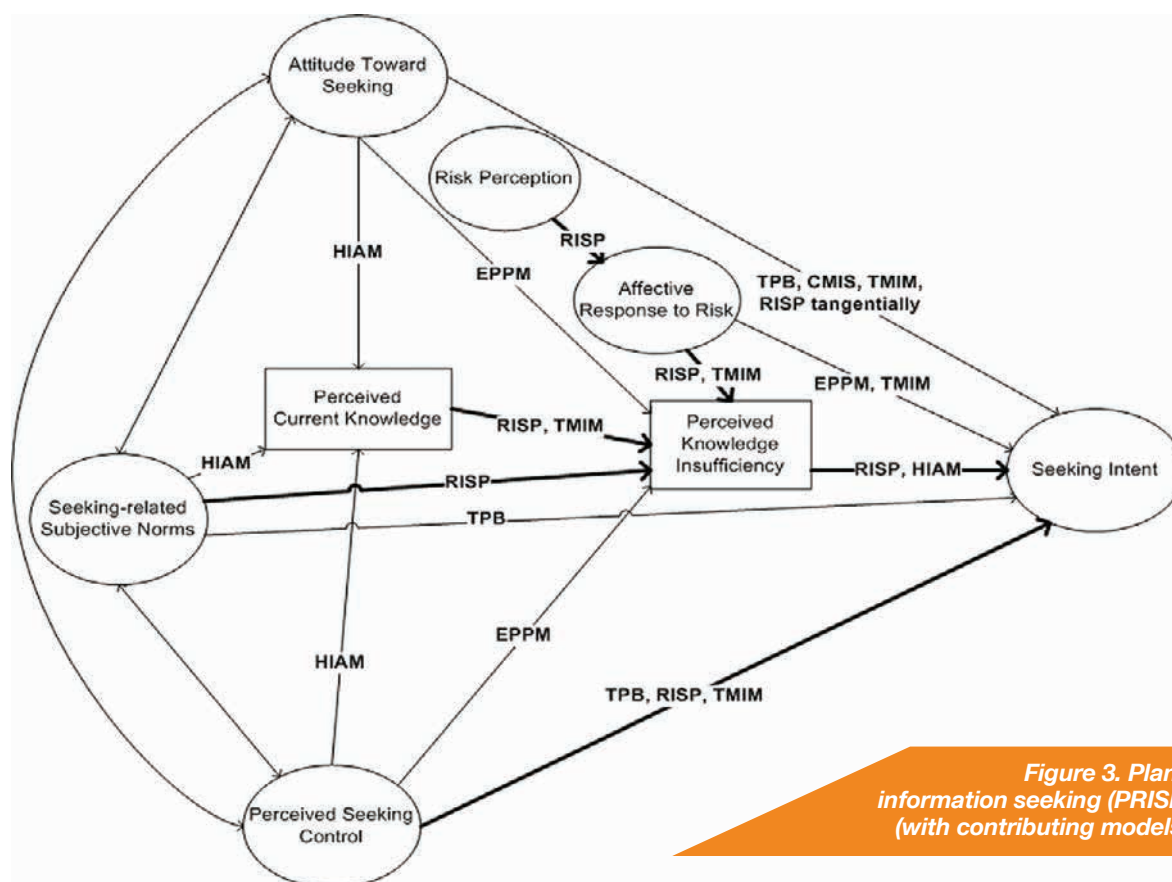


Figure 3. Planned risk information seeking (PRISM) model (with contributing models noted).





# The Des

## SYNOPSIS

A top-10 season by most metrics, the 2017 Atlantic hurricane season will be remembered for the widespread destruction throughout the Caribbean and along the Texas coast. Intense winds, heavy rainfall, and storm surge were all contributing factors and this article examines how hazards unfolded in three of the most destructive storms of the 2017 season.

*Devastation from Hurricane Irma in Key West. Photo by Flickr user Cayobo*



# destructive

## 2017 Atlantic Hurricane Season

### Introduction

Across the globe, tropical cyclones are responsible for loss of life, destruction of property, and disruption of local economies. Hurricane Katrina in New Orleans, Typhoon Haiyan in the Philippines, and Cyclone Nargis in Myanmar are just a few examples of storms with devastating impacts. As a result, tropical cyclones (known as hurricanes in the Atlantic Ocean) remain phenomena of interest for emergency managers, public officials, and meteorologists to improve hurricane preparations and forecasts.

Why do hurricanes cause such destruction? Hurricanes are intense circulations of clouds and heavy rain powered by heat released from the condensation of rising water vapor. In strong hurricanes, a mostly cloud-free eye with calm winds forms at the center. Outside the eye, strong low-level counterclockwise winds and heavy rain occur, where the most intense winds lie just outside the eye in the eyewall. The powerful winds and rainfall can cause structural damage and flooding, respectively. Since the average hurricane is approximately 300 miles across, hurricanes can impact a substantial region. Additionally, the large area of strong winds pushes the underlying water. Near coastlines, water piles up on the right side of the storm track. This storm surge, defined as water exceeding the tide, can sweep away people and vehicles.

We use wind speed to classify hurricane intensity, known as the Saffir-Simpson Hurricane Wind Scale. But a 2017 study by Edward Rappaport revealed that only 8% of hurricane-related fatalities from 1963-2012 were attributable to high winds. Storm surge accounted for 50% of all fatalities, and 25% were attributable to intense rainfall. Storm surge and rainfall are not necessarily related to the storm intensity; the storm size, track, speed, and local bathymetry/topography are all important contributors. Furthermore, while wind speeds maximize in the eyewall, surge, and rainfall can occur far from the storm center. As an example of how these hazards can unfold, this article examines a few storms from the 2017 Atlantic hurricane season.

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Philip Klotzbach, Research Scientist, Atmospheric Science, Colorado State University;

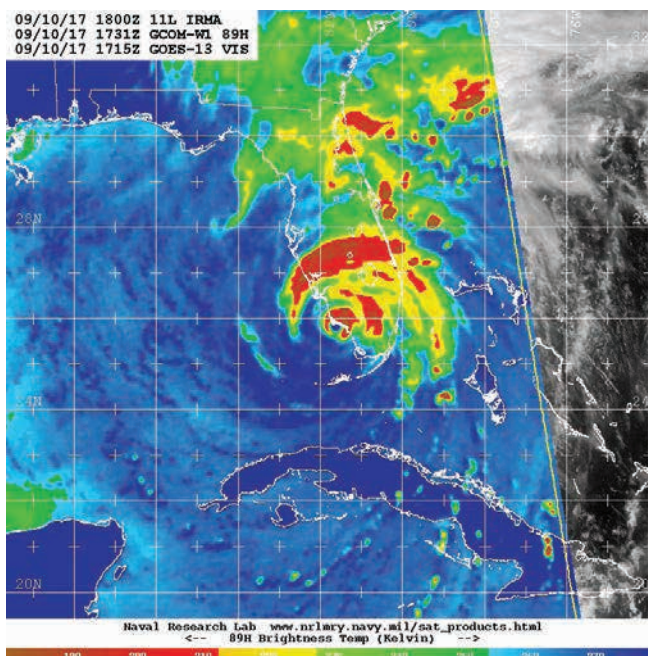
Michael Bell, Associate Professor, Atmospheric Science, Colorado State University

### 2017 Large-Scale Environment

North Atlantic annual hurricane activity is modulated by variations in atmospheric and oceanic environmental parameters. Three important predictors in assessing the environmental state are sea surface temperatures (SSTs), sea level pressure, and low-level trade winds. SST anomalies indicate how suitable the ocean is for TC activity. SSTs in both the Northeast Pacific and North Atlantic Oceans modulate tropical cyclone activity in both ocean basins. With a warmer than normal eastern tropical Pacific (e.g., an El Niño event) and a cooler than normal tropical Atlantic, Atlantic hurricane activity is typically reduced. SSTs also drive sea level pressure variations that indicate the strength and direction of low-level winds, which helps to assess the likely path and the rate of intensification or decay of a storm. Low-level trade winds also capture the strength of vertical wind shear, the difference in wind between lower and upper levels of the atmosphere, or wind resistance a storm is likely to encounter.

The 2017 hurricane season was characterized by weaker-than-normal vertical wind shear and anomalously high SSTs in the North Atlantic region with near average SSTs in the eastern tropical Pacific. Anomalously high tropical Atlantic SSTs were observed throughout the hurricane season due to a weak North Atlantic Subtropical High (a region of high





Microwave satellite imagery of Hurricane Irma from the 89-GHz channel, where warm colors indicate the presence of upper-level ice, overlaid on top of visible satellite imagery from GOES-13 at 18:00 UTC on September 10th, 2017. Image courtesy of the Naval Research Laboratory Monterey.

sea level pressure with a maximum at approximately 40°N), resulting in reduced trade winds, vertical wind shear, and evaporation over the Atlantic. With warmer waters and enhanced moisture in the atmosphere, storms were able to become more intense. All of these factors contributed to an exceptionally conducive environment for an active tropical cyclone season. A more detailed study of the 2017 large-scale environment may be found at <https://tropical.colostate.edu/>.

## 2017 Storms

Overall, the 2017 Atlantic hurricane season was a top-10 season by most metrics, including the number of major hurricanes (category 3 or higher) and Accumulated Cyclone Energy (ACE). Hurricanes Harvey, Irma, and Maria were three storms that occurred during an abnormally active late August through September and had notable impacts across the Gulf Coast and Caribbean.

### Hurricane Harvey

Harvey was an unprecedented storm in Texas, setting many hydrological records. Harvey initially made landfall just northeast of Corpus Christi around 10:00 pm CDT on August 25, 2017 as a Category 4 hurricane (with sustained wind speeds of ~130 mph). Rockport experienced wind gusts as high as 150 mph, and areas near Corpus Christi and Victoria experienced hurricane-force winds ( $\geq 74$  mph). Widespread structural damage occurred as a result. Across the Texas coast, storm surge reached a couple of feet, producing some damage to coastal

communities. Just over twelve hours later, Harvey had weakened to a tropical storm (wind speeds  $< 74$  mph). But Harvey's motion stalled, moving only 200 miles over the next 60 hours. Although winds weakened, Harvey's lengthy stay near coastal Texas supported persistent southeasterly flow over southeast Texas. This synoptic setup transported moisture-rich air from the Gulf of Mexico and produced strong rainfall near Houston and Beaumont for several days.

By the time Harvey dissipated, 60 inches of rain fell in Nederland, Texas, setting an United States record for precipitation from a tropical system. Equally noteworthy, over 20 inches was observed from the Louisiana border to midway between Corpus Christi and Houston. The vast majority of the rain occurred after Harvey had weakened to a tropical storm. This large area of intense rainfall had severe consequences locally: 69% of river forecast sites hit major flood stage, and 46% of these locations set record highs. Catastrophic flooding occurred in Wharton, Harris, and Galveston counties. In Harris and Galveston counties, the Harris County Flood Control District estimated that 136,000 structures and 7,000 homes and businesses were flooded.

### Hurricane Irma

On September 5, 2017, Hurricane Irma became a Category 5 hurricane with wind speeds of 175 mph as it approached the Lesser Antilles. By reaching 175 mph winds, it became the strongest Atlantic hurricane on record outside of the Gulf of Mexico and western Caribbean. Irma tore through the northern Caribbean, leaving a trail of destruction in Antigua, Barbuda, St. Martin, Anguilla, St. Thomas, and the British Virgin Islands due to intense winds. After weakening slightly, Irma intensified back to a Category 5 hurricane as it approached Cuba. Tracking along Cuba's northern coastline, Irma weakened to a Category 3 hurricane as its circulation was disrupted by Cuba's mountains, but Cuba was battered by winds and rain.

After moving over the Florida Straits, Irma intensified to a Category 4 hurricane as it turned north towards Florida. On September 10, 2017, Irma made landfall 30 miles east of Key West, Florida with sustained wind speeds of 130 mph. Roof damage was widespread throughout the Florida Keys, where peak gusts ranged from 100-150 mph. Although a fortuitous eastward shift in Irma's track prevented the forecasted 12 feet of surge from becoming a reality in Tampa Bay, flooding due to surge occurred along the Florida, Georgia, and South Carolina coasts, even after Irma had weakened considerably due to landfall. Jacksonville, Florida set a flood record of 5.57 feet and the storm tide in South Carolina, defined as the sum of the storm surge and predicted tide, exceeded 4 feet in places.

### Hurricane Maria

Just one week after Irma barreled through the northern Caribbean, Maria marched through the Lesser Antilles, devastating




several Caribbean islands in the process. Hours before moving over Dominica, Maria rapidly intensified into a Category 5 hurricane with wind speeds of 160 mph. Widespread damage was sustained on Dominica. After passing Dominica, Maria continued tracking northwest towards St. Croix and Puerto Rico. Maria's center passed just south of St. Croix early on September 20 2017, meaning the island bore the brunt of intense winds in the northern eyewall. Many houses were destroyed, and thousands of trees were torn down. Additionally, heavy rainfall triggered flooding and landslides across the island.

At 6:15 am AST on September 20, 2017 Maria made landfall in Yabuoca, Puerto Rico, as a Category 4 hurricane (with sustained wind speeds estimated at 155 mph). Extreme structural damage occurred, with thousands of homes destroyed. The worst wind damage occurred on the south-east side of the island, near the point of landfall. At the same time, a sizeable portion of Puerto Rico saw over 20 inches of rain, with a maximum observation of 37.9 inches. The highest rainfall was observed in the mountains, where greater

lift enhances the conversion of water vapor to liquid drops, producing more rainfall. Widespread landslides occurred, which isolated some communities from relief efforts.

### How We're Helping

Our research group at CSU studies hurricanes on a wide range of timescales and from several different angles. Our research currently examines the major drivers of large-scale environmental patterns that influence hurricane activity. Polarimetric radar data, which provide details about the size, shape, and diversity of raindrops and frozen particles, helps us understand the processes that control rainfall duration and intensity. We also issue Atlantic Basin seasonal hurricane predictions each year, using the large-scale climate factors discussed in this paper to project how active the season is likely to be.

*References cited within the article are available in the online PDF version of Colorado Water located here:*  
<http://cwi.colostate.edu/newsletters.asp> 

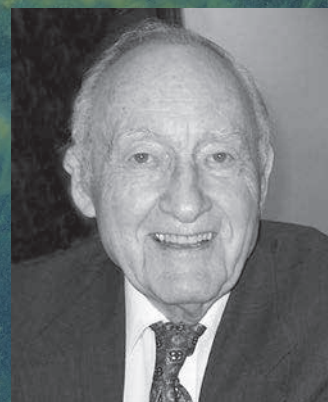
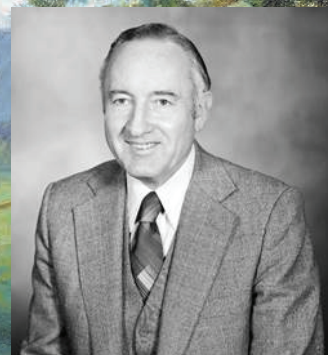
## In Memory of Dr. Norman Allen Evans

1922-2018

### Innovative and Influential

Norm was an advocate for Colorado water resources and irrigation engineering. He passed away on January 25, 2018. He led a profound career in the College of Engineering, now known as the Walter Scott, Jr. College of Engineering at Colorado State University (CSU). Evans was one of the first doctoral students in the engineering program and later became a faculty member within the department. He was the second Director of the Colorado Water Resources Research Institute (CWRRI), now known as the Colorado Water Institute (CWI), serving from 1967-1988

and provided valuable support and guidance. Additionally, Evans was one of the founding members of the Colorado Water Quality Control Commission, which provided insight on water quality standards and management for the State. He was on the Fort Collins Water Board along with the Poudre Landmarks Foundation. In March 2016, the CWI and CSU Water Center held the first Norm Evans Endowed Lecture, focused on continuing Evan's legacy, including his passion for teaching, and support for water resources. He was an esteemed colleague and will be greatly missed by friends and family.







# Monitoring Indicates Best Management Practices Helping to Protect Water Supplies

Rich Edwards, Assistant Staff Forester, Colorado State Forest Service;  
Ryan Lockwood, External and Media Communications Program  
Manager, Colorado State Forest Service

## SYNOPSIS

To proactively protect water quality from nonpoint source pollution, the Colorado State Forest Service (CSFS) offers forestry Best Management Practices (BMPs) addressing activities such as road construction, work near streams, and timber harvesting actions. Because forestry BMPs are voluntary on private lands in Colorado, beginning in 2008 and biennially afterwards, the CSFS has monitored their application and effectiveness and summarizes the results here.

*(Above) Logging equipment can disturb the soil and cause nonpoint source pollution if BMPs are not properly applied.  
Photo by Meg Halford, CSFS*

**W**ater is a vital resource in Colorado, which must be protected from various threats. One of these human-induced threats is nonpoint source pollution, or that which comes from many diffuse sources and results from precipitation moving over and through the ground into water supplies.

In an effort to proactively protect water quality from nonpoint source pollution, Colorado offers Best Management Practices (BMPs) for various land use activities, including forestry-related activities. Forestry BMPs are a set of suggested water-quality protection measures and guidelines that provide direction on methods to mitigate potential water quality impacts from activities such as road construction, work in



Table 1. Colorado Forestry BMP 2016 field monitoring application results by landownership.

Ownership	Exceeded BMP	Met BMP Standard	Minor Departure	Major Departure	Gross Neglect	Total
Federal	2	63	4	0	0	69
	3%	91%	6%	0%	0%	100%
Private	4	52	13	11	0	80
	5%	65%	16%	14%	0%	100%
State	2	20	0	0	0	22
	9%	91%	0%	0%	0%	100%
Total	8	135	17	11	0	171
	5%	79%	10%	6%	0%	100%

Streamside Management Zones (SMZs), timber harvesting actions, pesticide and fertilizer use, construction of stream crossings, and fire management actions. Compliance with BMPs is voluntary in Colorado and administered within a non-regulatory framework.

### How is BMP Implementation Evaluated?

Because forestry BMPs are voluntary on private lands in Colorado, beginning in 2008 and biennially afterwards, the Colorado State Forest Service (CSFS) began to monitor the application and effectiveness of forestry BMPs in the state. A state audit steering committee and field monitoring team was formed, along with an ongoing program requiring team site visits. The main objectives for the monitoring are to determine if the forestry practices implemented on the land are being applied, and also how effective they are.

Each time a monitoring action occurs, a total of 79 BMPs are considered and/or rated for each site. Many of the determinations and lessons from BMP monitoring are in turn directly applied, through continuing education, to Colorado's Master Logger program (as implemented by the Colorado Timber Industry Association) and the American Tree Farm System's local groups. This education is also incorporated into the Sustainable Forestry Initiative/Central Rockies Forestry Education Program in order to improve both the knowledge and implementation of BMPs regionally in Colorado, South Dakota and Wyoming. Any recommendations from the BMP monitoring reports are used for educational and outreach purposes only, and all confidentiality of contractors and landowners is maintained throughout the written reports.

The CSFS has led efforts to monitor the application and effectiveness of BMPs in the state in 2008, 2012, 2014, and 2016.



In each of these years, the CSFS and its partners have conducted field visits to sample timber-harvest sites in the state to assess forestry BMP implementation. Each year, sites are selected from a combination of federal, private, and state lands.

To date, 24 field sites (eight federal, eleven private and five state) have been visited across 32 Colorado counties, eleven CSFS districts and seven National Forests. The most recent monitoring effort occurred in 2016, with a summary of these data below.

### 2016 Report Shows Continued Application of BMPs

In September 2016, an interdisciplinary team visited six timber-harvest sites along the southern Front Range of Colorado to assess Colorado forestry BMP application and effectiveness. The team consisted of resource professionals in the fields of engineering, forestry, geology, hydrology, soil science, and



Table 2. Colorado Forestry BMP 2016 field monitoring effectiveness results by landownership.

Ownership	Improved Conditions	Adequate Protection	Minor and Temporary	Minor/Prolonged or Major/Temporary	Major and Prolonged	Total
Federal	2	66	1	0	0	69
	0%	97%	4%	0%	0%	100%
Private	1	62	6	11	0	80
	1%	78%	7%	14%	0%	100%
State	0	22	0	0	0	22
	0%	100%	0%	0%	0%	100%
Total	3	150	7	11	0	171
	2%	88%	4%	6%	0%	100%

wildlife management from federal, state, and local government as well as the private sector. As done in previous years, sites were selected from a combination of ownership types, with two federal, three private, and one state land site assessed. In 2016, the sites were selected from an area representing nine counties, four CSFS districts, and two National Forests.

In general, BMPs were properly applied and largely effective in 2016. The monitoring efforts found that the general application of BMPs was met or exceeded 84% of the time (Table 1). Minor departures from application of the BMPs occurred 10% of the time, with major departures occurring 6% of the time and no gross neglect of BMPs observed. Also, BMPs were found to be effective overall, providing adequate or improved resource condition 90% of the time (Table 2). “Minor and temporary” adverse effects were observed 4% of the time, with the remaining 6% of observed BMPs showing minor/prolonged or major/temporary adverse effects at the sites. No “major and prolonged” effects were observed on any sites.

Timber sales on state lands scored the highest in terms of proper BMP application, having met or exceeded BMP standards 100% of the time. Federal timber sales scored the next highest with regards to BMPs being applied, having met or exceeded standards 94% of the time; also, only minor departures occurred on federal sites for the remaining 6% of BMP applications. Private land sites scored significantly lower, with only 70% meeting or exceeding BMP standards. The majority of departures from proper BMP application on private lands were minor (16%), but major departures occurred 14% of the time for these sites. As with the other sites, no gross neglect was observed.

With regard to perceived BMP effectiveness, the state land sites again scored highest and indicated no observed negative

impacts to conditions related to potential nonpoint source pollution, with these sites showing adequate or improved conditions 100% of the time. BMP effectiveness on federal forestlands was adequate or improved conditions 97% of the time, with “minor and temporary” effects accounting for the remaining 3% of BMPs evaluated for effectiveness. Private land sites again scored lower than state or federal sites, with only 79% of BMPs at the private sites adequately protecting or improving conditions. Minor/prolonged or major/temporary effects also were only seen on private lands, collectively represented 14% of the time.

The 2016 data will be further analyzed and the related field monitoring report will be published and made publically available in 2018. Based on the findings of this most recent assessment, the monitoring team already has made several recommendations to address specific questions or concerns related to SMZs, sale/treatment boundary spatial limits for monitoring, stream types, and ongoing monitoring. As well as improved operational guidance, additional, focused BMP outreach and training is needed for forestry/logging operators, landowners, and managers.

### Latest Results Mirror Earlier Monitoring Efforts

Table 3 illustrates the collective BMP application and effectiveness rating results for all landownerships for the 2008, 2012, 2014, and 2016 monitoring periods. The most recent monitoring effort shows results similar to those of prior periods. Overall, the percent of instances in which general application of BMPs was met or exceeded has ranged from 82 to 87% in the four separate years in which monitoring occurred, while the




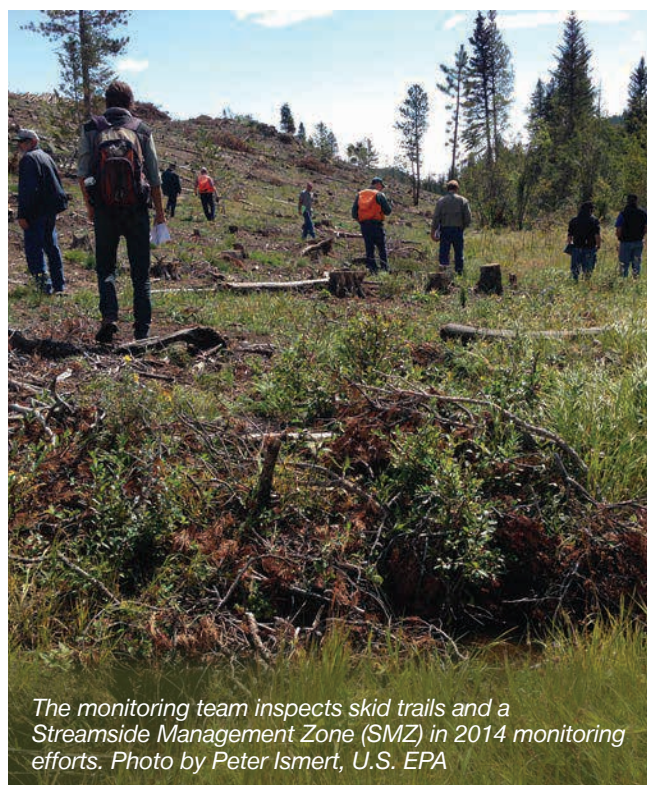
Table 3. Comparison of BMP application and effectiveness results by year.

Application	Exceeded BMP	Met BMP Standard	Minor Departure	Major Departure	Gross Neglect
2008	3%	84%	11%	3%	0%
2012	2%	84%	10%	4%	0%
2014	2%	80%	13%	3%	3%
2016	5%	79%	10%	6%	0%
Effectiveness	Improved Conditions	Adequate Protection	Minor and Temporary	Minor/Prolonged or Major/Temporary	Major and Prolonged
2008	1%	81%	15%	3%	0%
2012	2%	86%	12%	0%	0%
2014	1%	83%	16%	0%	0%
2016	2%	88%	4%	6%	0%

percent of cases where BMPs either improved site conditions or offered adequate protection has ranged from 82 to 90%.

The application results have remained relatively consistent when looking at the first two periods: 2008-2012 and 2016. By comparison, minor departures and gross neglect of BMP application increased slightly in the 2014 results, which decreased overall ratings for that period. Similarly, the effectiveness results improved slightly between 2008-2012, with more BMPs providing adequate or improved conditions. However, effectiveness results decreased again in 2014 before rising again in the latest monitoring period. It should be noted that adequate to improved resource conditions and overall effectiveness ratings were at their highest observed levels to date in 2016.

In summary, the monitoring team considers the 84% implementation and 90% effectiveness levels recorded for 2016 as an indication that BMPs are being properly applied and largely effective. The longer-term application/ effectiveness levels seen when combining the data from all earlier monitoring periods further support that BMPs are being implemented in Colorado. Collective BMP monitoring efforts to date indicate that forestry BMPs continue to be a leading means for helping ensure water quality protection in the state. 







# Keeping Irrigated Agriculture Productive and the Environment Healthy in Colorado's Lower Arkansas River Valley

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Christopher D. Shultz, MS Graduate Student, Civil and Environmental Engineering, Colorado State University;

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## SYNOPSIS

Studies by Colorado State University (CSU) have estimated how land and water best management practices would affect farm income and pollution in the surrounding environment of the irrigated Lower Arkansas River Valley. It was found that no practice can achieve all goals, but that with careful consideration, farmers, water managers, and other stakeholders in the region can choose solutions that best fit how they want to manage these different objectives.

Farmers in Colorado's Lower Arkansas River Valley (LARV) (Figure 1), depend on the Arkansas River, its tributaries, and groundwater to irrigate about 250,000 acres of some of Colorado's most productive farmland. The earliest decreed water right was in 1859, the river was fully appropriated by the 1880s, and claims for "junior" rights on the river continued into the 20<sup>th</sup> century (Abbott, 1985). Today, farmers grow alfalfa, grains, and famed Rocky Ford cantaloupes, contributing many millions of dollars to the economy every year. Sustainability of irrigated farming is at the economic and cultural heart of many communities in the region.

While irrigation plays a critical role in fueling the region's agriculture, its impacts on regional water quality are less favorable. Over the past 20 years, Colorado State University (CSU) research has produced a better understanding about the relationship between irrigation and the environment. Specifically,



studies of the LARV have linked irrigation to several troublesome environmental conditions including elevated selenium, uranium, nitrate, and salt concentrations in streams; shallow, saline groundwater; saline soils; and significant non-beneficial consumptive use of scarce water supplies (Seiler et al., 1999; Gates et al., 2009, 2016; Morway and Gates, 2012). To make matters worse, on-going growth strains water supplies and intensifies rivalry between states, regions, and individual users. A long-standing dispute between Kansas and Colorado, for example, led to the creation of the Arkansas River Compact in 1949, which requires that historical “stateline flow” must be maintained in usable quantity and availability. Urban water demands continue to rise with population, which steadily increases in the LARV’s most urban county, Pueblo, while falling in its more rural counties (Bent, Otero, Crowley, and Prowers).

Many best management practices (BMPs) have been proposed to curb the negative environmental impacts of irrigation. However, farmers have to balance irrigation decisions with the Compact, urban needs, and environmental concerns. A series of computational models have been developed by CSU to help water managers achieve this balance (Morway et al., 2013, Bailey et al., 2014, 2015, Tavakoli-Kivi and Bailey, 2017, Shultz et al., 2018). These models are tested against field data and account for how farming methods impact surface water flows, groundwater flows, and their interaction. They allow researchers to simulate how a BMP would affect irrigation along with flows and water quality in local streams and groundwater. Recently, this research was combined with economic impacts for a study region upstream of John Martin Reservoir (Figure 1) of the LARV (Orlando, 2017). Those results provide the first comprehensive look at the tradeoffs of BMPs across economic, flow, and water quality objectives for a major portion of the area. With leadership from the Arkansas River Management Action

Committee (ARMAC, [www.ColoradoArmac.org](http://www.ColoradoArmac.org)), farmers and other residents in the LARV can use these recent research results to better determine their best future.

## The Sustainability Challenge

The soils and geology of the LARV contain a variety of salts as well as the trace elements selenium and uranium. Irrigation water that is applied in excess of crop needs, along with water that seeps from earthen irrigation canals, builds up the groundwater levels and flows through the subsurface back toward the river. These flows combine with applied fertilizers to increase nutrients dissolved in the groundwater, which in turn react with the soils and rock to dissolve salts and trace elements and carry them, along with the nutrients, into the river. The evaporation of applied water from the crop and soils further concentrates the dissolved chemicals in these return flows. Additional water runs off field surfaces into the river and its tributary streams. These processes combine to create solute concentrations in groundwater, soils, and streams that decrease crop production and threaten the health of aquatic wildlife and humans. Crop yields are estimated to be down by 6-17% due to salinity. In addition to environmental degradation from salinity, selenium concentrations along the Arkansas River exceed Colorado chronic standards by a factor of two to four, uranium concentrations by a factor of about two in the downstream stretch of the river, and nitrogen concentrations are close to exceeding current guidelines. The test for the LARV is how to find cost-effective ways of altering these processes through improved land and water management practices to boost productivity and also enhance the environment.

## Economic and Environmental Tradeoffs

Researchers at CSU are considering five different BMPs: (1) reduced irrigation (RI), (2) canal sealing (CS), (3) lease

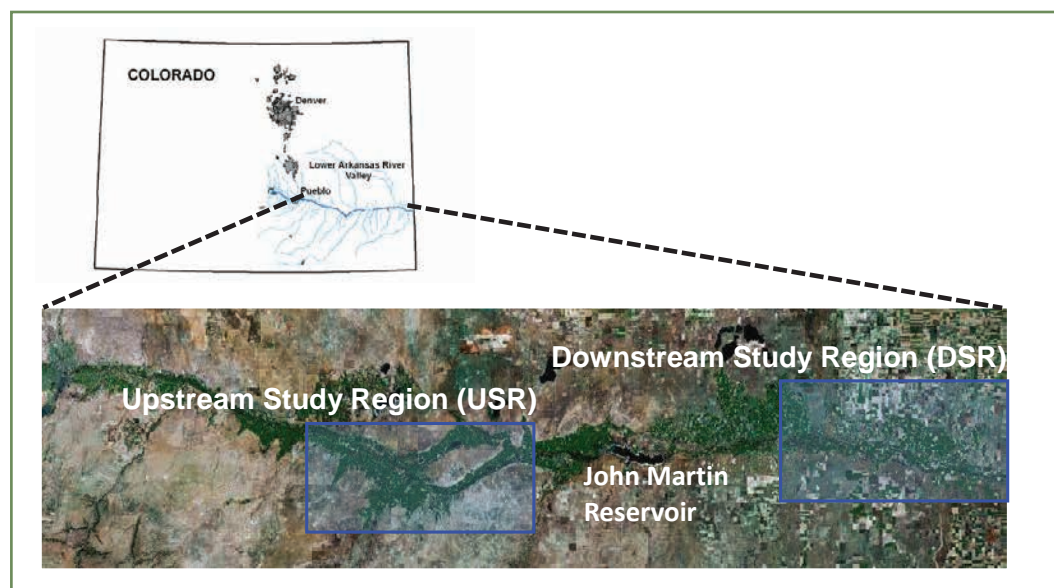


Figure 1. The Lower Arkansas River Valley showing CSU Upstream and Downstream Study Regions.



fallowing (LF), (4) reduced fertilizer application (RF), and (5) enhanced riparian buffers (ERB). Water BMPs (RI, CS, and LF) all reduce water movement through the system, which decreases overall movement of salts, selenium, uranium, and nitrogen. Land BMPs (RF and ERB) reduce or impede the input of pollutants into groundwater and surface water, respectively. RI is considered for irrigation reduction levels varying over 0-30%, LF for fallowing of 0-30% of total irrigated land, and CS for levels of canal seepage reduction varying over 0-80%. RI is assumed to be accomplished through the use of improved surface irrigation methods or installation of sprinkler irrigation, which is more efficient than the surface irrigation systems currently in use. Installation of sprinklers in the LARV has been slower than in other regions of Colorado, but has increased recently to about 20% of total irrigated acres. LF allows cities to lease water from a particular farmer and call on it three out of ten years, providing farmers with an income stream while leaving water on the farm the majority

of the time. A recent pilot program leased acres and provided water from the Catlin Canal Company to the town of Fowler, the City of Fountain, and the Security Water District. Lease rates were a little over \$1,000 per fallowed acre, which is considerably higher than producing most crops (Lower Arkansas Valley Water Conservancy District, 2016).

The CSU research shows how BMPs in the region impact water quality and economic returns. Four main criteria are considered: (1) net economic returns, (2) changes in soil salinity, (3) river selenium, and (4) river nitrate. The research team considered individual BMPs as well as combinations of BMPs.

The cost-effectiveness of proposed BMPs is analyzed using a linear programming economic optimization model (Orlando, 2017), coupled with output from groundwater and stream flow (MODFLOW-SFR) and reactive solute transport (RT3D-OTIS) models (Shultz, 2017). The combination of these models allows for a hydro-economic analysis of BMPs by identifying the trade-offs between regional economic net returns and

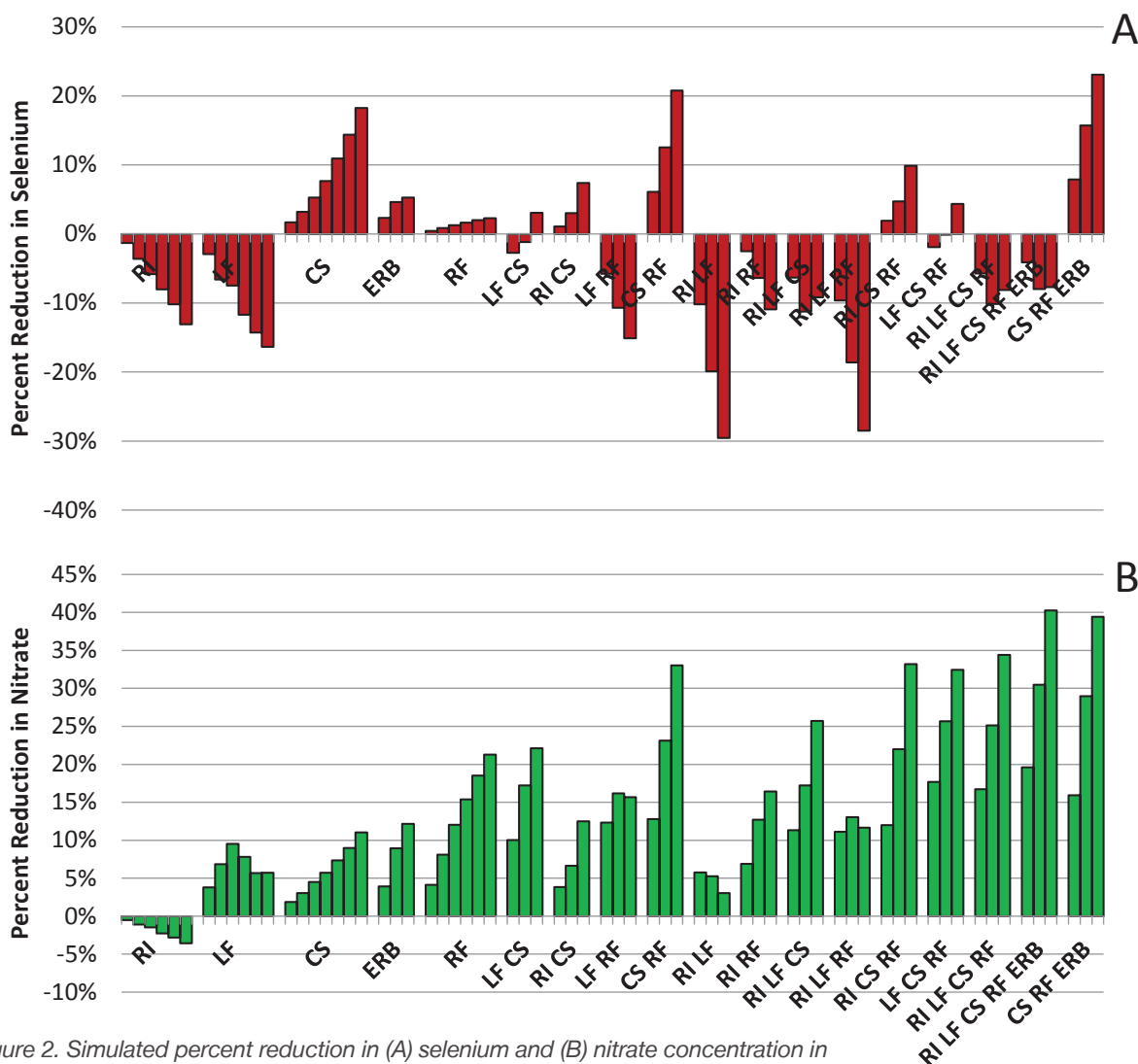


Figure 2. Simulated percent reduction in (A) selenium and (B) nitrate concentration in groundwater compared to baseline conditions.



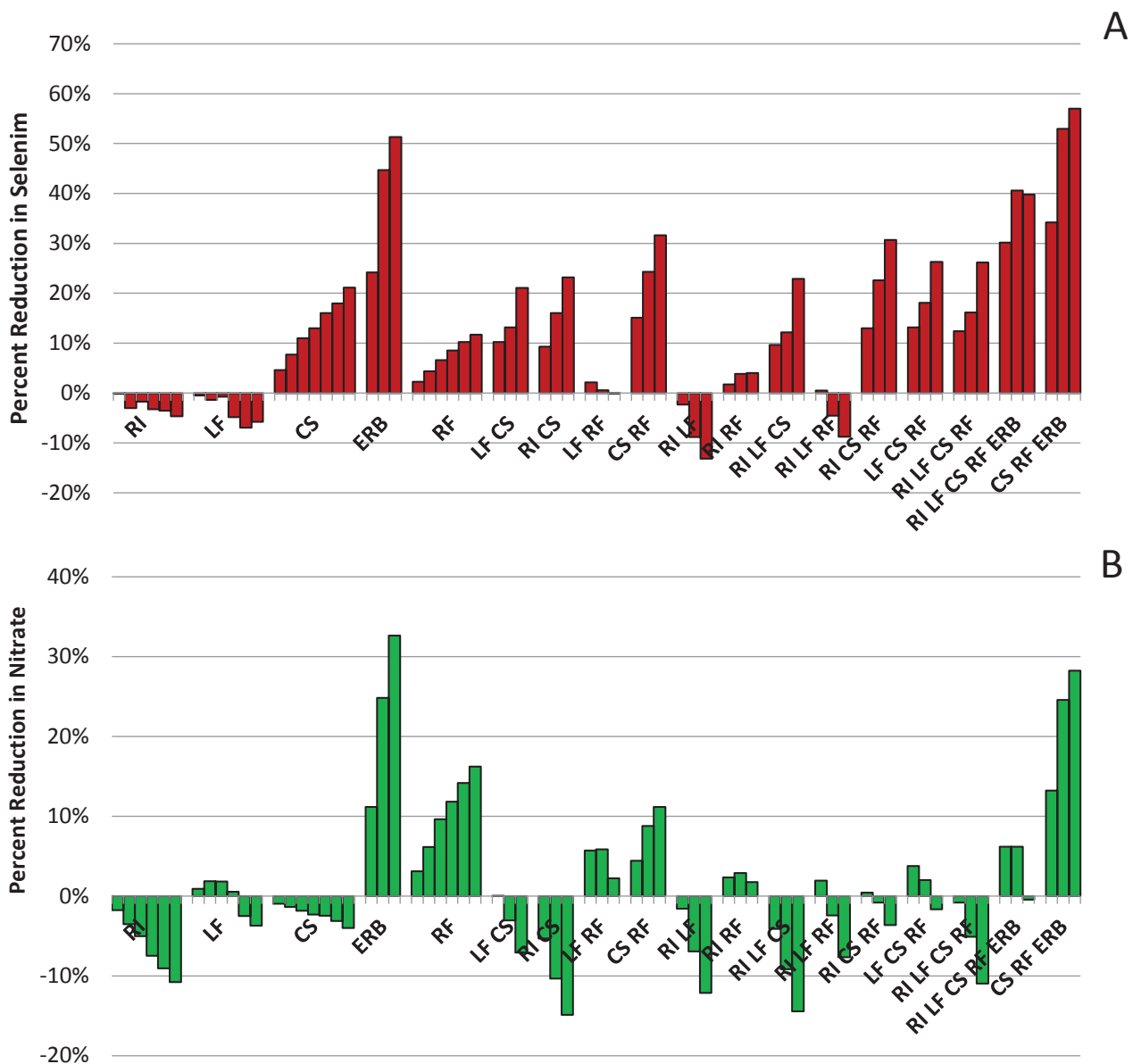


Figure 3. Simulated percent reduction in (A) selenium and (B) nitrate concentration in the Arkansas River compared to baseline conditions.

pollution abatement in local waters associated with various levels of BMP adoption. The models focus on six irrigation canals feeding about 50,000 irrigated acres and producing six major crops in an upstream study region near La Junta.

The basic results for selenium and nitrate-nitrogen in groundwater and the Arkansas River, respectively, are shown in Figures 2 and 3 (Shultz, 2017). The bar plots are grouped according to stand-alone and combined BMPs with the level of implementation increasing from left to right within the groupings. Broad application of CS, RF, and ERB BMPs, both alone and together, are predicted to reduce selenium in groundwater, compared to baseline (current) conditions by as much as about 20% and in the river by as much as about 50%. While all considered BMPs would lower nitrate-nitrogen in groundwater, only the land BMPs (RF and ERB) would be effective in reduc-

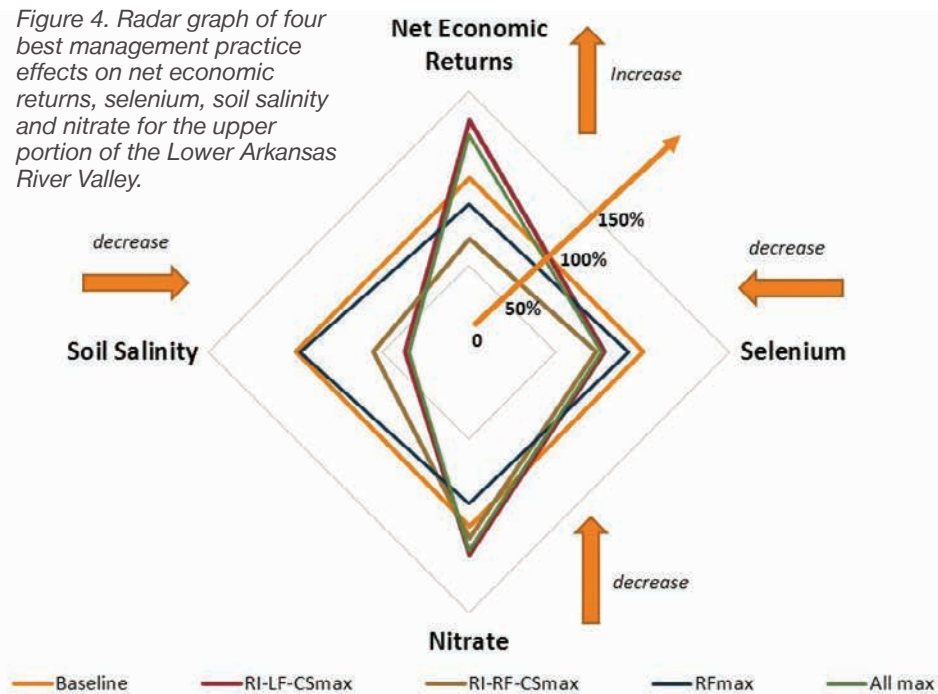
ing concentrations in the river. Though RI and LF are found to be ineffective as stand-alone BMPs, their joint implementation with CS enhances the effectiveness of CS alone. Overall, the CS-RF-ERB combination appears to have the greatest potential for driving down both selenium and nitrate pollution in the LARV.

Some of the water BMPs (RI, LF, and CS) also are found to lower the saline groundwater level in the study area. Using the analysis of Morway and Gates (2012), this is expected to reduce soil salinity and lead to increased crop yields.

It is apparent from the pollution modeling results that not everything can be accomplished with a single BMP. Also, while combining BMPs improves the ability of farmers and water agencies to address multiple environmental objectives, no combination can improve all four objectives at one time. If there were a BMP that made all four better at the same time,



Figure 4. Radar graph of four best management practice effects on net economic returns, selenium, soil salinity and nitrate for the upper portion of the Lower Arkansas River Valley.



the choice would be easy. Since that is not the case, farmers and other stakeholders in the region must make difficult choices about how to best balance their future actions.

One way that researchers can help make those choices easier is to compare tradeoffs in a meaningful way. Figure 4 is an example of a radar graph, also known as a spider plot, that compares multiple objectives at one glance. Each spoke, or axis, represents one of the four objectives. The light grey lines show how each objective compares to the baseline conditions, which is labeled as 100%. For example, the baseline conditions, or where the region stands on each objective today, are on the 100% line. Of course, 50% of baseline conditions is better for pollution but worse for economic returns. While we considered upward of 100 BMP combinations, we need only show a few, since only a handful were the best at accomplishing at least one objective. A BMP is represented by a colored line other than the baseline. For example, the BMP that combines all BMPs together at maximum levels (all max) provides the highest economic returns; at the same time, it reduces selenium and salinity. Unfortunately, it increases nitrate pollution compared to the baseline. The system that maximizes the level of all BMPs except reduced fertilizer (RI-LF-CS max) presents similar results, with slightly better results on profits and slightly less effective reduction in selenium and salinity. Not surprisingly, nitrate-nitrogen is reduced most by the RF option (RF max), but that BMP is among the worst at producing net returns. Other comparisons can be made in a similar fashion, allowing local LARV stakeholders and decision makers to quickly see the tradeoffs that they are facing.

Of course, LARV producers have other constraints that will affect which of these BMPs they can choose. For example, CS is not a feasible option currently due to certain rules that would

make it difficult to provide return flows owed back to the river. This research, however, shows that it would be one of the least-cost ways to reduce pollution. Therefore, changing the rules governing canal operations may offer more promise than accepting the limitations of those rules. For example, it may be economically feasible to acquire and use storage accounts in the Pueblo and John Martin reservoirs on the Arkansas River to store and release flows to make up for altered return flow patterns due to implementation of CS BMPs.

## Conclusion

Since no BMP or combination of BMPs is best for all four objectives at the same time,

local residents of the LARV will need to make some tough decisions. Which BMPs go the farthest toward getting them to sustainability? Some of the systems seem more promising. For example, the maximum application of RI and CS, with LF, will improve income and lower salinity and selenium levels. Nitrogen pollution will worsen, but currently nitrogen pollution is near acceptable standards and therefore it might be of least concern. Likewise, cost sharing that is available for center pivots to enhance RI strengthens the case for RI. Also, the growth, or lack thereof, of LF could have a profound impact on the region.

Of course, local preferences and politics will dictate the future direction that irrigated farmers and other stakeholders choose. The information that CSU research can provide about the likely economic and pollution tradeoffs should help focus that debate and provide better clarity on the consequences of local choices. That information can also provide an understanding about how rule changes could improve local choices. For example, we showed here that some additional flexibility in how canal return flows are accounted for could provide farmers with a lower cost option to reduce selenium and salinity.

On-going work is focusing on improved estimation of salinity impacts and on evaluating alternative BMPs in a downstream study region (Figure 1) of the LARV near Lamar. Attention also is being given to how different BMP implementation can be tailored to specific locations within the LARV to achieve the greatest benefits.

References cited within the article are available in the online PDF version of Colorado Water located here:

<http://cwi.colostate.edu/newsletters.asp>



# Kelly Curl

Kelly Curl, Associate Professor, Horticulture and Landscape Architecture, Colorado State University



Photo by Bill Cotton

Kelly Curl is an Associate Professor of Landscape Architecture in the Department of Horticulture and Landscape Architecture. Curl is originally from Pennsylvania, where she first learned about landscape architecture while attending the Pennsylvania Governor's School in the Agricultural Sciences at Pennsylvania State University. She continued to receive her Bachelors of Science in Comprehensive Science and Mathematics at Villanova University. In 2002, she received her Masters of Landscape Architecture at the University of Pennsylvania. After receiving her MLA, she moved to San Francisco and worked at PWP Landscape Architecture, Inc., and became an Associate in 2005. At PWP, Curl's past landscape architecture projects included the following: the Cleveland Clinic, National 9/11 Memorial, San Jose International Airport, Novartis Headquarters, and the University of California – Merced.

Curl was appointed as an Assistant Professor at CSU in 2010. In 2015, Curl was awarded the College of Agricultural Science's Charles N. Shepardson Faculty Teaching Award. In 2016, she was promoted to Associate Professor and was awarded tenure. Curl's previous research worked with land reclamation within post-mined landscapes. Her pedagogical research in landscape architecture is through analog, digital and hybrid illustration. Her essay, titled *Ideation of Landscape Representation* was published in the book *Representing Landscapes: Hybrid*. The chapter also includes selected CSU Landscape Architecture student drawings that display various techniques of making hybrid drawings. More recently, Curl was awarded the 2017-2018 CSU Water Center Faculty Fellow grant for her

research on the integration of green infrastructure in land use planning and water planning. She initially concentrated on the analysis of specific Case Study Briefs within the Landscape Performance Series that demonstrated successful stormwater management, water conservation, water quality, and enhanced flood protection. Curl is researching a local neighborhood, Bucking Horse, which has engaged in designed green infrastructure with a designed native grass restoration project. Her intent is to find social, economic, and environmental benefits within the Bucking Neighborhood that reflects the installed and planned green infrastructure network. Curl was recently selected to be part of the National Western Center (NWC) Sustainability Phase 2 team. She looks forward to continuing her research on green infrastructure and the water planning efforts on the NWC site design.

Curl has taught both undergraduate and graduate design studios, landscape drawing, digital methods, advanced site engineering, professional practice and design seminars. In the fall of 2018, she will begin teaching the landscape ecology courses. Her landscape performance research has provided opportunity to include the landscape performance topic within her pedagogy. Curl received a Landscape Performance Education Grant from the Landscape Architecture Foundation for the inclusion of landscape performance within her senior seminar course on designed landscapes in the fall 2017 semester.

Curl is very involved in many service activities at the College and Departmental level. She is actively involved as a member of the President's Commission for Women and Gender Equity Committee, the College and Departmental Scholarship Application Committee, and the Student Social Activities Committee. Curl is also faculty advisor for the Student Chapter of ASLA and assists the student group in the planning efforts of our annual LA Days spring lecture series. She also holds a position on the Steering Committee for the new CSU Richardson Design Center which is to be built by spring 2019 semester.



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# Water Calendar

## May

### 15-17 **Environmental Leader and Energy Manager Conference; Denver, CO**

This conference will provide the opportunity for individuals to learn how large enterprises are solving today's complex problems in energy management and corporate environmental sustainability. [conference.environmentalleader.com/](http://conference.environmentalleader.com/)

### 16 **Denver Metro Water Festival; Denver, CO**

An opportunity to volunteer or present water-related information to 6th grade students in the Denver metro area. [denvermetrowaterfest.org/](http://denvermetrowaterfest.org/)

### 23-25 **5th Water India Expo; New Delhi, India**

An event created to show case products, services, and solutions available in the water industry. [waterindia.com/](http://waterindia.com/)

### 29 - June 1 **Society of Wetland Scientists' 2018 Annual Meeting; Denver, CO**

The program will focus on the intercommunication of the most recent developments in wetland science, practice, and policy between the different sectors of SWS. The meeting forum will encourage collaboration and partnerships among wetland researchers, practitioners, managers, and policy makers, with the overall goal of improving wetland science [swsannualmeeting.org/](http://swsannualmeeting.org/)

## June

### 3-7 **World Environmental and Water Resources Congress; Minneapolis, MN**

Join leading environmental and water resource professionals to discuss the latest topics in water resources. [ewricongress.org/](http://ewricongress.org/)

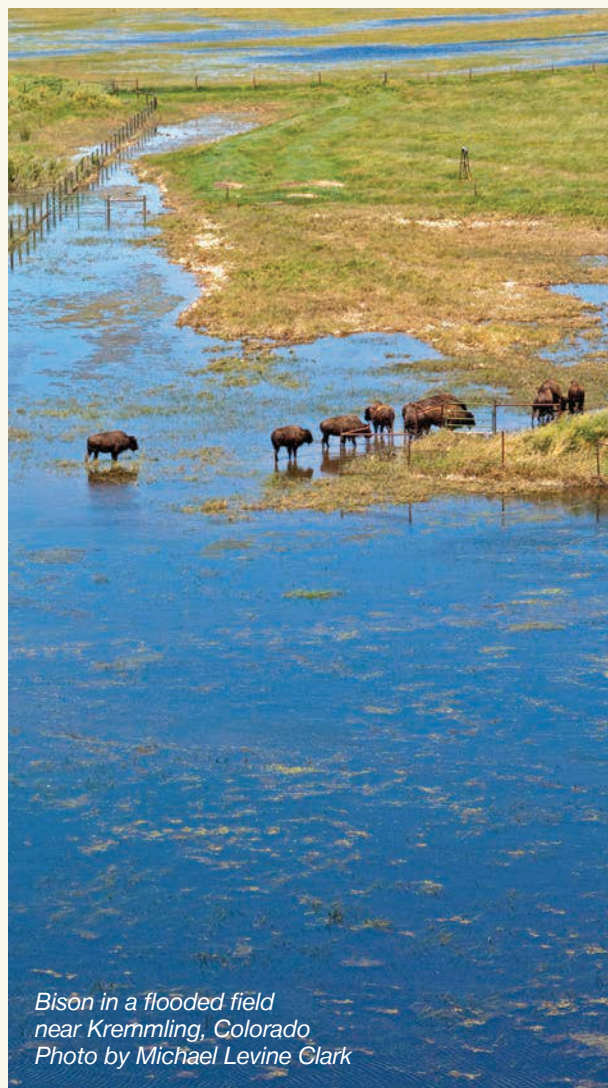
### 24-28 **9th International Congress on Environmental Modelling and Software (iEMSs); Fort Collins, CO**

The 2018 congress is themed "Modelling for Sustainable Food-Energy-Water Systems" with an objective to foster the exchange of ideas and solutions leading to methods and techniques for managing these systems effectively and efficiently. [iemss2018.engr.colostate.edu/](http://iemss2018.engr.colostate.edu/)

### 26-28 **2018 Universities Council on Water Resources/ National Institutes of Water Resources Annual Water Resources Conference; Pittsburgh, PA**

This joint-annual conference offers the opportunity for participants to learn how water is constantly changing the environment [ucowr.org/conferences/2018-ucowr-conference](http://ucowr.org/conferences/2018-ucowr-conference)

For more events, visit [www.watercenter.colostate.edu](http://www.watercenter.colostate.edu)



*Bison in a flooded field  
near Kremmling, Colorado  
Photo by Michael Levine Glark*



# Water Research Awards 8/31/17 — 11/6/17

**Andales, Allan A.**, Colorado Water Conservation Board, Determination of Consumptive Water Use of Winter Wheat in the Arkansas Valley (Year 2), \$50,178

**Andales, Allan A.**, U.D. Department of Agriculture-Agricultural Research Service, Understanding Water Use and Plant Responses of Crops Due to Deficit Irrigation, \$87,300

**Bailey, Ryan T.**, Colorado Department of Public Health and Environment, Selenium Characterization and Modeling for the Lower Arkansas River Basin, \$134,987

**Cabot, Perry E.**, Colorado River Water Conservation District, Measuring Consumptive Use for Alfalfa and Grass Hayfields Using Reflectance-Based Methods at Ground Surface, \$29,514

**Dell, Tyler A.**, Colorado Department of Transportation, CDOT Permanent Stormwater BMP Inspection and Maintenance Training, \$26,265

**Dell, Tyler A.**, City of Fort Collins, Stormwater Research Activities for the City of Fort Collins, \$23,000

**Dell, Tyler A.**, Colorado Stormwater Council, Winter Stormwater Chloride Deicing Study, \$10,000

**Gates, Timothy K.**, Colorado Water Conservation Board, Hydrologic and Water Quality Data Collection in Colorado's Upper Arkansas River Basin, \$9,430

**Ojima, Dennis**, Department of the Interior—U.S. Geological Survey, Evaporative Demand, Drought Monitoring and Assessment Across Timescales, \$99,950

**Parton, William J.**, University of Nebraska, National Drought Mitigation Center, University of Nebraska Lincoln Drought Information Services and Research for Agriculture Across the United States, \$24,750

**Schumacher, Russ S.**, Department of the Interior—Bureau of Reclamation, Colorado Weather Station Operation and Maintenance, \$22,500

**Simpson, Rodney, T.**, Battelle Memorial Institute, Water Chemistry Laboratory Analysis, \$99,660

## USGS Recent Publications



**Methane and benzene in drinking-water wells overlying the Eagle Ford, Fayetteville, and Haynesville Shale hydrocarbon production areas;** 2017, Environmental Science and Technology, 51(12) 6727-6734; P.B. McMahon, J.R.B. Barlow, M.A. Engle, K. Belitz, P.B. Ging, A.G. Hunt, B.C. Jurgens, Y.K. Kharaka, R.W. Tollett, T.M. Kresse

**Peak discharge, flood frequency, and peak stage of floods on Big Cottonwood Creek at U.S. Highway 50 near Coaldale, Colorado, and Fountain**

**Creek below U.S. Highway 24 in Colorado Springs, Colorado;** 2016, U.S. Geological Survey Scientific Investigations Report 2017–5107; 58, M.S. Kohn, M.R. Stevens, A. Mommandi, A.R. Khan

**Precipitation, streamflow, suspended-sediment, and water-quality data for the U.S. Army Garrison Fort Carson and Piñon Canyon Maneuver Site, Colorado;** 2017, U.S. Geological Survey Open File Report 2017-1072; 130, L.R. Arnold



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A C-130 Hercules equipped with a Modular Airborne Fire Fighting System supporting fire suppression efforts near Colorado Springs, Colorado



Photo by Staff Sgt. Stephany D. Richards, U.S. Air Force

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## An Overview of Drought Monitoring Indicators and Resources for Colorado

### Further Reading and Additional Resources

- Handbook of Drought Indicators and Indices  
<http://drought.unl.edu/Planning/Monitoring/HandbookofDroughtIndices.aspx>
- Drought Monitoring with the U.S. Drought Monitor (Video, 6 minutes)  
<https://www.youtube.com/watch?v=i7F6QwRqyVI>
- NIDIS Intermountain West Drought Early Warning System  
<https://www.drought.gov/drought/dews/intermountain-west>
- Colorado Water Conservation Board – Drought Planning Toolbox  
<http://cwcb.state.co.us/technical-resources/drought-planning-toolbox/Pages/main.aspx>
- National Drought Mitigation Center – Drought Planning Resources  
<http://drought.unl.edu/Planning.aspx>