

# Colorado Water

March/April 2019

## Data-Driven Water Management

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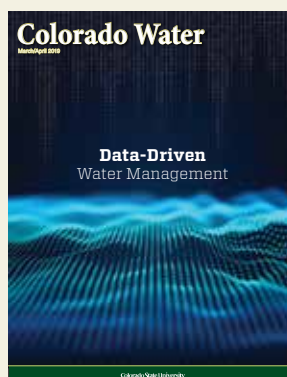
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*On the cover—New and emerging technologies increasingly allow water managers to collect and analyze large volumes of data, which may in turn improve the quality and quantity of our water resources in Colorado and beyond. Illustrations © iStock.com*

References can be found in the online version of this newsletter at <http://cwi.colostate.edu/newsletters.asp>

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# COLORADO WATER

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## Director's LETTER



Management guru Peter Drucker is often quoted as saying, “you can’t manage what you can’t measure.” Certainly, we can—and do—measure our water resources in Colorado, but the quest for more effective and accurate water data continues. Our challenge is to transform water quantity and quality data into information reliable enough for evaluating solutions and making informed decisions. Data collection consumes time and financial resources, yet investing in such efforts is critical to understanding current conditions and trends in our water supply, water quality, and the risks

associated with drought, flood, fire, over-appropriation, and pollution.

The standard approach to generating water data is to collect point data—whether at a stream gauge or SNOTEL site. Point data, while useful and generally reliable for a given parameter in space and time, has its limits. For example, should water managers rely on a few SNOTEL sites in or near their particular river basin to make critical reservoir fill-and-spill decisions, particularly when snowpack dynamics seem to be changing?

The field of data science is in the midst of a revolution, with new data acquisition tools rapidly coming online such as low-cost sensors, the internet of things (IOT), geospatial tools and satellite data, smartphone apps, and other tools. This digital data tsunami alone will not result in better management; we must transform data into clearly communicated information that is timely and reliable in order to make better decisions. Data science has recently emerged as a separate field of study in response to the avalanche of data from web-enabled sensors and the availability of cloud computing power for data storage and analysis. Several Colorado universities, including CSU, are now offering new degree programs in data science, and it can be expected that we will continue to develop and discover new approaches to the collection and analysis of data that can help water managers.

Much of data science is routine and goes largely unnoticed. It requires the continual operation and maintenance of networks and the concomitant funding. The USGS stream gaging network, CoCoRaHS, and CoAg-Met are examples of critical data infrastructure that continually struggle just for baseline funding for upkeep, much less improvement. The importance of precipitation and snowpack measurements to forecasting water supply and early detection of flood or drought risk should be an easy sell, but it is not. Routine data collection for drinking water protection, aquifer recharge, legacy pollutants such as abandoned mines, and watershed wildfire vulnerability seems obvious to water professionals but rarely reaches the level of public interest until the inevitable but random disaster occurs.

The advent of remote sensing, low-cost environmental sensors, and crowd-sourced data are important innovations that allow the collection of many more data points in both time and space. Combined with geospatial tools and models, they allow water managers to display and information in more accessible, real-time formats—increasing public understanding of complex issues. In general, geospatial data from remote sensing is only as good as the on-the-ground measurements against which it is calibrated, and crowd-sourced data must also be subjected quality control measures to ensure reliability. Nonetheless, the advent of “big data” analysis tools can help us spot trends, outliers, and risks much sooner than sparser point data. Organizations such as the Open Water Foundation and collaborative public data networks such as CoCoRaHS and Streamtracker increase the accessibility of and public interest in routine water data by engaging non-technical audiences in the process and using the results to create user-friendly, interactive data displays. This issue of *Colorado Water* reports on several ongoing projects that illustrate some of the promising applications of data science on water management.

*Reagan Wasson*

Director, Colorado Water Center



# Estimating Impacts of Salinity on Irrigated Crop Production using Electrical Conductivity Surveys and Multi-level Remote Sensing

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## ▼ SYNOPSIS

The Lower Arkansas River Valley in southeast Colorado has been a productive agricultural area since the 19th century, but over time, increased water table elevations and soil salinity have reduced crop yields. While the installation of subsurface tile drainage systems have helped alleviate these problems, the effectiveness of such systems is not yet well understood. This case study, conducted in the Fairmont Drainage District in Otero County, used geospatial technologies to better facilitate salinity and crop data collection.

The Lower Arkansas River Valley (LARV) in southeast Colorado has been a productive agricultural area since the introduction of extensive surface irrigation in the 19th century. However, like many irrigated regions around the world, excessive water application and canal seepage, in conjunction with underlying salt-laden geologic formations, have increased water table elevations and soil salinity, which in turn have reduced crop yields (Morway and Gates, 2012). Subsurface tile drainage systems were installed in the early 20th century and are managed by Drainage Districts (Daly, 2017) to help alleviate these problems. The Fairmont Drainage District (FDD) in Otero County, CO, comprises one of these drainage systems and is still functioning well after a century of use.

Although crop yield reductions and corresponding soil salinity measurements have been collected in many fields in the LARV (Morway and Gates, 2012), their severity and variability within tile-drained surface irrigated

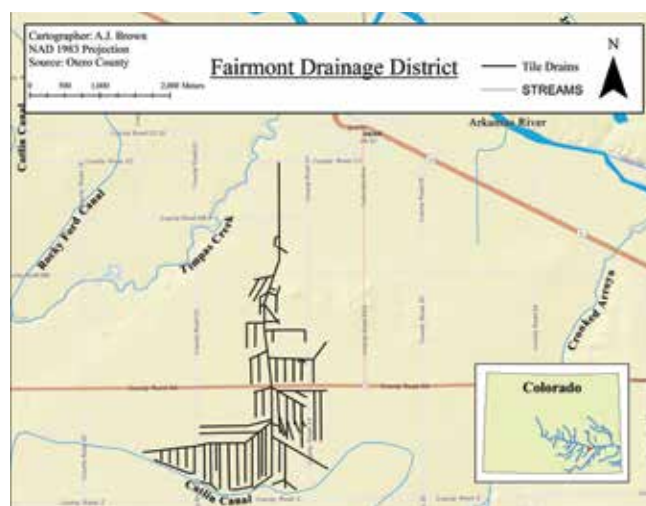


Figure 1. Map of the Fairmont Drainage District in the Lower Arkansas River Valley of Colorado. Map by A.J. Brown.

farms are not well understood. The goal of this ongoing study is to apply modern technologies at field and regional scales and, in turn, to boost this understanding in order to find better ways to control these problems. The FDD was selected as a case study (Figure 1). Given the size of the FDD tile drainage network (approximately 1,000 acres), we are using geospatial technologies including electromagnetic induction (EMI) surveys, internet of things (IoT) technology, and remote sensing to facilitate salinity and crop data collection. These geospatial techniques are being ground-truthed with intensive soil, water, and crop yield sampling from selected fields within the FDD.





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### EMI surveys for mapping severity of soil salinity across the FDD

The EMI field surveys were done to map apparent soil electrical conductivity ( $EC_a$ ; 0-1.5 m depth), which increases with increasing salt concentration in the soil water. Surveys were performed using a Geonics EM38-MK2 ground conductivity meter and a global positioning system (GPS) unit, both connected to a field computer (Figure 2). Georeferenced  $EC_a$  data were continuously recorded as operators walked along transects across each field. Measured  $EC_a$  values were processed with the Electromagnetic Sampling Analysis and Prediction (ESAP) software program to identify locations for sampling soils to estimate the EC of extractable water from saturated soil paste ( $EC_e$ ). A calibration equation was developed using  $EC_a$  to estimate  $EC_e$  values that were then used to create a spatial map of salinity (Figure 3). Ongoing research focuses on expanding the calibration procedure to regional levels using advanced statistical regression techniques.

Some corn fields were also instrumented with flumes to measure flows of applied irrigation water and tail water, and water quality measurements were made. Data loggers were fitted with custom built IoT cellular data microcontrollers, and soil sensors were installed to understand soil profile dynamics that influence salinity and crop growth. For example, multi-parameter probes were installed in a corn field during 2016, 2017, and 2018 within selected low (0-4 deciSiemens per meter [dS/m]), medium (4-6 dS/m), and high (6-12 dS/m)  $EC_e$  zones to monitor volumetric water content ( $\theta_v$ ),  $EC_a$ , and soil temperature at 10, 50, and 100-centimeter depths. Corn growth and yield were monitored at the probe locations over the growing season. Water table levels were measured in monitoring wells installed at the perimeter of each field. The  $\theta_v$  time series indicated that the high  $EC_e$  zones had prolonged exposure to saturated root zone conditions, influenced by shallow water table depths (0.34-2.85 m below ground surface). Average corn grain yields were 16,000, 12,000, and 8,000 kilograms



Figure 2. Kainat Kalhoro, exchange student from the US-Pakistan Center for Advanced Studies in Water, conducting an EMI survey of an alfalfa field using a Geonics EM38-MK2 meter and GPS unit. Photo by A.J. Brown.

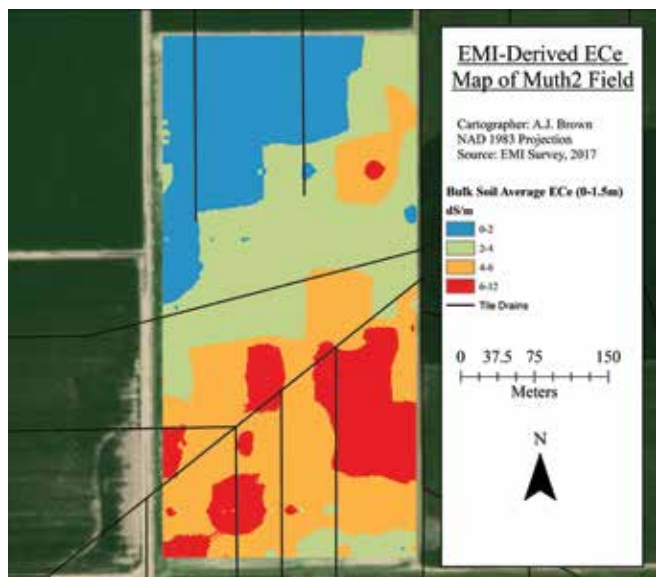


Figure 3. Example  $EC_e$  map of a field in the FDD. The map shows the spatial distribution of average salinity in the 0-to-1.5-meter soil profile. Map by A.J. Brown





Figure 4. Contrasting size of corn ears from a low- versus high-salinity zone in a corn field of the FDD. Photo by A.J. Brown

per hectare (kg/ha) within the low, medium, and high  $EC_e$  zones, respectively. Corn yields varied spatially with the severity of soil salinity and water logging, diminishing by as much as 50% in the high salinity zones.

### Correlating soil salinity with crop yields

The electrical conductivity of extractable water in the soil ( $EC_e$ ) indicates the level of salinity experienced by crop roots. Thus, the spatial distribution of crop yields can be correlated to the spatial distribution of  $EC_e$ . Soil salinity in the crop root zone makes it harder for the root system to take up water (physiological drought due to more negative water pressure). The crop can also experience ion toxicity due to the presence of harmful salts. Figure 4 shows an example of the impact of salts on corn grain yield in a field of the FDD. Using EMI surveys, an attempt is being made to perform regional mapping of crop yields using  $EC_a$  or  $EC_e$  and other factors. During the 2018 growing season, crop yield samples were taken at 165 locations across 10 fields (365 acres) in the FDD where  $EC_a$  also had been measured. Using the same regression tech-

Figure 5. Brian Craig taking readings with the MSR over bare soil. Photo by A.J. Brown.

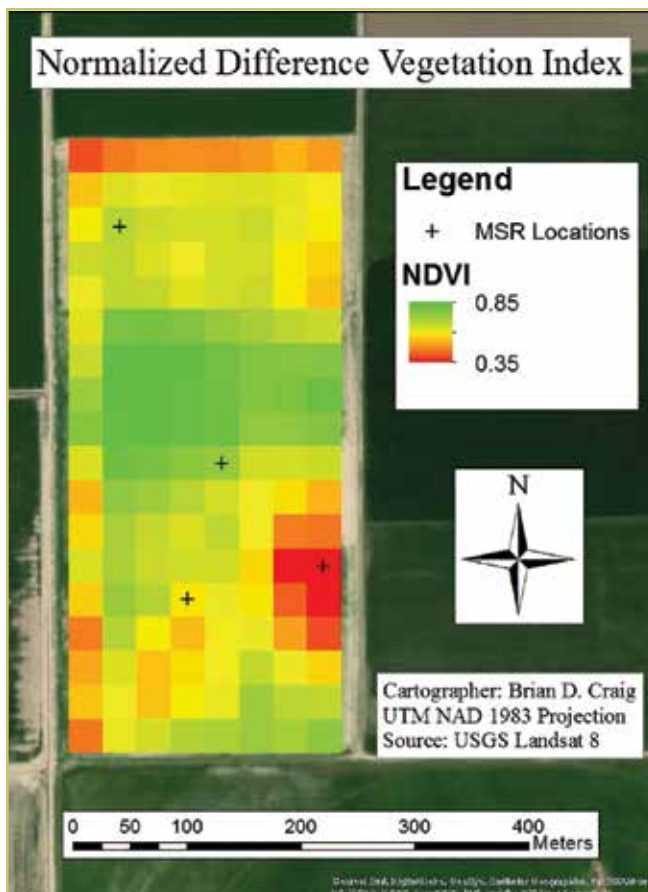


Figure 6. Landsat-derived raster of normalized difference vegetation index (NDVI) with locations of MSR ground-truthing points. Raster graphic by Brian Craig.

niques as mentioned previously, the relationship between crop yields and  $EC_e$  are being studied. Although soil salinity is only one factor that can impact yields, this study could reveal how  $EC_e$  mapping can be used to partially explain the spatial distribution of crop yields and identify areas that could benefit from salinity remediation.

### Multi-level remote sensing for monitoring crop condition and salinity

In this study, Landsat (satellite) images and ground-based radiometry were used to monitor crop response to different levels of soil salinity (e.g.,  $EC_e$  ranging 0.5-10 dS/m) by calculating vegetation indices and crop water use (evapotranspiration, ET). Level 2 Landsat 7 (L7) and Landsat 8 (L8) imagery were downloaded from the U.S. Geological Survey Earth Explorer online platform. Level 2 products are spatially-referenced and converted to surface reflectance (visible and near infra-red [NIR] bands) and surface radiance (visible, NIR, and thermal bands). Bands in the visible (blue, green, red) and NIR portions of the electromagnetic spectrum have a 30-meter spatial resolution. However, the thermal imagery has a spatial resolution of 100 meters. The satellite revisit period is 16 days, with the coverage of a given area by L7

and L8 eight days apart. Thus, provided that the imagery is cloud-free over the study site, there is potential for one satellite scene per week.

Landsat image bands were calibrated with surface reflectance and temperature data collected with a ground-based multispectral radiometer (MSR, Figure 5) from Crop-Scan, Inc. This radiometer has bandwidths like Landsat but reduces atmospheric effects. Landsat Red and NIR were used to produce vegetation indices (VI, Figure 6) that, along with surface temperature images, are used to estimate crop ET under variable soil salinity conditions. Both VI and ET maps are used in linear and non-linear multi-variate regression functions to model soil  $EC_e$  over a large spatial scale.

A network of soil water sensors (CS655, Campbell Scientific, Inc.) were installed within the crop root depth to collect daily  $\theta_v$  values. These data are being employed in a soil water balance method to estimate crop ET for use in evaluating the remote sensing-based ET maps used in the  $EC_e$  modeling effort.

### Future work

Future work will refine the method for predicting  $EC_e$  and crop yield using remotely-sensed data. We aim to expand the model for use with many crop types throughout the Arkansas River Valley and perhaps other similar semiarid regions. We will also focus on accounting for different types of soil salts in estimating salinity effects on crop yields. Traditionally, most crop salinity tolerance thresholds are based on experiments where sodium chloride (NaCl) and calcium chloride (CaCl) are the predominant salts present. The FDD contains primarily gypsum ( $CaSO_4$ ) and carbonate ( $CaCO_3$ ) salts, not as readily dissolved in water as NaCl and CaCl. Converting  $EC_e$  for these gypsiferous and carbonate soils into equivalent values for NaCl and CaCl soils would allow more accurate prediction of crop yield losses. A study similar to ours in the fields of Colorado's FDD is also being carried out in partnership with Pakistani researchers, who are studying salinity-affected irrigated fields of the Indus River Valley in Pakistan's Sindh region.

### Acknowledgements

This project is funded by the U.S. Agency for International Development (USAID) through the U.S.-Pakistan Center for Advanced Studies in Water ([water.muet.edu.pk](http://water.muet.edu.pk)). We appreciate the assistance of farmers Leon Golden and Philip Chavez (Diamond A. Farms), Dr. Michael Bartolo and Lane Simmons at the CSU Arkansas Valley Research Center, graduate student Kainat Kalhoro from Mehran University of Engineering and Technology in Pakistan, and CSU undergraduate student assistants Rustin Jensen, Luke Engler, and Ian Stockdill. 



# WHERE AND WHEN DOES RIVER FLOW ORIGINATE?

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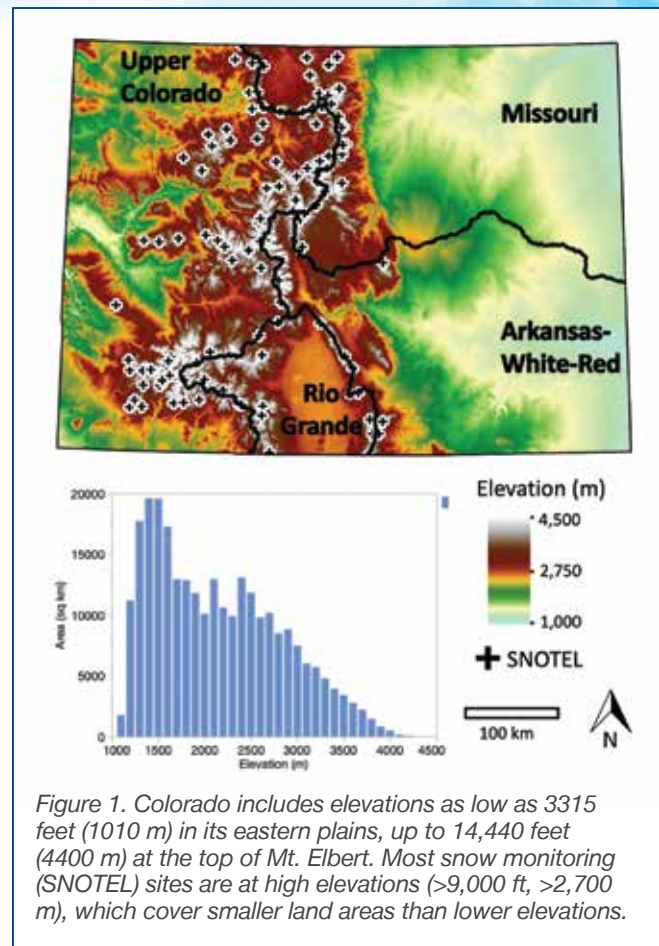
## ▼ SYNOPSIS

Snowmelt is incredibly important to Colorado's water supply, and monitoring stations track snow levels in the high mountains throughout the state. Less attention is paid to snow at lower elevations, despite it being an important source of river flow in some years. To better understand where and when river flows originate—information that is critical to meeting water demands as Colorado's population grows and future water supplies are increasingly uncertain—geospatial technology has been combined with crowdsourced stream data to paint a more comprehensive picture of how the state's watersheds function.

Colorado contains the headwaters of four major rivers, each beginning as small mountain streams fed by melting snow. Because of the importance of snow to our water supply, an extensive network of National Resources Conservation Service snow telemetry (SNOTEL) stations monitors snow in the high mountains throughout the state (Figure 1). The focus on high mountain snow has sometimes led researchers and water managers to pay less attention to lower elevations. Lower elevations do not have as much snow in the winter, but they cover much larger areas than the high mountain peaks and can be important sources of river flow in some years. As the state plans for growing population and uncertain future water supplies, a better understanding of where and when river flow originates can help managers protect critical water supply source areas. Geospatial technology provides many useful tools for examining rivers and their source watersheds. Here we highlight two examples: (1) using snow cover images from the MODIS (or Moderate Resolution Imaging Spectroradiometer) satellite sensor to map snow patterns and water yield and (2) using crowdsourced observations of headwater streams to identify which parts of watersheds contribute water to large rivers at different times of year.

### Snow and water yield

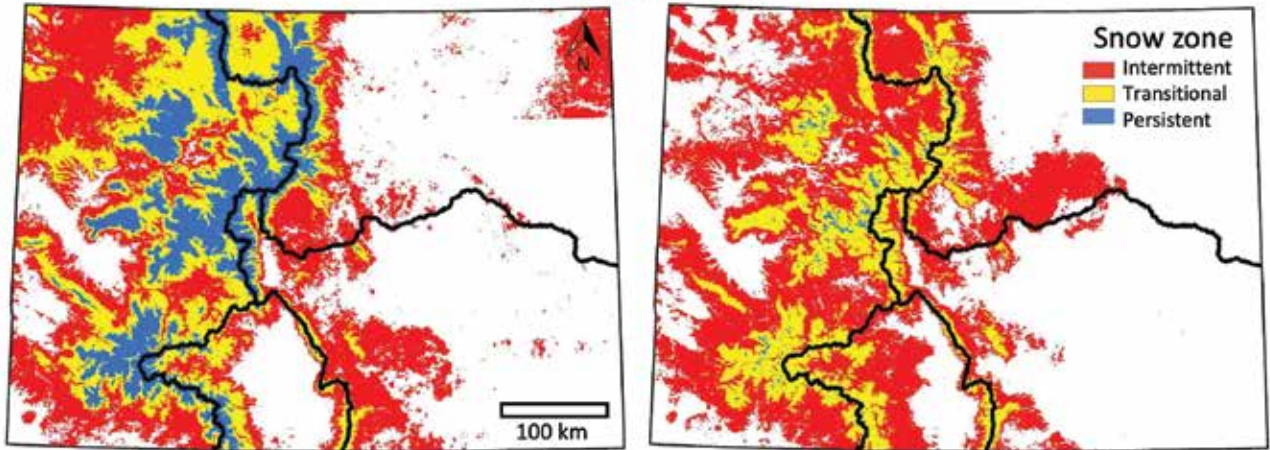
Since 2000, the MODIS satellite sensor has taken daily images across the globe that allow us to see where and when snow is on the ground. The persistence of snow on



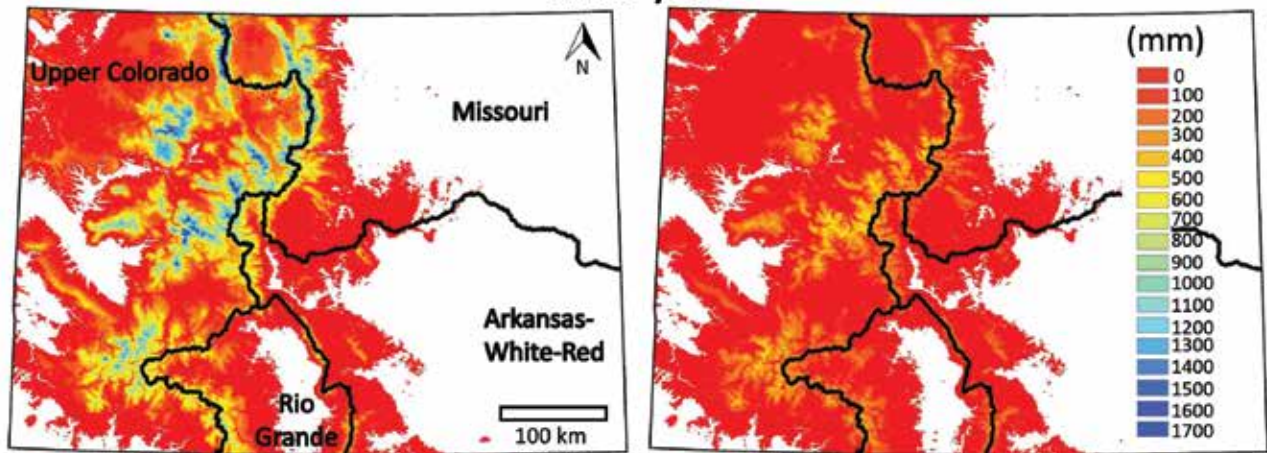
the ground, meaning how long it stays before melting, has a high correlation with annual total water yield in Colorado (Hammond et al. 2018), so we can use snow patterns to estimate how much streamflow is produced across the state. For example, during 2011, when most of the high mountains in Colorado had persistent snow that lasted until mid-May or later, some of the highest snow areas produced an estimated three feet of runoff, and statewide water yield was an estimated 30 million acre-feet (37 km<sup>3</sup>) (Figure 2). In 2012, which was a low snow year, very few parts of the state had persistent snow, with most parts of the state snow-free in April or earlier (transitional and intermittent snow). This led to less than half the 2011 water yield across all elevations, with estimated statewide water yield around 12 million acre-feet (15 km<sup>3</sup>).



### Snow persistence



### Water yield



2011

2012

Figure 2. Snow persistence and water yield for a high snow year (2011) and a low snow year (2012). Snow persistence is from the MODIS satellite sensor and is shown as snow zones, where the persistent areas have snow that lasts until mid-May or later; transitional areas have snow that lasts until early April; and intermittent areas have snow that does not stay continuously on the ground through the winter. Water yield is predicted from snow persistence using relationships developed for stream gauging stations in Colorado (Eurich data, Kampf et al. 2018).

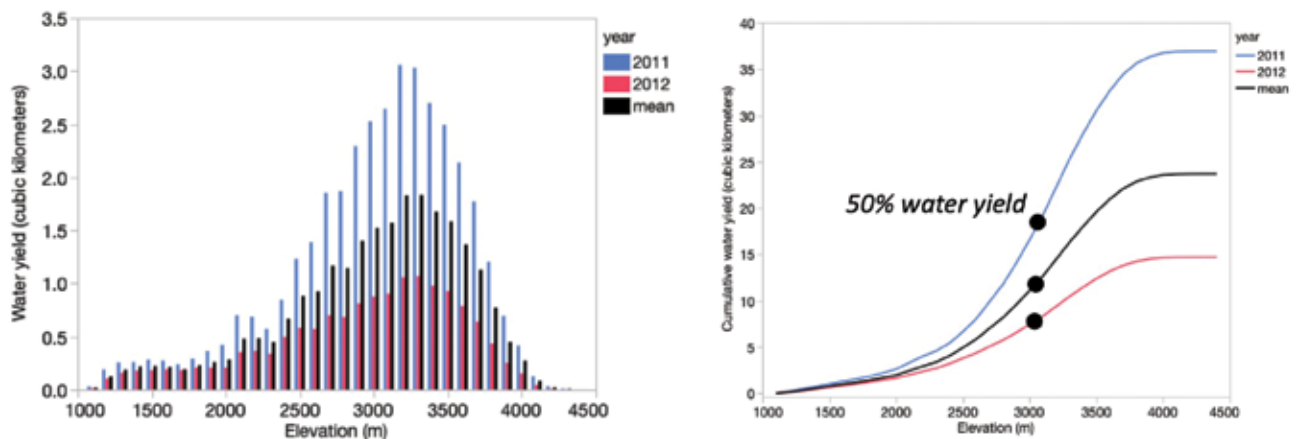


Figure 3. Estimated water yield produced by elevation across Colorado in water years 2011 and 2012 and the average water yield from 2001-2018. Elevations between 3,000-3,500 meters produce the highest water yield by volume (left), but lower elevations are also important contributors to water yield, with half of the statewide water yield coming from elevations less than around 3,000 meters (black circles, right).



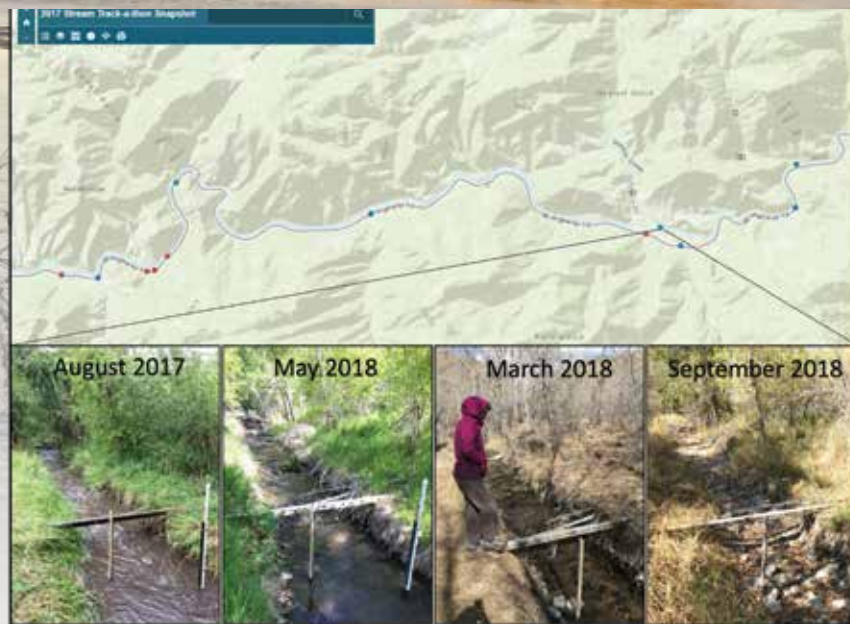


Figure 4. Snapshot of Stream Tracker monitoring points on tributaries to the Cache la Poudre River. Red dots indicate tributaries that were dry in September 2017, and blue dots indicate tributaries that were flowing. These points are displayed on an ESRI webmap linked through [streamtracker.org](http://streamtracker.org). Lower photos show one site, Hewlett Gulch, with high flow and turbid water after a summer thunderstorm, clear high flow during snowmelt, low flow before snowmelt, and a dry channel in September 2018. These photos and data are publicly accessible through the Stream Tracker project on [CitSci.org](http://CitSci.org).

High elevations are clearly important sources of streamflow across the state, with peak water yield generation at around 10,000-11,500 feet (3,000-3,500 m). However, about half of the estimated total water yield comes from lower elevations, particularly areas above 6,500 feet (2,000 m) (Figure 3). This means tracking snow conditions and streamflow in lower elevation areas is important for water supply planning, particularly because these areas may be most sensitive to warm winter temperatures. Even though SNOTEL stations are concentrated at high elevations, we can use geospatial technology to estimate streamflow contributions from lower elevations and identify priority areas for ground monitoring.

### Crowdsourcing data on headwater streams


Snow does not tell the full story of where river flow originates. On the ground, each of the thousands of headwater streams in Colorado is unique, and we have little if any information on flow conditions in most of these streams. This monitoring challenge led to the Stream Tracker project ([streamtracker.org](http://streamtracker.org)), a community monitoring network that focuses on crowdsourcing information about whether or not headwater streams are flowing. Volunteers can navigate to streams using a GPS unit or a mapping application on their mobile phone (Figure 4), then enter stream data either on their mobile phone or on the project website. Observers record whether they see flowing water, standing water, or a dry channel and are able to document their observation with a photo. When

these observations are entered frequently for headwater streams located throughout larger watersheds, they begin to reveal which parts of watersheds are supplying the water that reaches larger rivers. The expanding Stream Tracker network of over 470 volunteers now tracks more than 860 individual streams, 440 of which are in Colorado. This growing dataset of flow conditions can be used to improve maps, indicate where flow originates in headwater channels, and track how flow conditions vary between seasons and years.

### Connecting the pieces

Geospatial technology allows us to connect satellite imagery with on-the-ground measurements of streams to build a comprehensive understanding of how watersheds function, from the scale of large river basins down to small headwater tributaries. Statewide analysis reveals broad patterns of where river water originates, while measurements on the ground document the small streams that deliver this water to larger rivers. Both statewide snow products and small stream data are publicly accessible, and anyone is welcome to join Stream Tracker and help document the conditions of Colorado's headwater streams.

### Acknowledgements

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# Mapping Extreme Cities

## The Quest for Effective Water Data

Melinda Laituri, Ecosystem Science and Sustainability and Geospatial Centroid, Colorado State University

### ▼ SYNOPSIS

Extreme cities are urban environments that exhibit stark economic and environmental inequality. Access to clean water is often a challenge in these places, as are the threats of flooding and drought. The Secondary Cities Initiative works to better understand extreme cities and uses open-source geospatial technologies to collect data on these unique environments, which are typically poorly mapped and have limited information on infrastructure, land tenure, planning, and water resources. This data, in turn, can reveal information gaps around water in extreme cities and inform solutions and decision-making for more sustainable and resilient water resources management.

“Extreme cities” refer to urban environments that exhibit stark economic and environmental inequality and stratification of race, class, gender, and access to basic resources (Dawson 2017). Extreme cities are a product of multiple factors, including rapid growth, inadequate infrastructure, changing environmental conditions, and increasing vulnerable populations. An aspect of access to basic resources is water security—in-

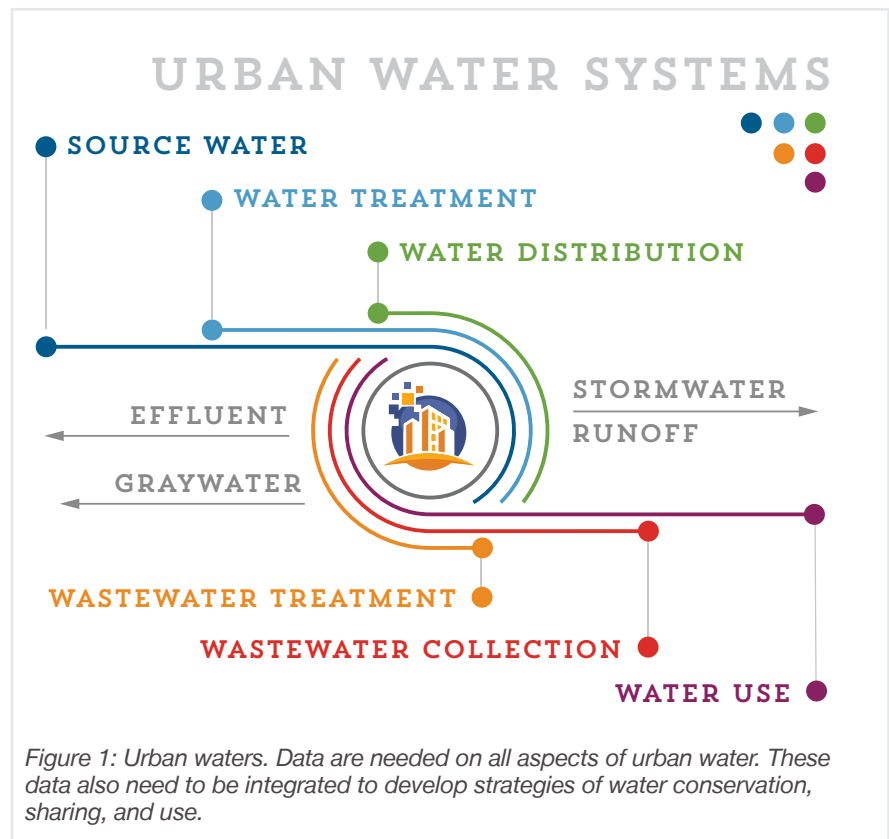


Figure 1: Urban waters. Data are needed on all aspects of urban water. These data also need to be integrated to develop strategies of water conservation, sharing, and use.

clusive of infrastructure for both supply and quality. However, water can also be a primary driver in unsafe city landscapes (i.e., too much water due to extreme weather causes flooding, and too little water creates drought). Integrated thinking for holistic, water-wise management is essential for extreme cities. As cities take center stage in the 21st century, water

management becomes more critical and central to sustainability planning (Purdy 2015). Key to understanding extreme cities is the need to effective and appropriate water data for urban water systems (Figure 1).

The Secondary Cities (2C) Initiative ([secondarycities.state.gov](http://secondarycities.state.gov)) provides a platform to examine extreme cities. Focusing on 16 cities around

Table 1: 2C Project Topics

2C City	Project Topic
Boke-Kamsar, Guinea	Urban planning
Cusco, Peru	Urban flows and emergency preparedness
Darkhan, Mongolia	Waste management
Denpasar, Indonesia	Oceanic waste management
Douala, Cameroon	Flooding and emergency preparedness
Esmeraldas, Ecuador	Water quality and water security
Indore, India	Health and well-being
Kharkiv, Ukraine	Urban springs and safety
Medellin, Colombia	Urban flows and city growth
Mekelle, Ethiopia	Water accessibility and planning
Pemba, Mozambique	Vulnerable populations and resource accessibility
Pokhara, Nepal	Disaster management and emergency preparedness
Port Harcourt, Nigeria	Vulnerable populations and resource accessibility
Santa Fe, Argentina	Flooding and vulnerable populations
Santiago de los Caballeros, Dominican Republic	Water management in vulnerable neighborhoods
Tijuana, Mexico	Waste management

Cusco, Peru © iStock.com

the world, the 2C Initiative uses open-source geospatial technologies to collect data needed for emergency preparedness, human security, and resiliency. These secondary cities exhibit many characteristics of extreme cities; they are the fastest growing urban areas in low-income countries, experiencing unplanned growth and development (Roberts, 2014). These cities are unique environments that have generally been poorly mapped, with limited data and information on infrastructure, land tenure, planning, and notably, water. Data derived about these cities provide the basis for comparison, where the urban ecologies of these cities (e.g., modified hydrology, urban fauna, and transportation networks) have more in common than their unique surrounding geographies.

Geographic information science is the platform for a place-based assessment of water data needs and how these data can inform solutions and decision-making. The process of transforming data into information into action provides the fundamental building blocks for long-term monitoring, sustainability planning (Hamilton & Price 2017), and meeting Sustainable Development Goal 6—ensuring the availability and sustainable management of water and sanitation for all ([sustainabledevelopment.un.org/sdg6](https://sustainabledevelopment.un.org/sdg6)). Using the 2C cities, current urban water issues and solu-

tions are examined through the lens of available data and remotely sensed data.

Project partners have generated data about their cities, focusing on a specific issue relevant to their cities (Table 1). These projects emphasize vulnerable populations—those who have limited or no access to resources and are often outside the built infrastructure of the city. All projects are closely linked with water-related issues that include water supply and quality, exposure to flooding and water-induced health risks, access to water resources, and waste management issues that often exacerbate water quality issues. Project partners collect data using open source tools and apps on smart phones and tablets, building geospatial data in concert with local government agencies. For many of these cities, the data may supplement their existing digital databases, many of which are often limited in scope and spatial extent. The 2C project provides a venue to enhance training, education, and capacity-building for both students and government personnel to improve local urban water data.

Preliminary results from the 2C Initiative are promising in how these data can be used for urban planning. In Douala, Cameroon, an analysis was conducted on the relation-



Figure 2: Douala, Cameroon, school location in floodplain.



Figure 3: Esmeraldas, Ecuador, neighborhood and point source pollution location with water quality data.

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## Focusing on 16 cities around the world, the 2C Initiative uses open-source geospatial technologies to collect data needed for emergency preparedness, human security, and resiliency.

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ship of the location of schools across the city and scenarios of sea level rise. As a coastal city, Douala's land managers are pondering how sea level rise, flood plains development, and local flooding events impact school locations and policies for climate change adaptation (Figure 2). In Esmeraldas, Ecuador, data are collected on sources of water pollution and water quality testing (Figure 3). These data have proven useful in comparing neighborhoods and their access to water resources. Denpasar, Indonesia, has generated data on waste management—mapping waste streams to better understand how to reduce oceanic waste. Kharkiv, Ukraine, partners developed a dataset of urban springs throughout the city and implemented a water quality testing program.

Urban water data are critical datasets for extreme cities in which planning, policy, and prediction are essential for the future. The 2C Initiative demonstrates the importance of collecting comprehensive local data for rapidly growing cities, where issues of water security are central to the following activities: 1) utilization of satellite imagery for change detection analysis of city growth and development over time; 2) establishment of a network of trained

data collectors; and 3) integration of global datasets to complement local data and improve predictive analyses. The increasing availability of satellite imagery and aerial photography (through unmanned aerial vehicles) are game-changers in developing data that are locally and regionally relevant for long-term planning and development.

The next stage of the 2C Initiative focuses on identifying data needed for addressing solutions for urban development. In 2010, Circle of Blue, a non-governmental organization, surveyed 1,200 international experts around the world to identify the top solutions to the global water crisis. While not all of the solutions are spatial, many are: water conservation, wastewater recycling, desalination plants, water catchment harvesting, rainwater harvesting, ecosystem management, urban forests, improved infrastructure distribution, identifying water footprints, and identifying sources of water pollution—to name a few. These solutions can be mapped, and stakeholders can identify where and how they can be implemented. The global freshwater solutions can be mapped for each city and recommendations for future water planning identified. 



# the water paradox

## ▼ SYNOPSIS

Ample scientific evidence points to over-use and scarcity of freshwater resources around the world, but these problems persist due to inadequate and poor water management. To avoid further crises, water managers and policymakers must redesign water governance. Such efforts must ensure that governing regimes and institutions have the capacity to adapt to the changing conditions of water availability and competing demands; they should also bring an end to the underpricing of water.

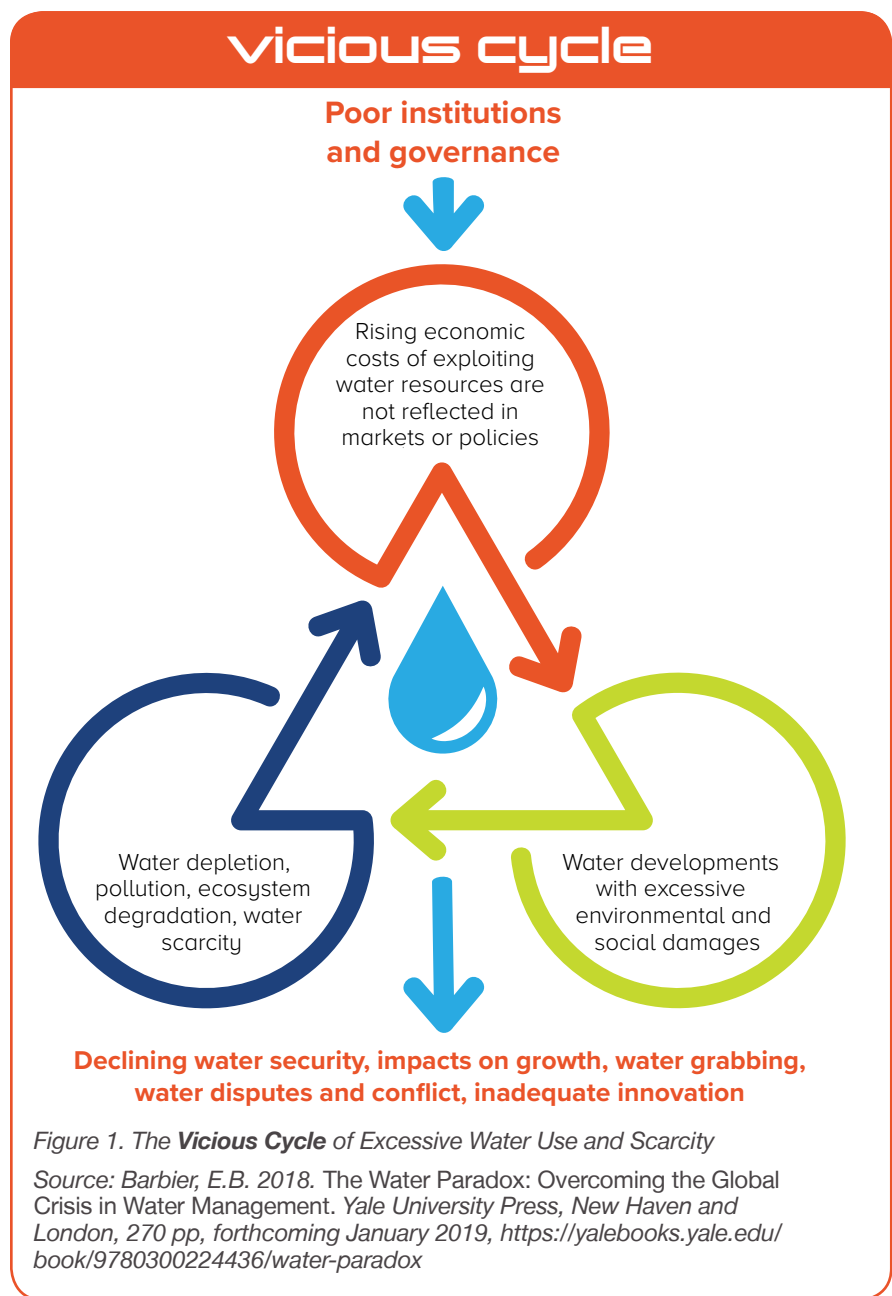
Edward B. Barbier, Economics,  
Colorado State University

If water is valuable and scarce, why is it so poorly managed?

When the history of the early 21st century is written, scholars will be perplexed by a puzzling paradox. With overwhelming scientific evidence pointing to growing over-use and scarcity of freshwater, why did the world not mobilize its vast wealth, ingenuity, and institutions to avert this crisis?

Explaining this water paradox—and offering possible solutions to resolve it—is the purpose of a recent book I have written. *The Water Paradox: Overcoming the Global Crisis in Water Management* (Barbier, 2018).

## Can We Act to Save a Scarce Resource?



The main message is straightforward: the global water crisis is predominantly a crisis of inadequate and poor water management.

In the near future, many countries, regions, and populations may face the rising costs of exploiting additional water resources, potentially constraining growth as well as making it increasingly difficult to meet the needs of impoverished populations and countries who face chronic water insecurity. If unchecked, water scarcity could increase the likelihood of civil unrest

and conflicts. There is also a risk of disputes over the management of transboundary water sources and “water grabbing” acquisitions.

Already, increasing uses of freshwater supplies are exacting a noticeable toll globally. In recent decades, many countries have experienced a sharp decline in per-capita water availability, which is expected to worsen with growing populations and economies (World Water Assessment Programme, 2012). Global water demand is anticipated to rise significantly, from about 3,500

km<sup>3</sup> in 2000 to nearly 5,500 km<sup>3</sup> in 2050, primarily due to increased use for manufacturing, electricity, and domestic purposes in developing countries (Organization for Economic Cooperation and Development, 2012). As a result, there are potentially billions of people who could be affected by water scarcity in the coming decades, and many will be located in poorer regions of the world. Climate change will also put water supplies at risk, which suggests that continuing economic development and population growth in low and middle-income countries will put even greater stress on available freshwater supplies.

Yet this crisis could be avoided. Inadequate policies, governance, and institutions, coupled with incorrect market signals and insufficient innovations to improve efficiency, underlie most chronic water problems. This process has become a vicious cycle (Figure 1). Markets and policy decisions currently do not reflect the rising economic costs associated with exploiting more freshwater resources. This, in turn, leads to freshwater infrastructure and investments that are accompanied by higher environmental and social damages. These damages are reflected in increased depletion of water resources, pollution, degradation of freshwater ecosystems, and ultimately, rising water scarcity. But because the economic costs of this scarcity continue to be ignored in decision making, the consequences for current and future well-being are underestimated. The end result is what I call the chronic *underpricing of water*, which poor institutions and inadequate governance structures perpetuate.

Unraveling this vicious circle and turning it into a virtuous one is one of the biggest challenges facing humankind. As depicted in Figure 2, it starts with designing water governance regimes and institutions suitable for managing the rapidly

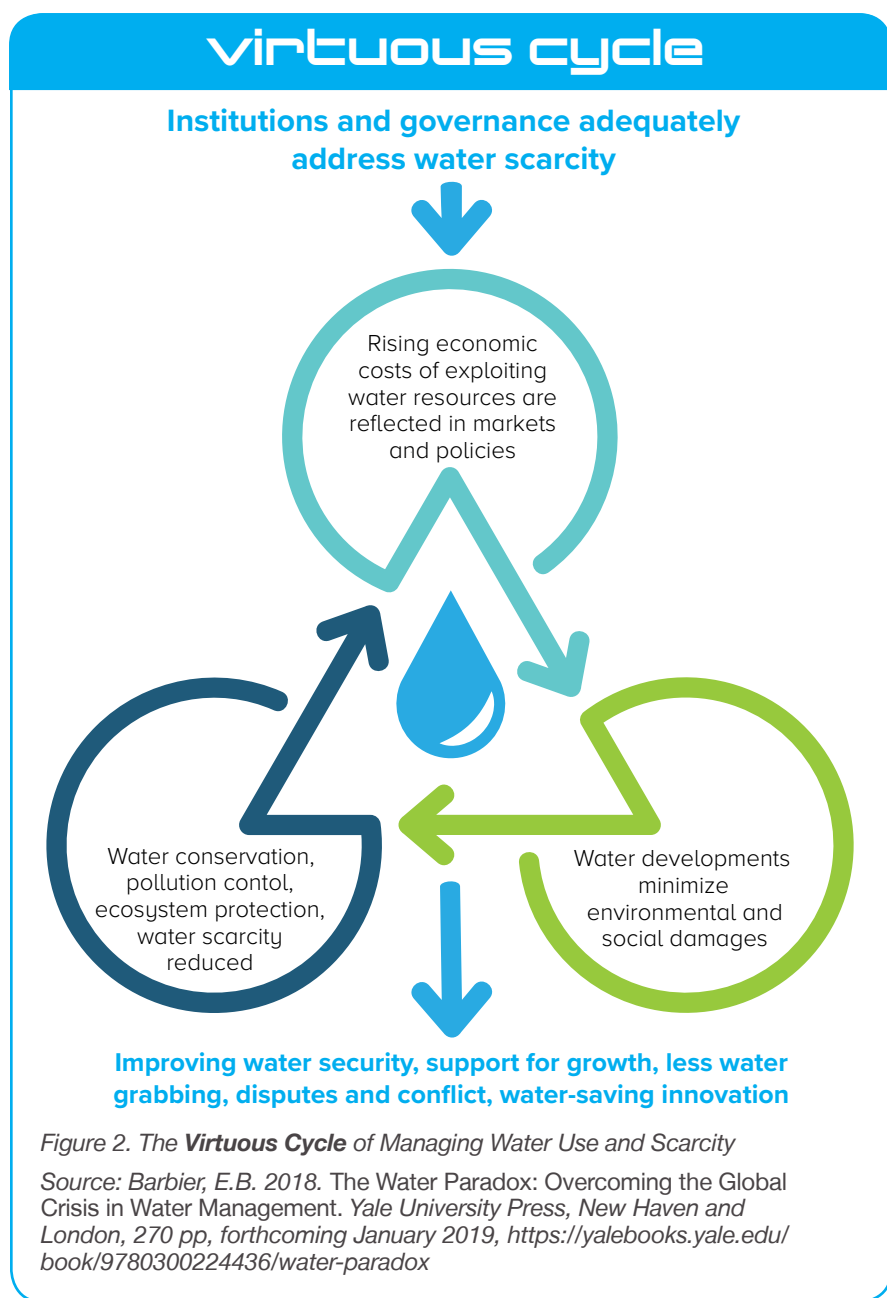


Figure 2. The **Virtuous Cycle** of Managing Water Use and Scarcity

Source: Barbier, E.B. 2018. *The Water Paradox: Overcoming the Global Crisis in Water Management*. Yale University Press, New Haven and London, 270 pp, forthcoming January 2019, <https://yalebooks.yale.edu/book/9780300224436/water-paradox>



Table 1: Comparison of Governance of Four Major River Basins

River basin	River length (km)	Basin area ('000 km <sup>2</sup> )	Catalyst for reform	Key governance features
Colorado, United States and Mexico	2,100	622	Environmental concerns	Multiple jurisdictions that coordinate actions across the basin; limited use of water markets to allocate water between and within states.
Yellow (Huang He), China	5,464	752	Severe drought	Single basin authorities plan and manage water across jurisdictions; top-down water allocations by central government.
Murray-Darling, Australia	2,589	1,061	Severe drought	Single basin authorities plan and manage water across jurisdictions; de-centralized administration and extensive use of water markets to allocate flows.
Orange-Senqu, Botswana, Lesotho, Namibia, South Africa	2,300	973	End of Apartheid in South Africa	Multiple jurisdictions that coordinate actions across the basin; limited use of water markets to allocate flows.

Source: Based on R. Quentin Grafton, Jamie Pittock, Richard Davis, John Williams, Guobin Fu et al. 2013. "Global insights into water resources, climate change and governance." *Nature Climate Change* 3:315-321.

changing conditions of water availability and competing demands, including the threat posed by climate change. Ending the underpricing of water also requires reforms to both markets and policies to ensure that they adequately capture the rising economic costs of exploiting water resources. These costs include not only the full cost recovery of water infrastructure supply but also environmental damages from degrading ecosystems and any social impacts of inequitable distribution. Incorporating these costs will ensure that all water developments will minimize environmental and social impacts, which in turn will lead to more water conservation, pollution control, and ecosystem protection. The result will be an efficient allocation of water among its competing uses, fostering of water-saving innovations, and further mitigation of water scarcity and its costs.

Implementing such solutions is not easy. As I note in *The Water Paradox*, the pricing of water is contentious, and designing and implementing a marketing mechanism for a resource that has long been underpriced pose major challenges.

But rising scarcity and the growing threat of water crises mean that it is time to grapple with these challenges and view pricing and markets as the basis for a new paradigm in water management.


In my book, I cite many signs of progress in the right direction. For example, one study has assessed the strengths and weaknesses of governance efforts to address water scarcity and improvement integration in four critical and large river basins: the Colorado in the United States and Mexico, the Yellow (Huang He) in China, the Murray-Darling in Australia, and the Orange-Senqu in southern Africa (Botswana, Lesotho, Namibia, and South Africa) (Grafton et al., 2013). Table 1 summarizes the key findings.

As Table 1 indicates, governance across the four river basins varies considerably. Nevertheless, the authors of the comparative study conclude that there are five important insights into river basin governance and management that could be useful to all countries:

- » Crises can provide a catalyst for reform.

- » Economic valuation of freshwater ecosystem services is needed to evaluate the trade-offs between consumptive and instream uses.
- » Water management plans should take into account the inherent variability of rivers and streams shared between water users and instream uses for environmental benefits.
- » The use of water markets and trades can help reduce the costs of reallocating water to environmental benefits, especially during times of low in-stream flows.

Centralized and nested water governance structures within basin-wide management institutions can contribute to revisions of water allocations as environmental conditions, scientific knowledge, and societal values change.

Ultimately, ending the underpricing of water means resolving the water paradox. Only through developing efficient, fair, and sustainable institutions, incentives, and innovations can we adequately manage water in a world of growing freshwater scarcity. 

# Improving Water Quality without Injuring Water Rights in the Lower Arkansas River Valley

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## ▼ SYNOPSIS

Pollution from irrigation return flows can be harmful to both the land and the river ecosystem in Colorado's Lower Arkansas River Valley. Concentrated through evapotranspiration processes, pollutants then accumulate in adjacent aquifers and streams. To combat this problem, best management practices have been developed to lower pollutant concentrations and boost agricultural productivity in ways that also conform to regulatory standards and reduce ecological impacts. Geospatial technologies have been developed to evaluate the efficacy of such practices and to identify additional avenues for mitigating future damages to the river basin.

Colorado's Lower Arkansas River Valley (LARV) has been experiencing the damaging effects of waterlogging and salinization, along with high selenium (Se), uranium (U), and nutrient concentrations, both on the land and in the river ecosystem. This pollution arises primarily from irrigation return flows resulting from inefficient irrigation practices and seepage from unlined canals that dissolve elements from subsurface geologic formations. It is then concentrated through evapotranspiration processes and accumulates in adjacent aquifers and streams.

Since 1999, intensive data collection by Colorado State University has focused on a study region upstream of John Martin Reservoir (USR) and another downstream study re-

*The Lower Arkansas River basin pictured near Lamar, Colorado. Photo by Bill Cotton.*





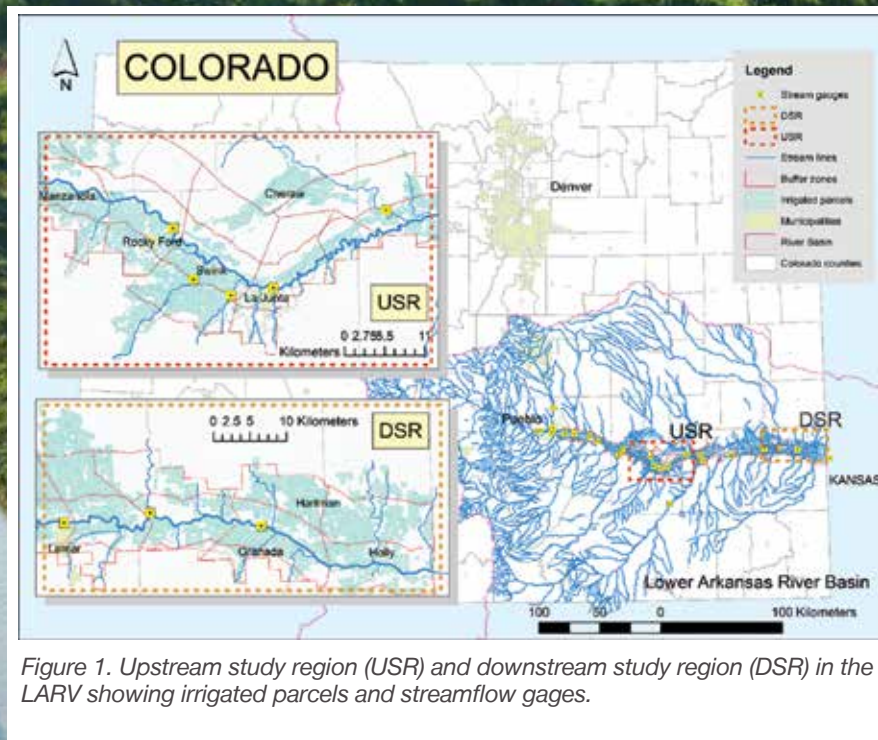


Figure 1. Upstream study region (USR) and downstream study region (DSR) in the LARV showing irrigated parcels and streamflow gauges.

The Lower Arkansas River basin pictured near Lamar, Colorado. Photo by Bill Cotton.

gion (DSR) near the Colorado-Kansas border (Figure 1). Analysis of these data reveal saline shallow water tables and salinized soils that are contributing to an estimated 6% and 17% reduction in crop yields over the USR and DSR, respectively (Morway and Gates 2012). Concentrations of dissolved Se species in groundwater and overland return flows have resulted in designation of all segments of the Lower Arkansas River as “water quality limited” with respect to Se and in their placement on the current Clean Water Act 303(d) list for development of Total Maximum Daily Loads (TMDL).

Gates et al (2016) report measured total dissolved Se concentrations in the USR and DSR as between 1.4 and 3.7 times, respectively, the chronic standard of 4.6 micrograms per liter ( $\mu\text{g/L}$ ) for aquatic life protection. Nitrogen (N) is also a pollutant of growing concern in the LARV, with elevated concentrations of nitrate ( $\text{NO}_3$ ) observed in both LARV surface waters and groundwater, presumably due to over-fertilization of cultivated fields. Median measured concentrations of  $\text{NO}_3\text{-N}$  are about 1.5 mg/l, approaching the Colorado interim standard of 2 mg/l for total N-sampled locations. Possible implications of high  $\text{NO}_3\text{-N}$  concentrations, in addition to the effects on Se, include eutrophication of ecosystems and human health impacts.

### Modeling of Regional-Scale BMPs for Water Quality Improvement

A variety of land and water best management practices (BMPs) have shown potential to lower solute concentrations, boosting agricultural productivity while conforming to reg-

ulatory standards and reducing ecological damage. Some of the most effective practices involve improving irrigation efficiencies and lowering seepage losses from unlined canals using low-cost polymer applications. Evaluation of BMP performance in reducing pollution is based on the USGS saturated-unsaturated groundwater flow models MODFLOW-UZF (Niswonger et al. 2006), which have been calibrated and tested for the USR and DSR (Morway et al 2013).

To describe baseline conditions and explore the prospects for alternative BMPs to reduce the polluting impacts of irrigation return flows (IRF), the USR flow model was used to inform calibrated groundwater-stream reactive transport models, based on RT3D-OTIS, to simulate groundwater concentrations and stream loadings (Tavakoli-Kivi and Bailey 2017; Shultz et al 2018a, 2018b). These linked models have been applied to simulate groundwater concentrations, loading rates to streams, and stream concentrations for Se and N under baseline conditions over the period 1999-2009. Moreover, they have been utilized to explore the potential for alternative BMPs to lower pollutant concentrations toward compliance with regulatory standards and performance goals.

The following BMPs have been examined for various levels of implementation across the study regions: reduced fertilizer application (RF); reduced irrigation application (RI); canal sealing to reduce seepage (CS); rotational lease-fallowing of irrigated land (LF); enhanced riparian buffers (ERB); and various combinations of these BMPs. Results from numerous simulations using MODFLOW-SFR2 (which links MODFLOW-UZF with the streamflow routing package) and



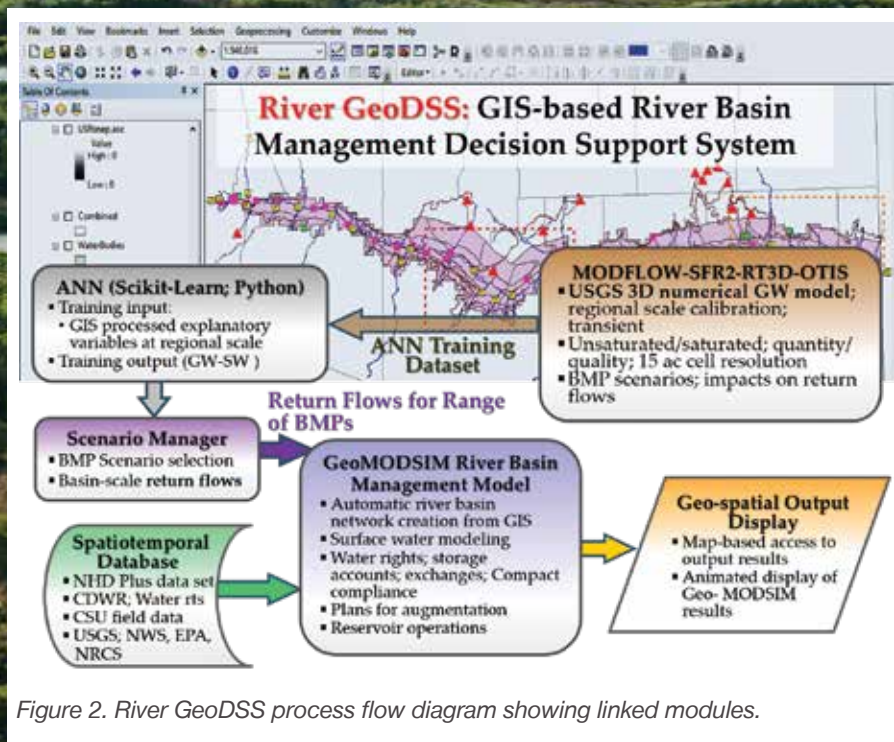


Figure 2. River GeoDSS process flow diagram showing linked modules.

RT3D-OTIS indicate the potential to reduce average concentrations along the Arkansas River within the USR by as much as 20 to 35% for Se and 10 to 25% for NO<sub>3</sub> over a period of several decades. Simulation results also show that these BMPs would lower saline shallow water tables in the region, leading to decreased soil salinity and increased crop yields.

### River GeoDSS for the Lower Arkansas River Basin

River GeoDSS (Figure 2) is a geospatial decision-support system for river basin management that integrates modules for river basin modeling, database management, and graphical user interfaces. It is fully implemented into a geographic information system (GIS) platform for powerful geospatial modeling and analysis. The centerpiece of River GeoDSS is Geo-MODSIM, a generalized river basin network flow model developed at CSU to model the physical and hydrologic aspects of river basin management, along with legal and institutional mechanisms governing allocation and use such as water rights.

With reductions in irrigation canal diversions associated with increased irrigation efficiencies and reduced canal seepage, it follows that changes in rates and patterns of irrigation return flows will likely occur. The resulting alterations in flow patterns within the receiving streams could potentially injure senior water right holders, as well as negatively impact compliance with the Colorado-Kansas Arkansas River Compact. For this reason, the basin-scale model River GeoDSS (Triana et al. 2010) is applied to developing river basin management strategies that consider

various levels of BMP implementation while assuring compliance with basin water rights and the Compact.

### ANN Module for Stream-Aquifer Interaction

The River GeoDSS process flow chart (Figure 2) shows that instead of directly linking MODFLOW-SFR2 with GeoMODSIM for accurate calculation of irrigation return flows for input into the river basin network flow model, an artificial neural network (ANN) is trained and validated using BMP scenarios. Explanatory input variables are used as input datasets, with the corresponding output datasets comprising the MODFLOW-simulated irrigation return flows resulting from a wide range of BMPs. The ANN is trained and validated using these large input-output datasets as generated from numerous MODFLOW-SFR2 simulations for BMPs at various levels of implementation in order to act as a reasonably accurate surrogate for the compute-intensive MODFLOW model. The ANN method is preferred since computational cost is significantly lower (on the order of minutes) compared to direct MODSIM-MODFLOW coupling (on the order of hours to days).

The enormous time and cost requirements for monitoring and collecting the necessary field data makes calibrating and validating a MODFLOW model for simulating groundwater return flows over the entire LARV prohibitive. An additional advantage of ANNs are their well-documented data extrapolation capabilities, where they could be applied in LARV regions where extensive data collection has not been conducted. Therefore, GeoMODSIM employs ANN-generated stream-aquifer interaction values instead of directly interacting with MODFLOW-SFR2.



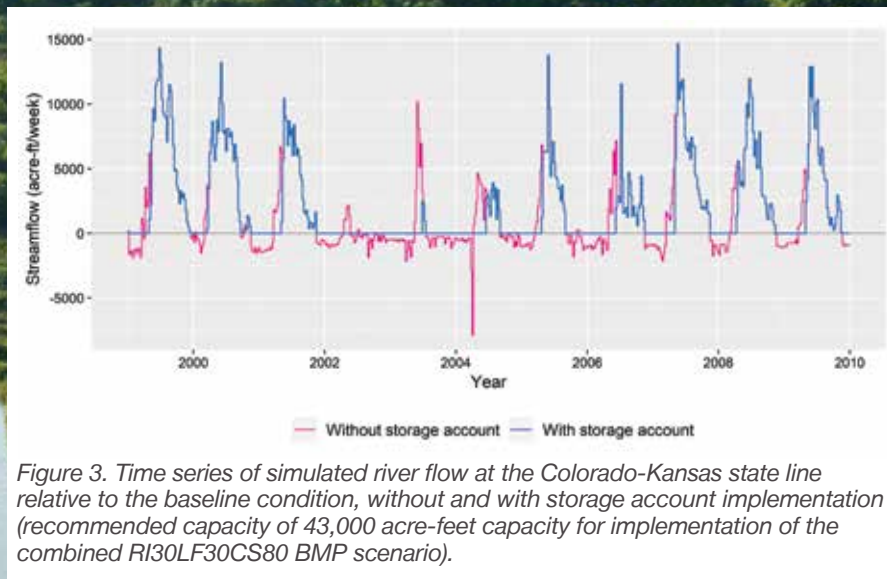


Figure 3. Time series of simulated river flow at the Colorado-Kansas state line relative to the baseline condition, without and with storage account implementation (recommended capacity of 43,000 acre-feet capacity for implementation of the combined RI30LF30CS80 BMP scenario).

### Proposed Storage Account in John Martin Reservoir

GeoMODSIM, with inclusion of the ANN-based stream-aquifer system module, was applied to simulate the impacts of implementing numerous alternative BMPs for improving water quality over the entire LARV from Pueblo Reservoir to Kansas, with baseline simulations first conducted *without* the assumed BMP applications. For both the historical baseline, as well as BMP simulations, the basin-scale GeoMODSIM model was run in weekly time steps over the period of 1999-2012. Irrigation demands were defined in the network based on actual measured canal diversions for irrigation during that period, even if the flows were less than the adjudicated water right, but allocated according to water rights priority.

Since Colorado was in compliance with the Compact during this simulation period, the demands for flows at the state line were defined as the actual measured historical flows during this period. As a demonstration, Figure 3 shows the deviation of the simulated river flows at the Colorado-Kansas state line in relation to the Compact-compliant historical flows for the modeled implementation of the following combined BMP over the LARV: RI30 (30% reduction in applied irrigation due to efficiency improvements), LF30 (30% of irrigated area placed into a lease-fallowing program), and CS80 (80% reduction in seepage in all canals). The relative flows plotted in Figure 3 clearly show substantial instances of negative net deviations, indicating non-compliance with the Compact with implementation of this BMP.


Since BMP implementation means that less water is diverted from the river to the canals due to the efficiency improvements, a proposed option for overcoming these Compact violations is to capture and store the un-diverted flows in a storage account in John Martin Reservoir. This would allow carefully timed releases from this account to

eliminate the negative depletions at the state line. It is assumed in this demonstration that junior water right holders would not be allowed to divert flows above their historical diversions by taking advantage of the efficiency improvements, which leave more water in the river.

Again, as a demonstration, GeoMODSIM was applied to simulating this scenario and determining the best scheduling of releases to comply with the Compact for various possible capacities of the storage account. For implementation of the same combined BMPs, it was determined that a storage account capacity of about 35,000 acre-feet would be required, which, as shown in Figure 3, results in zero depletions from the Compact-compliant flows.

In conclusion, River GeoDSS, a generalized river basin modeling tool, embeds GeoMODSIM streamflow network modeling system, database management system, GUI, and an ANN module into a fully functional integrated river basin management decision support system that can also model institutional requirements. The completed system is being used to evaluate the impacts of BMP scenarios on flow conditions within the LARV system, especially at the downstream end of the basin where the Colorado-Kansas Compact's requirement exists. The systems is also being applied to find ways of mitigating any expected damages. The current version of River GeoDSS serves as a firm foundation for subsequent model development to better address the pollution problems in the LARV while maintaining senior water right priorities and provisions of the Kansas-Colorado Arkansas River Compact Agreement.

### Acknowledgements

This work was supported primarily by grants from the United States Department of Agriculture National Institute of Food and Agriculture, the Colorado Agricultural Experiment Station, and the Indonesia Endowment Fund for Education. 

# Extraordinary Drought, Past and Present



Images courtesy of PxHere

Steve Mumme, Political Science, Colorado State University

## ▼ SYNOPSIS

U.S.-Mexico water management targets both the Rio Grande and the Colorado Rivers, and while existing international treaties address the concern of “extraordinary drought,” the term is ill-defined and has been cause for disagreement between the two nations. However, recent co-management efforts highlight that this ambiguity has not been as problematic as many anticipated, and that it may well have engendered more creative approaches to diplomacy.

Where U.S.-Mexico water management is concerned, few terms are as freighted with ambiguity or as controversial as these two words: *extraordinary drought*. The term appears in two treaties with reference to both the Rio Grande River and the Colorado River. In fact, it is applied twice to the Rio Grande River, in each case with different shades of meaning.

The treaties in question, the 1906 Rio Grande River Convention and the 1944 U.S.-Mexican Water Treaty, both employ the term but fail to specify its meaning. Both treaties are foundational documents governing the binational allocation of water on the rivers to which they apply. In each usage, the term is meant to trigger treaty-specified drought management procedures applicable to the river of reference. At the time the treaties were negotiated, the diplomats involved thought it best to leave the term undefined, considering the hydrological and political complexity of ascertaining whether a drought

was sufficiently severe to justify a rationing response.

It is a matter of historical interest that both the negotiators of the 1944 Water Treaty and the leading legal publicists examining the agreement after it was signed thought that national differences over the term’s meaning had the potential to provoke serious dispute should prolonged drought occur. Disputes have arisen, but arguably, none have been characterized by the severity some analysts expected. Contrary to such expectations—even as the specter of drought has threatened the Desert Southwest and Northern Mexico—binational cooperation has trumped conflict in managing the rivers.

## Historic Perspectives on Extraordinary Drought

To appreciate why drought might have gone badly on the rivers, and why for the most part it has not, it is necessary to look at the treaties’ use of the term and what analysts thought of this language in an earlier period of time.

In the first case, the 1906 Rio Grande Convention, the term was applied to the water allocation on the upper Rio Grande River, defined as the stretch of the river extending from the headwaters to the point where the Rio Conchos joins the Rio Grande, roughly 90 miles southeast of El Paso, Texas. Here, the focus was on water utilization by irrigators below Elephant Butte Dam and in the vicinity of the cities of El Paso and Ciudad Juarez, Chihuahua. Mexico was given 60,000 acre-feet of the river flow, with the U.S. retaining the rest. In the event of extraordinary drought, each nation’s





*Signing of the 1944 Treaty. Photos courtesy of IBWC-US of the International Boundary and Water Commission, United States Section*

allocation was to be reduced in the same proportion. Because the delivery sites were established, determining proportionality was straightforward based on the reduction of deliveries to the affected irrigation districts in New Mexico. The actuality of drought, while not stipulated in the treaty, was understood to be a condition determined upstream, in the U.S. This system has worked well to date.

As the term is used in the 1944 Water Treaty, things get more complex. On the Rio Grande, it applies to the stretch of the river below its confluence with the Conchos, where Mexico has the headwaters, and the U.S. is allocated 350,000 acre-feet of water annually. The hitch is that the U.S. allocation is calculated as an average over a five-year cycle. If Mexico, on account of extraordinary drought, is unable to deliver its quota in a given year, and if it cannot make up the shortfall in that cycle, it may roll over the arrears to another five-year cycle. Yet another hitch affecting the calculation of the deficit is that when the storage capacity of the river's two major international dams, Amistad Dam and Falcon Dam, is filled, any then-existing Mexican debt is cancelled. In this circumstance, the drought call appears to lie with Mexico.

The extraordinary drought prescription is different for the Colorado River, from which Mexico is given 1.5 million acre-feet of water annually, and the U.S. retains the rest. Here, the procedure appears similar to that for the upper Rio Grande. In the event of extraordinary drought, water is reduced to each country in proportion. The catch, however, is that the proportional reduction to Mexico is based on the reduction of consumptive uses upstream, making it difficult to deliver the Mexican entitlement. Though not specified in the treaty, it was largely assumed by negotiators that the U.S. would make the call.

These three versions of how to deal with extraordinary drought have historically led to complications. For one thing, it is obvious that the solution on one river, or one section of the river in the Rio Grande case, does not easily



*IBWC Mexican Commissioner Roberto Salmon (left) and U.S. Commissioner Ed Drusina (right) sign Minute 323.*

translate to the others. These are separate cases. There is also the question, left dangling in the treaties, of who determines whether such a drought exists; the assumption that the upstream party should make the call, subject to the treaty's right to verification by the other party, was for many years a tad indefinite.

And there is more. On the Rio Grande River, the 1944 Treaty's Article 4 only refers to one debt rollover, but what should happen if owed monies persisted into a third cycle? On the Colorado River—whose basin encompasses seven U.S. states and where the U.S. quotient is administered under rules set by the 1922 Colorado River Compact (which divides the river's bounty between the lower and upper Colorado River basin states)—how was a drought to be determined? Would a drought in one part of the basin suffice to justify a claim of extraordinary drought? What about the effect of the storage dams on the river? If water was available at Lake Mead to sufficiently satisfy lower basin needs, could upper basin drought justify a Mexican reduction? How was the condition of difficult delivery to be determined? And, given that reduction of the Mexican quota was tied to consumptive uses upstream, how was that to be determined?

Unofficially, Mexico and the United States answered these questions differently. On the Rio Grande, for example, Mexican experts thought Mexico held the cards, never expecting a drought to persist more than a decade. Neither, in truth, did U.S. treaty negotiators, though they thought the U.S. should have a hand in determining whether an extraordinary drought call was valid. U.S. negotiators put the emphasis on Mexico's annual obligation, while Mexican negotiators emphasized the elasticity of the five-year cycle. On the Colorado River, Mexican negotiators thought a localized drought upstream was insufficient to invoke reductions to its quota, while most U.S. analysts disagreed. The great U.S. international law expert at the State Department, Marjorie Whiteman, sided with the Mexican perspective on account of the storage capability at Lake Mead. Mexico also differed with U.S. experts over the

procedures for determining drought, believing the U.S. had an obligation to share its consumptive use data, a view not universally accepted in the United States. The U.S. took the position that a determination of difficulty to deliver would be as much a political decision as a hydrological one, taking account of its Colorado River basin stakeholders. Mexico was not so sure.

### Recent Experience on the Treaty Rivers

The potential for the ambiguity surrounding extraordinary drought and its operating language to cause problems in managing the Treaty Rivers has been seriously tested in recent years. The most contentious and lingering dispute is seen on the Rio Grande, not on the Colorado River, as most experts expected. Here, persistent, region-wide drought that set in the 1990s led to a series of conflicts and stand-offs tied to Mexico's periodic failure to deliver its treaty quota. Mexico invoked its Article 4 prerogative to roll over its debt in 1997 and then again in 2002, leading to Texas' accusations of bad faith and failure to comply with the 1944 Treaty. Among other complaints, Texas blamed Mexico for expanding its consumptive uses in the Rio Conchos basin and hoarding water in its national reservoirs to the detriment of the U.S. Protracted negotiations led to greater Mexican flexibility with water releases and U.S. support for water conservation investments in Mexico, with the saved water dedicated to treaty compliance. That, coupled with Mother Nature's occasional compliance in the form of torrential rains that filled the international reservoirs, has mitigated some of Texas' concerns; however, serious differences remain as to how Mexico has construed its extraordinary drought obligations.

On the Colorado River, things have gone differently. Here too, severe sustained drought has threatened the basin since the 1990s. But a broader set of stakeholders has altered the equation. Belt-tightening on the Colorado River alarmed environmentalists who entered the water allocation fray in 1999, hoping to save the ecology of the Colorado Delta, threatened as it was by upstream conservation. Environmentalists succeeded in pushing the International Boundary and Water Commission (IBWC) to study the problem in 2000 and then succeeded in 2007 in persuading other stakeholders to study the international problem in tandem with new drought-sharing protocols agreed upon by the seven basin states and the U.S. Bureau of Reclamation. Mexico remained wary of these developments. But after an earthquake destroyed many of its irrigation canals in 2010, the opportunity for Mexico (which needed to store its treaty water in Lake Mead) to join with the U.S. (which needed Mexican water to hedge against Lake Mead's diminished water storage) in exploring a new binational approach to drought sharing presented itself.

The resulting agreement, IBWC Minute 319 in 2012, embraced a formula for binational sharing of water shortage


and provided a limited amount of water for ecological restoration below the international boundary. It also agreed to explore new and underutilized water sources and technologies, including desalination, as a means of augmenting water availability in the lower Colorado River's international zone. That agreement, though temporary, was effectively consolidated in IBWC Minute 323, signed in 2017. Minute 323 applies through 2026, when the success of these arrangements will be evaluated for revision and renewal.

A striking feature of these recent agreements, Minutes 319 and 323, is that they sidestep the question of extraordinary drought. In fact, although both agreements clearly and deliberately address the problem of protracted severe drought on the Colorado River and invoke the 1944 Treaty in doing so, neither agreement refers at all

## Would defining the term facilitate greater binational understanding and amicable settlement of shortage disputes?

to the term or its operating language. Each government retains the option of trying to define and apply the term to the Colorado River scarcity problem in advancing its respective national interest, but neither government has exercised this option. Instead, they have chosen—so far—to negotiate rather than litigate, using the diplomatic tools the 1944 Treaty makes available for this purpose.

What recent practice on the two rivers reveals is that failure to define the term *extraordinary drought* is not as great a problem as many experts originally thought it would be. Would defining the term facilitate greater binational understanding and amicable settlement of shortage disputes? Perhaps, but judging with 20/20 hindsight, the term's ambiguity in each case appears to have been conducive to creative diplomacy. Recent negotiations have generated cooperative and binational solutions to the threat of prolonged region-wide drought that reveal the resiliency of the treaty regime, not the opposite. And that is good news for all U.S. and Mexican stakeholders on the Treaty Rivers, especially with a changing climate and greater hydrological variability affecting these rivers going forward.

*This article is abstracted from the article "Extraordinary Drought in U.S.-Mexico Water Governance," by Stephen P. Mumme, Oscar Ibanez Hernandez, and Bruno Verdini, published in the Journal of Water Law, Vol. 26 (1) (October 2018).* 



# THE EVOLUTION OF MEASURING DROUGHT

Noah Newman, Colorado Climate Center

## ▼ SYNOPSIS

Drought is spatially and temporally varied and thus often difficult to measure. Improved data collection and analyses have allowed scientists to better identify and document drought, but this information must be supplemented by local knowledge of the impacts of drought. To address this data gap, the Community Collaborative Rain, Hail & Snow Network at CSU helps connect volunteer weather monitors with drought scientists and decision makers.

There is more than one way to experience drought. To quote Ernest Hemingway's perspective about how one goes bankrupt: "[there are] two ways. Gradually, then suddenly." There is a great challenge in measuring the slow-moving freight train of drought—and especially its severity—at any given time. That droughts can look different from one region to the next further complicates matters. Areas that typically receive sparse amounts of precipitation might appear to be in drought even in a wetter-than-normal year. Other areas with wetter climates might still be flush with green while experiencing a drought.

There are several resources for accessing drought information including the U.S. Drought Monitor (USDM, [droughtmonitor.unl.edu](http://droughtmonitor.unl.edu)), the Colorado Drought Response Portal, Federal Emergency Management Agency (FEMA), Colorado State Extension,

and the Western Governors' Association's Drought Forum. But how have these entities gathered the information they need to relay their findings to the public? When the actual definition of drought is "a prolonged period of abnormally low rainfall," how can one measure something that is not there? Can a ruler measure the depths of the cracks in the dirt? Should relative humidity be tracked over time? How in the world do we measure a drought?

Simply put, it is complicated. Fifteen years ago, drought assessments were much cruder. Over time, improved data have allowed decision makers to be increasingly detailed (Figure 1). Starting on a scale with D0 to indicate abnormally dry, all the way to the most extreme level of D4 for exceptional drought, decision makers compare current conditions to the known long-term normal conditions to form a quantitative percentile ranking.

### Finding Volunteer "Experts"

One major challenge for drought scientists has always been that they cannot be everywhere. They can look at a number of different sources of data ranging from ground-based monitoring stations to satellites in space, but they also need local reports from people on the ground. Temperature, precipitation, evaporation, soil moisture, reservoir levels, snowpack, and other variables are obtained from weather stations. Satellites can gauge soil moisture and vegetative health by using spe-

cialized instruments. These datasets are the primary inputs used to determine drought category. Yet the identification and documentation of drought lacks a significant piece of the bigger picture: the impacts. How does a drought affect sectors such as agricultural, water municipalities, recreation, tourism, and public health?). More importantly, how can the impacts of drought be relayed to the scientists at the National Drought Mitigation Center (NDMC), and how are they weighed when combining both qualitative data and quantitative narratives?

There has always been a strong need for local experts to assess local conditions; however, anecdotal evidence requires careful scrutiny. Decision makers need to engage volunteers who provide honest and accurate information, yet many of the observers who submit reports also have a stake in the matter. A recent study by the Carolinas Integrated Sciences & Assessments (CISA) showed that both observers and decision makers had concerns about the subjective nature of these reports, but because the observers are truly the best experts at determining the varying degrees of wetness and dryness in their local areas, decision makers find the reports more useful than not.

For the past 20 years, the Community Collaborative Rain, Hail & Snow Network (CoCoRaHS, [cocoahs.org](http://cocoahs.org)), founded and based at CSU, has trained and equipped thou-

sands of backyard weather watchers to set up a rain gauge and submit precipitation data to their website. Volunteers also have the ability to add comments and notes to their reports, and stakeholders began to notice many comments related to drought. This prompted an effort in 2010 for CoCoRaHS to launch a new data entry protocol called “Drought Impact Reports.” Here, volunteers who were experiencing drought conditions could report their economic impacts alongside a choice of a sector, such as agriculture or tourism. Concurrently, the NDMC provided a portal for members of the public to submit specific economic impacts related to drought called the Drought Impact Reporter. (Visit [droughtreporter.unl.edu/submit-report](http://droughtreporter.unl.edu/submit-report) to learn more.) Updated in 2011, the newest version added CoCoRaHS Drought Impact Reports to their map (Figure 2). Now, decision makers are able to use the reports in conjunction with their qualitative data to determine the drought category.

### Improving the System

Beginning in 2013, CISA began a pilot project called the Citizen Science Condition Monitoring Project. In conjunction with CoCoRaHS, the project goal was to improve the process of monitoring drought by surveying stakeholders’ needs and working closely with volunteers to test a new method of drought impact reporting, which provided them with a new data entry form to submit “Condition Monitoring Reports.” Rather than focusing on situational drought, the pilot

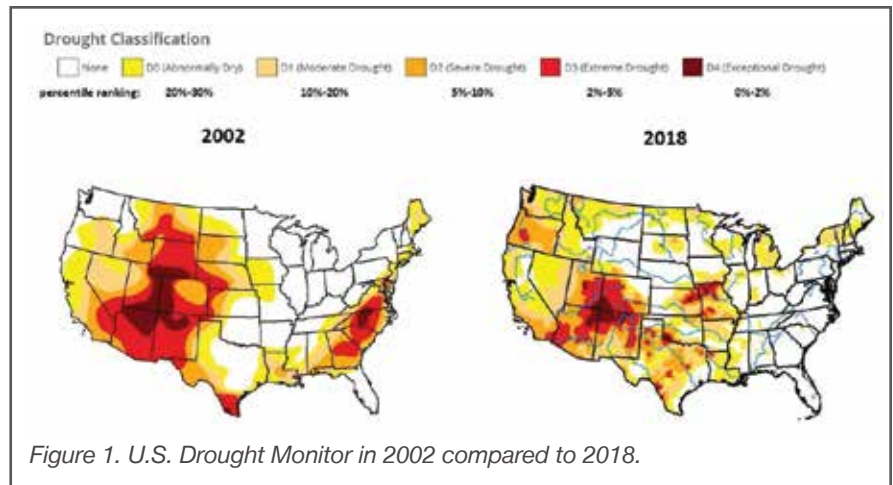


Figure 1. U.S. Drought Monitor in 2002 compared to 2018.

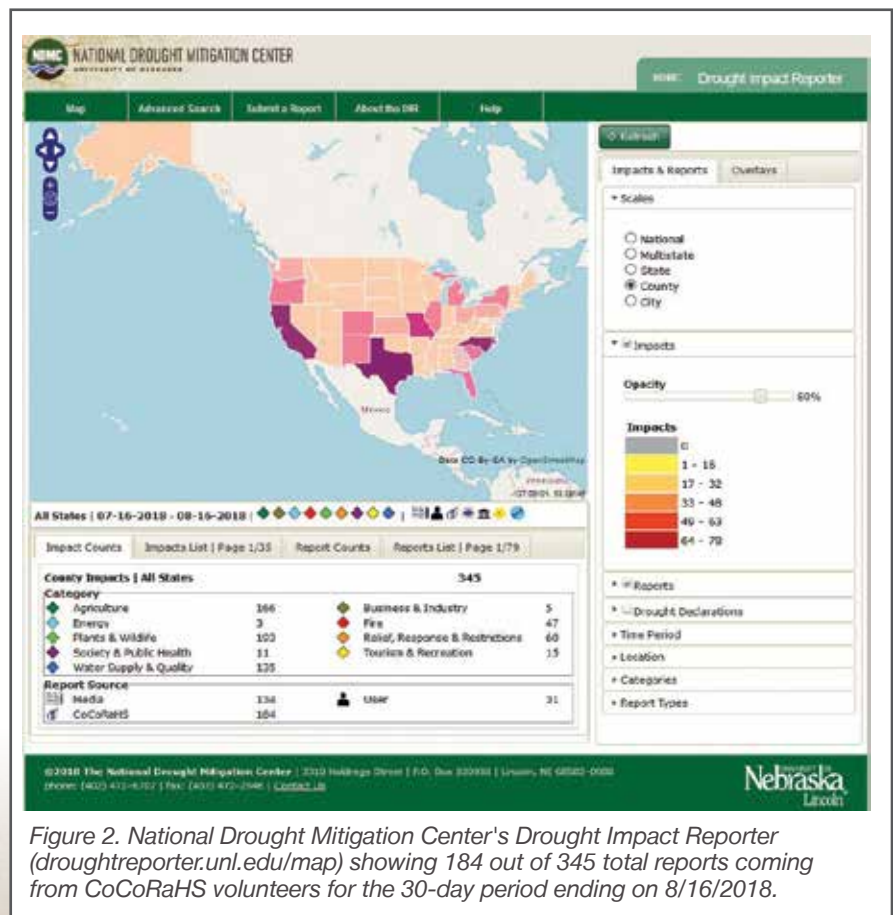


Figure 2. National Drought Mitigation Center's Drought Impact Reporter ([droughtreporter.unl.edu/map](http://droughtreporter.unl.edu/map)) showing 184 out of 345 total reports coming from CoCoRaHS volunteers for the 30-day period ending on 8/16/2018.

Farmer and sons walking in the face of a dust storm. Cimarron County, Oklahoma. Arthur Rothstein, 1936. Library of Congress.





took a new approach: encouraging regular weekly reports of the volunteers' overall conditions, with the hope that this was a more effective way for the NDMC to track the subtle changes that occur between the onset, intensification, or recovery of drought. A new sliding-scale bar provided observers with choices ranging from "severely dry" to "severely wet" (Figure 3), as well as a new mapping product to view the reports (Figure 4). This multi-phased project worked with both observers and data users to improve the reporting process and to facilitate the reports' utility. This extensive work—including recruiting volunteers, testing the platform, and soliciting feedback from both volunteers and decision makers—resulted in enhanced trust between all parties.

### The Future

CISA's pilot project, after almost five years in the making, expanded nationwide in late 2016. It concluded with a report and recommendations that will be a helpful guide for moving forward—both for CoCoRaHS and the USDM. These recommendations include additional support for volunteers, engaging decision makers, technological improvements, regional guidance, and improvements to data analysis.

Volunteers need consistent training, communication, and engagement. Proposed improvements to the project include increasing the communication between the project leaders and the volunteers about the importance of their data. The more a volunteer knows their data are useful to decision makers, the more inclined they will be to submit regular and consistent reports. Another improvement will be to test a "train the trainer" model, in which regional and local CoCoRaHS coordinators receive direct training for the purpose of recruiting new volunteers through their local networks, rather than recruitment efforts coming from the national level.

Decision makers play an important

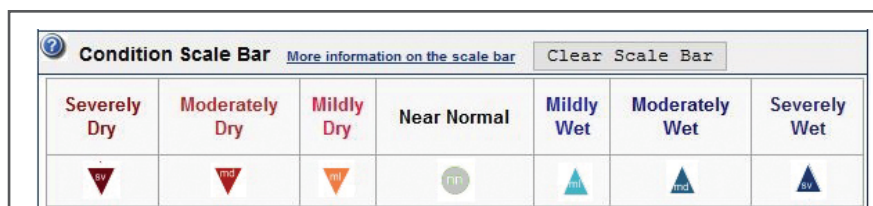


Figure 3: The Condition Monitoring Scale Bar for CoCoRaHS volunteers



Figure 4: The Condition Monitoring Map showing CoCoRaHS CM Reports and the current USDM drought designations, for the week of August 10-16, 2018.

role as well, and drought scientists are not the only group who can benefit from the data. Engaging potential users, including National Weather Service (NWS) forecast offices, could create increased demand for more data and potentially identify other uses for existing data.

Many volunteers responded to surveys with a strong desire to submit data through a mobile app. Currently, CoCoRaHS volunteers can submit precipitation data through a smartphone app, but adding condition monitoring could be a big improvement for both current and future volunteers. Additionally, the capability to add photos would help supplement a volunteers' narrative and could provide more evidence for the decision makers who use the data. Data storage limits and other technical roadblocks make this a challenge, but the high demand for photo capability makes this one of the top priorities for moving forward.

Enhanced data analysis is another area in need of improvements. Since

2016, over 22,000 condition monitoring reports have been submitted to CoCoRaHS. Some basic tools have been created with which reports can be compared to each other over time or location. However, since a large part of the report is a narrative from the volunteer, new analyses that capture word counts or key phrases will be utilized without the need of reading every word from thousands of reports.

Collecting valuable drought information will always be a challenge, yet improvements in data resources have led to a remarkable level of detail that was previously unattainable. Other advances in technology have facilitated a direct line between local experts and drought scientists, and there is an increasing understanding between both parties that anyone with the desire to report their impacts related to drought are the exact local experts who are needed most. Anyone with that desire is encouraged to join CoCoRaHS, where they are empowered to submit drought impact reports of their own.

# Supplemental Guidance on Water-saving Measures Integrated with Land-use Planning



Anne Castle, Getches-Wilkinson Center for Natural Resources Energy and the Environment, University of Colorado, Boulder;

Erin Rugland, Babbitt Center for Land and Water Policy, Lincoln Institute of Land Policy;

Richard Alper, Confluence Collaboration

## ▼ SYNOPSIS

The Colorado Water Conservation Board is working to help Colorado water providers and municipalities conserve water through better land-use planning. The goals are to reduce water demand, foster collaboration, and increase resiliency. Because Colorado water providers have diverse needs and capacity, guidelines for more than 100 different land-use practices are provided.

**O**n January 28, 2019, the Colorado Water Conservation Board (CWCB) approved new guidance that helps Colorado water providers and municipalities implement water conservation through land-use planning efforts. According to Rebecca Mitchell, the Director of the CWCB, “This new guidance provides step-by-step instructions for water providers for collaboration with their land use authorities to configure new development in a way that reduces overall water demand.” She describes the new guidance as a “smart from the start” approach that improves water providers’ ability to absorb new growth and increase the resiliency of existing supplies.

The new guidance was prompted by Senate Bill 15-008, which requires water suppliers to evaluate best management practices for integrating water conservation with land-use planning in their Water Efficiency Plans. Colorado’s Water Plan also establishes a similar objective.

Mindful that Colorado water providers have diverse needs and capacity, the new guidance contains more than 100 land-use practices and hundreds of examples and case studies with direct weblinks for more detail. Water providers can tailor these practices and examples to their local conditions, customer base, and conservation objectives.

The new guidance document is a joint project of the Getches-Wilkinson Center for Natural Resources, Energy and the Environment at the University of Colorado Law School and the Babbitt Center for Land and Water Policy, a center of the Lincoln Institute of Land Policy. Working together and funded by a grant from the CWCB, the two centers undertook an extensive process to develop the new guidance, including a literature review, interviews with Colorado water providers, a workshop for prospective users, and several drafts vetted by an advisory committee of practical experts. The project partners are now in the process of organizing education and outreach efforts to ensure that water providers can take full advantage of the new guidance and better reach their water efficiency goals.

More information on the new guidance can be found on the CWCB’s Water Efficiency Planning website (<https://bit.ly/2Fk6QMT>), Colorado’s Water Plan implementation website (<https://bit.ly/2Y7ZTWf>), and the Babbitt Center’s website (<https://bit.ly/2WaG5jr>).



## Colorado’s Water Plan Measurable Objective

By 2025, 75 percent of Coloradans will live in communities that have incorporated water-saving actions into land-use planning.



Jamestown, Colo., Sep. 15, 2013  
FEMA photo

# State Agencies Partner to Meet Post-Flood Restoration Needs

Ryan Lockwood, Colorado State Forest Service

## ▼ SYNOPSIS

Following historic floods along the Front Range in 2013, the Colorado Water Conservation Board initiated its Emergency Watershed Protection Program to restore healthy riparian corridors, which are critical to the success of watershed-scale recovery projects. The Colorado State Forest Service Nursery was able to produce the more than a quarter-million plants needed for the effort. Revegetation wrapped up in May 2018, with the nursery's stock utilized throughout Boulder, Jefferson, Larimer, and Weld counties.

Over five days in September 2013, historic rainfall hit the northern Front Range of Colorado. Some areas received up to 17 inches of precipitation in only a few days, and the catastrophic flooding that resulted—from Fort Collins down to Colorado Springs, and out onto the northeastern plains—resulted in ten deaths, billions of dollars in damage, and degraded ecosystems.

As with any recovery effort, the response for a disaster of this magnitude required teamwork and interagency cooperation. Emergency infrastructure repair and rebuilding needs—chiefly to address roads, bridges, and water delivery systems—were of immediate concern to the state, along with flood cleanup actions. But stream channel recovery efforts and associated revegetation in riparian areas, con-

ducted through the Emergency Watershed Protection (EWP) Program by the Colorado Water Conservation Board (CWCB, [coloradoewp.com/program-information](http://coloradoewp.com/program-information)), were also a top priority. Through this program, the CWCB was tasked with protecting life and property, and it implemented a “bioengineering” approach—or, the use of plants to stabilize stream banks—to meet its objectives.

In short, the CWCB intended to get as many trees, shrubs, and other plants into the ground as soon as possible to re-stabilize stream banks in targeted watersheds and to enhance ecological functions. There was just one problem: they were going to need a *lot* of plants.

“We realized on the front end of this that we were not going to have nearly enough stock,” said Chris Sturm, stream restoration coordinator for the CWCB.

## State Nursery Steps Up

In the fall of 2016, Sturm approached the Colorado State Forest Service Nursery with an important question: Did the nursery have the capacity to provide more than 100,000 riparian restoration plants to meet the demand for 2017-2018 revegetation efforts along the Front Range? And could the nursery generate the necessary stock of tall-pot container seedlings needed for targeted riparian plantings—using a type of container never before offered by the nursery?

The primary challenge facing the massive vegetation





*A riparian area planting along Left Hand Creek in Boulder County.  
Photo courtesy of the Colorado Water Conservation Board.*

propagation effort related to the limitations of the EWP Program, which only allows a roughly seven-month period for external parties to generate outputs once funding has been distributed to them. Yet producing thousands of the appropriate seedling trees, shrubs, and cuttings for project work often takes much longer than that.

“Normally, it takes us years to plan and grow thousands of plants for specific projects, from procuring the best seed to delivering seedlings of necessary size, and that is if we are dealing with familiar species and methods,” said Josh Stolz, CSFS Nursery manager. “A request for such a rapid turnaround was not going to be an easy one to meet.”

Still, Stolz said that in the face of such major flood damage and recovery need, there was only one option: “We committed to joining the effort.”

### **The Emergency Watershed Protection Program**

Revegetation efforts to ensure healthy riparian corridors are critical to the success of watershed-scale recovery projects. Vegetation that stabilizes stream banks and reduces erosion can be scoured away in severe flood events and often takes many years to recover without intervention. The vision of the EWP Program ties directly into this concern, with a vision “to implement watershed recovery projects that reduce risk to life and property, enhance riparian ecosystems, and gener-

ate long-term stream system resilience.”

The program provided funding to implement emergency recovery measures for the long-term 2013 flood recovery to address hazards to life and property in affected watersheds. This included providing financial and technical assistance—in this case, via container-grown seedlings, willow cuttings, and other plants—to local project sponsors to reduce erosion and the threat of potential flooding, while also protecting stream banks and restoring habitat. The program’s 2013 Flood Recovery Phase II is funded and administered by the USDA Natural Resources Conservation Service and managed by the CWCB on behalf of the state.

Each EWP project requires a local sponsor to ensure successful implementation. These sponsors, which have included watershed coalitions and nonprofits, municipalities, counties and utilities, provide legal authority to do recovery work in addition to applying for assistance, contributing to project costs, obtaining necessary permits, and committing to at least three years of project maintenance.

### **Ensuring Plant Survival**

The CWCB wanted to ensure that the local sponsors would be able to obtain plant material grown from ecotypic (i.e., regionally endemic and locally adapted) seed sources, which are more likely to be resilient to local environmental conditions. Over time, plants grown from ecotypic seed



sources have higher survival rates than those obtained from non-regional sources of the same species and are thus preferred by restoration ecologists.

“They could have gone outside Colorado and gotten a lot of these plants, but because we could provide site-specific seed sources, we were able to provide the plants most likely to succeed in the long run,” Stolz said.

Prior to the 2013 flooding, the CWCB had the foresight to work with members of the consulting group Great Ecology to create a restoration matrix that helped identify the best species for restoration plantings in Colorado based on elevation, soil type, soil moisture, and many other factors. The board utilized this matrix to determine which plants would be most desired for various sites impacted by the flooding and how many units of each species would be needed.

Species identified by the matrix and that the nursery would need to provide for projects were extensive and included riparian and adjacent upland varieties such as willows, cottonwoods, plums, chokecherries, dogwoods, and currants, as well as non-woody species. Many of the seeds and cuttings to be used for the restoration efforts were collected and provided by staff from Great Ecology’s regional office in Denver, once again contracted by the CWCB. The group also reviewed EWP planting plans to ensure that they would meet site needs and worked with the nursery and EWP to determine the order and number of each species that would need to be grown to meet specific project deadlines.

What the CWCB and its local sponsors needed in terms of revegetation material was a high number of seedlings that were of the ideal species and would be easy to plant. Many of these also needed to be seedlings provided in a deep-root format, which are more likely to survive than shallower-rooted seedlings because they are able to utilize existing soil moisture further underground. The nursery typically focuses more on seedlings offered in smaller tubes used for agricultural windbreaks, traditional reforestation, and post-fire restoration, but in this case, it needed to quickly produce seedlings in a never-before-offered variety of “tall-pot” container for each desired species, grown in 14-inch-deep tubes.

In addition to these tall-pot container seedlings, team efforts required harvesting, preparing, and propagating thousands of willow cuttings—essentially turning the cuttings into rooted willows ready for planting. Finally, the nursery had to provide yet another product it had never offered before: “wetland plugs,” or root-bearing wads of sedges or rushes, grown from seed until ready for planting along stream edges. Though a significant challenge, Stolz said that the nursery recognized the opportunity to expand its outputs in the process.

“Besides helping out with recovery efforts, we wanted to build credibility for the CSFS Nursery as a resource for a broader range of seedling use projects, including for riparian restoration efforts,” Stolz said.



*An Estes Valley Watershed Coalition, Youth Corps Volunteer planting using CSFS stock. Photo courtesy of Great Ecology.*





*Emergency Watershed Protection Program container stock at the CSFS Nursery. Photo courtesy of Great Ecology.*

### **A Successful Effort**

By the spring of 2018, the nursery had managed to successfully grow, propagate, and otherwise provide the majority of the more than a quarter-million plants utilized for post-flood restoration efforts. In all, the EWP's revegetation contractors successfully planted over 143,000 tall-pot trees and shrubs, 60,000 willow cuttings, and 83,000 wetland plugs, with 70 different species represented in the restoration efforts.

The final planting efforts occurred by the end of May 2018, with the nursery's stock utilized throughout Boulder, Jefferson, Larimer, and Weld counties. Riparian and upland plant species were planted at locations on flood-affected streams, including Left Hand Creek, St. Vrain Creek, Big and Little Thompson Rivers, South Platte River, Coal Creek, and Fall River.

"The CSFS Nursery pulled off an amazing feat," Sturm said. "They produced an incredible amount of plants in a very short time period."

Besides generating so many seedlings and cuttings for the 2017-2018 plantings, the CSFS also assisted with EWP efforts as a partner helping collect the native willow cuttings from public lands for revegetation of flood recovery projects. CSFS Nursery staff worked to gather cuttings from State Trust Lands on the Front Range and in the Colorado State Forest and from county and municipal lands. Other partners involved in these efforts included Jefferson County Open Space, Denver Parks & Recreation, Boulder County Parks & Open Space, and the City of Longmont. The nursery stores these cuttings in climate-controlled coolers until they can be utilized.

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"Besides helping out with recovery efforts, we wanted to build credibility for the CSFS Nursery as a resource for a broader range of seedling use projects, including for riparian restoration efforts"

— Josh Stolz, CSFS Nursery manager



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According to Stolz, the nursery continues to increasingly engage with partners focused on ecological restoration, including CSU's Center for the Environmental Management of Military Lands (CEMML). This Warner College of Natural Resources-based center recently utilized CSFS willow cuttings for projects focused on rehabilitation and restoration at the U.S. Air Force Academy. CEMML staff have indicated that they intend to continue to utilize the CSFS Nursery when future restoration opportunities arise.

"Our goal is to provide the best seedlings possible to meet the state's conservation goals," Stolz said. "We will always be willing to explore new techniques to ensure that we can meet this goal." 



# Optimistic Investments Propelled Arkansas Valley Irrigation

By Patricia J. Rettig, Water Resources Archive, Colorado State University Libraries

All photos by Terry Nash, courtesy of Colorado State University Libraries, or from Arkansas Valley Sugar Beet and Irrigated Land Company Photographs, Water Resources Archive, CSU Libraries

## ▼ SYNOPSIS

The Arkansas Valley Sugar Beet and Irrigated Land Company can be seen as a microcosm of early twentieth-century Colorado water issues. Irrigators faced water quality and over-allocation challenges, interstate litigation posed a variety of legal challenges, dams and reservoirs were initiated at the federal, and the national and natural disasters of the Great Depression and the Dust Bowl plagued the region. This era of the Arkansas Valley's history is documented in the Colorado State University's Water Resources Archive.

**T**hese photographs taken to show the extensive canals to their new corporate owners convey a sense of pride, though they are unable to disguise the area's stark isolation. Taken in the early twentieth century amid the arid plains surrounding Holly, Colorado, the prints were sent to the Arkansas Valley Sugar Beet and Irrigated Land Company board of directors in New York City.

Those wealthy Easterners, whose daily occupations involved banks, railroads, and life insurance, surely wondered what they had gotten themselves into. Some likely saw dollar signs in those photographs, knowing how many millions had been invested in land purchases and canal construc-



tion. Others probably looked at the black-and-white prints with optimism, anticipating delivery of copious amounts of Arkansas River water through the conveyances, with increasing numbers of farmers profiting from the burgeoning sugar beet industry, causing a rise in land prices.

One investor who had himself looked at the land in 1895 with optimism was no longer around when the photographs arrived. Henry B. Hyde passed away just four years after visiting Prowers County and encouraging investment there. *The Lamar Register* reported on November 16, 1895, that Hyde stated “that this country is more prosperous than any portion of the country he has found in his travels this year.” Similar optimism would draw in visionaries from across the United States, significantly influencing the development of the lower Arkansas Valley.

Along with his extensive connections, Hyde’s money and the eventual settlement of his estate after his 1899 death were important to the formation of, and ongoing investment in, the Arkansas Valley Sugar Beet and Irrigated Land Company (AVSBILC), which acquired the Great Plains Water Company and the Amity Land Company. Hyde was the founder and president of the Equitable Life



*W. S. Partridge, Joy Morton, Mrs. Morton, Mrs. Fisher, and Leon O. Fisher visited the Amity Canal Model Dairy Farm in April 1920.*

Assurance Society, which he grew into the world’s largest life insurance company. Given his prominence and financial status, Hyde sat on the boards of directors for several other institutions, including the Western National Bank, which received a controlling interest in the Amity Land and Irrigation Company (a predecessor of both the Amity Land Company and the Great Plains Water Company)

as collateral on a defaulted loan in 1894.

Hyde was so committed to the Amity lands that in 1897, as a director of the Mercantile Trust Company, he and others arranged, via a common but questionable business practice, to loan an employee money for the purpose of taking over this Western National Bank collateral. Thus arose an ongoing entanglement of Hyde’s personal estate with his business, significantly concerning the Amity interests. Equitable historian R. Carlyle Buley summarized the situation: “Not one of Equitable’s larger investments, but one of its most persistent, complicated, and interesting was that in the Arkansas Valley Sugar Beet and Irrigated Land Company, which it had taken over from the Mercantile Trust Company in the settlement between the Society and the Henry B. Hyde estate.”

Incorporated in New Jersey in 1901 while Hyde’s estate



*Outlet channel from NeeNoshe reservoir, 1909.*



Amity Canal & Reservoir Co.

Infographic showing the evolution of the Arkansas Valley Sugar Beet and Irrigated Land Company. Photo by Terry Nash, courtesy of Colorado State University Libraries.

Amity Canal, Reser-  
Improvement Co.

William J.  
Hallack

was in litigation, the AVSBILC had arisen from negotiations conducted in Chicago among Eastern investors and sugar beet interests. The backers, including men associated with the American Beet Sugar Company and the Oxnard Construction Company (which had been created to build sugar beet factories), had high expectations of capitalizing on the national sugar beet boom, and like Hyde, recognized the Arkansas Valley as a promising location. With vast lands, significant reservoirs, and over a hundred miles of canals stretching from above Lamar, Colorado, east to Kansas, AVSBILC held much potential for great success.

Already, the American arm of an international organization had come to the same conclusion. In 1897, sharing in the optimism for the region, the Salvation Army established just west of Holly its Fort Amity, one of three colonies it started in the U.S. to relieve urban poverty. Unfortunately, Fort Amity's land, purchased from the Amity Land Company and chosen for the promise of prosperity through irrigated agriculture, suffered from issues of drainage and salinity. Despite experimentation and education coming in part from Colorado Agricultural College (now Colorado State University), the colony disbanded by 1909.

Back in New York, after a decade of litigation and investigation of Hyde's estate, the AVSBILC became a subsidiary of Equitable in 1910 and remained so for more than half a



Stock certificate showing ownership in the Arkansas Valley Sugar Beet and Irrigated Land Company, incorporated in New Jersey. Photo by Terry Nash, courtesy of Colorado State University Libraries.

century. Over the years, the company faced numerous lawsuits and brought a few of its own. Most prominently, the cases known as the Moran suit and the Markham suit finally settled water rights issues for the irrigators. The case of *Arkansas Valley Sugar Beet and Irrigated Land Company vs. L. Wirt Markham* caused the Colorado Supreme Court in 1936 to order mutualization (the opposite of privatization) of the Amity system. Today, the Amity Mutual Irrigation Company continues to operate out of Holly.

Interestingly, starting in 1905 and completed by 1917, mutualization of Equitable was another result of Henry Hyde's passing. He had planned for his only son, once he turned thirty, to take the reins as president of the life insurance company. Others there increasingly objected to this plan after James Hyde turned 29 in 1905 and ostentatiously enjoyed his vast fortune in ways deemed inappropriate for the company's reputation. Mutualization would allow policyholders to vote for the members of the board of directors, instead of the board seats being held by the largest shareholders, namely James. Unlike with Amity Mutual, the mutualization of Equitable did not last and was reversed in the 1990s.

When it became part of Equitable in 1910, AVSBILC benefited from refreshed optimism and additional investments, along with turnover in leadership there. Among other prom-



Amity Canal conveying vast amounts of Arkansas River water to sugar beet fields, c. 1905-06.



Land + Irrigation Co  
6-13-1893  
d canals lands from  
Hollack 7-1-1893 (dek.  
10-14-1893).  
A considerable number  
of large blocks

Conveyed lands (with w.r.)  
to Ark Valley S.B. + S.L. Co.  
7-1-1901, some of which of  
which lands were subject to  
long time lease contracts, call-  
ing for w.r. as located by  
Deeds + Forms B, D + F

Adopted new form of deed  
(Form D), on lease of basis  
defining each w.r. sufficient  
for 40 acres annual assess-  
ment 50¢ per acre, later ad-  
justed to 75¢ per acre

inent decision makers to get involved with the company over the succeeding years was Joy Morton, brother of Paul Morton (president of Equitable 1905-1911) and founder of the Morton Salt Company, based in Chicago.

Closely connected to substantial national movements, people, and events, the Arkansas Valley Sugar Beet and Irrigated Land Company can be seen as a microcosm of early twentieth-century Colorado water issues. The irrigators supported by the company faced issues with water quality and over-allocation. The sugar beet boom eventually went bust. Water law challenges came in the form of interstate litigation, especially the ongoing *Kansas vs. Colorado* case, as well as nascent river compacts. Federal intervention arrived in the form of John Martin Dam and Reservoir, authorized in 1936 and governed operationally by the 1948 Arkansas River Compact. The company also had to deal with the twin national and natural disasters of depressions and droughts, including the Dust Bowl.


The AVSBILC lasted until 1966, when the last of its assets were distributed. It had mutualized another irrigation canal system as the Buffalo Mutual Irrigation Company in 1950. It sold off lands and other assets gradually, until all that remained were mineral rights in the area. These it transferred to Equitable to retire more than \$7 million of debt. The secretary of state of New Jersey issued a certificate of dissolution on June 15, 1966.



Drop structure in Satanta Canal, c. 1907-08.

That certificate and an accompanying nineteen boxes of documents and photographs documenting this complex history had been stored in the archives of AXA Equitable, the company's current name, until the fall of 2018, when it was all donated to Colorado State University's Water Resources Archive. AXA Equitable's goal was increased public access, and that is exactly what the Water Resources Archive is providing. More than sixty years of letters, reports, meeting minutes, and other docu-

mentation being sent between Holly, Colorado, and New York City now can be accessed in the state where the investors' money and decisions made such a huge impact. The Archive is working on posting a collection inventory online and hopes to digitize large portions of the collection for universal access.

This collection joins another containing mainly photographs of the AVSBILC properties received by the Archive in the spring of 2017. That collection of nearly 1,000 photographs, now mostly digitized and online ([hdl.handle.net/10217/189686](https://hdl.handle.net/10217/189686)), covers the first two decades of the twentieth century, showing dam and canal construction and maintenance, flood damage, tours for visiting company directors, dairy cattle, parades, and buildings, including sugar factories. Together, the two AVSBILC collections offer a wealth of detail that will help us all gain greater understanding of irrigation development in Colorado's Arkansas Valley, as well as its nationwide connections. 





# Matthew Ross

Ecosystem Science and Sustainability Department

I am an Assistant Professor in Ecosystem Science and Sustainability, working mostly on issues surrounding water quality with a fundamental interest in human-environment interactions. I grew up in the dense ponderosa pine stands of the Black Forest, Colorado, near the divide between the Platte River Basin to the north and the Arkansas Basin to the south. I did not go far for college, attending the University of Colorado-Boulder (CU), where I studied ecology and evolutionary biology with a minor in French. While at Boulder, I worked in the lab of Dr. Nichole Barger. We did research near the Needles District of Canyonlands National Park in Utah. In these pinyon-juniper wood-



Matthew Ross

lands, fire mitigation efforts provided funds to trim down large swaths of trees, and we studied the effects of these efforts on the soil, vegetation, and biological soil crusts. It was in this stark, remote landscape where I first started to understand just how far the impacts of mankind have spread on Earth. This landscape, despite being several miles from any serviceable road, was completely shaped and influenced by a history of human decisions, from the introduction of cattle in the early 1900s to the more recent fire mitigation efforts.

After graduating from CU, I hoped to take a break from ecological research and taught English in a French high school for a year. Despite the interesting work, a brief stint as a book translator, and the challenging language acquisition, I could not stop thinking about human controls on ecosystems. In the Massif Central of France where I lived, millennia of sheep grazing on the tops of local volcanic mountains had created high-mountain prairies surrounded by dense, manicured forest. Yet recent economic changes meant that these traditional sheep-grazing practices were declining, and the forest was encroaching on these high-biodiversity prairies. My neighbors and friends were focused on restoring the landscape to the sheep-pastures. This was a shocking reversal of how I thought of restoration. Coming from the United States, restoration often implies *removing* human influences.

With these persistent thoughts of human decisions as the ultimate control over most modern ecosystems, I decided to go back to graduate school. I went to Duke University to work with Drs. Emily Bernhardt and Martin Doyle. Martin and Emily had both written extensively about ideas of stream restoration, ecosystem services, and the ever-increasing influences that people have on ecosystems, and we worked on of

the most heavily impacted landscapes in the world: the mountaintop mining region of West Virginia.

Mountaintop mining is an especially destructive and widespread form of surface mining used in Appalachia to access shallow coal seams. During my research at Duke, we found that more than 6.4 cubic kilometers of waste rock have been dumped into headwaters as a result of mountaintop mining activities. This geological reorganization has long-term impacts on downstream water quality and surface vegetation, turning the streams of Appalachia more saline and leaving behind plateaus with sparse tree cover and ample grass. These entirely novel ecosystems cover approximately 6,000 square kilometers of land, and their long-term future is relatively unknown.

The large-scale impacts from mountaintop mining led me to do a post-doc at UNC-Chapel Hill with Dr. Tamlin Pavelsky, where we used satellite remote sensing to look at water quality change at continental scales. This work has continued as I started my job at CSU, and I hope to more deeply integrate remote sensing tools into aquatic ecosystem ecology. The backbone of this work is supported by millions of data points collected by the USGS and other organizations. I use modern data science techniques to use this public and open-access data to better understand water quality change, whether in a local watershed or at a continental scale. I am grateful to work with such robust and well-maintained datasets and hope to contribute to the open-access and reproducible research movements by publishing all of my code and data.

My vision for my research lab and teaching is to enable broad public engagement with environmental data and ecological knowledge. I am hopeful that demystifying and sharing insights from my water quality and ecosystem research can nudge the structure of our cities, mines, and agricultural systems towards more ecologically-based designs that promote environmental justice for all.



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# USGS Recent Publications

**Improved enrichment factor calculations through principal component analysis: Examples from soils near breccia pipe uranium mines, Arizona, U.S.A;** 2019, *Environmental Pollution*; Bern, C.R., Walton-Day, K., Naftz, D.L.

**Pulsed salmonfly emergence and its potential contribution to terrestrial detrital pools;** 2018, *Food Webs*, 18; Wesner, J.S., Walters, D.M., Zuellig, R.E.

**Real-time streambed scour monitoring at two bridges over the Gunnison River in western Colorado, 2016–17;** 2018, U.S. Geological Survey Scientific Investigation Report 2018–5123; Henneberg, M.F.

**Quantifying uncertainty in simulated streamflow and runoff from a continental-scale monthly water balance model;** 2018, *Advances in Water Resources*, 122, p.166-175; Bock, A.R., Farmer, W.H., Hay, L.E.

**Elevated Manganese Concentrations in United States Groundwater, Role of Land Surface–Soil–Aquifer Connections;** 2018, *Environmental Science & Technology*; McMahon, P.B., Belitz, K., Reddy, J.E., Johnson, T.D.

**Linking the Agricultural Landscape of the Midwest to Stream Health with Structural Equation Modeling;** 2018, *Environmental Science & Technology*; Schmidt, T.S., Van Metre, P.C., Carlisle, D.M.

**Effects of Antecedent Streamflow and Sample Timing on Trend Assessments of Fish, Invertebrate, and Diatom Communities;** 2018, *Journal of the American Water Resources Association*; Zuellig, R.E., Carlisle, D.M.

**Geometric Versus Anemometric Surface Roughness for a Shallow Accumulating Snowpack;** 2018, *Geosciences*, 8(12), 463, p. 1-10; Sanow, J.E., Fassnacht, S.R., Kamin, D.J., Sextone, G.A., Bauerle, W.L., Oprea, I.

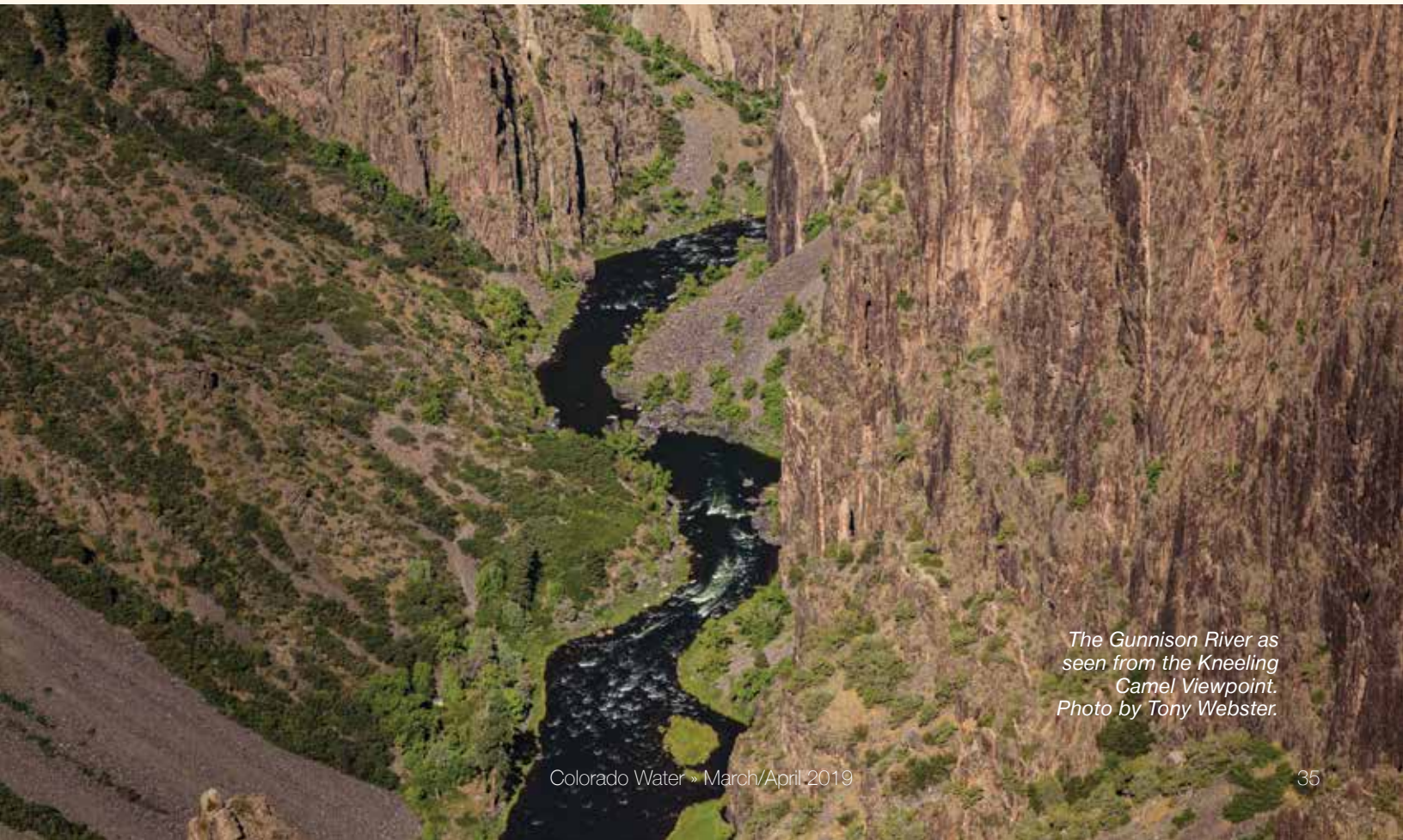
**Contaminants of Emerging Concern in the Environment: Where We Have Been and What Does the Future Hold?;** 2018, *Water Resources IMPACT*, 20(60), p. 8-11; Battaglin, W.A., Koplín, D.W., Furlong, E.T., Glassmeyer, S., Blackwell, B., Corsi, S.R., Meyer, M. T., Bradley, P.M.

**Estimating Metal Concentrations with Regression Analysis and Water-Quality Surrogates at Nine Sites on the Animas and San Juan Rivers, Colorado, New Mexico, and Utah;** 2018, U.S. Geological Survey Scientific Investigations Report 2018–5116, 68; Mast, M.A.

**Groundwater Chemistry and Water-Level Elevations in Bedrock Aquifers of the Piceance and Yellow Creek Watersheds, Rio Blanco County, Colorado, 2013–16;** 2018, U.S. Geological Survey Scientific Investigations Report 2018–5142; Thomas, J.C., McMahon, P.B.

**Topographic Survey and Streambed-Sediment Data of Fountain Creek between Colorado Springs and the Confluence of Fountain Creek at the Arkansas River, Colorado, 2018;** 2018, U.S. Geological Survey data release; O'Shea, P.M.

**A paradox of warming in a deep peri-Alpine lake (Lake Lugano, Switzerland and Italy);** 2018, *Hydrobiologia*, 824(1), p. 215-228; Lepori, F., Roberts, J. J., Schmidt, T. S.



*The Gunnison River as seen from the Kneeling Camel Viewpoint. Photo by Tony Webster.*



# Water Calendar

## April

**16 Rivers of Lost Souls Book Signing and Lecture;**  
Fort Collins, CO

Author Jonathan Thompson will talk about his book *River of Lost Souls*, which focuses on the 2015 Gold King Mine spill. He will cover the history of mining and associated water quality issues in Colorado, an essential and fascinating topic for anyone who uses water in the state or downstream.  
[lib.colostate.edu/about/news-events/author-series](http://lib.colostate.edu/about/news-events/author-series)

**16-18 Water in Africa Symposium;**  
Fort Collins, CO

The symposium will focus on the Sustainable Development Goals (SDG) and how they relate to water-related challenges throughout sub-Saharan Africa. Water is fundamental to many of the SDGs. As such, this symposium will take a broad view of how various SDG targets interact with water resources.  
[sustainability.colostate.edu/event/water-in-africa-symposium](http://sustainability.colostate.edu/event/water-in-africa-symposium)

**24-25 2019 Arkansas River Basin Water Forum;**  
Pueblo, CO

As one of the most important natural resources in our state, the water future of the Arkansas River Basin depends on education, dialog, and a deeper understanding of all sides of water issues. The Arkansas River Basin Water Forum has been at the forefront of this conversation for 25 years.  
[arbwf.org](http://arbwf.org)

**24-26 2019 Partners in the Outdoors Conference;**  
Breckenridge, CO

The Partners in the Outdoors Conference brings together organizations, agencies, schools, businesses, and communities engaged in the future of Colorado's conservation and outdoor recreational opportunities.  
[cpw.state.co.us/aboutus/Pages/2019-Partners-In-The-Outdoors-Conference.aspx](http://cpw.state.co.us/aboutus/Pages/2019-Partners-In-The-Outdoors-Conference.aspx)

**29-30 2019 Water for Food Global Conference;** Lincoln, NE

*Water for a Hungry World: Innovation in Water and Food Security.*  
[waterforfood.nebraska.edu/news-and-events/events/2018/08/2019-water-for-food-global-conference](http://waterforfood.nebraska.edu/news-and-events/events/2018/08/2019-water-for-food-global-conference)

## May

**7-9 10<sup>th</sup> International Conference on Sustainable Water Resources Management;**  
Alicante, Spain

This conference will present recent technological and scientific developments, associated with the management of surface and subsurface water resources.  
[wessex.ac.uk/conferences/2019/water-resources-management-2019](http://wessex.ac.uk/conferences/2019/water-resources-management-2019)

**8-10 10<sup>th</sup> International Conference on River Basin Management;**  
Alicante, Spain

This conference will examine growing international interest in the planning, design, and management of river basin systems and address aspects of hydrology, ecology, environmental management, floodplains, and wetlands.  
[wessex.ac.uk/conferences/2019/river-basin-management-2019](http://wessex.ac.uk/conferences/2019/river-basin-management-2019)

**13-15 Environmental Leader and Energy Manager Conference;** Denver, CO

This conference brings together industry changemakers to share their wealth of experience and tried-and-tested best practices and provides attendees with an arsenal of new information, tools to maximize efficiency and performance, and a wide network of elite peers from across industries.  
[conference.environmentalleader.com](http://conference.environmentalleader.com)

**15 Denver Metro Water Festival;**  
Denver, CO

Hosted by Denver Water, the Suburban Distributors of Denver Water, the One World One Water Center at Metropolitan State University of Denver, and Red Rocks Community College, the Denver Metro Water Festival is a unique opportunity to provide unbiased water-related education to sixth graders in Denver Water's extended service area.  
[denvermetrowaterfest.org](http://denvermetrowaterfest.org)

**19-23 World Environmental and Water Resources Congress;**  
Pittsburgh, PA

*Resilient Infrastructure for a Changing Planet.*  
[ewricongress.org](http://ewricongress.org)

**28-31 Society of Wetland Scientists' 2019 Annual Meeting;** Baltimore, MD

*The Role of Wetlands in Meeting Global Environmental Challenges: Linking Science, Policy, and Society.*  
[sws.org/Sample-Content/annual-meeting.html](http://sws.org/Sample-Content/annual-meeting.html)

**29-31 Western Water Futures Games;** Gunnison, CO

Three intensive days of brainstorming, collaborating, and contending with future and current western water leaders over evolving water issues in serious need of new thinking and new ideas.  
[western.edu/colorado-water-workshop](http://western.edu/colorado-water-workshop)

## June

**6-7 2019 Getches-Wilkinson Center Summer Conference;**  
Boulder, CO

*Charting a Better Course for the Colorado River: Identifying the Data and Concepts to Shape the Interim Guidelines Renegotiation.*  
[getches-wilkinsoncenter.cu.law/events/2019-gwc-summer-conference](http://getches-wilkinsoncenter.cu.law/events/2019-gwc-summer-conference)

**9-12 National Association for Community Development Extension Professionals (NACDEP) Conference;**  
Asheville, NC

Join us for Tools, Insights and Connections to enhance your work using Community Development Practice. We welcome all disciplines to enrich and inspire our learning together.  
[nacdep.net/2019-nacdep-conference](http://nacdep.net/2019-nacdep-conference)

**11-13 2019 Universities Council on Water Resources/ National Institutes of Water Resources Annual Water Resources Conference Conference;**  
Snowbird, UT

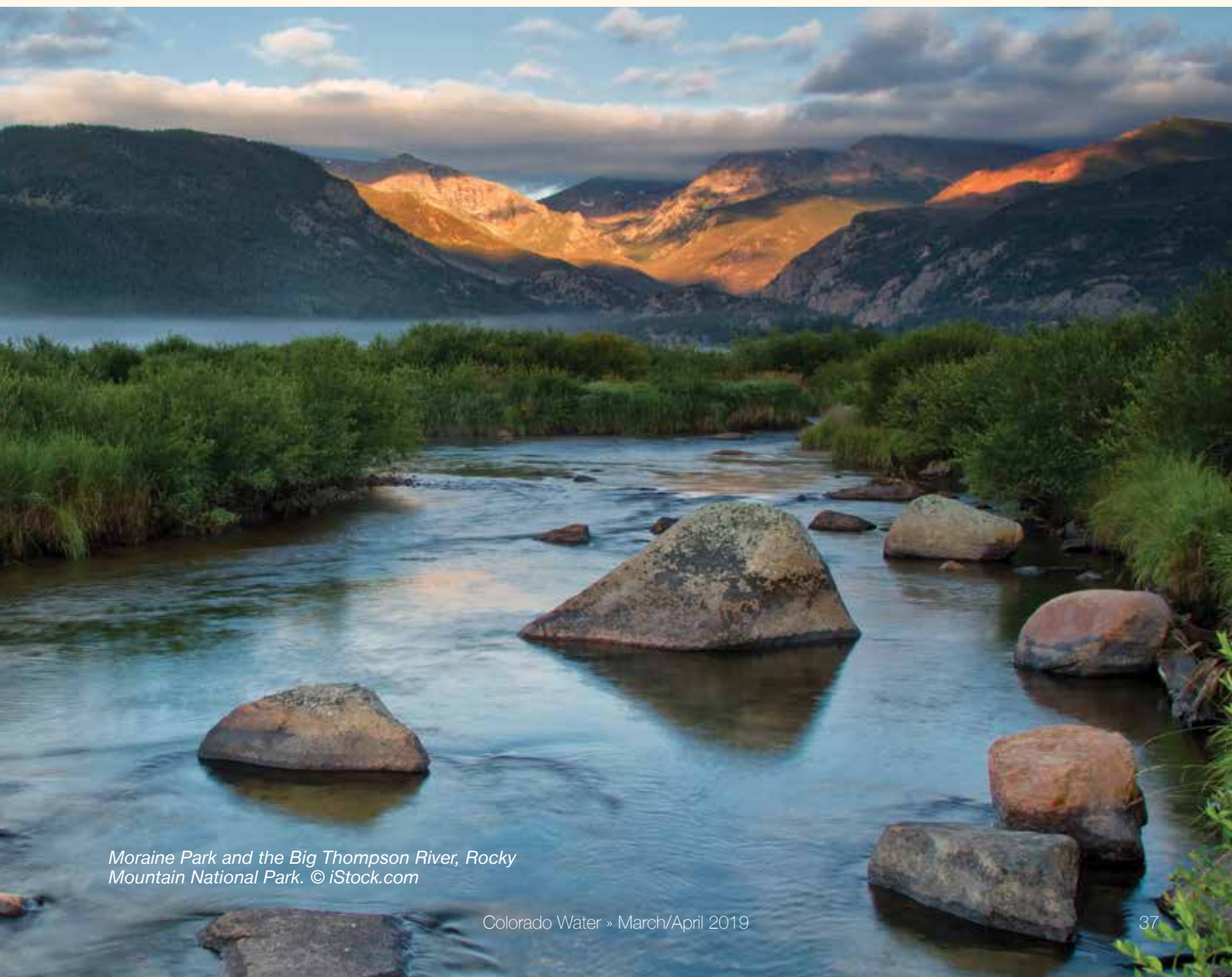
Join leading researchers, educators, water managers, and other professionals from across the country to address some of the most compelling and important challenges facing water resources. This year's conference will highlight the many unmet challenges in a newly uncertain cultural and regulatory climate.  
[ucowr.org/2019-conference](http://ucowr.org/2019-conference)

**16-19 Summer AWRA Conference;**  
Sparks, NV  
*Improving Water Infrastructure through Resilient Adaptation*  
[awra.org/Members/Events\\_and\\_Networking/Events/Summer\\_2019\\_Specialty\\_Conference.aspx](http://awra.org/Members/Events_and_Networking/Events/Summer_2019_Specialty_Conference.aspx)

**18-20 Rocky Mountain Stream Restoration Conference;**  
Estes Park, CO  
*Constrained Realities: The Role of Restoration in the Reality of Watershed Extremes.*  
[rockymountainstream.org](http://rockymountainstream.org)

**21-24 River Rally;**  
Cleveland, OH  
*Hosted annually by River Network, River Rally provides an inspiring and energy-infused touchpoint for nonprofit groups from across the U.S. and beyond, as well as for agency and foundation representatives, industry innovators, philanthropists, academics, students, and community leaders.*  
[rivernetwork.org/connect-learn/river-rally](http://rivernetwork.org/connect-learn/river-rally)

**24-28 Federal Interagency Sedimentation and Hydrologic Modeling Conference (SEDHYD);**  
Reno, NV  
*Improving Resiliency and Sustainability of Watershed Resources and Infrastructure.*  
[sedhyd.org/2019](http://sedhyd.org/2019)



Moraine Park and the Big Thompson River, Rocky Mountain National Park. © iStock.com





### Colorado Water Online

Visit [cwi.colostate.edu](http://cwi.colostate.edu) to access a PDF version of our current newsletter. To download past issues of our newsletter, click on Newsletter Archives.

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Arkansas Valley Sugar Beet and Irrigated Land Company officials visited the Arkansas Valley in May 1909. See page 30. Photo from Arkansas Valley Sugar Beet and Irrigated Land Company Photographs, Water Resources Archive, CSU Libraries.

## Estimating Impacts of Salinity on Irrigated Crop Production using Electrical Conductivity Surveys and Multi-level Remote Sensing

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