Spring 2022

Emerging Technologies *to* Improve Water Resource Management *in* Colorado

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Mortenson Center in Global Engineering
UNIVERSITY OF COLORADO BOULDER

COLORADO WATER CENTER
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Emerging Technologies *to* Improve Water Resource Management *in* Colorado

This report is published by the University of Colorado Boulder Mortenson Center in Global Engineering & Resilience, and the Colorado State University Colorado Water Center in response to State of Colorado House Bill 21-1268 "Emerging technologies for water management study". This report was prepared and edited by Kat Demaree, Melanie Holland and Evan Thomas of the University of Colorado Boulder and Amy Kremen of Colorado State University. Co-Authors include: Rep. Brianna Titone, Sen. Cleave Simpson, Kate Ryan, Rana Sen, SJ Maxted, Carley Weted, K. Kelly Close, Alison Witheridge, Andrew Antonio, Ben Livneh, Stephanie Tatge, Alex Johnson, Chris Thomas, David Primozich, Elliot Hohn, Scott Campbell, Jeffrey Deems, Taylor Winchell, Stephanie Kampf, Abby Eurich McNamara, John Hammond, Gigi Richard, Joel Sholtes. This report was funded by the State of Colorado, the Moore Foundation and the Irrigation Innovation Consortium.

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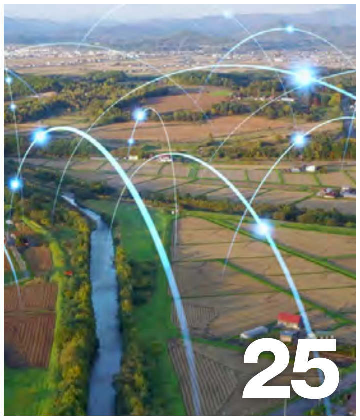
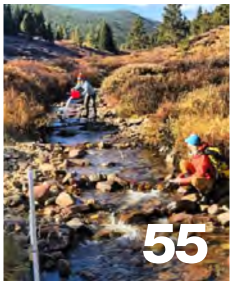
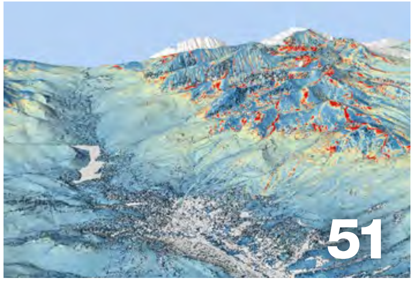






Foreword

Representative Brianna Titone is the State Representative for House District 27 and has served on the Agriculture Committee for 3 years. She has a Master of Science degree in Low Temperature Geochemistry from Stony Brook University and has worked in the environmental and mining consulting fields for a total of 11 years conducting groundwater monitoring, groundwater flow modeling, testing, well installations, and mine drainage studies. She was a registered professional Geologist in North Carolina from 2006 to 2016. Because of her background in water, she has taken a keen interest in water, water quality, and water conservation in Colorado to preserve our most precious natural resource.

Senator Cleave Simpson Senate District 35 which consists of 16 counties in rural southern Colorado where irrigated agriculture is the dominant economic driver for most of the rural communities. He has a Bachelor of Science degree in Mining Engineering from the Colorado School of Mines and worked nearly two decades in the surface mining industry in the U.S. and Australia. Cleave returned home to Alamosa in the San Luis Valley several years ago to carry on the multi-generational farming/ranching operations with his family as well as stepping up to lead the Rio Grande Water Conservation District as its General Manager. Having been born and raised in the San Luis Valley, the water security issues and challenges are obvious and paramount here and across the state. Emerging technologies for water management will play a critical role in our journey to better balance ever increasing demands for water with what has been ever decreasing supplies.

If you ask anyone in Colorado who is a water user, you'll hear real concern. The old phrase, **"Whiskey is for drinking and water is for fighting"** is becoming truer every year.

Federal officials are calling for "extraordinary, urgent" actions to save the drought-strapped Colorado River, right now. Colorado is experiencing a 'megadrought': the worst in 1,200 years of records. As of April 2022, the entire State of Colorado is under every level of drought from abnormally dry to extreme drought. Our climate is changing, driven by anthropogenic release of carbon and methane in our atmosphere. We continue to develop and add more demand, but we are not doing enough to conserve. At the headwaters, and the source of water for several states and Mexico, we have legal responsibilities through compacts and agreements with our downriver states.

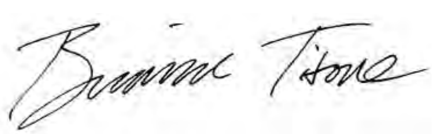
We are constantly trying to legislate water usage and maintain senior and junior rights and adhere to our complex water laws. We can't make the best decisions without the best data in hand. It's imperative that our agencies are equipped to collect and analyze quality data and communicate that to the General Assembly so we can do the best work that makes the best impact with the fewest unintended consequences.

The question behind HB21-1268 is how we can better manage our water resources and obtain the highest quality and most useful data. We need to be able to know if we are within our means and our obligations and be able to predict when we may reach the tipping point. There are wonderful high-tech methodologies being developed, some right here in Colorado, that we can use to understand our most precious resource. The data we collect will inform our groundwater basins, our water districts, our ski industry, and our municipalities on the state of our water with better accuracy and precision. We need to be making decisions with the best data and the best interests of the State of Colorado.

We took advantage of the world class research of Colorado State University and the University of Colorado to take stock of what gaps we have in our water resources. This report shows data from the people on the ground doing the work. They are identifying what gaps there are and the best ways to account for and fill those gaps. This is an important step to identify what we can do better. Knowing what ways we can account for water is critical. Knowing where our water is located is also an important part of this accounting. As technology, like LIDAR, satellite imagery, and remote sensing gets less expensive and more accurate, we will be able to metaphorically track every 'flake of snow and drop of rain' from where it lands to where it leaves the state.

This report doesn't look into the future very much, but it's often difficult to determine exactly what 'will be' available later. We could see blockchain being important in transparency and adhering to water agreements and priorities. Our imaginations may not be able to conceive of how technology will evolve. But rest assured, because of the importance of water in Colorado, necessity will be the mother of invention and we will find even more creative and innovative methodologies.

This work cannot come at a more important time. As we see the Colorado River becoming 'endangered' and other areas such as the Rio Grande in similar peril, and with drought and fire seasons not letting up, we must be ever more vigilant in our quest to be more efficient and conserve our most precious resource. We can achieve this through technology and policy. It won't be easy, but working together, through science, we can be better stewards of our state's water.



Representative Brianna Titone
State Representative for House District 27

Senator Cleave Simpson
Senate District 35

Executive Summary

An ongoing megadrought in the western United States is stressing Colorado's water resources. Over the past two decades, decreasing precipitation and increasing temperatures have caused persistent meteorological and agricultural drought in the state and increased pressure on water resource availability. Considering this, the state legislature passed House Bill 21-1268, "Study Emerging Technologies for Water Management", in July 2021, tasking researchers at the University of Colorado Boulder and Colorado State University with investigating how technologies could aid in the management, monitoring, allocation, and conservation of Colorado water resources. Technologies under consideration include innovations in remote sensing, telemetry, digital water transaction platforms including blockchain, and advanced aerial observation platforms, such as high-altitude balloons and drones.

The research team used informant interviews with water experts statewide and complementary surveys to explore the following themes:

1. Identification of monitoring gaps in Colorado water management
2. Main challenges for Colorado water managers across basins and sectors
3. Perceptions of technology use and barriers to adoption across Colorado

Qualitative coding methods were used to analyze transcripts from informant interviews, and relative frequency and statistical approaches were used to analyze survey results to determine areas of improvement in Colorado water management and monitoring. We found technological gaps in the following categories: monitoring groundwater use, snowpack modeling, streamflow prediction, and water rights trading and transactions. In response to the results of this analysis, we identify eight case studies of technologies with the potential to address potential gaps in Colorado water management, and we explore the concept of the digitization of water.

Across the state, water managers are faced with increasing challenges. Drought and climate change continue to tax already strained resources while rampant population growth and extended wildfire seasons become the new normal. These issues affect every sector and basin in unique ways, but stakeholders agreed that working together is the only way towards success. Improved efficiency in agriculture, more complete snowpack monitoring and streamflow forecasting, and monitoring watershed health are key areas that can assist water managers in facing these daunting realities. Finally, tools that help people share ideas and data can help facilitate working together to find solutions to Colorado's water management problems.

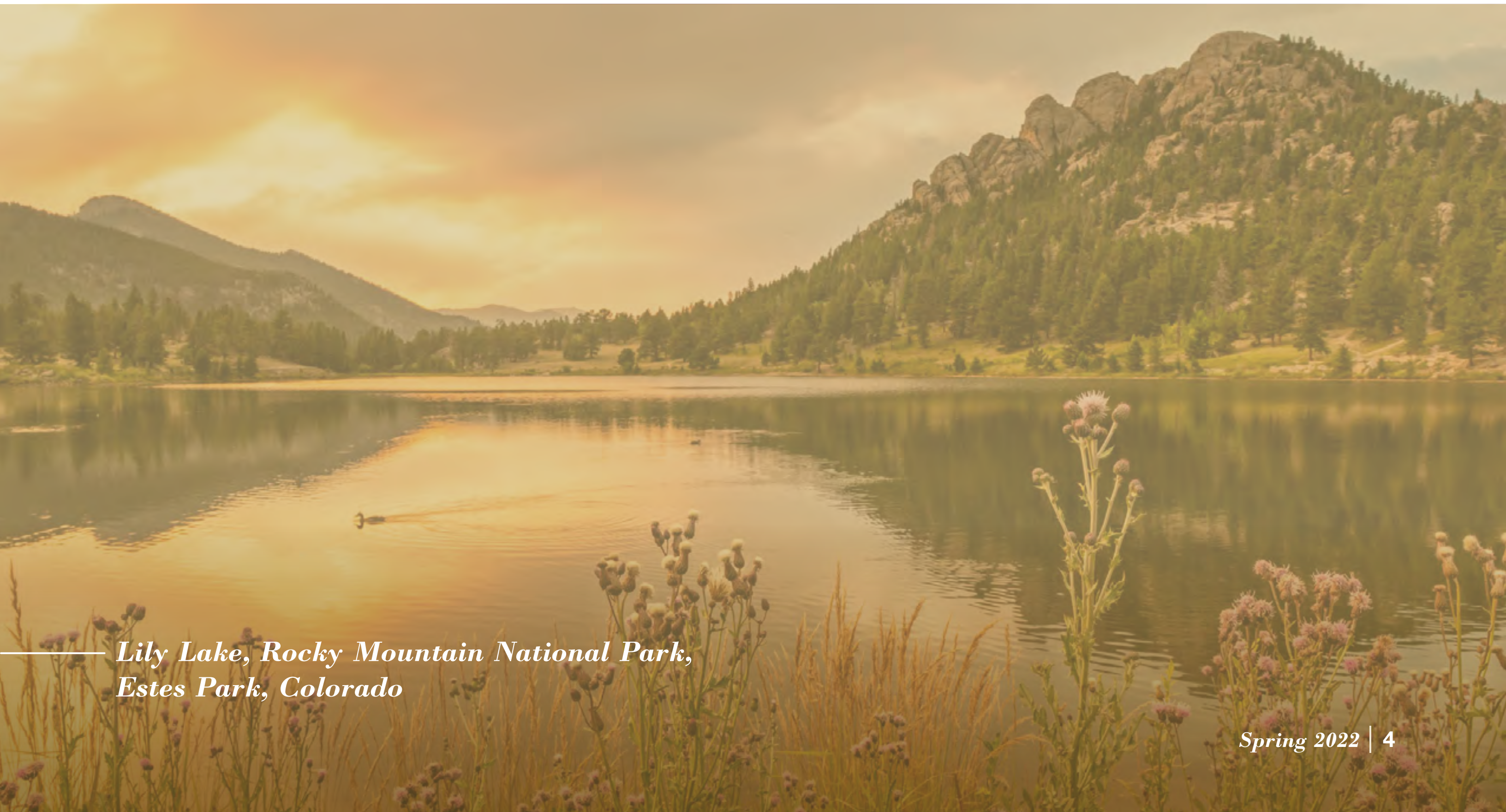
From the informant interviews and survey results, factors of reliability and cost were determined to be the most critical when deciding on whether to invest in improved solutions. The climate and topography of the Rocky Mountains make it imperative that technology can withstand a variety of conditions to be considered by water managers. As funding is often limited, technology needs to be cost-effective and demonstrate its value in order to be adopted by water users and managers. Conversations surrounding public perception and concern over data collection were also frequently present in interviews, highlighting a need for increased communication and security. Technology also needs to be easy to use and accessible to water managers, as over-complexity discourages adoption.

The case studies highlight tools and programs developed and deployed in the western United States to address water management challenges. These include: a watershed management dashboard to optimize economic and agricultural decisions in Southern Colorado; a groundwater monitoring tool in the Central Valley of California in response to increasing regulation; advanced aerial observation using microballoons in the stratosphere for low-cost, high-resolution surveying; snowpack monitoring method to provide high-quality, basin-wide data; an online water rights and transactions platform to increase transparency and accessibility for water users along the Arkansas River; an improved streamflow predictive data tool to provide insight into ungauged flows; an open-source, satellite-based evapotranspiration data set, encouraging collaboration and data sharing in Colorado while delivering critical information to water managers; and two programs that encourage education about the adoption of precision agriculture and efficient irrigation tools and techniques.

Drought and climate change continue to tax already strained resources while rampant population growth and extended wildfire seasons become the new normal.

To address the needs and interest around the digitization of water rights and transactions, we collaborated with experts in Colorado water law and digital innovation, outlining the digital future of water rights in Colorado. This discussion includes an overview of Colorado's legal and policy environment and opportunities to reduce cost and complexity by digitizing some elements of trading and allocations. While digitization could improve the fluidity, transparency and effectiveness of transactions for water users across the state, we also discuss barriers to implementing a solution of this kind.

Climate change impacts on hydrologic systems highlight the importance of deliberate efforts to improve water conservation and management across Colorado and the western United States. HB21-1268 and this report are intended to spur innovation and focus dialogue, funding, and legislative activity to support advancements in water conservation and the use of water management technologies in Colorado and neighboring states. This report's findings illustrate the importance of gathering qualitative insights from water managers and decision-makers engaged in dealing with water resource challenges across Colorado.



Lily Lake, Rocky Mountain National Park, Estes Park, Colorado

Introduction

Kat Demaree, Melanie Holland, Evan Thomas
University of Colorado Boulder

Colorado is home to the headwaters of several major river systems in the western United States, providing an essential water source throughout the region. As a headwater state, most of the precipitation that falls in Colorado flows into neighboring states, making the monitoring of this resource imperative to meet interstate regulations. There are seven river basins designated as water divisions by the State of Colorado: the Arkansas, Colorado, Southwest, Gunnison, Rio Grande, South Platte/Republican, and Yampa/White/North Platte River Basins.

In the southwest corner of the state, the San Juan and Dolores River basins originate in the San Juan Mountains. The San Juan River reaches Navajo Reservoir before flowing through New Mexico and Utah, eventually merging with the Colorado River. The Dolores River flows to McPhee Reservoir before it exits the state to Utah and joins the Colorado River. Communities and agricultural producers rely on this crucial water system, including the Southern Ute and Ute Mountain Ute Tribes. Just north of the San Juan and Dolores River basins is the Gunnison River Basin, which originates at the continental divide and encompasses 8,000 square miles in western Colorado. The Gunnison River is a major tributary of the Colorado River and contributes approximately one-fifth to one-sixth of the Colorado River Basin's total annual flow that leaves the state (*Gunnison Basin Implementation Plan*, 2022).

Towards the south and southeast corner of the state are the Rio Grande and Arkansas Basins. The Rio Grande flows 1,896 miles from its headwaters on the eastern side of the San Juan Mountains to Texas where it forms the international boundary between the United States and Mexico. The Rio Grande provides water for 22 tribes and is used for a range of applications including municipal, agricultural, and industrial uses. The Arkansas River Basin, which is the largest by area in Colorado covering more than 28,000 square miles, originates in the Rocky Mountains and is a major tributary to the Mississippi River. This extensive system supplies water to approximately 1 million people in Colorado (*Arkansas Basin Implementation Plan*, 2022; *Rio Grande Basin Implementation Plan*, 2022).

In the north and northeast part of the state lie the South Platte and Republican River Basins. The South Platte River Basin, which is the most populous basin in the state, originates along the Continental Divide, and flows towards the metropolitan area of Denver County. The Republican River originates in the northeastern High Plains and flows into Nebraska and Kansas. Most land use in this basin is agricultural. Moving to the west, the Yampa, White, and North Platte River Basins cover approximately 7,660 square miles with primary land uses including grazing and recreation (*South Platte Basin Implementation Plan*, 2022).

South of the Yampa, White, and North Platte River Basins is the Colorado River Basin. This expansive system of tributaries and rivers spans seven states, making it one of the largest river networks in the world. The Colorado River Basin provides water to nearly 40 million people for municipal use, supplies water to irrigate nearly 5.5 million acres of land and delivers water to 22 federally recognized tribes (*North Platte Basin Implementation Plan*, 2022).

However, ongoing drought conditions have had consequential impacts on all of these vital river systems in Colorado. In July 2021, Lake Powell reached its lowest level since it was filled in 1969. Declining levels at Lakes Powell and Mead resulted in the seven basin states signing a Drought Contingency plan in 2019, which included prescribed reductions in usage for lower basin states and a process to perform drought operations at Colorado Storage Project reservoirs. Continued declining levels have resulted in implementation of those agreed upon reductions in deliveries to lower basin states in 2021. Strained water availability in Lake Powell and other water storage projects across the western United States have drastic implications for water resource management in the western United States.

To date, there is no consistent statewide standard or expectation related to water-management technology implementation, nor statewide evaluation of the effectiveness of current technologies, metrics, and data tools used in Colorado.

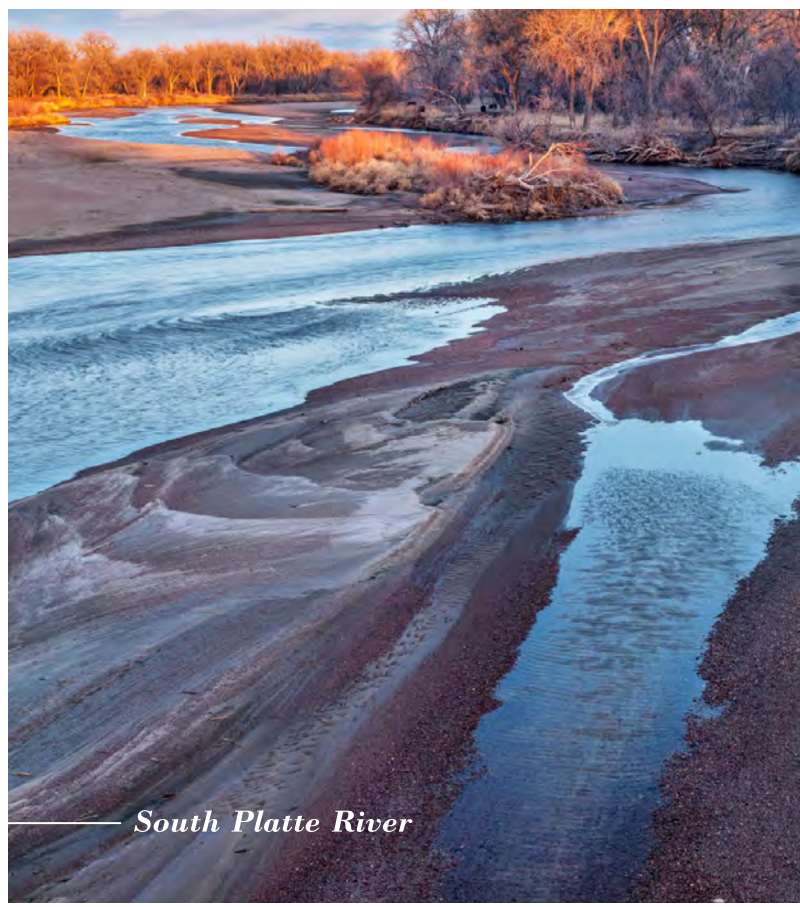
Temporally inconsistent and spatially varied groundwater measurements gathered at the federal and state level – for example, by the U.S. Geological Survey and the Colorado Department of Natural Resources – provide only some of the data needed to support near-term, effective decision-making and management to support longer-term, beneficial impacts. These sources primarily collect groundwater level and quality data. Most of the major groundwater users in the South Platte, Arkansas River, Republican River, and Rio Grande basins are required to also report the quantity, timing, and location of groundwater withdrawals, but not all withdrawals are reported.

At the Basin level, the Colorado Decision Support System (CDSS), developed by the Colorado Water Conservation Board (CWCB) and Division of Water Resources (DWR), provides data analytic tools and visualizations, and management resources. The CDSS uses various models to depict crop consumptive use (StateCU), groundwater (MODFLOW), surface water (StateMod), and the water budget (StateWB). The system also incorporates tools to view water rights and changes to those rights, such as changes from irrigation to municipal use. In some instances, entities such as counties, municipalities, and water districts have contracted with engineering firms and non-governmental organizations to create management tools for their water rights. These tools don't typically communicate with each other, which is a challenge when determining overall impacts of multiple systems in a watershed.

Although surface water is more routinely monitored than groundwater throughout the United States, methods of monitoring surface water vary, with neighboring sub-basins often using different technologies to measure different spatial and temporal values. Additionally, access to monitoring technologies or water management projects may be hampered by insufficient funding and perceived water-related risk. Basins typically implement a water monitoring scheme if there is sufficient financial means to support a project, if there is community support, and if there is a pressing need, often due to regulatory and/or water resource pressures.

Public perceptions of hydrologic systems and climate events are integral to water management projects and can influence which projects receive funding. Studies consistently find that policymakers' actions reflect public preferences and opinion (Burstein, 2010). Management of risks such as extreme weather events are subject to public debate and input, and perceptions of these risks are of considerable interest to local planners and policy makers (Bostrom et al., 1994; Johnson & Tversky, 1983). The growing importance of public participation in environmental hazards planning is well-documented, and it is evident that public risk perception plays a role in shaping natural hazards policy and management response systems (Godschalk et al., 2003; Slovic, 2000).

In the past two decades, Colorado experienced decreasing precipitation and increasing temperatures, causing persistent meteorological and agricultural drought (Diffenbaugh et al., 2015). In this era of ever-limited water resources, managers in Colorado are faced with the complex challenge of managing a diminishing resource to supply a growing population amid increased climate variability. This report summarizes findings from informant interviews and a complementary survey conducted to explore and better understand gaps in tools and data, opportunities, and perceptions of water-monitoring issues. Our inquiry investigated the following questions: How can we use tools and other resources more effectively and efficiently to monitor water resources better? What are the most pressing water-monitoring needs across the state of Colorado, and how do they vary from basin to basin?



South Platte River

Background

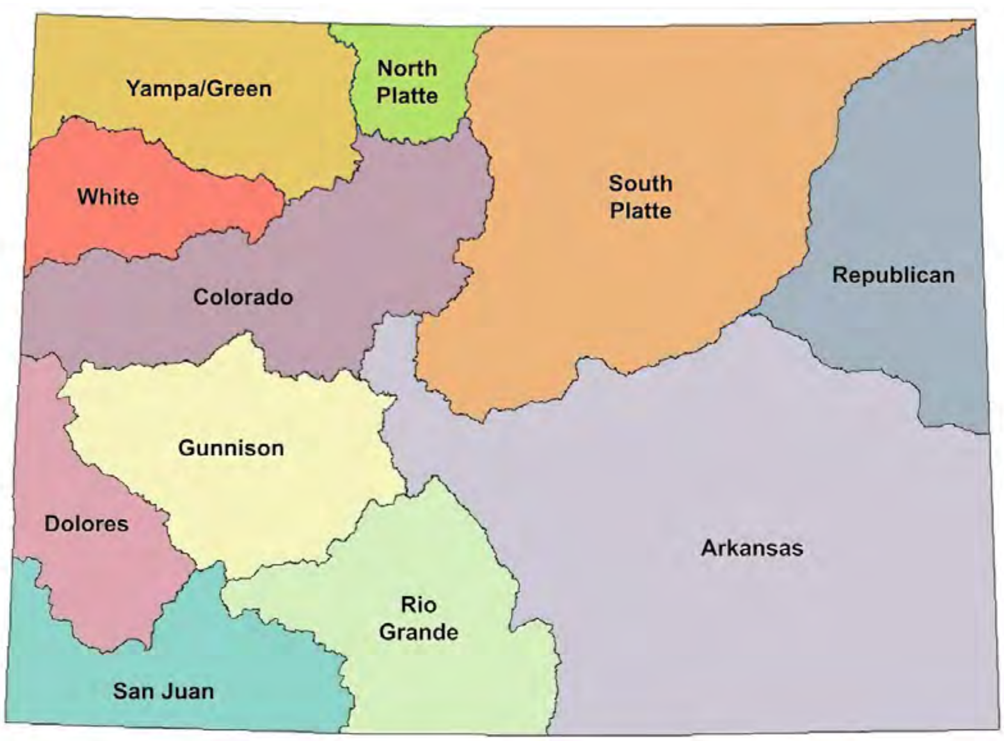
Colorado Water Policies and Compacts

State water policies and compacts influence or underpin many decisions that Colorado water managers must make. Interstate compacts are designed to settle existing or mitigate future controversy between two or more states concerning water use by stipulating water allocations. Colorado has intrastate and interstate water agreements among stakeholders, including nine interstate compacts, two U.S. Supreme Court decrees and one international treaty that govern how much water the state is entitled to use (*Read The Plan | DNR CWCB,* n.d.). These agreements determine the amount of surface water allocated between and within each state. However, due to the interdependent nature of surface and groundwater, they can also impact how much groundwater is available for each state to pump.

Colorado Water and Basin Implementation Plans

In November 2015, the Colorado Water Conservation Board (CWCB) established a statewide framework to raise the visibility of and help address Colorado's water challenges. The resulting Colorado Water Plan is produced in part by gathering extensive input from water-use stakeholders and managers from across the state and presents strategies to ensure that the state's future water needs will be met through informed policy development and smart actions by Colorado citizens. The CWCB describes the Water Plan as prioritizing a "productive economy, vibrant and sustainable cities, viable and productive agriculture, a strong and healthy environment, and a robust recreation and tourism industry" (*Read The Plan | DNR CWCB*, n.d.). The plan includes Basin Implementation Plans drafted by each of the state's eight Basin Roundtables, which highlight regional values and present strategies for addressing each basin's future water needs at the local level. Focusing on and

Figure 1: *Boundaries of primary Colorado basins, delineating the extent of interbasin implementation plans across Colorado.*



highlighting basin-specific successes helps integrate local government, utilities, and community efforts to maximize impact. The next update of the Water Plan will be released for public comment in the summer of 2022.

Previous Findings

Technology use for water management has been studied in a variety of regional contexts. The use of innovative irrigation technologies to support agriculture was examined as part of an effort to demonstrate the need, complex impacts, and potential benefits of more efficient irrigation systems. Several studies have explored the impact of drought on farmers and demonstrated how drought experience influences drought perception in agricultural communities (Diggs, 1991). More recent work has suggested the emergence of drought conditions in over half of global land surface (with the exception of Antarctica) in the next 60 years putting further pressure on existing systems to adapt to the new 'normal' characterized by 'unprecedented aridification' (Stevenson et al., 2022). In a 2018-2019 survey, more than 1000 producers from across the High Plains agreed that groundwater should be conserved to protect operations and crops in future droughts (Lauer & Sanderson, 2020). Technology uptake to manage these efforts has increased in recent years; the products and tools available or in development, and scientific efforts to improve management practices and strategies are areas of increasing focus, prompted by recent droughts of record. Improvements in irrigation efficiency techniques have allowed producers to fully irrigate lands while diverting less water from the stream; however, this doesn't result in reduced consumption and more water in the stream below their fields. Extensive resources and efforts are needed to clarify and quantify the environmental, economic and practical impacts of advanced irrigation management technologies, particularly in light of drought conditions anticipated to persist through 2022 and beyond, with many models estimating a 30-year period for the current megadrought (Williams et al., 2022).

Snowmass, Colorado

Motivation

Colorado's water supply is a critical driver of the state's economy, whether in agriculture, industry, municipalities, or recreation. Colorado's water is also key to biodiversity and ecosystem services, such as increasing groundcover and reducing erosion. Due to climate variability, intensified weather extremes, and the need to support a growing population, Colorado anticipates increasing water shortages and must find ways to adapt. Increased temperatures and changes in precipitation patterns cause increased uncertainty about water availability and the timing of snowmelt events in western snow-dominated basins, which is anticipated to exacerbate future drought conditions disrupting current water management systems (Anderson & Woosley, 2005; Faunt et al., 2016; Livneh & Badger, 2020). Fassnacht et al. explored long-term trends related to climate impacts on temperature and snowpack, finding that snow-water equivalent (SWE) was increasing at lower elevations and decreasing at higher elevations, with greater variability in temperature and precipitation trends (Fassnacht et al., 2016). Since climatic patterns are increasingly difficult to predict, water managers must prepare for a range of scenarios and be informed with the most accurate and up-to-date information.

More than 50% of the coterminous United States experienced moderate to severe drought conditions in 2002, with record or near-record precipitation deficits throughout the western United States (E. R. Cook et al., 2004; Waple & Lawrimore, 2003). This drought highlights the extreme vulnerability of water resources within the western United States due to precipitation deficits and the need to efficiently manage these resources. As droughts persist, water managers rely more on groundwater to meet demand, in some cases depleting aquifers faster than they can be recharged. Figure 3 shows the groundwater resources in the state of Colorado (excluding alluvial aquifers), including vital aquifers that supply large portions of agricultural and municipal water, which are the principal or sole water source for some rural Colorado communities.

Decreases in precipitation and SWE lead to regional water shortages in the west. As mentioned in the introduction,

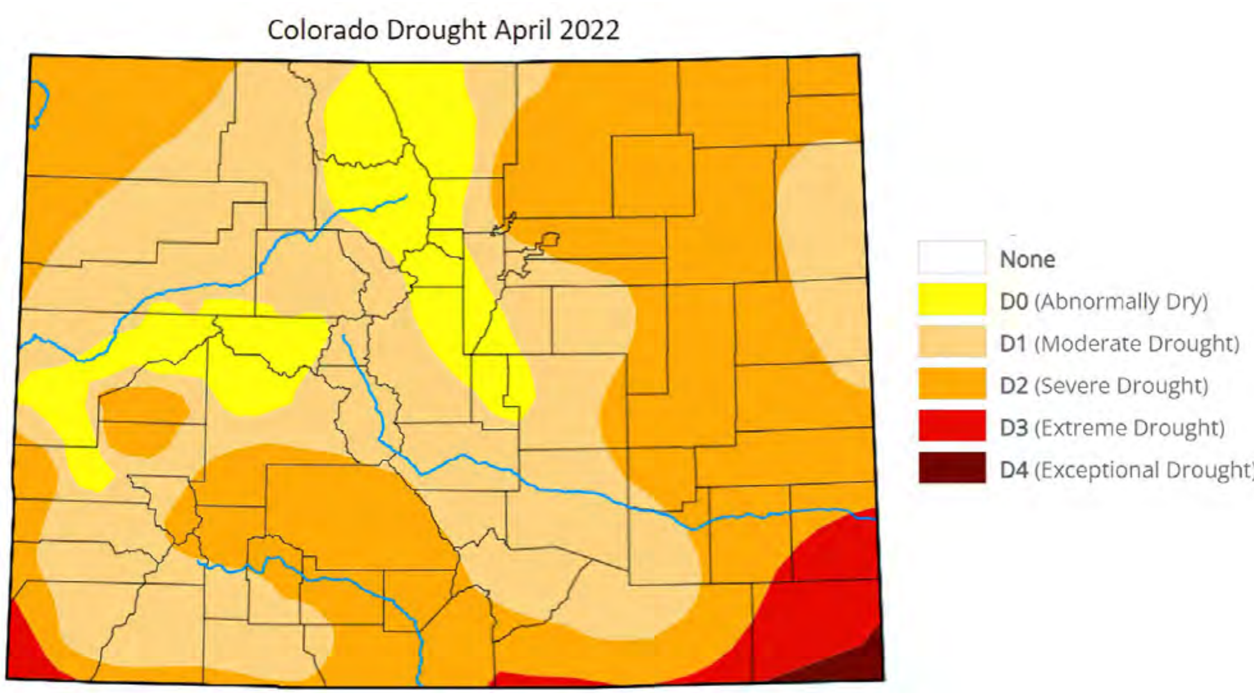


Figure 2: Map of Colorado drought status on April 26, 2022, from the U.S. Drought Monitor (Colorado | U.S. Drought Monitor, n.d.). The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration.

Figure 3: Map of aquifer locations in Colorado. Blue shaded areas represent aquifers, including the Ogallala or High Plains aquifer system in the east, the San Luis Valley aquifer system in the south, the central Denver Basin aquifer system, and the Leadville Limestone aquifer and Dakota aquifer systems in the west (United States Geological Survey, 2022).

declining water levels at Lake Powell and Lake Mead have resulted in significant changes to operations in the seven Colorado River basin states, including drought response operations releases from Blue Mesa and Flaming Gorge Reservoirs and agreed upon decreases to deliveries to lower basin states. At the time of this publication Blue Mesa Reservoir, Flaming Gorge Reservoir, and the McPhee Reservoir in the Upper Basin are all facing lower water allocations for water users or recreational closures, demonstrating the immediate repercussions of these lows (Mimiaga 2022; Sakas 2022; Bleizeffer 2022). Even before the historic impacts to these reservoirs, the Colorado Legislature was preemptively working to solve challenges in Colorado water management. In early 2020, House Bill 20-1072 was proposed by the Colorado Water Resources Review Committee with the hope of funding research to improve the effectiveness of water management. With the onset of the COVID-19 pandemic later that year, HB20-1072 was postponed. It was revisited in 2021 and received bi-partisan support on the Colorado Water Resources Review Committee as House Bill 21-1268. The bill tasked researchers at the University of Colorado Boulder to work with the Colorado Water Center at Colorado State University to collaborate on a report detailing emerging technologies that could support water management across the state.

These technologies can aid in managing, monitoring, allocating and conserving Colorado water resources, and include innovations in remote sensing, telemetry, digital water transactions such as blockchain, and advanced aerial observation platforms such as high-altitude balloons and drones. This report provides an overview of some water management technologies used in the state of Colorado. Further, it identifies opportunities to support innovation and application of new technologies by targeting funding and developing legislation to encourage their use in ways that will increase water conservation and improve water management in Colorado and neighboring states.

Methods

Kat Demaree, Melanie Holland
University of Colorado Boulder

In this analysis, we used informant interviews to develop a survey to determine omissions in Colorado water management and monitoring. Qualitative coding methods were used to analyze transcripts from informant interviews, and relative frequency and statistical approaches were used to analyze survey results.

Informant interviews are qualitative, in-depth interviews used to engage in discussion and collect information from a wide range of experts in the field of study (Wilhite et al., 2007). Utilized for decades in studies on climate and water related issues, they improve understanding of stakeholder experience and perception, (Dai, 2013). A 2014 study used informant interviews to investigate state drought programs in the western United States and found that state officials recognized a need for better data to improve and inform drought predictions and monitoring (Fontaine et al., 2015). This investigative tool was also employed to explore expert opinions on science and policy, identify scientific gaps, and gather agriculturalists' views on climate change and drought perception (Creswell, 1998; Elmendorf & Luloff, 2006).

Likewise, surveys are used extensively to discern public perception of drought and water availability and investigate barriers to technological adoption. To the best of our knowledge, this report's findings are the first of their kind to present geographical variations in perceptions about water management across the state of Colorado.

Informant Interviews

Using these approaches, we interviewed a panel of Colorado water experts to understand water management challenges. This information ultimately supported the development of a widely distributed water monitoring survey.

Twenty-eight informant interviews were conducted from September 2021 to February 2022 with a range of water managers and experts statewide, including state legislative representatives, indigenous community leaders, and agricultural producers. Interviews followed a semi-structured line of questioning that allowed for in-depth conversation, as conversation-style interviews allow for greater exploration and contemplation of a topic (McCracken, 1988).

With consideration for statewide and local policy on COVID-19 precautions, interviews were conducted in person when appropriate, with social distancing and masking in use always or held online using Zoom. All interviews had a duration of approximately 60 minutes, with some involving follow-up discussions when needed for additional information or clarity. While most of the 28 participants will remain anonymous, interviews were recorded and transcribed with the full consent of the interviewees to enable qualitative coding analysis later.

Cleave Simpson, Colorado State Senator and General Manager of the Rio Grande Water Conservation District, at his ranch in Alamosa, Colorado, during an interview. Photo by Melanie Holland

The semi-structured interview approach was modified as needed based on stakeholders' backgrounds, but generally covered the following topics:

- Data sources and collection
- Current monitoring practices and regulations
- Perceived gaps in monitoring, data collection and collaboration
- Greatest challenges facing Colorado water management

Interviews were qualitatively coded using ATLAS.ti 9, a software that enables systematic analysis of qualitative data for content analysis. From this initial analysis, themes of water monitoring challenges were used to create lists of nominal classifications. Codes appearing in interviews with the highest frequency were compiled in a code frequency table displaying topics of greater incidence in darker shades of blue: higher co-occurrence appears dark blue while codes appearing together less frequently are lighter blue, as seen in the results section, below. Code frequency values were also displayed in this matrix comparing code occurrence by participant sector and basin region. Frequently occurring codes and their co-occurrences were used to determine monitoring gaps and challenges in Colorado water management, across sectors and basins.

Throughout the interview process specific topics and themes emerged that were used to develop a survey tool, supported by a literature review. The survey elaborated on topics of frequent discussion in the expert interviews with an eye towards management technologies and monitoring metrics that present challenges to stakeholders. The information gathered through both inquiries supports understanding of water manager and user perceptions within and across Colorado.

Stakeholder Survey

A survey study was conducted to gather information and diverse perspectives on technology use and data gaps related to Colorado's water management. The survey was designed in Qualtrics and disseminated to members of the Colorado Water Congress and affiliated organizations. In contrast with the informant interviews, surveys can reach a wider audience and collect public opinion. For this study, a survey tool was designed to gather data on technology use across Colorado and understand stakeholders' perceptions of emerging technologies and water-related challenges. This data can be used to inform the feasibility of implementing technologies based on public perception.

Survey questions covered the following topics:

- Monitoring Metrics: What current metrics are monitored, and what is the perception of these? Are there inefficiencies in current methods of monitoring, or are additional metrics needed?
- Monitoring Technologies: What is the level of satisfaction with current and emergent technologies used for water management? What are the perceptions of these technologies?
- Platforms and Tools: What is the level of satisfaction with current platforms and tools that are used? What are the perceptions of these tools? What are areas of improvement?
- Greatest Challenges: What are the most pressing challenges faced in Colorado water management, considering both current and future conditions?

The survey included four types of questions: multiple choice, rank order, Likert scale, and free response. The relative frequency of responses was calculated to determine how often a response is selected. Relative frequency describes the portion of responses that fall into a category as a percent of total responses. This metric was used to compare the frequency of responses with sectors and basins throughout Colorado.

Horsetooth Reservoir, built in 1949 in Northern Colorado, provides water for Fort Collins, Greeley, and other communities in the South Platte Basin. Photo by Kat Demaree

Results

Informant Interviews

Water managers throughout Colorado and the Western United States are facing increased pressure to conserve and allocate dwindling resources with caution and care. To determine which emerging solutions might best assist them, it is necessary to obtain a thorough understanding of where management tools are being implemented successfully or are lacking, and why. This section describes themes that emerged from informant interviews with stakeholders in Colorado water to determine the challenges and management gaps experienced across the state. While the interview analysis is qualitative, code co-occurrence data was included to provide insights into topic frequency alongside basin and sector data.

Among discussions of where Colorado could improve water management practices, the following challenges emerged as most relevant:

- Groundwater monitoring
- Streamflow forecasting and snowpack data
- Water transactions and trading
- Watershed health and management

Most interviewees were kept anonymous to maintain their privacy, but some quotations are given with sector or basin information to provide context.

From rural mountain communities to high-desert metropolises, Colorado presents diverse topography and economies across the state. Although the state is experiencing exponential growth overall, some areas remain sparsely populated while others are becoming denser (America Counts Staff, 2021). These varying situations affect the way water is consumed and managed. Where and how water is sourced also varies in Colorado. Areas with low precipitation might rely heavily on groundwater while others might only use surface water from the Colorado River or its tributaries. These variations present water management challenges. The research sought perspective on water monitoring needs and challenges across basins and sectors in Colorado. While not a complete picture, stakeholder interviews allowed a range of voices and expertise to describe the issues facing their communities and the state. Figure 5 illustrates the most frequently described challenges facing water managers in Colorado.

While identifying challenges and potential solutions is important to improving water management, understanding

	Academia	Agriculture	Conservancy District	Engineering	Environmental Services	Municipal Services	Governmental	Tribal
Groundwater	0.02	0.27	0.24	0.01	0.01	0.01	0.25	0.13
Snowpack	0.16	0.01	0.02	0.02	0.04	0.02	0.01	0.00
Streamflow	0.05	0.07	0.07	0.07	0.07	0.02	0.08	0.05
Surface Water	0.00	0.07	0.09	0.02	0.03	0.01	0.05	0.09
Watersheds	0.03	0.02	0.00	0.01	0.16	0.10	0.01	0.00

Figure 4: Code co-occurrence table for data gaps in water management by stakeholder sector. Higher co-occurrence appears dark blue while codes appearing together less frequently are lighter blue. Co-occurrence values representing the frequency at which two codes were linked to the same interview quotations are displayed in the matrix.

	Academia	Agriculture	Conservancy District	Environmental Services	Municipal Services	Governmental	Tribal
Climate Change	0.08	0.04	0.04	0.07	0.06	0.05	0.02
Community	0.07	0.05	0.05	0.08	0.08	0.10	0.07
Drought	0.05	0.06	0.03	0.06	0.04	0.08	0.10
Floods	0.01	0.00	0.00	0.02	0.01	0.01	0.01
Population Growth	0.02	0.04	0.06	0.01	0.08	0.00	0.02
Wildfires	0.07	0.02	0.01	0.07	0.11	0.03	0.00

Figure 5: Code co-occurrence table describing greatest challenges facing water managers in stakeholder sectors. Higher co-occurrence appears dark blue while codes appearing together less frequently are lighter blue. Co-occurrence values representing the frequency at which two codes were linked to the same interview quotations are displayed in the matrix.

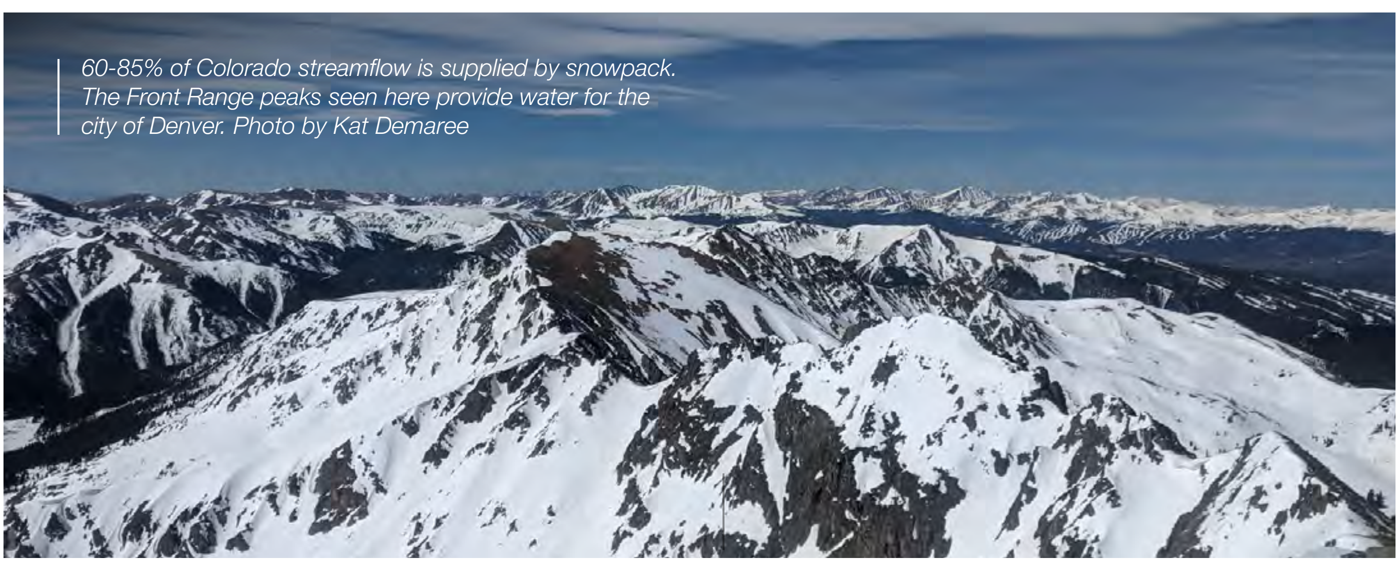
	Academia	Agriculture	Conservancy District	Engineering	Environmental Services	Municipal Services	Governmental	Tribal
Accessibility	0.02	0.00	0.01	0.03	0.01	0.02	0.02	0.02
Cost	0.06	0.06	0.06	0.05	0.04	0.07	0.03	0.01
Reliability	0.11	0.06	0.08	0.16	0.05	0.10	0.11	0.07
Security	0.00	0.01	0.03	0.02	0.03	0.01	0.01	0.01
Transparency	0.00	0.00	0.01	0.02	0.02	0.00	0.02	0.00

Figure 6: Code co-occurrence table describing the most important factors and barriers to technology adoption in stakeholder sectors where accessibility refers to ease of use and understandability of data collected through technologies. Transparency here is used to describe what data is being collected, who it is being shared with, and how it is being stored.

public perception of technology and its role is equally critical. Therefore, questions of feasibility were asked of stakeholders to identify factors that could encourage or inhibit technology adoption. Key terms and themes (including accessibility, cost, and security) were explored through inquiries related to current and hypothetical technology use. As a lot of water storage is at high elevations or rural, alpine locations, it became apparent that technology reliability is one of the principal concerns for most water managers. Snow drifts, high winds, and "hard environments" or "dangerous" conditions (as described by stakeholders) were commonplace in these discussions, emphasizing the need for durable and dependable monitoring devices. Frequently discussed terms were coded with factors related to technology adoption, such as accessibility, security, and cost. These discussions were centered on improved understanding of barriers to utilization of new management technologies and strategies. This section also sought to determine what factors influence the adoption and use of emerging technologies in water management across the state.

Qualitative analysis of informant feedback found that the most critical monitoring gaps for water managers in Colorado are: (1) improved accuracy and accessibility of groundwater monitoring; (2) streamflow forecasting and improved understanding of Colorado snowpack; (3) increased transparency and ease of water rights transactions and trading (sales and leases of water between parties); and (4) advanced and effective methods of managing watersheds. Challenges presented to Colorado managers varied by stakeholder basin and sector but were found to include: (1) continued population growth and development, and the transition of water from agricultural to municipal use; (2) changes in hydrologic systems because of extended drought, climate change and related human use impacts; and (3) negative impacts of intensifying wildfire seasons on water quality and watershed health.

A consistent theme when discussing these challenges was a desire to promote community and statewide collaboration in water management throughout Colorado. There was strong agreement across sectors and basins that the best way to address these mounting hurdles is to encourage sharing of ideas and solutions across the state. Finally, upon exploration of key considerations expressed by stakeholders for the adoption of novel management technologies, interviewees identified four factors as most important: cost, reliability, accessibility, and security. Stakeholders expressed hesitancy at adopting new technologies if they do not demonstrate resilience in Colorado's harsh climate and rugged conditions. They also expressed that ease of use and installation encouraged the adoption of new management measures. These themes were explored in greater detail through the widespread survey tool.



60-85% of Colorado streamflow is supplied by snowpack. The Front Range peaks seen here provide water for the city of Denver. Photo by Kat Demaree

Stakeholder Survey

The survey investigating Colorado water challenges, metric use, and technology implementation was distributed to various organizations and individuals in the Colorado water community. A total of 95 responses were collected from the following sectors: agriculture, municipal, government, non-government, academic, judicial, conservation districts, engineering, and environmental. Survey responses were collected from all basins throughout Colorado. Figure 7 shows the number of responses from each sector and basin.

The survey tool was designed to examine challenges in the monitoring, management, and future of Colorado water by investigating current metrics and the perception of those metrics. One goal of the survey was to gather widespread perspectives on potential inefficiencies in current monitoring methods, or additional metrics needed. We investigated monitoring technologies to identify the level of satisfaction with current and emergent technologies for water management and perceptions

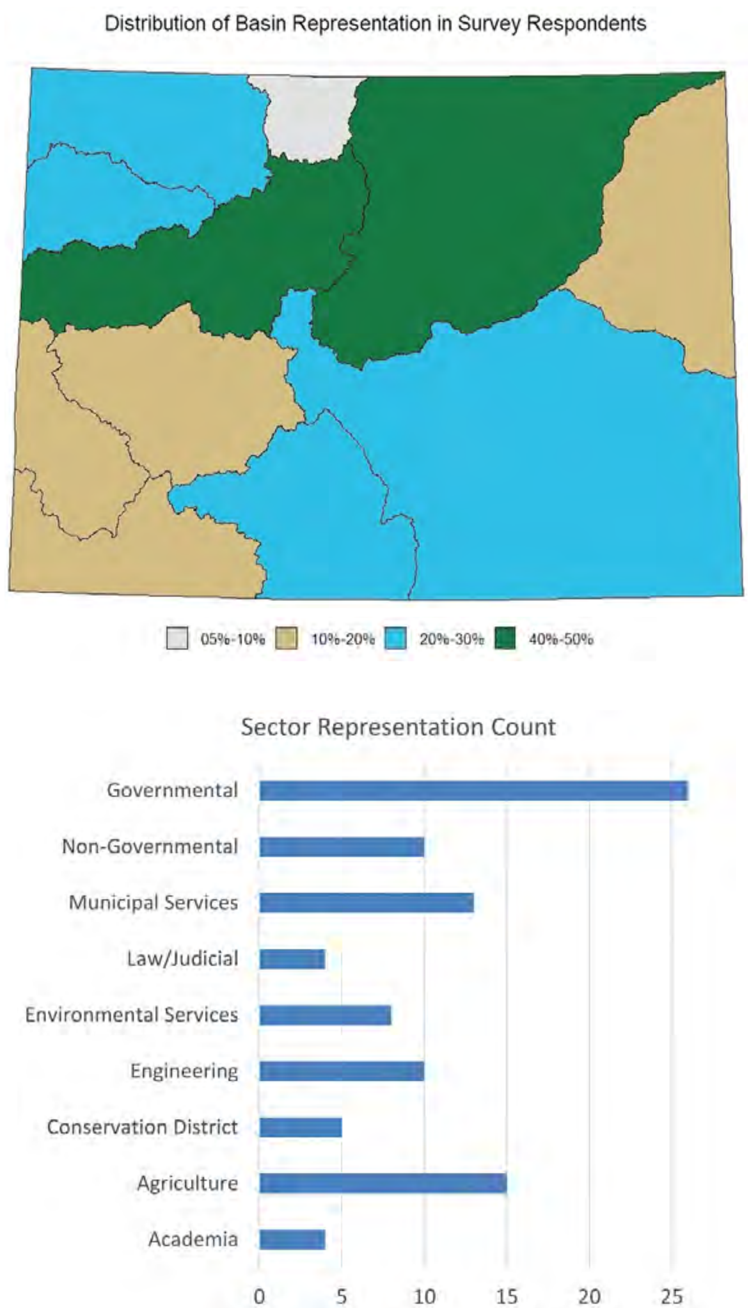


Figure 7: *Demographics of survey respondents. Top panel: Map of percent of total respondents from each basin. Bottom panel: Number of respondents from each sector.*

of these technologies. Finally, platforms and tools were investigated to determine the level of satisfaction with and perceptions of these, and potential areas for improvement.

Challenges

Colorado faces challenges in monitoring and management of water resources. To gather a thorough understanding of how stakeholders view challenges within the state, survey respondents were asked to select all the items that applied from a list of potential challenges. Since respondents were able to select multiple answers, the figures below illustrate the normalized percentage of respondents who selected each item as a relevant challenge.

Figure 8 describes the selection frequency for a variety of management challenges. Notably, ensuring the accuracy of data sources ranks amongst the most frequently selected challenges for most sectors; 100% of respondents from conservancy districts, 76.9% of respondents from the governmental sector, and 75% of respondents in the environmental sector find that the accuracy of data sources is an important challenge. Overall, 61% of the total number of survey respondents selected the accuracy of data sources as an important challenge. Likewise, meeting compact compliance was selected by 42% of total survey respondents, the ease of data access was selected by 40%, and adherence to prior appropriation was selected by 36%, indicating that these management challenges are of the greatest concern within the water community.

Which of the following are important challenges in the management of Colorado water?

Selection	Academia	Agriculture	Conservancy District	Engineering	Environmental Services	Law/Judicial	Municipal Services	Non-Governmental	Governmental
Ease of trading water units	0.0%	0.0%	20.0%	25.0%	12.5%	25.0%	23.1%	40.0%	23.1%
Equitable allocation of water for ag., mun., and ind. needs	0.0%	30.8%	40.0%	8.3%	62.5%	25.0%	30.8%	30.0%	38.5%
Monitoring illegal diversions	0.0%	7.7%	60.0%	41.7%	37.5%	25.0%	15.4%	40.0%	38.5%
Ensuring redundancy in water supplies	0.0%	7.7%	40.0%	41.7%	37.5%	25.0%	46.2%	30.0%	34.6%
Maintaining data privacy	0.0%	0.0%	20.0%	0.0%	25.0%	25.0%	0.0%	10.0%	7.7%
Meeting compact compliance	0.0%	30.8%	40.0%	50.0%	62.5%	25.0%	23.1%	60.0%	50.0%
Accuracy of data sources	50.0%	7.7%	100.0%	58.3%	75.0%	50.0%	61.5%	70.0%	76.9%
Ease of data access	25.0%	7.7%	60.0%	41.7%	62.5%	25.0%	30.8%	50.0%	50.0%
Adherence to prior appropriation	0.0%	23.1%	60.0%	50.0%	50.0%	25.0%	15.4%	30.0%	46.2%

Figure 8: *Percent of respondents who selected each factor as an important challenge in the management of Colorado water. Respondents were able to select multiple items, and the frequency of responses was normalized by the total number of respondents in each sector.*

Figure 9 illustrates the frequency of responses for potential challenges for the current and future sustainability of Colorado water. Evidently, resilience to drought conditions is considered a primary challenge amongst the plurality of sectors, with 100% of respondents from conservancy districts, 90% of respondents from the non-governmental organizations, and 87% of respondents in the environmental sector reporting drought resilience as a challenge. Of the total number of survey respondents, 74% selected drought resilience as a challenge to the current and future sustainability of Colorado water. Proceeding in consecutive order, forecasting water availability was selected by 68% of total survey respondents, optimizing irrigation practices was selected by 65% of total survey respondents, resilience to wildfires was selected by 62% of total survey respondents, and maintaining aquifer health was selected by 57% of total survey respondents. It is noteworthy that, although a normalized quantity, the frequency of response selections in Figures 8 and 9 are related to the number of survey respondents in each sector, and that more survey responses would result in a more accurate portrayal of the views and insights of Colorado water stakeholders.

Which of the following are important challenges for the current and future sustainability and resilience of Colorado water?

Selection	Academia	Agriculture	Conservancy District	Engineering	Environmental Services	Law/Judicial	Municipal Services	Non-Govermental	Governmental
Resilience to drought conditions	25.0%	38.5%	100.0%	58.3%	87.5%	75.0%	84.6%	90.0%	84.6%
Resilience to flood events	25.0%	15.4%	60.0%	25.0%	37.5%	50.0%	38.5%	60.0%	50.0%
Resilience to wildfires	25.0%	7.7%	60.0%	75.0%	87.5%	75.0%	76.9%	80.0%	65.4%
Forecasting water availability	25.0%	46.2%	100.0%	66.7%	87.5%	75.0%	61.5%	80.0%	73.1%
Maintaining aquifer health	0.0%	30.8%	80.0%	58.3%	75.0%	75.0%	38.5%	80.0%	65.4%
Maintaining environmental flows	0.0%	7.7%	60.0%	25.0%	50.0%	50.0%	46.2%	80.0%	53.8%
Ensuring energy conservation in water systems	0.0%	15.4%	60.0%	16.7%	62.5%	75.0%	15.4%	50.0%	26.9%
Optimizing irrigation practices	25.0%	30.8%	60.0%	83.3%	87.5%	75.0%	61.5%	70.0%	73.1%

Figure 9: Percent of respondents who selected each factor as an important challenge for the sustainability of Colorado water. Respondents were able to select multiple items, and the frequency of responses was normalized by the total number of respondents in each sector.

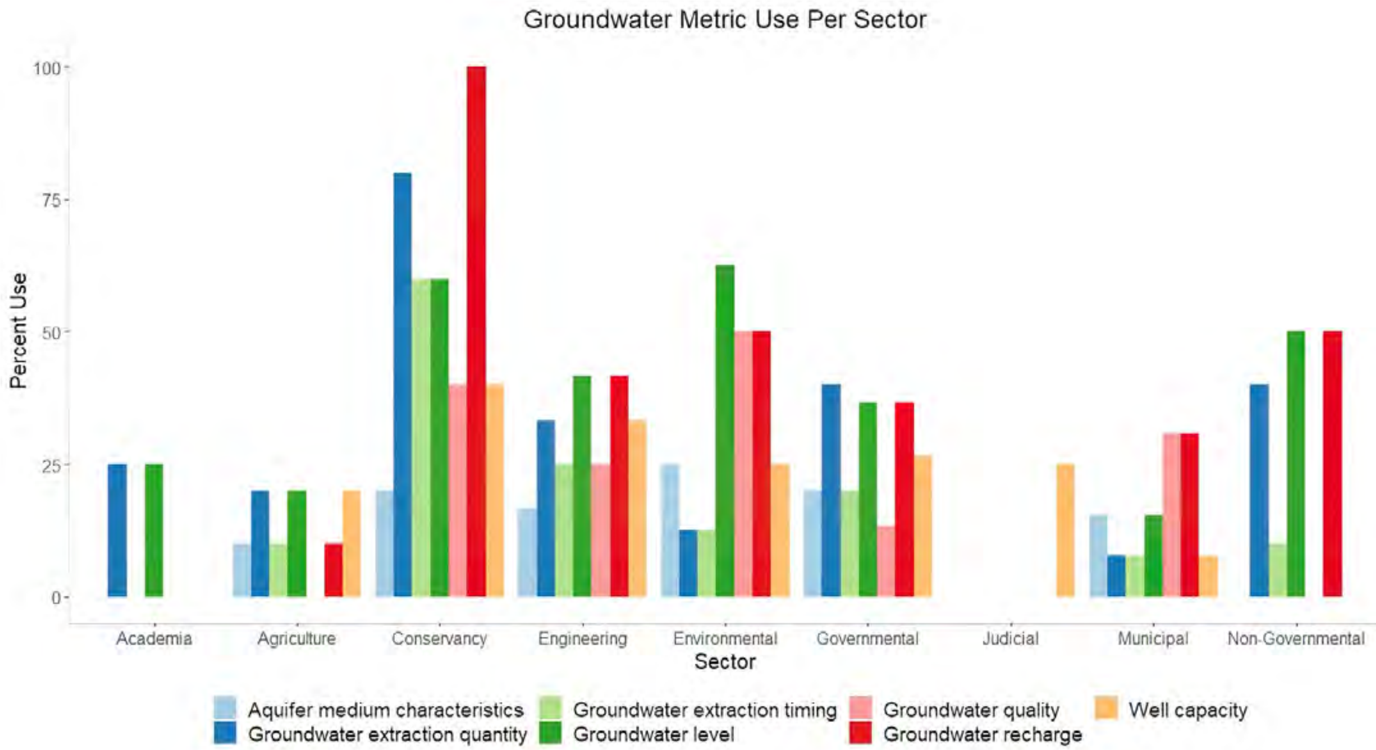


Figure 10: Percent of respondents who utilize or monitor each groundwater metric.

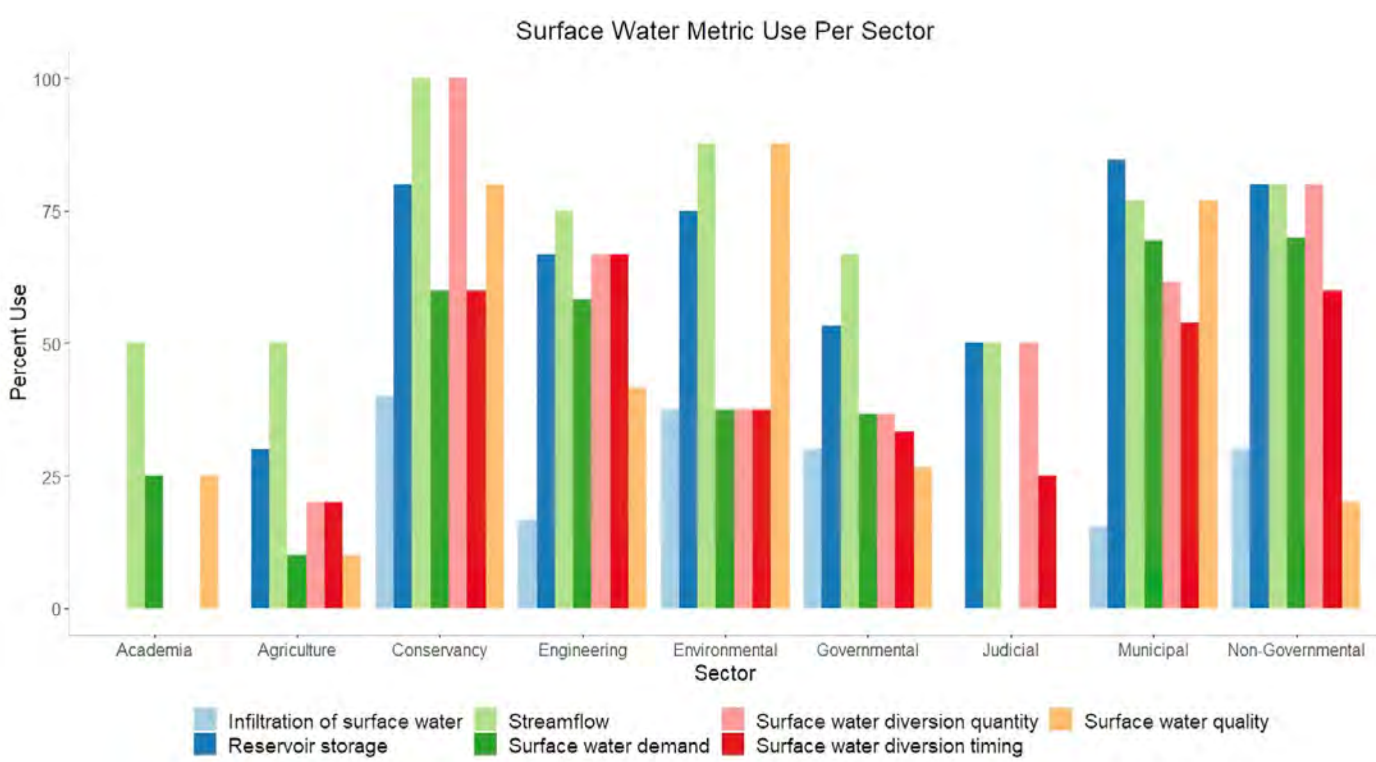


Figure 11: Percent of respondents who utilize or monitor each surface water metric.

Metrics

Additionally, the survey tool investigated water monitoring metrics and data gaps in Colorado water. A predefined list of thirty metrics, ranging from water quality to land surface metrics, were included in the survey based on interviewer comments, expert opinion, and stakeholder outreach. These metrics were organized into five overarching categories: surface water, groundwater, land surface parameters, hydrologic parameters, and 'other'. The results of this analysis are reported as relative frequencies with respect to each sector and basin and focus on surface water and groundwater metric use.

Figures 10 and 11 show the metrics used by each sector for all groundwater and surface water variables. Conservancy district respondents reported to have collected or utilized the highest percentage of both surface and groundwater metrics; this is a logical result, as some conservancy districts oversee augmentation plans where accounting relies on a range of metrics from diversions, to recharge, to replacement water and are therefore required to collect large amounts of data. Across all sectors, groundwater data was collected or utilized far less than surface water data. This data gap may be explained by the quantity of groundwater regulations compared to surface water regulations, which may disincentivise groundwater data collection.

Groundwater data collection differs among basins in Colorado, with each utilizing groundwater data for varying purposes. Figure 12 shows the percentage of survey respondents who reported to collect or use groundwater data in each basin, calculated as the total number of respondents who reported to use or collect one or more groundwater metric normalized by the number of respondents from each basin. The results show that 100% of survey respondents from the Republican Basin reported to collect one or more groundwater metrics; 80%-89% of respondents from the Rio Grande Basin and Yampa/White/Green Basins; 70%-79% of respondents from the Arkansas and Gunnison Basins; 60%-69% of respondents from the South Platte, Colorado River, Dolores, and San Juan Basins; and 50%-59% of respondents from the North Platte Basin. It is important to note that these numbers are only representative of survey respondents, and therefore does not incorporate all possible groundwater data users. All basins have interest in collecting groundwater data, but some rely on it more than others. For example, districts in the South Platte and Arkansas basins are turning more to groundwater to ensure sufficient water supplies as arid conditions persist.

While there is much surface water and groundwater collection across Colorado, the quality of data collected

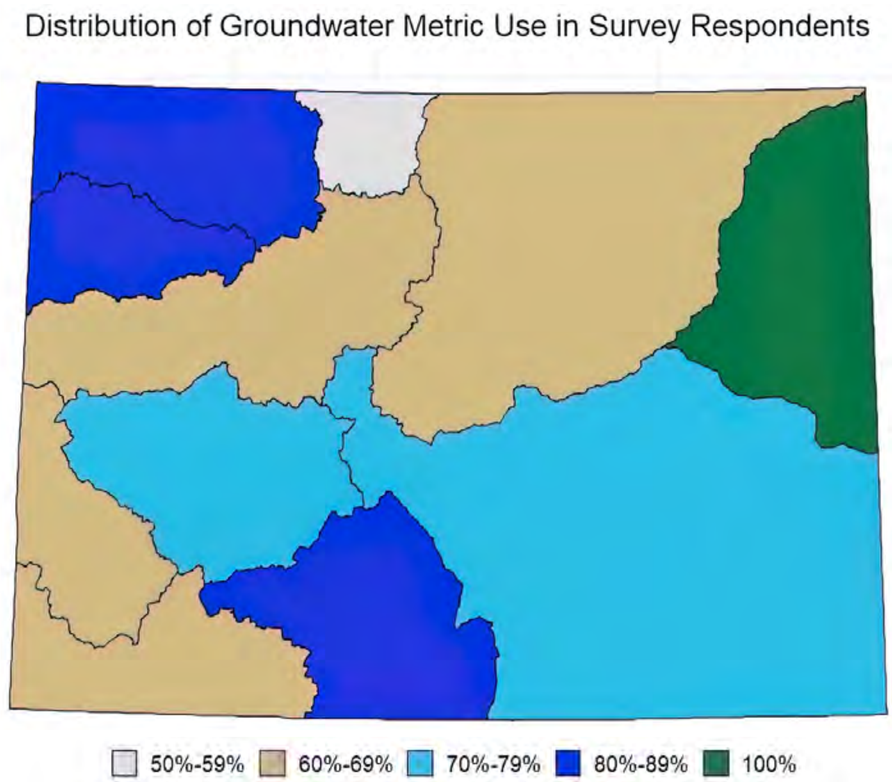


Figure 12: Percent of respondents who reportedly use or collect one or more groundwater metrics for each basin. Ranges of percentages are displayed for clarity, and values are normalized by the number of respondents from each basin.

could pose issues for water users and stakeholders. To gather information on the quality of data, survey respondents were asked to rate their satisfaction with the metrics or data sets as “Highly Satisfied”, “Somewhat Satisfied”, “Somewhat Unsatisfied”, or “Highly Unsatisfied”. Each rating was given an associated value of 2, 1, -1, and -2, respectively, to calculate overall satisfaction with each metric. Figure 13 shows the average satisfaction rating for each metric or data set.

Of the metrics listed, respondents felt least satisfied with data on unaccounted-for losses (pipe leakage), groundwater and surface water exchanges (inflow of groundwater to surface water), and soil moisture. Metrics that scored highly indicate that they are well understood and have robust data sets. These include many land surface and surface water data, including land surface elevation, ground temperature, streamflow, and precipitation.

Metrics that scored highly indicate that they are well understood and have robust data sets. These include many land surface and surface water data, including land surface elevation, ground temperature, streamflow, and precipitation.

Figure 13: Average satisfaction of each metric or data set. Survey respondents were asked to select their satisfaction as “Highly Satisfied”, “Somewhat Satisfied”, “Somewhat Unsatisfied”, or “Highly Unsatisfied”. Each rating was given an associated value of 2, 1, -1, and -2, respectively, and averaged to obtain an overall satisfaction ranking.

Technologies and Platforms

An understanding of barriers to adoption is essential to addressing data and technology gaps. Here, we investigated potential barriers to technology adoption and perspectives on the most important factors when choosing a new technology.

Of total respondents, 43% said that the accuracy of the technology was an important factor when choosing a new technology. The greatest barriers identified include acquiring funding for technology implementation, compatibility between new technologies and old systems, and the labor required to implement or maintain technologies. To address technological and data gaps in Colorado water management, accurate, low-cost options are needed. Funding opportunities are needed to aid in implementing technologies that can improve state-wide water management.

Respondents were asked to select the technologies they use from a predetermined list of technologies used for a variety of applications and with varying novelty. Results show a relatively high satisfaction with established technologies and data management services implemented across the state, such as cloud-based data storage and remotely automated gates. There was moderate satisfaction with other widely

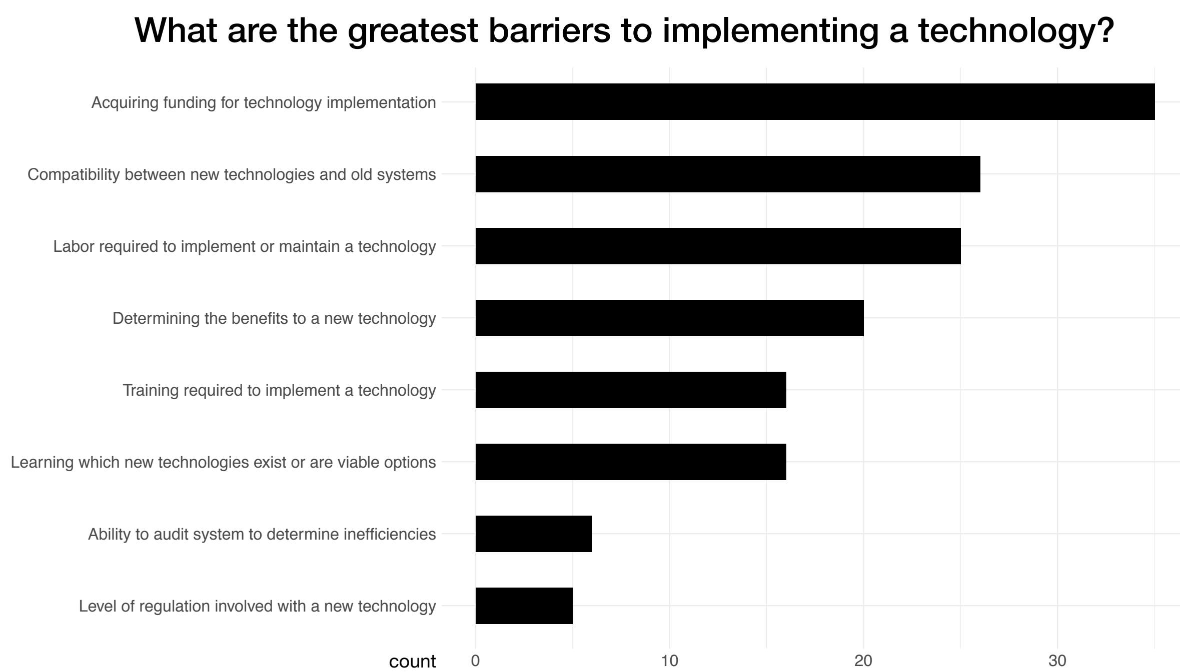
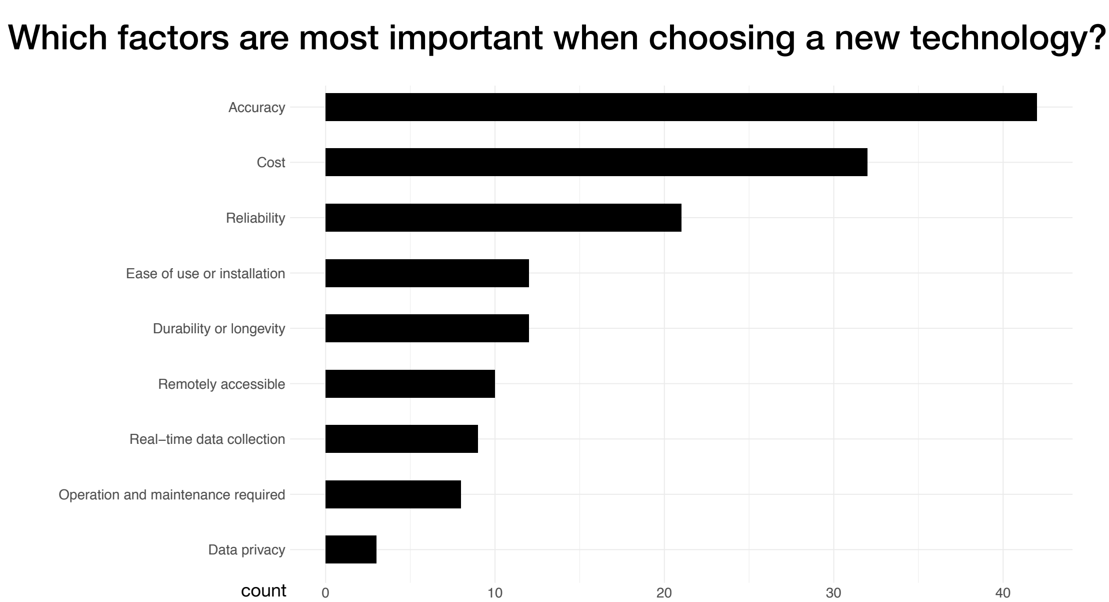
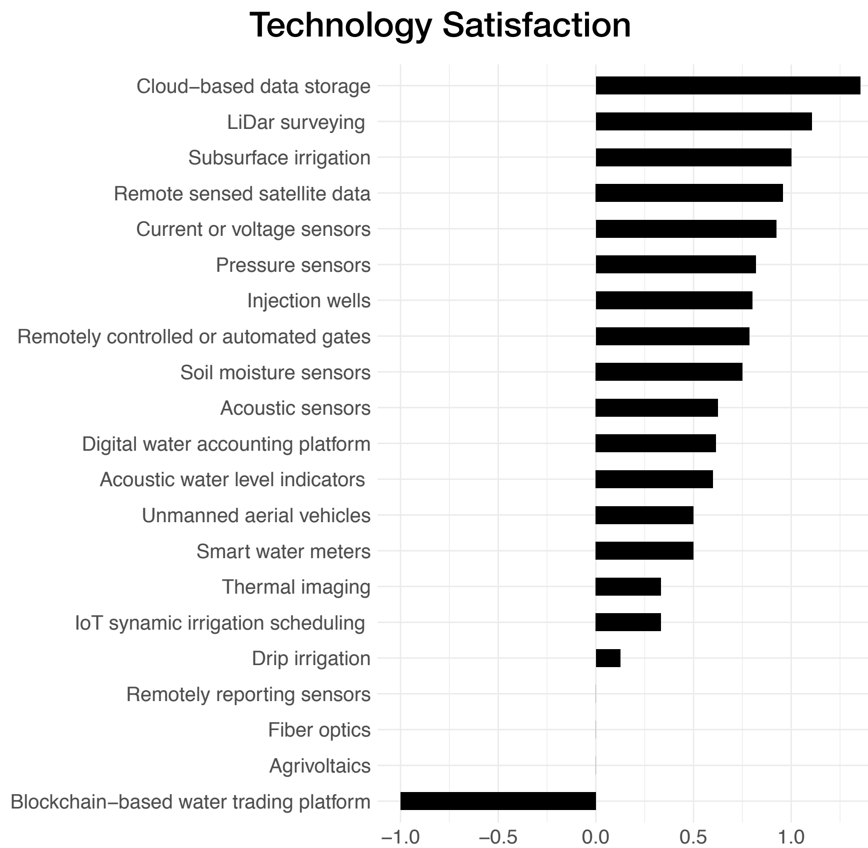


Figure 14: Factors and barriers to technology adoption reported as the total number of times each item was selected. Respondents were asked to select as many items as were applicable. Top panel: Frequency of total responses for each potential barrier to technology implementation. Bottom panel: Frequency of total responses for each potential factor in selecting a new technology.

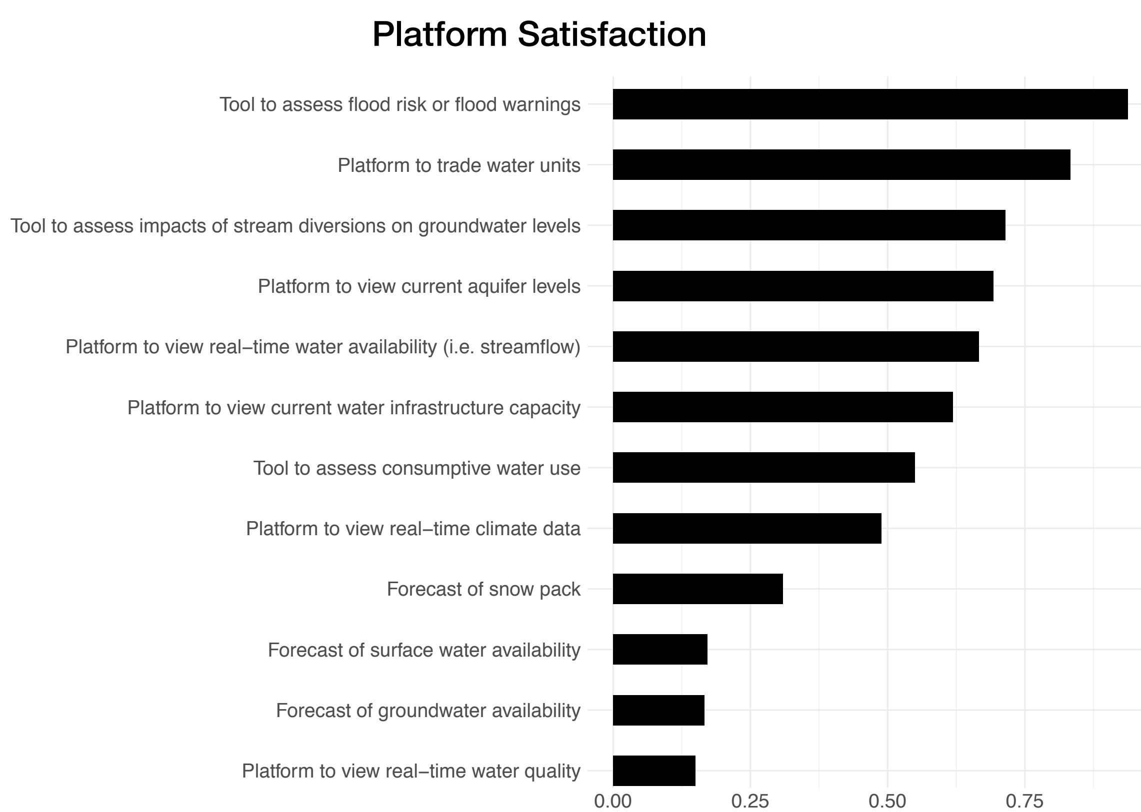


used technologies, including smart water meters, which are becoming common in residential and agricultural settings, and various types of acoustic, pressure, and electrical sensors. Satisfaction among blockchain-based water trading users ranked the lowest, indicating that this technology has not been successfully implemented in Colorado to meet user needs.

Various data visualization and management tools exist to aid watershed stakeholders in the management of resources. Respondents were asked about their use of a range of platforms and to rate their satisfaction with each. All platforms had a positive average rating, indicating general satisfaction with the platforms listed. The highest ratings were for tools to assess flood risk and to trade water units, while the lowest ratings were for platforms to view real-time water quality and forecasts of surface and groundwater availability.



▲ *Figure 15: Average satisfaction of each specified technology. Survey respondents were asked to select their satisfaction as "Highly Satisfied", "Somewhat Satisfied", "Somewhat Unsatisfied", or "Highly Unsatisfied". Each rating was given an associated value of 2, 1, -1, and -2, respectively, and averaged to obtain an overall satisfaction ranking.*



▶ *Figure 16: Average satisfaction of each specified platform. Survey respondents were asked to select their satisfaction as "Highly Satisfied", "Somewhat Satisfied", "Somewhat Unsatisfied", or "Highly Unsatisfied". Each rating was given an associated value of 2, 1, -1, and -2, respectively, and averaged to obtain an overall satisfaction ranking.*

Discussion

The results of the informant interviews and stakeholder survey showed opportunities to improve the management of Colorado's water with better monitoring. Based on these results, the following technological or monitoring gaps were identified across Colorado:

- Water availability from snowpack and streamflow prediction
- Ease of data access and understanding of water rights and transactions
- Monitoring groundwater and subsurface soil moisture
- Impacts of wildfire on water management
- Watershed health management
- Data sharing and collaboration

Other challenges include evapotranspiration data collection, high-resolution data collection, and precision agriculture methods such as improved irrigation techniques. Management gaps relating to these are analyzed below.

Groundwater Use

In the informant interviews, discussions of groundwater were most frequent in basins with higher groundwater reliance, i.e., the Rio Grande Basin, which sits on top of a 70,000 square-mile aquifer (*Ground-Water Depletion across the Nation*, 2003). Other basins with a strong interest in groundwater management include the San Juan-Dolores-San Miguel Basin and the eastern South Platte Basin, which accesses the Ogallala Aquifer (*Ground-Water Depletion across the Nation*, 2003). Likewise, survey analysis shows that, across all basins and sectors, groundwater data was less widely used or collected than surface water and land surface data. There is increasing interest and concern regarding groundwater use in the western United States. When water is pumped from an aquifer faster than its rate of recharge, it can create groundwater overdraft leading to declining groundwater levels overall (*Ground-Water Depletion across the Nation*, 2003). In consideration of extreme overdraft, California passed the Sustainable Groundwater Management Act (SGMA) in 2014, putting responsibility on water managers to understand and report groundwater levels. In Colorado's most over-appropriated basins, pumping of groundwater that is connected to surface water requires the replacement of senior water rights. The Rio Grande basin is the only area in Colorado with a statutory aquifer sustainability requirement. Allocation of water in the Denver Basin and nontributary basins

A groundwater pump seen in the San Luis Valley, Colorado. Groundwater overdraft has become a serious issue across the western US in recent years and could be improved with increased monitoring.

allows the use of only a fraction of water underlying a property. Some of Colorado's Designated Groundwater Basins, primarily on the eastern plains, are closed to new appropriations to limit groundwater withdrawals while some remain open to new appropriations. "You don't want the state's heavy hand to come in," commented one conservancy leader when referencing regulations surrounding groundwater use in the district.

Snowpack Monitoring and Streamflow Forecasting

Across the Rocky Mountains, snow is a crucial fixture of the hydrologic cycle, with about 60-85% of Colorado streamflow originating as snowmelt (Woelders et al., 2020). Understanding snowpack is a major part of water management in Colorado and can present a challenge when there are monitoring gaps or inaccurate data. Snowpack and streamflow forecasting were two of the management aspects cited most frequently in both informant interviews and the survey. Streamflow forecasting, which influences water supply management and use, relies on monitoring snowpack evolution from winter into spring (Woelders et al., 2020). Understanding the amount of water contained in snowpack, or snow water equivalent, is a complex process that involves understanding changes in snow depth and density over time. The majority of SWE data is obtained through point observations, but this method lacks the overview that can be achieved with more spatially explicit monitoring. While observations with more spatial coverage would require greater effort and more tools, they provide a fuller picture of snowpack and may contribute to better streamflow models and forecasts.

Water Trading and Transactions

Water law in Colorado dates to the 1860s and relies on the Doctrine of Prior Appropriation which is embedded in the state constitution. Stakeholders agree that the current system of water rights and transactions will not undergo major change in the coming decade. Colorado recently passed a measure studying issues surrounding speculation that are relevant to the future of water transactions (Moyer et al., 2021). Considering this, discussion of emerging technologies was confined to how digitization could improve existing frameworks for water transactions.

Present methods of water rights transactions, water trading or "water markets" across Colorado show extreme regional variability (Richter, 2016). For example, the Northern Colorado Water Conservancy District's Colorado-Big-Thompson project (C-BT) allows the leasing of water rights "shares" through a straightforward process (Dunn, 2022). However, due to the nature of Colorado Water Law which limits the use of a water right during a time of call to the decreed place of use and type of use, unless changed through the water court process this is not possible which is typically more narrowly defined than for the C-BT project this system of market trading is not reproducible in other parts of the state (Banks & Nichols, 2015). Informant interviews found need and interest surrounding the digitization of water rights and water transactions in Colorado, and several stakeholder discussions centered on "interest in increased transparency and access to information in water transactions." Currently, water transactions across the state can be an expensive, lengthy, and complex process. While this might discourage speculation, a digital future for Colorado water rights has the potential to improve fluidity, transparency, and effectiveness in water transactions (Richter, 2016).

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Wildfire Impact Mitigation

Recent years saw Colorado wildfires increase in size and frequency. Stakeholders from municipal sectors in the South Platte basin, which houses the city of Denver, expressed the strongest concern about the potential for wildfire impacts on water resources. In one interview with a municipal stakeholder, wildfires were cited as "the biggest risk to our water supply." These discussions focused on water quality issues that are commonplace after watersheds burn. In the wake of a wildfire, debris, and runoff increase, polluting the water and causing expensive problems for municipal water supplies. Damaged watersheds struggle to retain water in the soil at rates equal to healthy watersheds, leading to higher flood risk and slow vegetation regrowth. Monitoring water quality and watershed health are key pieces of water management as wildfires continue to be a feature of the Colorado climate. Discussion of forest management was also frequent in discussions of wildfires, with informants citing poor forest management as a factor in increased occurrence. Stakeholders expressed the belief that improving forest health could lead to improved water supplies and decreased wildfire risks.

Watershed Health Management

The term "watershed" refers to the drainage area over which water flows to collect in a central source such as a lake or stream. These are dynamic systems that influence water quality and ecosystem health (Naiman et al., 2017). Especially in basins where surface water is prioritized, watershed management is an integral part of water management strategies. With the increasing frequency of wildfires in Colorado, maintaining healthy watersheds can be a challenge. Stakeholders mentioned the difficulty and expense of assessing restoration projects on watersheds where log erosion barriers had been set up. Watersheds also exist in rural areas at high elevation, making manual monitoring time- and labor-intensive. Conversations around watershed health and management often included interest in aerial observation technology, suggesting possible solutions to this challenge through the use of drones or high-altitude balloons. One municipal stakeholder commented, "aerial imagery is so powerful, particularly looking [at watershed health] over time." These technologies would allow managers to monitor more remote watersheds with increased frequency and reliability, enabling improved water quality and resource management.

Community and Collaboration

A hopeful theme that emerged from the findings of this research was that of community and collaboration. Across the state, stakeholders agree that the challenges facing water supply management can only be addressed by coming together to find solutions: "what we need now more than ever is radical collaboration. We've got to work together." There is a wealth of innovation and research across the state in all the areas addressed above, from water access to wildfires. Better methods are needed to fuel collaboration and share data. Several informants and the survey results touched on the need for improved data visualization platforms to enhance communication between basins and sectors across the state.

A Digital Future for Colorado's Water

Legal Context

Kate Ryan
The Colorado Water Trust[1]

Colorado uses a prior-appropriation system to assign the relative priorities of water rights. Water rights established earliest are assigned senior priorities relative to water rights established later. Priority is assigned to a water right when the claimant files to adjudicate the right in water court, and the water court confirms other attributes of the right, including rate or volume and decreed locations and uses for the right. Once adjudicated, a water right may be permanently changed to other uses through further court proceedings or temporarily changed to other uses through administrative proceedings conducted by the Division of Water Resources (DWR).

When a change of use is confirmed, the original priority date of a water right is maintained. This attribute of prior-appropriation water rights makes senior water rights particularly valuable from a financial and reliability standpoint, and it creates demand for water right transactions in Colorado. Water users with needs that cannot be satisfied with junior water right appropriations invest in permanent or temporary interests in senior water rights, and they go through the water court or administrative processes to change water right use. At this point in time, change proceedings and the maintenance of senior priority is critical for new water users, since many of Colorado's rivers are fully or even over-appropriated, and acquiring a senior water right is the only way for a new water user to satisfy their supply needs.

For example, a growing municipality might secure senior irrigation water rights and change them for current or future water supply. When the water rights are changed, the water court will confirm their historical consumptive use (HCU) for their originally decreed purposes, and that HCU will serve as a limit on the amount of water available for new purposes. Limits on the use of changed water rights ensure that other water rights in the stream system are not injured due to an expansion of use when water rights change purposes.

In another example, the Water Trust might lease a senior irrigation water right and change it to instream flow use by the Colorado Water Conservation Board (CWCB). The CWCB is the sole entity in Colorado authorized to use water for instream flow purposes, and it does so under a statutory program authorized in 1973. Since 1973, the CWCB has made instream flow appropriations and, soon afterwards, gained water rights acquisition authority. While the instream flow program has over 1700 water rights statewide appropriated to preserve the environment (*Instream Flow Program | DNR CWCB*, 2022), those water rights are extremely junior to the water rights that were decreed for agricultural, industrial and municipal uses beginning around the time of Colorado's statehood in 1876 and the 1903 Water Rights Adjudication Act. Many rivers were over-appropriated before the state's instream flow program began and would be deprived of opportunity for streamflow protection without the legal mechanism for water right acquisition. Accordingly, environmental water right transactions are critical to protect streamflow in Colorado. To date, instream flow water rights transactions protect flows on only 35 stretches of water statewide (*Instream Flow Program | DNR CWCB*, 2022). If streamflow protection is a priority for Colorado, the availability and fluidity of water right transactions must be improved.

Changing demographics and climate pressures further limit water resources for new uses, making water right acquisitions necessary, particularly in circumstances where water users can enter transactions that enable them to share in the use of a water right (*Read The Plan | DNR CWCB*, 2022). Acquisitions can lead to senior water rights being used for new purposes, and for multiple shared purposes to meet water supply gaps and preserve agricultural heritage and local economies. Colorado's water rights system is fully adjudicated, with nearly all rights having been confirmed in water court decrees, whereas several other western prior-appropriation states are still in the process of adjudication. While the discrete identification of water rights in Colorado facilitates acquisitions, there are many complexities that could be addressed through emerging technologies.

Acquisition Complexities

A primary barrier to water right transactions in Colorado is the lack of acquisition opportunities. Given an acquisition opportunity, additional barriers arise, including complex and uncertain due diligence processes, high transaction costs in the form of engineering and legal fees, and uncertainties inherent in the scope of a water right after it has been through change-of-use proceedings. Each of these and the reasons behind them is discussed in this section.

Market Weaknesses

Colorado has specific water markets, but no single, comprehensive market (Moyer et al., 2021). Unlike the Multiple Listing Service system for real estate sales, there is no singular database available to market water rights for acquisition. Transactions for some end-uses, including environmental water transactions, are often identified through individual communications and negotiations between a water rights owner and the acquiring entity. There are also a handful of water brokers who facilitate transactions. These endeavors are time consuming and require specialized knowledge in water rights and water right transactions. For example, Water Trust staff spend hundreds of hours each year doing outreach to water users about its Request for Water program, and this work develops only a few acquisition leads annually (*Request for Water Process | Colorado Water Trust*, 2022).

Additionally, many individual water rights are used to irrigate or otherwise serve real property. Irrigation and agricultural water rights tend to be a focus for acquisition in Colorado, since they comprise more than 89% of water consumed statewide (*Instream Flow Program | DNR CWCB*, n.d.). If irrigation rights are transferred to a disassociated use, the transfer could negatively impact the value of the land where the water was used (*Upper Basin Demand Management Economic Study in Western Colorado*, 2020). Consequently, there is a lack of a defined market and an imbalance between high demand for water rights and a slim supply of water rights available for acquisition.

> While the discrete identification of water rights in Colorado facilitates acquisitions, there are many complexities that could be addressed through emerging technologies.

Water right transactions that continue to benefit both an irrigated property and a new end-use are possible, but far from easy. For instance, the Water Trust and some municipalities implement lease-fallowing and other shared water arrangements (*Projects Map | Colorado Water Trust*, 2022). However, finding a match between sellers and buyers or lessors and lessees is difficult since their needs and the attributes of their water rights must align.

Over time, the Water Trust has found that few water right owners are interested in selling their assets. Water sharing opportunities and short-term leases are of much greater interest. However, the analysis required for a temporary change of water rights is nearly as detailed as that required for a permanent change, leading to imbalance between the escalating costs and diminishing benefits of such acquisitions. The analysis and legal issues that lead to such high transaction costs are described below.

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[1] This chapter describes the legal and policy environments in which water transactions occur from the perspective of the Colorado Water Trust (the "Water Trust"). The Water Trust is a nonprofit organization with a mission to restore flows to Colorado's rivers in need. A group of water attorneys founded the Water Trust in 2001 to complement the state's instream flow acquisition program, and the Water Trust continues to use a model of acquiring water rights by acquisition or lease so they can be used for environmental purposes.

Due Diligence

Once an acquisition opportunity is identified, certain steps must be undertaken to make the transaction successful and accomplish a change of water rights. These include due diligence and title review, completing the engineering necessary to ensure that a change of water rights will not expand use of the right or injure other water users, and completing an application for judicial or administrative proceedings to confirm the change of use. In some acquisitions of water rights, a change of use is not required, such as for acquisitions of stored water rights that are already decreed for an end-user's desired purposes. Outside of these circumstances, change of use proceedings are required if water will be used for a new purpose or in a different location.

Due diligence is costly and detailed. It is also crucial for water right transactions since there is no title insurance for water rights. Title research is done using the same county records maintained for real property, but it is not automated, and title companies do not conduct title review because of its complexity and potential for error. Many water right transactions are performed by legal counsel, which can be costly. Title review for water rights involves reviewing records maintained at the Clerk and Recorder's office for the county in which a water right is located. Some of these are accessible via the internet, but many are not, depending on the location of a water right and its decree date. In those circumstances, time-consuming review of paper files and indices is required. Additionally, many water rights are located in and subject to transaction in multiple counties, doubling the time and effort required for title review.

Due diligence for a water right transaction also necessitates review of the historical use and diversion history of a water right. Since the diversion rate of water acquired in a transaction will differ after change-of-use proceedings, a buyer or lessor will often work with attorneys, water resource engineers, or both prior to a transaction to ensure that the water right they are acquiring has a good history of use. In Colorado, idled water rights are subject to abandonment under certain circumstances or a diminished allocation after change proceedings if they were underutilized.[2] Therefore, purchasers and lessors must undertake detailed inquiry prior to acquisition. Even when inquiries are made, the Division of Water Resources might not have historical diversion and use records for a particular water right. This results in the need for undefined research methods into the history of use of a water right based on professional experience. Results are uncertain and the process is time-consuming. The Water Trust, for example, typically spends a year or more in the due diligence phase of project development prior to completing an acquisition.

Engineering Support for Change Proceedings

Professional engineering analysis is required to conduct almost all change-of-use proceedings. The analysis typically needs to describe the impact of the historical use of a water right on a river, including patterns of diversions, return flows, net depletions, and HCU in time, place, and amount. It is a complex and frequently expensive endeavor. In the Water Trust's experience, water right change engineering analysis typically costs tens of thousands of dollars and is unpredictable. However, it is also useful to structure projects undertaken using water right acquisitions.

Uncertainties add to the complexity and expense of water right change engineering. These include determining a representative period of time to describe the use of a water right, lack of appropriate diversion or use records, and the range of assumptions that go into calculating the consumptive use of a water right, such as evaporative losses, irrigation efficiencies, and soil moisture balance. There are some engineering analyses that use standardized inputs to measure water right use, but in many other instances the analyses required to change a water right are subject to climate or streamflow measurements that might be incomplete and require substitution using professional judgment.

Legal Support for Change Proceedings

Legal counsel is also required for most change-of-use proceedings. In Colorado, a water right owner is entitled to represent themselves pro se in water court. But in the experience of the Water Trust, legal representation is vital to a successful water court application and for temporary change-of-use proceedings that maximize the amount of water available for change to new uses. The Water Trust has in-house counsel, but the time dedicated to legal work for most change-of- use proceedings costs tens of thousands of dollars, and it is unpredictable.

Water court applications and administrative proceedings may be decided through trial before a judge, but they are more often decided based on negotiated settlements between applicants and opposing parties. In some circumstances, these proceedings take only a couple of months and involve little opposition. In other circumstances, including most circumstances on heavily used rivers, water court proceedings take two years or more to resolve and involve several opposing parties.

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[2] The Colorado water right abandonment statutes include section 37-92-401 to -402, C.R.S. (2022) and standards for change of water right proceedings are in section 37-92-305, C.R.S. (2022)

[3] The statute requiring terms and conditions on a changed water right to avoid injury to other water users is section 37-92-305(3)(d), C.R.S. 2022.

Accordingly, legal fees are high. Additionally, the terms and conditions attached to changed uses of water can be something an applicant never predicted but decided to accept in order to complete the change process. Also, despite best efforts at due diligence and engineering analysis, a change-of-use applicant often learns of ways in which their new use might injure other water users only after an application is underway, resulting in unanticipated constraints on the new use[3]

Barriers

Prior to implementing the opportunities presented in this report, barriers need to be considered. Colorado has a robust water planning administrative agency in the CWCB, a comprehensive water rights administrative agency in the Division of Water Resources, and regional communities of water users deeply engaged and protective of their water rights and livelihoods.

Water users might oppose increasing transparency regarding their water rights, particularly since there is a perception that "use it or lose it" legal principles threaten their water rights. The use of water rights is as complex as the legal and policy environment of Colorado, so water right owners might be understandably reticent to open a window into examination of the practices in which they engage.

Through "buy and dry" acquisitions, facilitating water right acquisitions also threatens rural communities dependent on agriculture. This threat was once seen as coming primarily from the pressures of urban growth, but lawmakers recently became aware of pressure imposed by investment opportunities. They strive to avoid it by investigating statutory anti-speculation measures. Digital platforms should not be used to create a market so fluid that it becomes subject to investment based on speculation in water rights (Moyer et al., 2021). Investment-based speculation also threatens new water users like the Water Trust, who could be outcompeted by financial investors were water rights acquisitions to be overly fluid. On the other hand, if digital platforms can be used to assist anti-speculation measures as well as to increase the fluidity of water right transactions, that technology is more likely to be palatable to Colorado's water rights stakeholders.

Water users might oppose increasing transparency regarding their water rights, particularly since there is a perception that "use it or lose it" legal principles threaten their water rights.

Opportunities for Digitization & Technology Solutions

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Amid increasing challenges in managing Colorado's water resources, there are opportunities to digitize water transactions[5], making them more transparent, secure, and trustworthy. This section explores how technology can be used to digitize water right transactions and provide benefits to water users in the western US. Some benefits of digitized water right transactions might be increased efficiency, greater transparency, and stronger security in water transactions. However, there are valid concerns around implementation of such technologies. This section lays out an overview of what digitization would mean, then discusses technology solutions that could be leveraged to create digital records and strengthen data supporting the transactions system. It discusses platforms that could support the data, explores a blockchain-enabled solution, and concludes with steps to ensure the creation of non-speculative markets.

Water users generally face a crisis as droughts increase and water use exceeds the natural limits to sustain needed levels. Some distinct challenges faced by water users may be addressed through increased technology use leading to a digital future for water. Missing, inaccurate or intermittent data on water can lead to mismanagement of water and quality data is necessary to achieve better results. This highlights a potential area for technological advancement: updating sensors with more real-time or near-real-time monitoring. Second, where water rights are traded, transactions are slow and difficult. Water users could benefit from a system that helps them understand and visualize their needs and match them to opportunities to access water for sale, trade, or lease. This highlights the second technology need: a record and transaction management system.

This article summarizes opportunities for digitization and transaction systems for water management. As discussed above and described in the case studies that follow, there is opportunity for technology to digitize water rights transactions and provide benefits to water users in the western US.

What is digitization?

Real-time monitors and sensors, and the technology behind them provide effective methods to address some

[4] As used in this document, "Deloitte" means Deloitte Consulting LLP, a subsidiary of Deloitte LLP. Please see www.deloitte.com/us/about for a detailed description of the legal structure of Deloitte LLP and its subsidiaries. This communication contains general information only, and none of Deloitte Touche Tohmatsu Limited ("DTTL"), its global network of member firms or their related entities (collectively, the "Deloitte organization") is, by means of this communication, rendering professional advice or services. Before making any decision or taking any action that may affect your finances or your business, you should consult a qualified professional adviser. No representations, warranties or undertakings (express or implied) are given as to the accuracy or completeness of the information in this communication, and none of DTTL, its member firms, related entities, employees or agents shall be liable or responsible for any loss or damage whatsoever arising directly or indirectly in connection with any person relying on this communication.

[5] In this chapter 'transactions' is used to indicate sales and leases

of the challenges water users and stakeholders face. Combining smart technology with digital platforms creates a monitoring system that provides real-time data, clear communication, and the possibility of secure, transparent transactions. By utilizing smart sensors, water data collection will be faster, provide more direct data, increase transparency, and will allow for better monitoring in real-time, to provide corrections where needed (Chalmers, 2020). Connecting smart technology will allow for a digitized, more functional water management ecosystem. Creating smarter, more connected functionality starts with implementing "systems of systems" thinking: one way to encapsulate this goal is through Internet of Things (IoT) devices connected to infrastructure to increase efficiency.

By digitizing water monitoring, water rights owners can scale up from volumetric measurement to water quality monitoring, using connected smart devices. The IoT infrastructure provides large quantities of data to a centralized source where metrics can be visualized and communicated. The more data is available, the more possibility for informed decisions if data is analyzed and shared in accessible, usable ways. Digitized water – in other words, water monitored in a way that data is easily collected and utilized through connected devices that can inform human action – is technology deployed for the greater good. There are many innovative approaches to utilizing "smart" water monitors discussed in this report, and the implementation of these, along with validated data to ease transaction barriers, will create a more sustainable, resilient water system for Colorado and the western United States more broadly.

What would digitization look like?

Digitization of water rights can take many forms, as highlighted by the opportunities listed in the Colorado General Assembly bill HB21-1268 (Study Emerging Technologies For Water Management, 2021). While there are limitations, effective implementation of technology has the potential to increase transparency, trust, and efficiency, overcoming those barriers and creating opportunities for better water management. While the Division of Water Resources maintains:

- a database of all adjudicated water rights and changes of water rights,
- digitized documents related to water court cases and well permits,
- data on groundwater levels, streamflows, climate stations, and diversions (many in near real-time),

And makes all of this available online through the Colorado Decision Support System (CDSS)[6] together with a mapping system where much of this can be viewed geographically, there is no current system to track water right transactions, either digitally or otherwise. By increasing the amount of digitized water records and increasing data production and management, stakeholder understanding of water can be improved – its stressors and availability – and choices about how water is used can be better informed. Enhanced functionality will come through the use of sensors providing real- or near-real time data, paired with transaction systems to manage security and efficiency and increase transparency of sales and leases. Colorado could consider linking water rights data to ownership data in a useful way.

Understanding gaps in history and rights maintenance will allow for more thorough water usage and conservation, increasing transparency. Understanding water use in this way will increase transparency among water users and potential players and give information to those interested in protecting the sustainability of the water system in Colorado. Transparent transactions based on stored data and monitored usage will enhance functionality. If housed on a platform that incorporates a transaction and record management system like blockchain or a similar digital ledger network, security is built-in, ensuring transactions and usage data are immutable and creating a permanent record.

> Understanding water use in this way will increase transparency among water users and potential players and give information to those interested in protecting the sustainability of the water system in Colorado.

While there may be pushback to increasing transparency from farmers concerned about "use it or lose it" legal ramifications, benefits such as increased availability for trading or borrowing may alleviate concerns. Additional concern could arise over security breaches in which a blockchain or similar ledger system is hacked. Given that the ledger here is a transaction record system to ensure faster, easier movement of allocations (legal rights) rather than a trading system for digitized assets, the value to be gained by hacking this type of blockchain is low. Additionally, given the transparency, breaches are likely to be noticed quickly by the system administrator and/or water users, and water rights can be reallocated to the owner by the administrator if the situation were to arise. Although there will need to be oversight to ensure

[6] https://dwr.colorado.gov/services/data-information/imaged-documents

good management, benefits for regulators also exist, as transactions will become more efficient and transparent for them to track as well.

Building a digital water system, which integrates new digital information and previously digitized data, for the state will increase efficiency for water users, water regulators and water courts. Having more historical data digitized and real-time monitoring and use data readily available will ease the pressure the system faces from lengthy data searches and high transaction costs. To accomplish this, technological innovation in monitoring and data collection will be paramount: more affordable, valid, precise measurements that provide granular data will form the base of any digital water system. Efforts to develop such technologies are being pursued, and some promising work is described in the following section.

Monitoring & Software Development

Sensors and observations are key to providing data for any online platform that digitizes the water transactions market. There are a multitude of efforts to increase the scope and quality of data, some of which are discussed in the case studies in the following sections of this report. There are clear benefits to hardware sensors: quality control of water and chemical levels, quantity measurements, identification of waste points (leaks, non-revenue water), monitoring wear/tear or condition of equipment, etc. These benefits make increasing sensors and data seem like a non-controversial initiative, but the cost frequently stymies progress. As with any technology, upfront capital costs as well as ongoing maintenance costs can cause concern, but the benefits to water users over time are likely to outweigh these, given the alternative is less data or unreliable, manual readings.

> By creating hardware at lower costs, similar efforts can be implemented to deploy innovative solutions that increase resilience of water systems more broadly.

Many technology developers focus on providing validated data at low cost to encourage participation and use among water stakeholders. This is a worthy endeavor, especially considering that sensors and observation techniques could allow for the optimization of human resources but frequently require large, upfront capital costs that slow implementation. Systematically deploying lower-cost, automated systems, such as those that monitor resource use and level, can shift the focus to strategically allocating resources rather than just keeping track of them. An example of traditional, higher-cost implementation that combines real-time monitoring and web-based software to monitor groundwater is an effort at Moose Creek Dam. The Cold Regions Research and Engineering Laboratory (CRREL) installed piezometers along the dam, paired with instrumentation to feed data to a web-based network system, building a tool to monitor and indicate distress during flooding events[3]. By creating hardware at lower costs, similar efforts can be implemented to deploy innovative solutions that increase resilience of water systems more broadly.

Current efforts focus on two main types of monitoring: hardware sensors and aerial/satellite observations. This work depends on educating water stewards in proper techniques and management processes and enabling innovators to develop new processes.[7]

Some case studies in the next section of this report focus on development of hardware – monitors or sensors – working with infrastructure to provide data. These include:

- CSU efforts to model ungauged streamflow predictions through reliance on low-cost monitors
- CU Boulder work to predict groundwater abstraction from groundwater levels through validated hardware

Other cases studies focus on remote sensing, which provides data to a central platform. These include:

- Urban Sky and Denver Water testing low-cost, zero-emission, remote sensing balloons to provide aerial images of critical source water watersheds
- Open ET providing easily accessible satellite-based estimates of evapotranspiration (ET) for improved water management across the western US
- Airborne Snow Observatories' ability to measure snow depth and retrieve snow water equivalent (the liquid depth of water stored in the snowpack) across large river basins at high spatial resolution, using airborne lidar and imaging spectrometer sensors coupled with a snow dynamics model

Some case studies discuss work on software development or centralized platforms that take in data from sensors such as the ones listed above.

[7] See the case study on CSU's Master Irrigator Program for insight into best practices for this type of education, and the case study on CSU's Testing Agriculture Performance Solutions for insight into innovation production.

These include:

- Colors of Water, which focuses on improving communication about water through digitization of accounting spreadsheets
- The Freshwater Trust's Decision Support Tool (BasinScout), which maps the costs and benefits of conservation efforts across watersheds, providing geospatial outputs

Other software that can be integrated with hardware once the sensors or monitors are installed and functional could include forecasting software and water quality automation. Software platforms exist or are being developed that rely on matching hardware to data to increase the functionality and resilience of water systems. While development of specific monitors and software is not explicitly analyzed in this section, data input from new technology such as IoT sensors will likely encourage innovation to create software that is interconnected and aids in resilience. ClearCarbon™, being developed by Deloitte, is an example of a platform integrating data inputs to manage project creation, documentation, and certifications. The platform is designed to provide insights, workflow management and project oversight capabilities to participants in carbon offset and inset marketplaces by decreasing time, reducing expense, and increasing accuracy of data collection, measurement, monitoring, reporting and verification activities. A platform like ClearCarbon™ could be developed or built out for other natural resource monitoring and trading as a digitization option integrating innovative technologies.

Matching hardware with software to create and inform digital platforms

Using the hardware and software innovations discussed previously will enhance monitoring techniques in a new way. More tracking of continuous data through technology allows for a more centralized system of water monitoring and trading. Given that the data resulting from many of the sensors and aerial observation techniques mentioned are entered into digital systems, automating the delivery of data to a digital platform for monitoring and transactions is a natural next step.

Linking sensors and observation techniques directly to a digital platform allows increased visibility and transparency among users and regulators, and between buyers and sellers or lessors and lessees. Through a digital platform, water users will have access to more data and can better understand the broader system in which they operate. There is abundant opportunity for creativity in broadening the data provision from hardware to a software-based system of management. While ease-of-use, transparency and centralized records are distinct benefits, other opportunities for water rights (which could require policy or regulatory changes) could increase water resilience through sharing information on and balancing water use. Some opportunities that could arise are:

- *The application of sensors and observations to reduce water consumption in agriculture.* If irrigation is improved, there is space for market transactions to provide unused/saved water for municipal use. Seasonally, the system could facilitate temporary and/or seasonal transfers, where an agriculture-based venture could lease unused water to municipalities during non-production, or where industrial water users could lease to agriculture during irrigation season, creating a more balanced, productive community of water users.
- *Types of transaction beyond water allocations.* Opportunities for water quality tracking, compliance and auditing exist. Having a platform to house data from all types of sensors is beneficial to the water system and integrating a transaction and record system is an additional value. It is easy to imagine extending such technology advances to other natural resources, all with a central platform to store data and manage transactions as needed.

The combination of near-real- or real-time data inputs with software designed to encourage more sustainable water use has many benefits. Chief among them is improved water user experience through access to a digital platform. This access is likely to yield sustainable behavior change in curbing overuse and waste, especially if water users have the ability to make decisions based on their personal use data and dynamic pricing models based on the data. Simultaneously, from both water users' and regulators' points of view, enhanced data and its visualization could provide further insights into the day-to-day and season-to-season water environment, which can be leveraged for evidence-based decision-making (e.g., to help structure key investment projects).

Blockchain to track water resource sharing and encourage collaboration

Using innovative and connected sensors (IoT or otherwise) allows data to be maintained in one location. Most platforms are developed to be accessed by water users and stakeholders. For example, all farmers within a watershed or basin who have sensors on their wells would have access to the platform. Similarly, one can imagine a larger platform would publish data to users with a stake in the water data being utilized. This would present one barrier to speculation by making access to the platform and data contingent on having a proven stake in the water system. As platforms and webpages are provisioned with improved data, they would benefit from a secure, immutable method of transactions based on data and use, like the one The Freshwater Trust built as part of a demonstration of IoT sensors and blockchain transactions California.[8]

One example of a technology that could take in water rights data and allow transactions is blockchain. Blockchain is a distributed records management system that allows for secure, transparent transactions. It manifests as a network of ledgers, where each user holds a copy of the network. The transactions make up "blocks," which rely on consensus, or agreement among the users (achieved through an algorithm) to verify the transactions. Once made, the transaction records are tamper-proof and locked into the chain. Blockchain technology is valuable for systems that require trust, security, and transparency, involve multiple stakeholders, and need immutability. This technology would function well with increased data input and stakeholders concerned about their water rights and the state of the water system (*The Promise of Public Interest Technology*, 2019).

In Australia, a peer-to-peer trading platform called the Water Ledger was piloted to encourage efficiency and transparency. An example of blockchain-based water

[8] https://www.thefreshwatertrust.org/state-of-california-tackles-drought-with-iot-blockchain/

> By using IoT to obtain the data and blockchain to structure the transactional part of the platform, water markets could be transformed into responsive, resilient systems.

market trading, the Water Ledger allows for water trades and updates through consensus algorithms. The verifiable, immutable, traceable tracking of the program through real-time data and updates promotes transparent water trading, and the reduction of intermediaries lowers transaction costs and time. In one demonstration, Water Ledger's blockchain system reduced transaction time for trades from over 90 days to under 7 days, a reduction of 90% (Donaghy et al., 2021). As with any new technology, pilots and demonstrations highlight challenges. These challenges are addressed in the next section.

Blockchain technology for digitizing a state system of water transactions is exemplary in the provision of benefits outlined above. Two complications in water rights and transactions are a lack of clarity and information about the rights, and questions about the ability to transact them based on use type, owner, and location. A decentralized, distributed ledger would solve some of that by creating digital records to address each of those complications, ensuring buy-in from all users, and encouraging accountability. A platform that hosts the database and blockchain ledger would allow water users to access their rights and view the data, reducing the time spent tracking down historical records and use patterns. A filtering capability could allow the platform to show rights based on use or location. This functionality would automate many of the information issues that have been described.

A ledger system like blockchain would require validated sensors to enable verified transactions and tracking. By using IoT to obtain the data and blockchain to structure the transactional part of the platform, water markets could be transformed into responsive, resilient systems. According to a report by Arup[6], blockchain is likely to be relevant for water market purposes in quality, trading, access, treatment, and billing. Importantly, within water trading, blockchain could "allow real-time monitoring and auditing of water trading activity and improve security and efficiency in regulatory compliance requirements." There are other digital database technologies that, when used in tandem, could work as well or better than blockchain, such as other trading tools, accounting software, and audit programs. However, blockchain integrates all the needs of a water market into one system, providing a functional, holistic option.

Increasing data provision and tying it to historical data could allow fair transactions at higher speeds, vastly increasing efficiency. To be successful, a database system like blockchain would rely on good data input, likely coming from new, smart sensors and monitoring. Because of the technology used in a blockchain ledger, records would be unalterable, allowing for continuous checking and matching against history of use and price. This functionality, remotely accessible, could overcome some barriers to the introduction of new technology to the water system in the state of Colorado. While blockchain presents challenges – energy consumption being one – there are others it overcomes.

Challenges and Solutions

While greater digitization, enhanced monitoring, and the introduction of digital water transactions have potential benefits such as increased transparency and data sharing for water users, they also bring potential challenges. The first relates to the willingness of water users to install, use, and maintain sensors and data-sharing, given their fear of "use it or lose it" legal frameworks. The second relates to introducing a transaction platform that might encourage speculation in the water market.

Therefore, this section lays out a process to encourage buy-in among stakeholders through ensuring engagement and clarification of benefits; it also explores the idea of a statewide or regional process for identifying and prohibiting water speculation (as investigated by SB 20-048 work group), through oversight and regulation on the digital platform. Solutions will need to build collaboration between urban and rural users to create holistic management for Colorado water systems. By demonstrating and promoting the benefits to different water users and continuing to respect the seniority of existing adjudicated water rights, the integration of new technologies might be more widely accepted and encourage resilience across the entire water system.

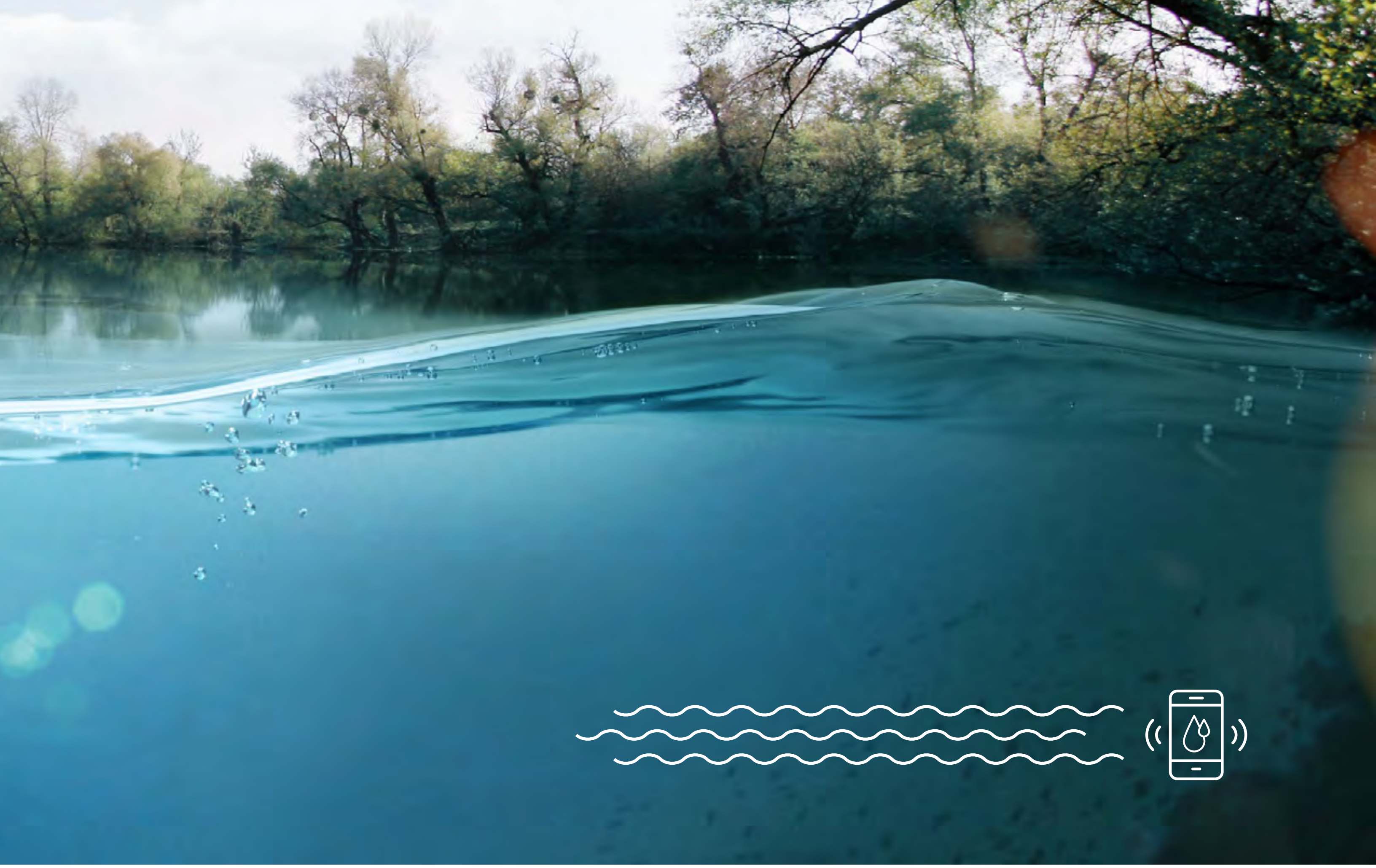
> A digital marketplace solution provides legal clarity for parties to engage in smart water transactions and ensure that Colorado water is protected.

There is much to do on the regulation side if enhanced monitoring and digital transaction markets are to be implemented. However, regulators must first ensure water users are protected. Historically, there is a divide between rural and urban water users in Colorado, a pattern also seen in other western states. This divide is a source of concern over how and where water is appropriated and put to beneficial use within the state and includes potential changes to historic uses and mechanisms in place to govern and appropriate water. New challenges stemming from the purchase of water rights by large asset managers creates an interest in the laws governing water use solely for investment purposes. Identifying and prohibiting investment speculation requires improved data management and a strong regulatory mechanism. A digital marketplace solution provides legal clarity for parties to engage in smart water transactions.

To be successful, a transformative digital solution to manage and account for water transactions needs to work closely with regional water users. Garnering buy-in from key players at rural water users' associations, water districts, and individual farmers will be critical. By bringing their unique perspectives to the table early and often, regulators can work to ensure that these users are part of the solution design, development, and implementation plan. As shown in many of the case studies that follow, demonstrations in water-user communities will help show how technology can bring transparency and security to water transactions. Focusing on benefits salient to water users in agriculture-based and rural communities could help build champions of the solutions. These benefits include lower transaction costs and less time and resources spent obtaining water.

An example of buy-in from water stakeholders exists in Australia, where Deloitte is developing a Drought Resilience Self-Assessment Tool (DR.SAT). DR.SAT takes external data (benchmarking standards) and internal data (on-farm monitoring) to create current resilience benchmarks, which are then used to create risk treatments that help build resilience. By engaging with independent farmers and encouraging sharing of data to create manageable pathways to resilience, DR.SAT is working to combine remote sensing, satellite imagery, and farmer input to improve water system outcomes and drought resilience (Drought Resilience Self-Assessment Tool - DAWE).

Coloradans value water. Farmers, municipal users, and other stakeholders understand that water and water resilience are important. They might generally understand that change is needed or valuable but lack access to and understanding of an efficient mechanism to monitor changes in water use. Integrating new technology for a statewide system of water rights, transactions, and usage will give Colorado a more secure, transparent, and efficient



process. Water users and regulators will be able to track water allocations to ensure use type and rights, and they will ensure secure and valid water transactions moving forward. Providing continuous, near-real-time data will keep water usage data transparent, allowing a systematic check on speculation as water market users and regulators will be able to see if water is used as claimed rather than bought and kept to hold until its value rises.[9] There are other options to combat speculation, including a method The Freshwater Trust uses in their demonstration of a blockchain system for water rights: depreciation.[10] In the demonstration, water allocations left unused depreciate by 10% yearly. This would require extensive work to gain buy-in from users but remains an option. Because all records will be held perpetually and readily accessible, the system will likely stymie water transaction speculation where water rights are purchased and then not used, if regulated properly. Such a system would not address water speculation where water continues to be used.

Ultimately, a regulatory body will have to govern any new technology integration, especially a digital marketplace platform. While it would take effort to implement and regulate, the benefits from such work may outweigh the initial regulatory burden. Through improvements in efficiency, transparency and security, water users and the state may see the benefits of a decentralized water rights digitization project that integrates innovative monitoring through sensors and aerial observations. New and innovative technology is being developed to support better data (monitors and sensors) and better data management (database and record management software). With proper regulation, the opportunities for digitization of water continue to grow.

[9] The SB20-48 Report described that a major challenge with speculation in Colorado is that investors buy a water right and continue to use it by leasing the water to irrigators. In such situations, this checking of water use or penalizing non-use will not address the speculation that is still based on intent to profit from increased value of water. In Colorado, water that is not used is subject to abandonment, and therefore, non-use combined with speculation is not a likely issue.

[10] https://www.thefreshwatertrust.org/state-of-california-tackles-drought-with-iot-blockchain/

Case Studies

The informant interviews and survey discussed in previous chapters were deployed to gain a better understanding of stakeholder perceptions of Colorado water management and identify areas of improvement via technology. Based on the themes discussed by users and experts, technology solutions to include in this report were profiled. Some of the tools applied in the following case studies were mentioned specifically in one or more informant interviews and others were provided by collaborators at Colorado State University. All the emerging technologies discussed were included for their relevance and potential to address management challenges facing Colorado water.

Table 1 provides an overview of the case studies in this section along with the reasoning for their inclusion, while answering the following questions:

- What management gaps could be addressed by this technology?
- What underlying challenges might be exacerbating these management limitations?
- What makes these tools ready for public adoption and use?
- What management issues are not addressed by these solutions?

While not all these technologies are applied in Colorado, examples occurring in neighboring states with similar climates and management concerns have relevance for Colorado. Some of these projects are ongoing but convey opportunities for further application to meet the management gaps previously described.

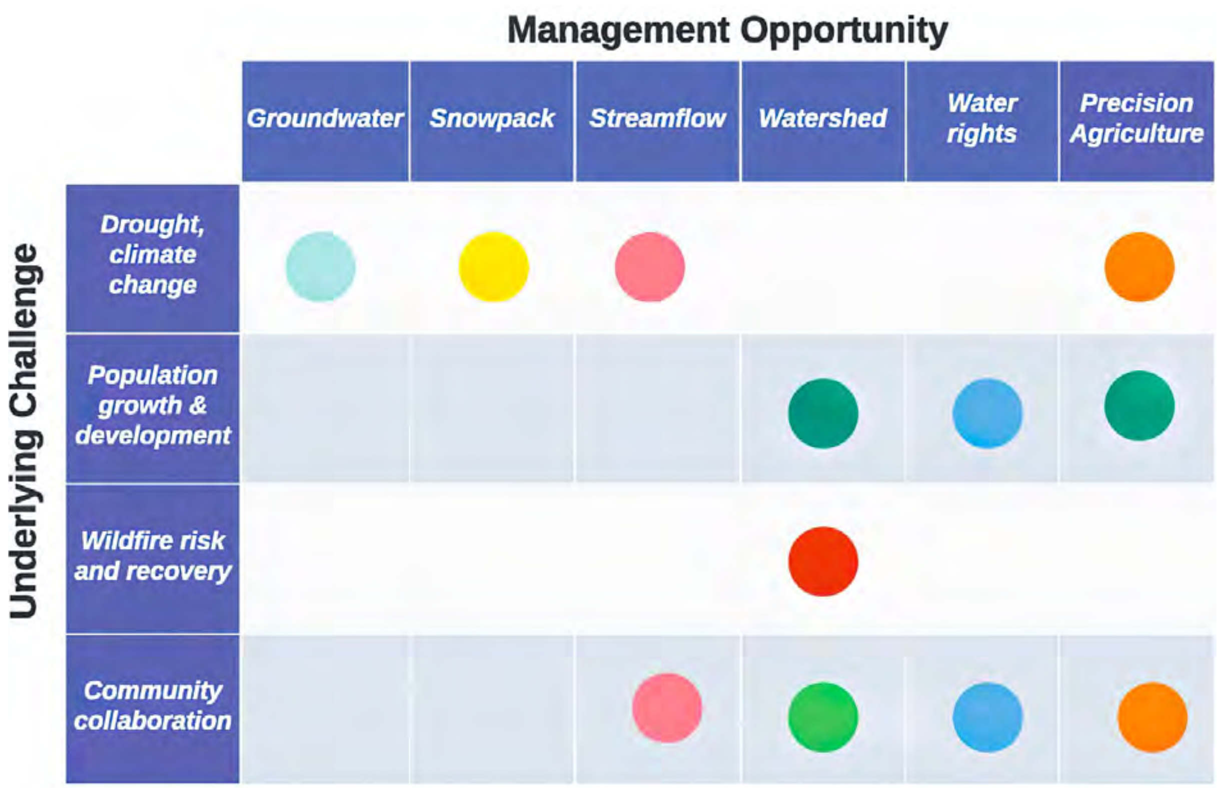
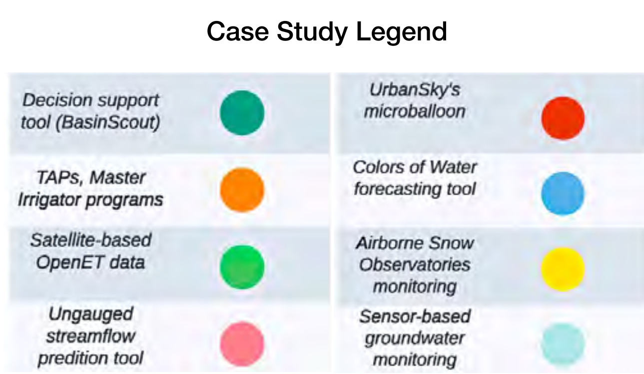


Figure 17: Above matrix pairs the monitoring gaps and underlying challenges discussed in informant interviews and the survey study with relevant case studies of emerging management technologies. A guide to corresponding case studies can be found in the legend below. Some case studies are shown multiple times.



Arkansas Basin: "Colors of Water" Operational Tools

K. Kelly Close, P.E.
LRE Water, Inc.

Introduction

The Arkansas River Basin in southeast Colorado is administered by the Division 2 office of the Colorado Division of Water Resources (DWR). Along with collecting streamflow data and overseeing water infrastructure, this office handles thousands of requests for water allocations each year, and dozens every day during the irrigation season. Division 2 staff review and approve these requests individually and incorporate them into a water accounting spreadsheet. This accounting tracks the administration of water rights along the Arkansas River to the Kansas state line in real-time including:

- Reservoir releases and storage
- Reservoir trades and transfers (changing ownership of water without physically releasing or diverting the water)
- Water exchanges (substituting water in one location with water from another location)

While this process is open to public review, there has historically been a lack of transparency for water users who wish to follow these transactions, simply because the spreadsheet-based accounting is not readily accessible to those outside the Division 2 office. If it were accessible, it still would not be usable by those most interested because water rights accounting is complex and difficult to understand without training and experience. These two challenges – accessibility and usability – are barriers to transparency for water users and the public.

In 2014, a group of water users and experts in Division 2 set out to change this. The Arkansas Water Users Group comprises representatives from the Colorado Water Conservation Board (CWCB) and DWR as well as cities, utilities, and ditch companies that hold Division 2 water rights. This group meets regularly to discuss opportunities to improve efficiency and processes around water management. They secured funding through the Arkansas River Decision Support System (ArkDSS) project and developed a plan to develop an innovative, web-based set of tools to improve communication about water administration in the basin, improve recordkeeping overall, and provide transparency around daily and sub-daily water transactions. This case study focuses on the improved transparency aspect of this effort. Therefore, the methods and results discussed below are a portion of the overall project.

In addition to transparency for water users in Colorado, the development of these tools was seen as a step toward more efficient and accurate administration of Colorado's water rights system (see Future Work below).

Methods

Development focused on the creation of a pilot system that operated for three years, followed by a permanent system put in place in 2019. The pilot project leveraged Google Sheets to work out the logic needed to automate the publication of the Division 2 accounting spreadsheet on a website where it could be accessed, visualized, and understood.

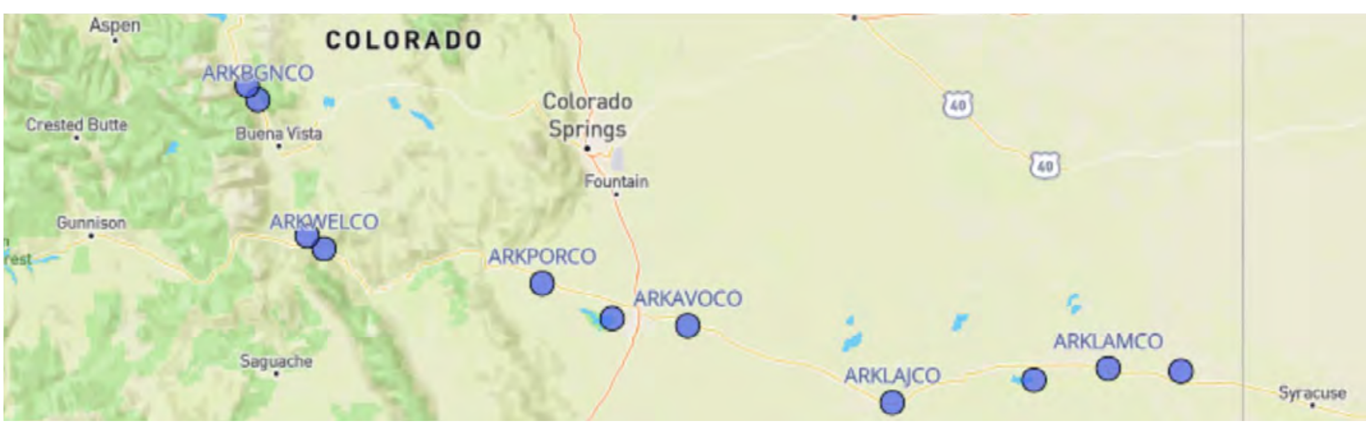


Figure 18: Key Stream gages on the Arkansas River in Colorado.

Figure 19: *Visualization of water accounting data.*

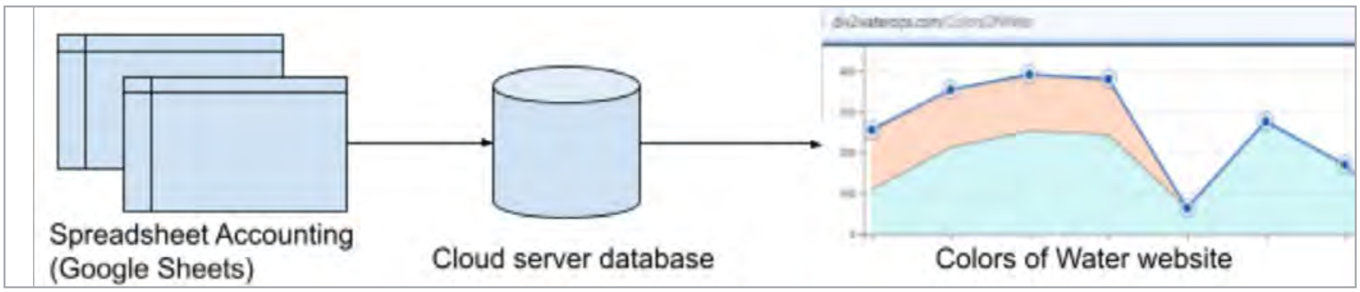


Figure 20: *Automated water accounting data publication process schematic.*

A key aspect of the pilot effort involved converting the Excel-based spreadsheet to Google Sheets. This was done without changing the accounting format or processes but made it possible to automate publishing the data frequently throughout the day. With the accounting data accessible through secure Google Sheets links, it was possible to create interactive and intuitive visualizations on the web. This publicly accessible and graphical version of the accounting was dubbed the "Colors of Water" tool because it visually shows the different types of water in the river at given nodes as colored stacked-area graphs (see additional examples and illustrations in the Results section, below).

Once the pilot system was tested and proved successful, the final system was developed, which was also based on open-source software and cloud resources. The accounting was kept in Google Sheets, but automation was moved to scripts housed on the cloud server that could be run on a schedule. Management and long-term storage of data was moved to a relational database (see system specifications below). The web-based user interface was constructed using an open-source, industry standard content management system providing secure management of user logins and administrative control over all aspects of the system by Division 2 staff. The Colors of Water visualization tools are open to the public without a login.

System specifications include:

- Google Sheets-based water rights accounting operated by Division 2 staff
- An Ubuntu Linux server hosted in the Amazon Web Services cloud with:
  - Apache (web server)
    - PostgreSQL (database)[11]
    - Drupal (content management system)[12]
  - JavaScript (custom modules developed specifically for this project)
  - PHP (scripting language)

The cloud server runs several scripts every 30 minutes, which call down the latest data from the Google Sheets accounting spreadsheet. These data are saved to tables in the database, archived and processed for the website. Custom functions in the database format the data and make it available to the visualizations programmed into the Drupal website.

Results

Anyone may explore the Colorado Arkansas Basin Colors of Water tool online.[13]

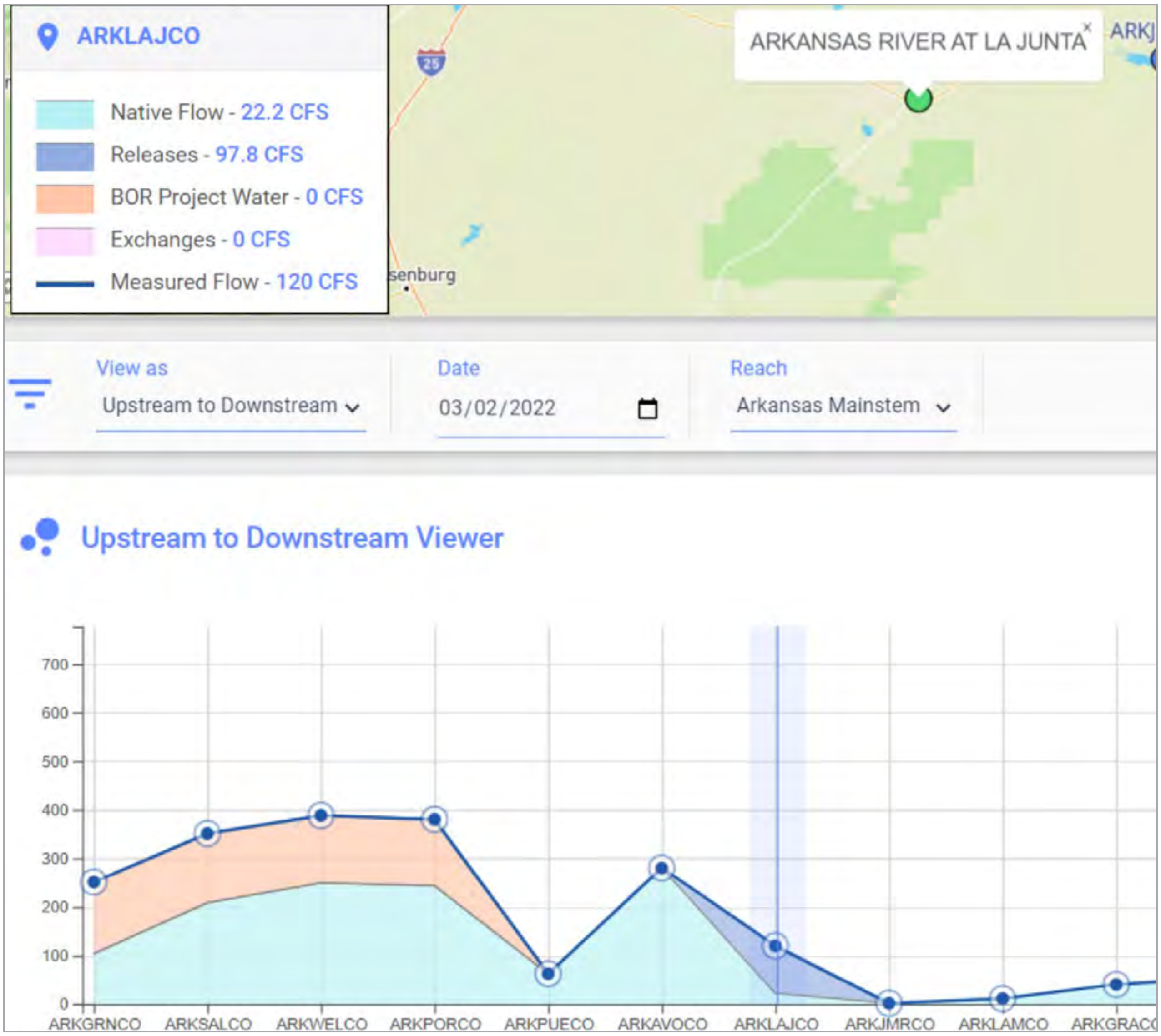
The Colors of Water tool displays the colors of water that comprise the river flow at key stream gages along the Arkansas River on a daily basis. An interactive map lets users bring up the data by location and see the gauged river flows "sliced" into different colors according to the source of the water at that gauge.

For example: On March 3, 2002, there were 120 cubic feet per second (CFS) flowing at the La Junta stream gauge.

[11] https://www.postgresql.org/

[12] https://www.drupal.org/

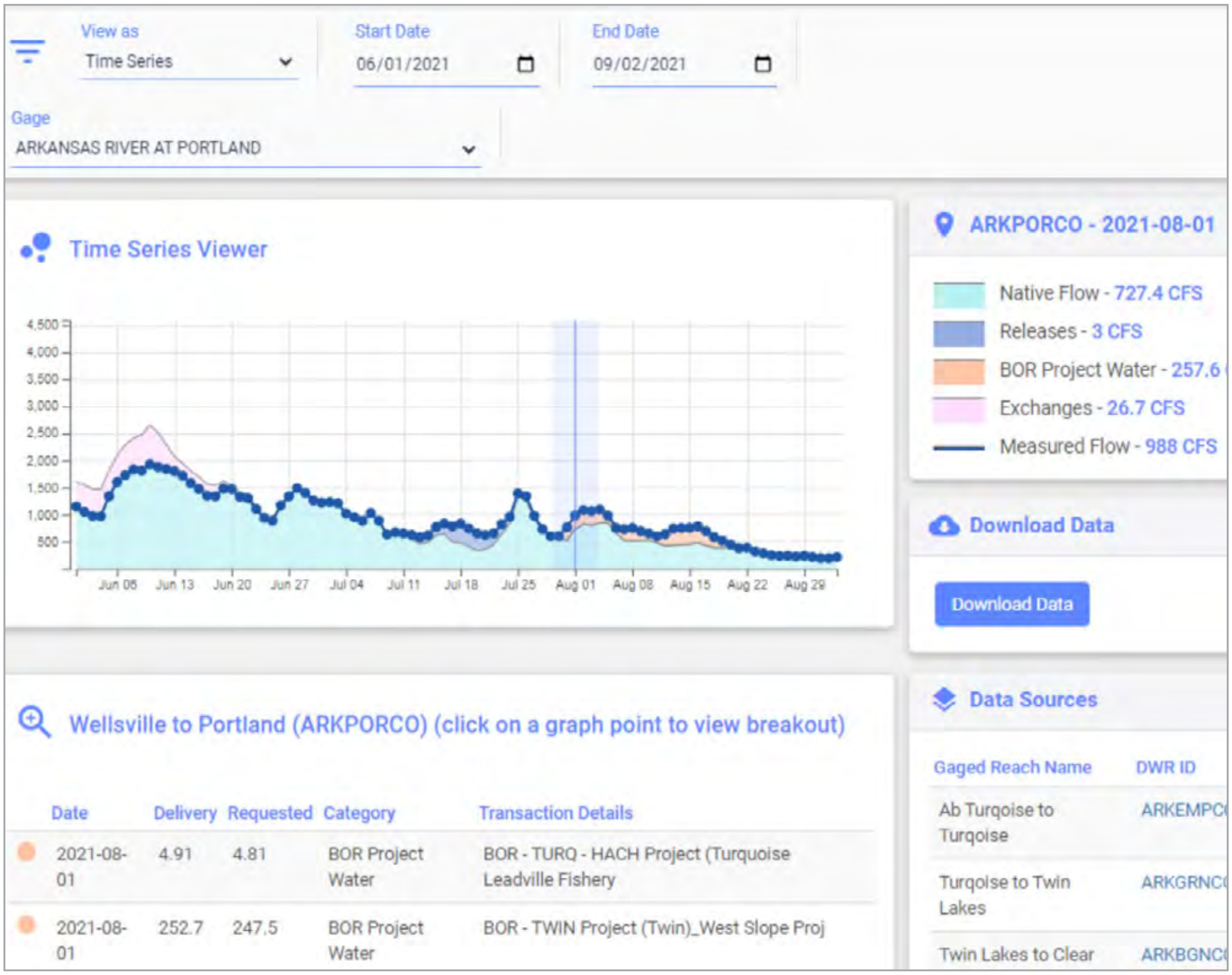
[13] http://div2waterops.com/ColorsOfWater



| *Figure 21: Colors of Water Tool upstream to downstream view.*

Division 2 accounting specifies that 22.2 CFS was native streamflow and 97.8 CFS was a combination of releases from upstream reservoirs. The Colors of Water tool shows the 22.2/97.8 split summarized as a stacked area graph. Clicking on the graph reveals a table showing the individual transactions making up that 97.8 CFS (see Figure 21).

Users can look at an upstream-to-downstream view (see Figure 20) in this Colors of Water graph to get a "full river" view of the water administration on a specific day. Alternately, users can switch to a time-series view, which displays daily transactions at one location over a selected period of time.



| *Figure 22:* Colors of Water Tool time series view and details table.

Future Work

The DWR and CWCB are working toward extending the Colors of Water tools to include modeling of transit losses. Including real-time transit loss modeling in this process will improve the accuracy of the release volumes shown at each gauge location by taking into account stream losses from the point of release. The incorporation of these models will also open the door to forecasting more accurate flows at downstream locations based on reservoir release requests and requests for water exchanges before these transactions are executed.

Water users will be able to use these forecasting tools to make more accurate requests and be more efficient with their own supplies. Division 2 water administrators will be able to better anticipate downstream conditions and ensure proper administration of reservoir releases, exchanges, and other operations.

CASE STUDY

Denver Water: Leveraging Low-cost Stratospheric Monitoring Capabilities for Watershed Management

Andrew Antonio
Urban Sky

Alison Witheridge
Denver Water

Introduction

Denver Water is Colorado's oldest and largest water utility, serving high-quality water to 1.5 million people in the City of Denver and surrounding suburbs. Denver Water established the Strontia Springs Watershed Sediment Management Plan in 2021 to address sediment erosion and transport to Strontia Springs Reservoir from the upstream watershed. This plan, championed by Alison Witheridge, a watershed scientist at Denver Water, developed strategies to reduce watershed sediment yield that threatens hydroelectric power generation, dam safety, water quality, and storage capacity at the Strontia Springs Reservoir. Timely, low-cost, broad-area, high-resolution aerial imagery is needed to support planning and design of initial watershed sediment management projects.

For this program, Denver Water is working with Urban Sky, a Denver-based small business that develops, builds, and operates zero-emission stratospheric remote sensing vehicles that provide high-resolution, broad-area, aerial imagery at costs significantly lower than satellites, fixed-wing aircraft, and drones. Denver Water is interested in deploying Urban Sky's technology to support two high-priority projects in need of timely, high-resolution imagery.

The Lower North Fork of the South Platte River Sediment Retention and Riparian Buffer Project focuses on the lower reach of the North Fork above the confluence with the main stem of the Upper South Platte. Riparian treatment opportunities are being evaluated to retain sediment and reduce sheetwash along the riverbank. Denver Water is investigating several treatment techniques, including (1) planting willow poles in void spaces and open areas along the stream bank and in the riprap and (2) installing post-assisted log structures (PALS) at the fringes of banks, islands, and mid-channel deposit features. In addition, in June 2021, the Platte River Fire burned approximately 30 acres of the steep colluvial slopes adjacent to this channel within Denver Water and United States Forest Service (USFS) land. Timely, high-resolution aerial imagery would support identification of the best locations for these restoration techniques.

The Denver Water Property Emergency Access Road Repair, Unauthorized Road and Trail Decommissioning, and Hillslope Treatment Project is located in the Last Resort Creek watershed on the north side of the North Fork. This 3,680-acre property is owned by Denver Water and is adjacent to the Colorado Trail, and the Jefferson County Open Space North Fork Trail goes through the

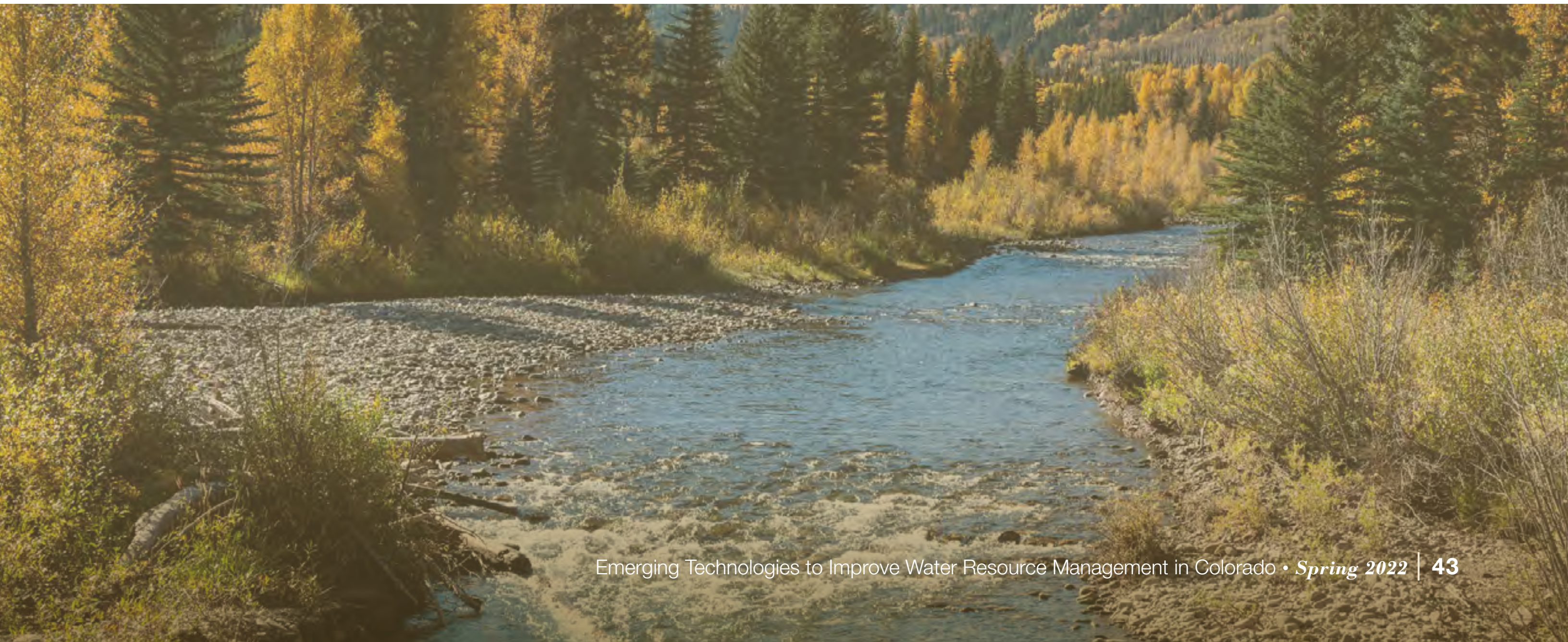


Figure 23: *Sample image frame from Strontia Watershed mission with Denver Water.*

property. Several watershed stakeholders rely on roads on the property for emergency access. Historical narrative accounts and existing aerial imagery indicate frequent land movement and sediment washouts from the property directly into the North Fork. Denver Water is evaluating treatment opportunities in this area that include repairing, stabilizing or realigning emergency access roads, decommissioning off-highway motor vehicle (OHV) trails, and installing hillslope treatments. Working with watershed and access road stakeholders, additional aerial imagery and site assessments are needed to locate and design specific treatments.

Methods

Timely, high-resolution, broad-area aerial imagery is critical to enabling environmental analysis and effective deployment of watershed treatment methodologies. Aerial imagery coupled with powerful geographic information system (GIS) analytical tools and software can support Watershed Scientists in their research and planning efforts at scale. Combined, these enable efficient, widespread monitoring of watersheds and can direct restoration efforts more effectively and quickly.

Historically, capturing broad-area, remote, high-resolution (<15cm GSD) aerial imagery has proven expensive and time-consuming. Traditionally, aerial imagery is captured via satellite, aircraft, or drone. Each of these platforms has unique limitations. The best satellites in the world capture imagery at a resolution of >28cm GSD, which is generally too coarse to see critical details like sheetwash erosion or sediment movement. Satellites are also limited in their imaging capacity and orbital paths, often producing imagery at a minimum price of 25km2 of data collected. For Denver Water, a one-time purchase of this imagery would equate to nearly USD 22,500 for the project-area in question (~900km2). Fixed Wing Aircraft, in comparison, offer much higher resolution and higher-quality imagery (~3-15cm GSD), but generally at a steep increase in cost. Because of the costs associated with operating these platforms, aerial imagery is often captured infrequently above remote areas of environmental interest. Aerial imagery is typically captured above these areas at a rate of once per year or less. Drones, in contrast, fly very low to Earth (generally below 400 ft. AGL), restricting this imaging platform's ability to capture large, wide-scale areas, and limiting their use to deployment above much smaller, more compact areas of interest.

Results

Urban Sky executed two successful stratospheric imaging missions above the Strontia Watershed in May of 2022. Urban Sky is currently post-processing the imagery collected from the missions, totaling over 200 sq. km of broad-area data within Denver Water's Area of Interest (AOI). This summer, Denver Water will analyze the imagery to support the determination of efficient deployment and utilization of the aforementioned mitigation efforts. A sample image frame from the collection is depicted below. This is likely the first time in history that aerial imagery from a stratospheric balloon has been used for watershed restoration analysis.

Future Work

Denver Water envisions leveraging Urban Sky's technology for routine, low-cost imaging missions in support of regular watershed monitoring and project effectiveness assessments.

CASE STUDY

Groundwater Monitoring in Solano County, California

Melanie Holland, Ben Livneh, Evan Thomas
University of Colorado Boulder

Stephanie Tatge, Alex Johnson, Chris Thomas
The Freshwater Trust

Introduction

Aridification in the western United States is jeopardizing water security and drastically increasing water stress for communities and agricultural producers, while incentivizing the implementation of new groundwater-focused policies (Williams et al., 2020). In the past decade, these unprecedented droughts stressed surface water availability and caused significant financial losses through crop and property damages (Cook et al., 2015). As surface waters are depleted and drought conditions continue, water managers rely more heavily on groundwater for domestic, agricultural and industrial use.

A severe drought from 2011 to 2016 prompted passage of the Sustainable Groundwater Management Act (SGMA) in 2014, which requires management of medium- and high-priority groundwater basins. SGMA authorizes local agencies to take on management of the resource by becoming a Groundwater Sustainability Agency (GSA).[14] Local GSAs must develop a Groundwater Sustainability Plan (GSP) for their basin by early 2022 and achieve sustainability within 20 years. SGMA requires that GSAs determine the basin-wide rates of groundwater recharge and abstraction to equalize the water budget.

To fulfill the requirements of SGMA, agencies must actively monitor groundwater trends to establish management plans and demonstrate progress towards California's policy requirements. Measurement of groundwater use is often considered a prerequisite to effective management. However, by extension, such measurements are only effective if they are accurate, trusted, cost-effective and actively incorporated into enforceable water conservation practices and policies (Molle & Closas, 2021).

To fulfill the requirements of SGMA, agencies must actively monitor groundwater trends to establish management plans and demonstrate progress towards California's policy requirements. Measurement of groundwater use is often considered a prerequisite to effective management. However, by extension, such measurements are only effective if they are accurate, trusted, cost-effective and actively incorporated into enforceable water conservation practices and policies (Molle & Closas, 2021).

To demonstrate how in-situ, remotely reporting, satellite-connected sensors could be used to estimate and predict local groundwater abstraction, this study installed eleven current clamp sensors between April 2019 and April 2020 on groundwater wells in Solano County, California, and recorded daily run-time and electrical usage for each. Satellite connected sensors were provided by Virridy (www.virridy.com). Subsequently, groundwater abstraction at each site was estimated using a power-conversion coefficient obtained from on-site pump tests. This data was used to create a groundwater abstraction model, which can be used to predict local groundwater need.

Methods

California designated the Solano Sub-basin, part of the Sacramento Valley Groundwater Basin, a medium-priority basin subject to SGMA compliance. Two aquifers underlay Solano County. The shallower of these is the Alluvium aquifer, used primarily by private well owners, agricultural pumpers, and small community water systems. The deeper aquifer, known as the Tehama Formation, is the thickest water-bearing unit underlying the Solano sub-basin, ranging in thickness from 1500 to 2500 feet, and provides most of the municipal water supply in the basin (*Sacramento Valley Groundwater Basin Solano Subbasin Basin Boundaries and Hydrologic Features*, 2004). This study installed sensors on agricultural wells that abstract groundwater from the shallow alluvial aquifer.

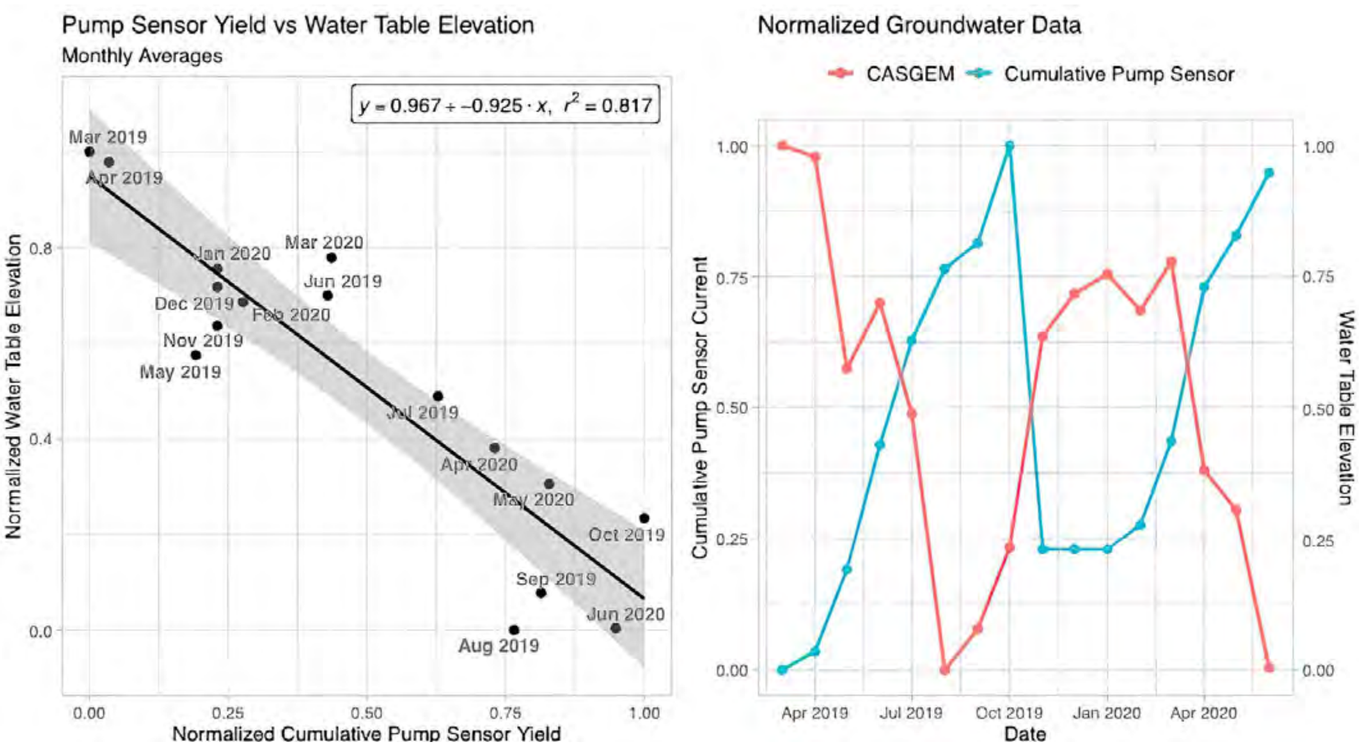
Solano County is a major agricultural community that relies on groundwater from the Central Valley Aquifer for irrigation. Due to high connectivity between aquifer systems in Solano County and the Sacramento-San Joaquin Delta system, this area is under intense scrutiny because it supplies water to major cities downstream. Therefore, Solano County is an ideal study area to investigate the impacts of in-situ groundwater abstraction monitoring under the context of regional and state-wide groundwater regulations. To investigate the use of in-situ electrical sensors for groundwater management, we deployed eleven sensors to develop a data-driven model that uses geophysical inputs from observations and simulated quantities.

[14] Cal. Water Code §§ 10723, 10724

| *Figure 24: Satellite connected sensors provided by Virridy and installation in Solano County project.*

A multiple-linear-regression predictive model was selected to quantify linkages between hydrologic indicators and seasonal groundwater abstraction at each sensor site. The predictive technique works by fitting coefficients to individual predictor variables (e.g., streamflow, evapotranspiration, soil moisture, temperature, precipitation, estimated yield from in-situ sensors, and groundwater level) with groundwater abstraction from in-line flow meters as the dependent variable. Predicted groundwater abstraction was verified with observed measurements from the in-line flow meters. The skill of each prediction model was determined by the coefficient of determination (R^2) and the percent bias. These metrics were chosen to capture both the explained variability within the model, the overall deviation from simulated and observed values, and the average magnitude of the errors in the modeled values.

The California Statewide Groundwater Elevation Monitoring (CASGEM) Program was initiated in 2009 with the goal of establishing a locally managed network of systematic groundwater measurements in all of California's alluvial groundwater basins. For each groundwater abstraction site, a neighboring California CASGEM site was selected as the depth-to-groundwater level predictor variable. Trends between individual CASGEM and sensor sites can provide insight into the timing and location of groundwater abstraction and make it possible to consider how differences in aquifer medium (i.e., sand versus loam), differences in borehole screened interval depths, and differences in borehole use (i.e., agriculture versus domestic) can be used to select a more accurate groundwater abstraction predictor variable.



| *Figure 25:* *Data obtained from Solano County groundwater project.*

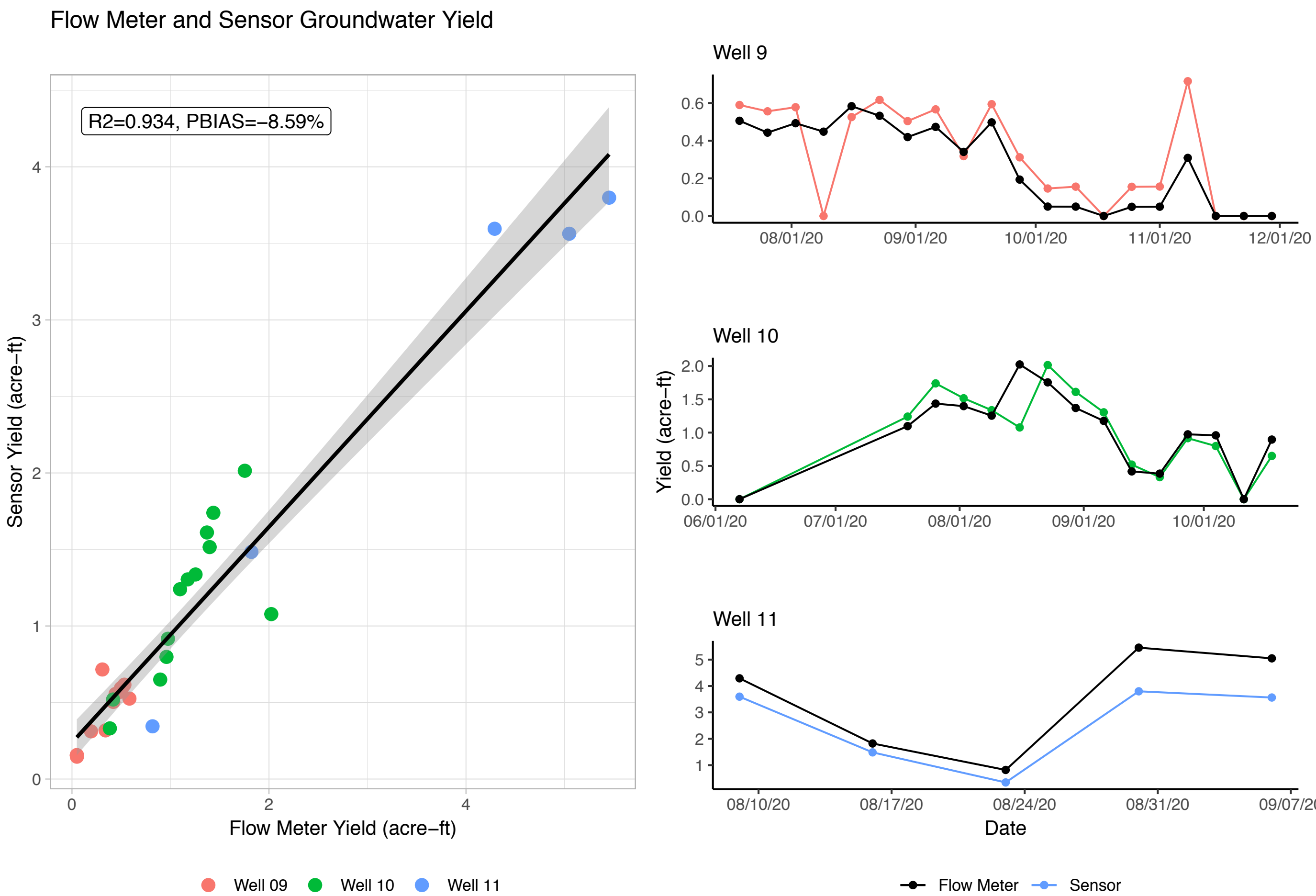


Figure 26: Data obtained from Solano County groundwater project.

Results

Over 18 months (April 2019-October 2020) there was a strong inverse correlation (R^2=0.937) between the monthly aggregated groundwater abstraction data and the monthly aggregated groundwater level data (Figure 24). To compare the trend between groundwater abstraction and groundwater level in Solano County, the mean depth-to-groundwater level from the 18 CASGEM sites and the mean cumulative groundwater abstraction from the 11 in-situ sensor sites were taken. Both data sets were normalized by their maximum respective values, and depth-to-groundwater was measured in reference to the North American Vertical Datum of 1988. Figure 24 shows a large decrease in depth-to-groundwater in October, which corresponds to the peak in cumulative groundwater abstraction at the end of the Solano County irrigation season. The aquifer replenishes from October through February, then decreases as pumping begins in March. This strong correlation between depth-to-groundwater and observed groundwater abstraction suggests that local groundwater levels can be a highly effective and reliable indicator and identifier of local groundwater abstraction.

The this analysis, flow meter data at three sites (Wells 9, 10 and 11) were assumed to be the actual groundwater abstraction. The right-side panel of Figure 25 shows a time series of the flow meter and estimated groundwater abstraction from the in-situ sensors, while the left-side panel shows the associated correlations between the groundwater yield estimate from the sensor data and corresponding coefficient obtained from on-site pump tests for each site, compared to the "ground truth" groundwater abstraction as measured by the in-line flow meters. The flow meter data in conjunction with the electrical current sensor data at these three sites indicated that the sensor measurements and associated conversion coefficients provide a reasonable estimate of groundwater abstraction.

The timing and magnitude of groundwater abstraction was largely retained between the flow meter and in-situ sensor measurements, especially for the wells that pumped smaller volumes of daily irrigation. Figure 25 demonstrates the variability between sites: for low flows (<4 acre-ft/day), the in-situ sensors captured the magnitude and timing of groundwater abstraction, while at high flows (>4 acre-ft/day), they underestimated the magnitude of groundwater abstraction. This is potentially explained using variable frequency drive (VFD) pump controllers, which provide for efficient energy use at higher yields. Since Well 11 typically experienced flows greater than 4 acre-ft/day, the overall accuracy of estimated groundwater abstraction at this site was diminished.

Future Work

This study examined how in-situ groundwater monitoring networks can be used to inform a statistically driven, multiple-linear-regression model to predict groundwater abstraction and groundwater levels in Solano County, California.

To expand on this research, additional sensors will be deployed in California to create a spatial groundwater use forecast. We will evaluate the ability of such a network to aid in groundwater management and policy compliance.

Deploying noninvasive technologies such as these to record data from existing groundwater infrastructure could remedy the current data gaps. Moreover, the required data management system could be developed as a web-based digital platform, making this data more accessible and useful. Importantly, the confluence of the required groundwater monitoring network, data management system, and elevation modeling potentially create an opportunity for GSAs to take the first step towards a market-based groundwater trading program by encouraging them to create a centralized and accessible platform that tracks groundwater use nearly instantaneously and models its implications. Once established, this type of platform could be refined and expanded to facilitate groundwater trading and ensure sustainable groundwater use.

Dixon, Solano County, California

CASE
STUDY

Decision Support Tool to Assess Conservation Management Scenarios in Pueblo County, Colorado

David Primozich, Elliot Hohn
The Freshwater Trust[15]

Scott Campbell
Innovative Conservation Solutions

Introduction

This project aims to link agricultural land and water management decisions at the field-scale to regional economic and environmental outcomes. The context is Pueblo County, Colorado, where there is a need to balance water resource usage and minimize the economic impacts of rural-to-municipal water transfers.

In 2009, the City of Pueblo acquired a 28% interest in the Bessemer Irrigating Ditch Company to dry up farmland and secure its municipal water supply. However, if not undertaken strategically, this move has the potential to take high-quality farmland out of production and create large economic losses. In 2015, a consortium of Pueblo County stakeholders launched the Bessemer Project to identify a viable path to a prosperous agricultural future in the face of the pending dry-up. Analyses commissioned by the group indicated that Pueblo Water's targeted dry-up area (over 5,000 acres) contains some of Pueblo County's best agricultural ground. The analyses went on to identify dry-up alternatives that could keep this high-quality farmland in production while providing Pueblo Water with its municipal yield. In 2017, the Bessemer Project Association worked with Pueblo Water to establish provisions that enable alternatives, such as a "substitution of dry-up" provision. This provision allows farmers to acquire highly productive ground that will otherwise be dried by Pueblo Water and move water to that ground from less productive areas, which are then dried instead. In studies undertaken with Bessemer farmers, substitutions were shown to result in higher yields and increased real estate values, significantly improving a farmer's bottom line. Substitutions can also improve water quality if marginal, more erodible land is taken out of production. In 2020, Palmer Land Conservancy and Innovative Conservation Solutions (ICS) produced an Economic Impact Analysis (EIA) of dry-up alternatives. In a "do-nothing" dry-up scenario, where Pueblo Water dries all the farms it purchased water from, the range of loss to Pueblo County would be between $8.4-17 million annually. But dry-up substitutions would create different outcomes, reducing and in some cases reversing the dry-up's economic impacts.

In 2021, Palmer commissioned The Freshwater Trust (TFT) to develop the Bessemer Decision Support System (DSS), a web application to inform decision making around these alternatives. The DSS allows stakeholders to dynamically evaluate the economic and environmental impacts of different production and dry-up scenarios. The Bessemer DSS guides efforts to strengthen Pueblo County farm communities, sustain agricultural economies, and protect the environment in a water-constrained future. Furthermore, it can help Pueblo Water develop its Bessemer shares for municipal use in a manner consistent with Pueblo County 1041 requirements, which mandate that water supply projects not adversely impact agricultural productivity or the local economy.

Methods

For the initial analysis, TFT used its BasinScout® toolkit, which applies field-level environmental and economic models across entire watersheds to identify feasible conservation actions, quantify the costs and benefits of those actions, and identify the most efficient actions to meet specific targets. To run BasinScout models, TFT aggregated a variety of existing datasets, including spatially explicit data on soil composition, irrigation methods, crop rotations, topography, farm field boundaries, and weather, as well as farm enterprise budgeting information. BasinScout standardizes these datasets for modeling, then evaluates the feasibility of implementing conservation actions for each field based on a set of heuristics that account for the field's characteristics as they relate to the limitations of each action. Next, a series of environmental and economic models (including the IMPLAN model for regional economic impact) are run for each field, based on current conditions and for all feasible conservation actions. This analysis provides cost and benefit information at the field and watershed levels when considering each combination of feasible field-level actions across the landscape. Finally, BasinScout uses mathematical optimization to identify the most efficient portfolio of conservation actions based on specific watershed targets and constraints.

Following the BasinScout analysis, TFT created the Bessemer DSS, a web application for stakeholders to modify targets and constraints, then visualize and compare the outcomes of different scenarios. This

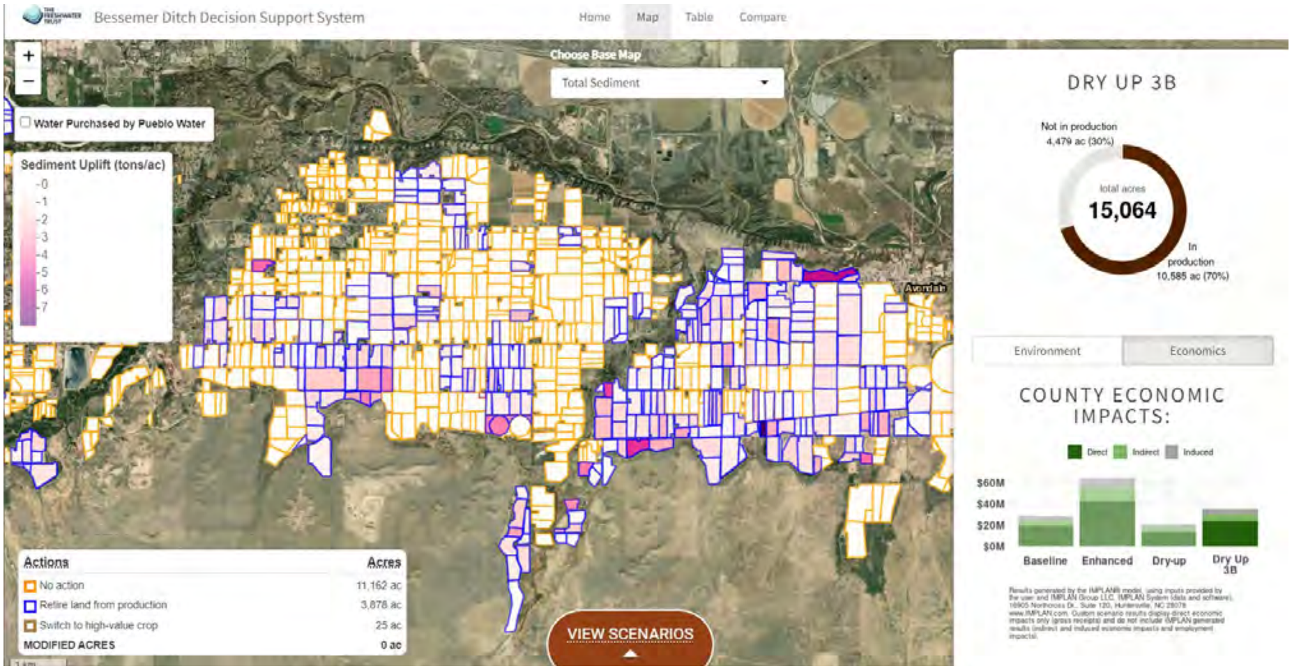


Figure 27: Map view from the Bessemer DSS showing a sediment reduction scenario that captures potential land management actions and economic impacts.

online dashboard illustrates current conditions (Baseline Scenario) and a set of predetermined scenarios (including Optimized Production and Anticipated Dry-Up). Additional scenarios are created by stakeholders using filters, sliders, and weighted functionalities, and can be compared to the predetermined scenarios.

On the Compare tab, users can see the economic and water quality impacts of scenarios in side-by-side comparisons. On the Map tab, users can explore the practices embodied in each scenario – from the field to the landscape level. On the Data tab, users can investigate factors such as the cost of irrigation upgrades recommended in a scenario or the amount of nutrient or sediment reduction that can be achieved through improved irrigation and/or land retirement practices. They can sort data using rankings that compare farmland protection, water quality, and irrigation improvement cost-benefit variables. Importantly, the automation of scenario building and analysis in the DSS allows for the rapid evaluation of more scenarios than would be feasible using manual evaluations.

Results

Palmer used the DSS to illustrate possible economic and environmental outcomes of dry-up scenarios to multiple stakeholders in Pueblo County. Farmers will be able to dry up less productive farmland and keep the best lands in production. Fallowed land can thus be restored to a more natural state. An important result was having a tool that is easy to use and clearly conveys complex ideas, allowing users to weigh the tradeoffs associated with any dry-up scenario.

A geospatial mapping project such as this presented challenges based on the frequent misalignment of land parcels and farm field boundaries. Moreover, the complexity of crop rotation and the challenge of forecasting future crop production meant the analysis had to rely on a snapshot in time for crop and land management inputs to models.

Future Work

The transformation of agriculture in the western US continues to have impacts on communities and ecosystems. The early results of this work are promising but require refinement. Additional applications of TFT's BasinScout analytical tool and Decision Support System are in the works. TFT is pursuing funding from foundations to apply the DSS to other basins in Colorado facing a water-constrained future. Work is expected to begin in late 2022. The DSS is also being applied to overdrafted groundwater basins in California's San Joaquin Valley, where legal settlements could force retirement of hundreds of thousands of acres of agricultural land to meet groundwater recharge obligations. Getting ahead of these transitions requires holistic approaches that enable stakeholders to make smart choices to support water, ecosystems, and local communities.

[15] The Bessemer DSS (https://thefreshwatertrust.shinyapps.io/bessemer_dss/) was developed by The Freshwater Trust and Innovative Conservation Solutions. The logic underpinning the Bessemer DSS is driven by The Freshwater Trust's BasinScout analytical toolkit. Partners include Palmer Land Conservancy, Lyons Gaddis, Anza, and Colorado State University. Major funding provided by the Babbitt Center, Robert Hoag Rawlings Foundation, Gates Family Foundation, and Colorado Water Conservation Board.

Questions about the Bessemer DSS should be directed to Scott Campbell, Innovative Conservation Solutions, scott@icsconsulting.biz. To learn more about BasinScout, visit: https://www.thefreshwatertrust.org/services/research-technology/.

CASE
STUDY

Improved Snowpack Monitoring with Airborne Snow Observatories

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Denver Water

Rachel Bash, Page Weil, P.E.
Lynker

Introduction

The two most critical properties for understanding the timing and magnitude of snowmelt runoff are the spatial distributions of snow water equivalent (SWE) and snow albedo. Despite the importance of these properties in controlling volume and timing of runoff, mountain snowpack remains poorly quantified, leaving constrained runoff and climate models and incomplete physical understanding of mountain snowmelt driven systems. Recognizing this gap in information, Airborne Snow Observatories, Inc. (ASO) utilizes a coupled scanning lidar system and imaging spectrometer to quantify snow depth, SWE, and albedo, offering unprecedented knowledge of snow properties and distribution for cryospheric science, and to provide spatially comprehensive, robust inputs to water management models and systems.

Ground-based observations (e.g. SNOTEL stations and manual snow courses) can be highly accurate but only at their specific locations, and were sited to support statistical runoff forecasts rather than to represent basin-wide SWE. The uncertainties in quantifying total snowpack from such sparse measurements leads to snowmelt runoff forecast accuracies of less than 80% half the time and less than 60% in one-in-five years. Satellite-based products provide broad coverage, but either measure only snow-covered area at a coarse horizontal resolution (1km+ cells) or snow depth with poor vertical resolution. Additionally, these measurements require clear-sky conditions, and satellite orbit dynamics do not allow adjustment of observation timing to sky conditions. Drone-based technologies can achieve similar snow depth resolution as ASO but provide limited geographic coverage. ASO is the only product that provides high-accuracy, high-resolution, and spatially complete measurements of snow depth (3m resolution), SWE (50m resolution), and albedo (50m resolution) at the basin scale (Figure 27).

ASO's objective is to generate comprehensive time-series maps of coincident SWE and albedo over large mountain basins. To do this, ASO combines repeat lidar and spectrometer over-flights with snow density fields simulated by an energy-balance snow model (iSnobal) and constrained by in-situ measurements to convert the lidar-derived snow depths to SWE. ASO over-flights are typically initiated in mid-winter, prior to peak SWE, and continue throughout the melt season. These data provide a reliable estimate of total snow accumulation and ablation, and its spatial distribution during the snow season.

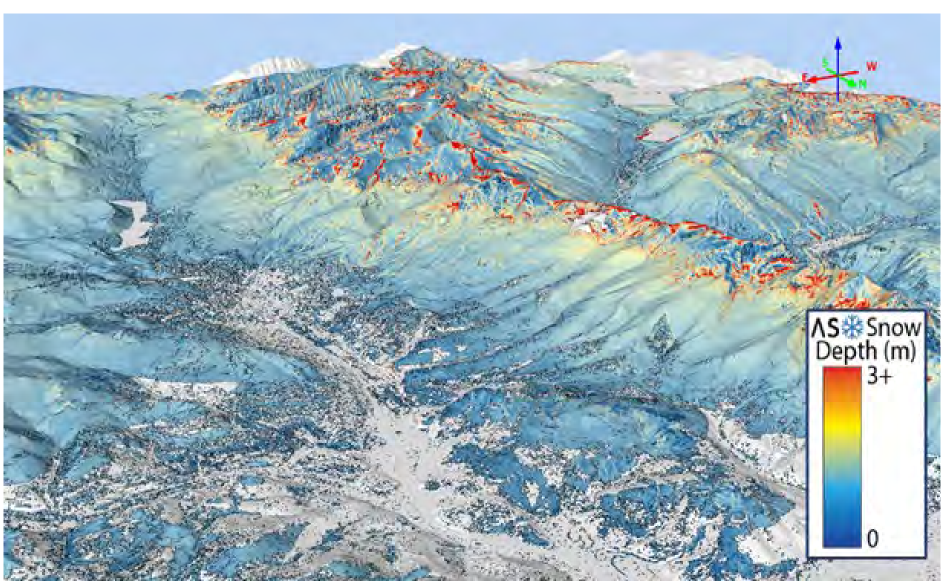

Figure 28: 3-meter resolution snow depth data from an ASO survey conducted on April 18th, 2021, in the Blue River Basin above Dillon Reservoir.

Methods

ASO uses aerial measurements of lidar, both with and without snow, to develop 3m gridded measurements of snow depth throughout a river basin. These lidar measurements are complemented with imaging spectrometer measurements to constrain the snow depth calculation and to measure snow albedo. Snow density is simulated using a distributed energy-balance model, constrained by in-situ measurements, and is combined with the snow depth grids to generate 50m gridded estimates of snow water equivalent (SWE). Historical data shows that these ASO measurements are within 2% of the actual water contained in the snowpack at the time of the flight, though runoff can vary due to a number of factors. Using ASO's current equipment, a single flight can cover a river basin of approximately 3500km2, equivalent to the entire watershed of the Roaring Fork River.

ASO was started by its current leadership at NASA's Jet Propulsion Laboratory (JPL) in 2013, with surveys in Colorado, California, and other western states establishing the measurement and processing techniques and operational readiness. Following technology transfer from NASA, ASO Inc.'s technologies and applications have seen continued development and refinement in close partnership with water managers. The initial applied-science-driven federal investment led to stakeholder adoption in several California basins and served as proof-of-concept for ASO technology and the utility of the data products over a series of dry and wet years. Consequently, interest in the program grew among neighboring watersheds and operators, growing the program with local and state funding. This drew the attention of the California Department of Water Resources (CADWR) and the California legislative delegation, with a state program established and a federal bill passed supporting the study and ASO snow monitoring within the Bureau of Reclamation. The California ASO program (now established under the CADWR Airborne Remote Sensing of Snow program, ARSS) is providing much-needed stability, enabling water users and agencies to transition to a new paradigm of complete-basin snow monitoring.

Since early 2021, there has been grassroots, stakeholder-driven effort to expand ASO flight coverage throughout the State of Colorado and build a long-term, ASO-focused snow measurement program. The workgroup, the Colorado Airborne Snow Measurement Program, or CASM, meets monthly throughout the year and hosts a weekly ASO flight coordination meeting during the late winter/early spring. CASM was awarded a State of Colorado Water Plan Grant in March 2022. The grant will provide $1.88 million to:

- expand ASO snow-on flights and support ASO-integrated streamflow forecasting in late winter and spring of 2022
- conduct snow-free work during summer 2022 to prepare basins for snow-on flights in the future
- host data workshops to expand the stakeholder reach of ASO data
- study ways to integrate ASO data with a variety of forecasting products
- continue CASM program coordination

The Water Plan Grant application received 37 letters of support – unprecedented for a water project. Moving forward, the CASM program will continue to meet and establish governance and sustainable funding for the program far into the future.

Results

Colorado had an unusual snow year in the spring of 2019. Several late season storms brought peak SWE well above average, resulting in higher-than-normal runoff in many of its river basins. This was also the first year Denver Water piloted ASO data to inform their operations.

Dillon Reservoir, located in Summit County, is Denver Water's largest reservoir. Snowpack that accumulates in the Blue River Basin flows into Dillon Reservoir and is the source of 30% of the water supply delivered to Denver and its surrounding suburbs.

ASO is Critical to Reservoir Operations

Above average snowpack in 2019 in Dillon Reservoir watershed caused higher than average inflows

A June ASO flight indicated more remaining snowpack above Dillon Reservoir than it had room for, prompting a ramp up of outflows

Accurate knowledge of snowpack from the ASO flight allowed managers to avoid significant downstream impacts and keep the reservoir full

ASO, Inc. conducted an airborne snow survey for Denver Water on April 19, 2019, over the headwaters of the Blue River, aiming to capture peak SWE for the entire Dillon Reservoir watershed. Data from this flight confirmed an unusually high snowpack and indicated a delayed melt. A second ASO flight on June 24 revealed that about 107,204 acre-feet of water in the snow remained above Dillon Reservoir. Several SNOTEL sites (Grizzly Peak, Hoosier Pass, Fremont Pass, and Copper Mountain), which sit at around 11,000 feet, had already mostly melted out. The figure below shows that, between the additional snowpack and Dillon Reservoir storage contents, there was more water stored as snow in the basin than the capacity of Dillon Reservoir, necessitating a significant release.

Too much outflow release or an overtopping of the reservoir spillway could result in flooding in the downstream town of Silverthorne. Conversely, had reservoir managers acted conservatively, they might have released more water than necessary to make space for the coming runoff, and Dillon reservoir might not have filled. Because of the ASO flight, Denver Water managers knew that they needed to begin ramping up outflows earlier than normal and continue them for additional weeks to avoid a peak release that was higher than acceptable.

There are numerous other examples of operational impacts of ASO data in various management contexts from Colorado and California. California stakeholder partners have estimated that the return-on-investment of the ASO program ranges from 40:1 for only water supply considerations, to 600:1 when other factors like hydropower production, flood avoidance, and operational flexibility are included.

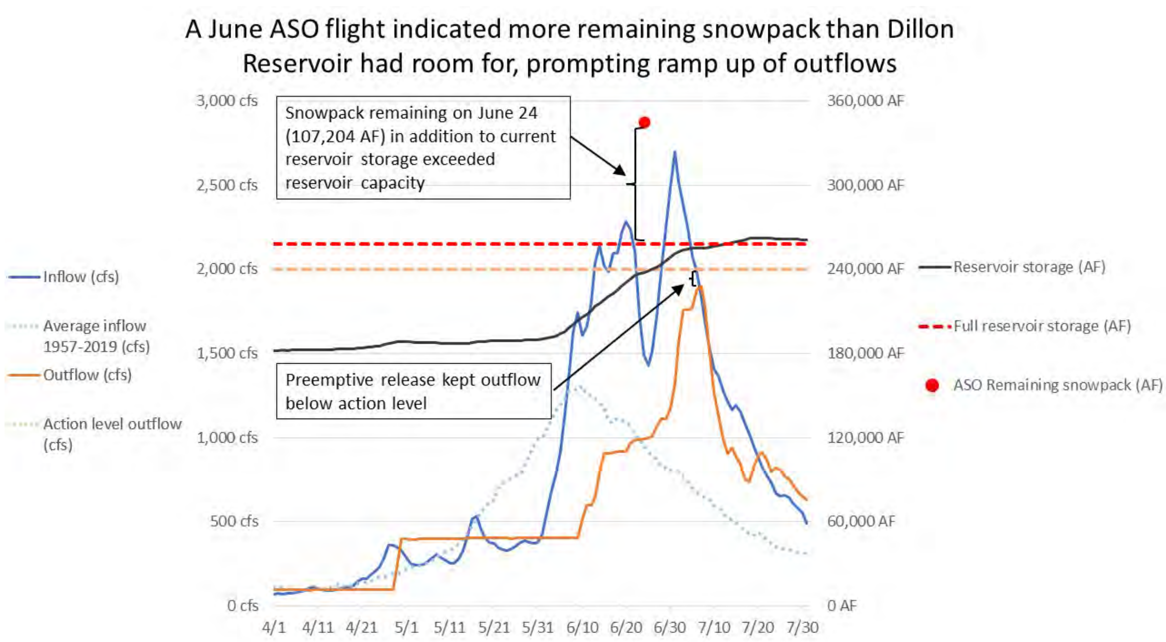

Figure 29: Dillon Reservoir operations in 2019 show that the June ASO survey was instrumental in delivering important data. The red dot indicates the snowpack remaining on June 24 in addition to the reservoir storage contents. If all the remaining snowpack had flowed into the reservoir without adjusting the outflow, the reservoir would have spilled over.

CASE
STUDY

Colorado Ungauged Streamflow Prediction

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Colorado State University

Gigi Richard
Fort Lewis College

Joel Sholtes
Colorado Mesa University

Introduction

Water right allocations in Colorado rely on information about streamflow quantity. Although some streams in the state are monitored to keep track of streamflow over time, most streams remain ungauged. To ensure that water rights are not over-allocated, tools are needed to estimate how much flow is likely in ungauged streams. This project (1) expanded monitoring in Colorado headwater streams and (2) developed an online tool for mean annual and mean monthly streamflow prediction.

Background

Ungauged streamflow predictions are an integral part of the USGS StreamStats tool. The StreamStats program uses statistical methods to predict streamflow based on watershed characteristics such as area, slope, and precipitation. In Colorado, StreamStats models were developed for five hydrologic regions: Mountain, Northwest, Plains, Rio Grande, and Southwest (Capesius & Stephens, 2009), using long-term data from stream gauging stations. Such models work well if:

1. the streams gauged span the breadth of watershed types in the region
2. the model input variables capture the features that affect streamflow quantity

Streamflow varies with watershed area, climate conditions, vegetation, underlying geology, soil, topography, and land and water use. Small watersheds have a narrower range of these characteristics in their drainage area. This makes small watersheds most useful for developing statistical streamflow prediction models. An ideal monitoring network to support ungauged streamflow prediction would include small watersheds distributed across the range of landscapes in the state. Instead, the existing stream gauging network was developed largely around water supply infrastructure, with a much higher density of stream gauges in the Mountain region, where many water intakes and reservoirs are located. In contrast, the Plains and Northwest regions have relatively few stream gauges (Figure 29).

Ungauged streamflow prediction models in most locations, including Colorado, have relied primarily on precipitation to describe climate (Capesius & Stephens, 2009). However, precipitation alone does not capture the influence of snow on streamflow generation in Colorado. Existing StreamStats regional regressions also do not incorporate land cover or underlying geology and soil.

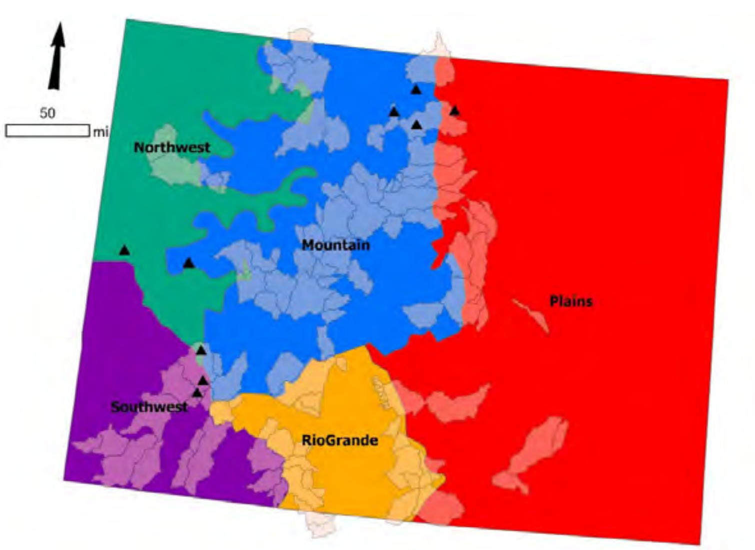

Figure 30: Map of Colorado hydrologic regions (Capesius & Stephens 2009) with areas of current gauged watersheds (US Geological Survey and Colorado Division of Water Resources), including only watersheds <600 mi^2. These are best suited for developing streamflow prediction models. Triangles indicate headwater monitoring locations described in this document.

Methods

For the first objective – expanded monitoring of Colorado headwater streams – we targeted the climate gradient between low and high elevations. We monitored headwater catchments (0.1-2 mi^2) in three transects on the Colorado Front Range, Grand Valley, and San Juan Mountains (Figure 29). For each transect we measured catchments in each of three snow zones: persistent, transitional, and intermittent. At each catchment we monitored precipitation, snow depth, soil moisture, soil and air temperature, and streamflow (Figure 30).

For the second objective – the streamflow prediction model – we created a statistical model similar to StreamStats but with several key differences:

1. We used only the time period from 2000-2018 to develop the model. While this period had drier conditions than the longer period of record used to develop StreamStats. It might be a more realistic representation of future conditions, given the warm and dry conditions predicted for Colorado.
2. We screened the stations for within-basin flow modifications (reservoirs, diversions) and transbasin diversions, and we excluded all watersheds with transbasin diversions from model development.
3. We added predictor variables, in particular mean annual snow persistence from MODIS satellite snow cover data (Hammond, 2020; Moore et al., 2015). Prior work has shown that snow persistence is strongly correlated with streamflow in this region (Hammond et al., 2018). Variables we added are slope aspect, dominant geologic group, and mean annual potential evapotranspiration.

More details on this model are available in Eurich et al. (2021).

Results

Headwater stream monitoring demonstrated a stark difference in streamflow between the persistent and intermittent snow zones along the Colorado Front Range (Harrison et al., 2021). The intermittent snow zone exported less than 20% of precipitation as streamflow, whereas the persistent snow zone exported over 57% of precipitation as streamflow. Exports in the intermittent snow zones of the Grand Valley and San Juan mountains showed a range of streamflow that appeared to relate in part to underlying rock type. Headwater streams in the persistent snow zone on the Grand Mesa had lower streamflow generation than comparable Front Range streams, likely due to greater groundwater export.

The new ungauged model predicted streamflow within 10% of observed mean monthly and mean annual flow from 2000-2018 (Figure 31 a, b). The new model also out-performed the USGS StreamStats models, which predicted monthly streamflows 0-42% higher than observed, and mean annual flow 25% higher than observed (Figure 31 c, d). The improved performance of the new model is likely due to the addition of snow as a predictor variable. We also found that the time period of data used for training the model is important for its performance. We developed the new model for a relatively dry period (2000-2018), whereas the StreamStats regressions used any period of record with data. Training a model using data from a wet period may cause bias when applied during a drier period (Eurich et al., 2021). The new model is available online.[16]

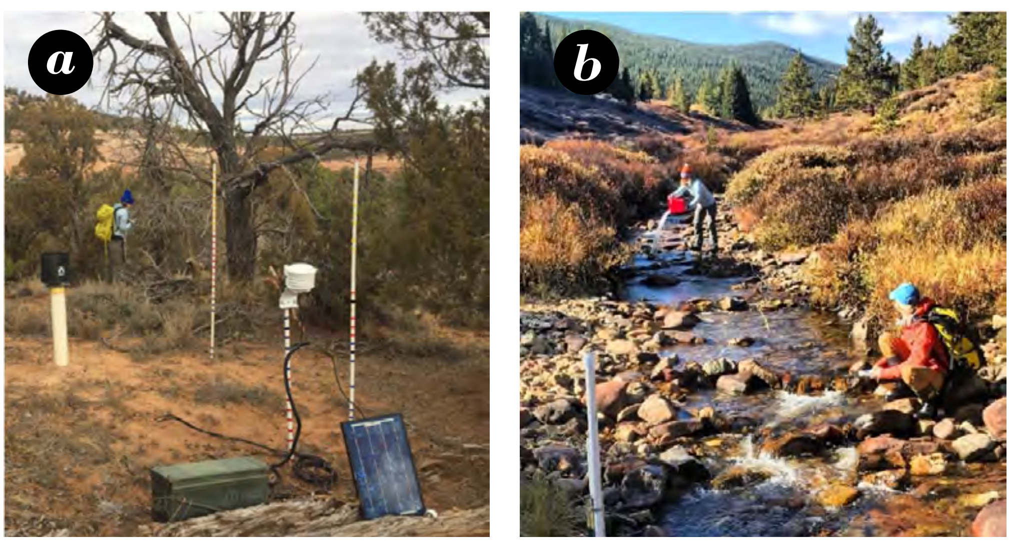

Figure 31: Examples of low-cost headwater catchment monitoring. (a) Cameras pointed at demarcated poles measure snow depth; (b) pressure transducers within PVC pipe track water depth in streams. Salt dilution stream discharge measurements are being conducted in (b).

[16] https://cuahsi.shinyapps.io/CO_streamflow/

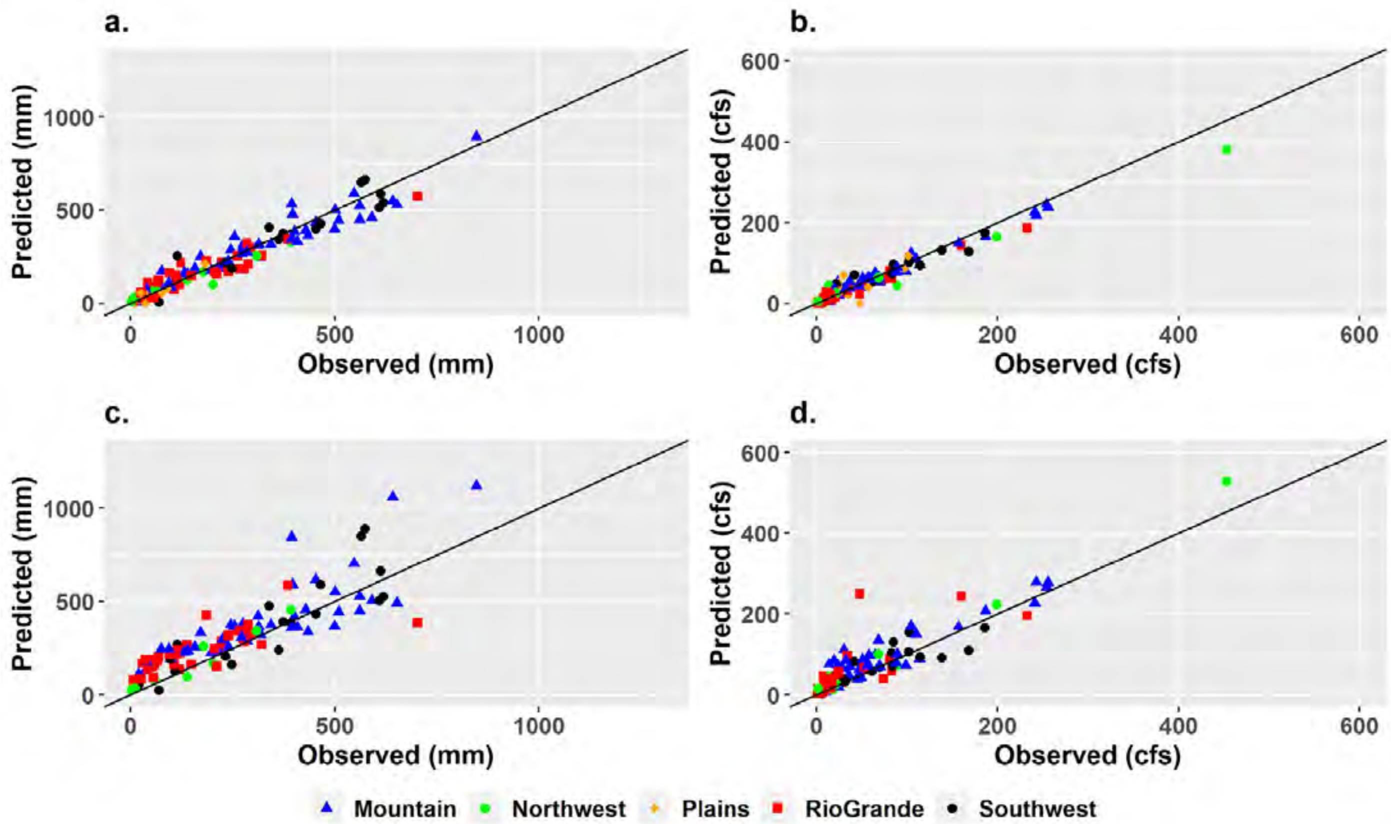

Figure 32: *Predicted vs. observed mean annual streamflow for the new model in (a) mm (area-normalized discharge) and (b) cubic feet per second (cfs), and for USGS StreamStats in (c) mm and (d) cfs.*

Future Work

An ungauged streamflow prediction model is only as strong as the data used to develop it. This type of model could be improved with better representation of watershed types in the stream gauging network. The current network lacks small watersheds in low-snow areas, particularly in the Plains and Northwest regions (Figure 29). Through headwater monitoring, we learned that underlying geology likely has an influence on streamflow, and future monitoring locations could be selected more strategically to evaluate this. We also learned that some watersheds are likely net exporters of groundwater (Kampf et al., 2020), and future work could examine what factors affect groundwater export in the headwaters. We know from headwater stream monitoring that loss of winter snow cover can be associated with extreme declines in streamflow generation (Hammond et al., 2018; Harrison et al., 2021), some streams might be more buffered against snow changes due to greater connection with deep groundwater, which allows them to produce a similar amount of streamflow through deep flow paths even with varying amounts of snow.

A statewide monitoring network could be designed to address questions about streamflow connections to groundwater, fill gaps where there is little information about streamflow, and contribute to improved ungauged streamflow prediction models that inform future water resource planning. Expanded monitoring can be implemented with relatively low-cost sensors; the greatest investment is personnel time to measure stream discharge in the field and process the data.

CASE STUDY

Testing Agricultural Performance Solutions Program

Amy Kremen
Colorado State University, Irrigation Innovation Consortium

Introduction

The Testing Agricultural Performance Solutions (TAPS) program supports experiential-learning competitions that focus on improving farm management by using direct and remote sensing technologies to inform decision-making. Since the program's launch in 2017, the competitions have involved hundreds of participants from Nebraska, Oklahoma, Colorado, Kansas, and Missouri. Participants compete to see who can produce a crop the most profitably and with the greatest input efficiency in terms of water and nitrogen applications.

TAPS supports sprinkler-irrigated corn and cotton competitions and subsurface drip-irrigated corn and grain sorghum and dryland wheat competitions. Each competition is designed to match real-world conditions and generates extensive, scientifically rigorous information. It also provides quantitative and qualitative input and feedback from participants and technical service providers, whose tools support irrigation and other input use decisions. To date, the competitions have been based in Nebraska and Oklahoma, with competitors able to participate remotely from anywhere in the High Plains and beyond. The competition platform facilitates peer-to-peer mentoring and fosters a community of practice supported by researchers, extension specialists, technical service providers, irrigation industry companies, agricultural lenders, commodity groups, and other irrigation stakeholders.

Since 2017, the competition results and insights into efficient and profitable crop production have been shared with stakeholders across the United States and abroad, primarily through extension. TAPS field days, tours, and banquets are popular and attended by thousands.[17]

Methods

Throughout the growing season, TAPS competitors control the following management choices: (1) crop insurance selection, (2) planting density, (3) hybrid selection, (4) marketing, (5) irrigation scheduling and amount, and (6) nitrogen fertilizer timing, amount, and method. Each team

TAPS is supported by irrigation stakeholders representing local, state, and federal public and private organizations and institutions, including a wide range of technology service providers. Image courtesy of UNL-TAPS.

[17] Access to competition reports, videos, newsletters, and other content from the Nebraska-led program is available at https://taps.unl.edu/. For more information about Oklahoma State's TAPS program, contact the Oklahoma Panhandle Research and Extension Center's Sumit Sharma by email at sumit.sharma@okstate.edu.

is randomly assigned three experiment-sized plots on the competition fields managed by university personnel to implement team decisions submitted online. Yields and costs for each team are captured using modified university extension crop production budgets and amplified to represent full-scale operations of a few thousand acres. This magnification enables teams to develop grain marketing strategies and consider the impacts that even small decisions have for a full-scale operation's productivity and profitability.

One goal of TAPS is to enable producers to test decision-support technologies to find out which seem to be most useful and intuitive. This approach helps sidestep financial and other real or perceived risks associated with trying and trusting technologies, which often impede their adoption. To this end, TAPS contestants are provided access to multiple kinds of technologies, along with data and research results to support their management decisions. Competitors are also encouraged to try management methods, marketing strategies and other approaches they determine can boost financial, productivity, and/or conservation outcomes that might be appropriate for their operations.

Results

Multiple years of TAPS competitions have generated a unique and extensive dataset that can be mined for insights into operational performance of water conservation technologies and practices, including interactions of hybrid performance with water and nitrogen timing and application amounts, and how trust and use in technology translate into production outcomes. The data gathered represent a special set of crowd-sourced knowledge, given that each set of decisions by teams is unique and has been applied on randomized, replicated plots.

Takeaways:

- Competitors do not need to be the best at marketing or the most input-use efficient. Rather, managers that are balanced and relatively strong in all areas tend to be the most profitable, and they do not need the highest yields to achieve that result. Just as in real life, the competitions show a wide range of production management approaches that are productive, profitable, and input-use efficient. The data collected enables researchers to tease out why different management approaches are successful in different weather years.
- Contestants are provided online access to data streams and outputs from some of the newest commercially available technologies, including soil water sensors, plant and canopy sensors, aerial/satellite imagery, field-level weather stations, irrigation and nitrogen management models, soil, and plant analyses, scouting reports, marketing, and tools. It is worth noting that competitors who could be hundreds of miles away and never physically visit the competition fields are able to navigate and use this information effectively when they have, in many cases, never used these kinds of tools and data before.

TAPS provides participants with data, tools, and other information to support their decisions throughout the growing season. Image courtesy of UNL-TAPS.

Future Work

Aside from competition reports that are widely shared, the research-grade data gathered through TAPS has barely been tapped. A multi-state team including Colorado collaborators is preparing to work in 2022-23 on organizing and analyzing the multi-year TAPS dataset to clarify and identify:

1. The operational and financial benefits and challenges of water conservation technologies and management practices
2. The influence or contribution of management practices (irrigation, nitrogen, and hybrid selection) on water-use benchmarks and greenhouse gas calculations with respect to crop type, water availability, risk tolerance, and energy costs of pumping and nitrogen manufacture
3. The gap and outcomes between best management practices and producers' decision making
4. The combined and interrelated roles and responsibilities of industry and the irrigation sector at large, land grant institutions, and government agencies in driving adoption and understanding of the short- and long-term economic and environmental benefits of water conservation and profitable practices

In a separate but related effort, a team in Colorado will work with other TAPS teams during 2022 to develop a Colorado TAPS program hosted at Colorado State University, supported through a Colorado Water Conservation Board Water Plan grant awarded in 2021.

CASE STUDY

Colorado Master Irrigator

Amy Kremen
Colorado State University, Irrigation Innovation Consortium

Introduction

Colorado Master Irrigator is a non-profit organization established in 2019 to deliver courses that help agricultural irrigators in the Republican River Basin and San Luis Valley improve water and energy conservation as well as irrigation efficiency. The curriculum is designed to be interactive, encourage peer-to-peer exchange, and cover the areas of greatest interest and need of participants. Though a growing number of advanced irrigation management tools, technologies, best-practice recommendations and guidance are available through university extension and technical service providers, adoption of these remains modest. Interrelated factors contribute to this gap. For example, every operation is different (soil types, access to water, organizational management, access to capital, risk tolerance), and determining the potential benefits (water, labor, other savings) of making changes or upgrades can be difficult to discern. Producers' knowledge of soil water holding capacity or agronomy varies widely, along with their trust or experience in irrigation scheduling or soil moisture probes to inform when and how much to irrigate.

The costs (time, effort, money) of making irrigation system upgrades or changing field management practices to target and time water applications dynamically based on crop water needs might not be supported by family members, consultants, lenders, or incentive programs. Given the inefficiencies inherent in aging irrigation systems, many producers might be overwatering crops, particularly in normal-to-wet years, in ways that do not improve productivity. Impacts include spending unnecessary energy on pumping and potentially leaching valuable nutrients below the root zone, even as groundwater quality and quantity decline and regulatory pressures to improve practices increase.

Inthis context, Colorado Master Irrigator provides comprehensive, in-depth coverage of science- and practice-based topics in a manner that helps producers regardless of their level of knowledge, experience, and methods. The program equips graduates with a peer network and incentives to assist their efforts to manage water in their operations. The goal is to support incremental changes and upgrades that result in significant water and energy savings for the state, while sustaining agricultural productivity and profitability. Over time, the impacts should include:

- slowing or limiting permanent dry-up of irrigated acres
- addressing the gap between "future water needs and available water provisions" identified for the South Platte Basin
- supporting compliance with interstate water compact requirements[18]
- sustaining confined and unconfined aquifers in accordance with Senate Bill 04-222
- operating within the State Engineer's new Rules and Regulations for the San Luis Valley identified in the Rio Grande Basin Implementation Plan[19]

Methods

The Republican River Basin and San Luis Valley chapters of Colorado Master Irrigator are guided by local advisory committees of producers, staff and extension based at CSU; groundwater management district leaders; technical service providers, state, and federal agency staff; and others. The committees work with their local coordinator to determine the year's curriculum and invite speakers with extensive practice- and science-based understanding of their topics, who are charged with engaging the class in discussion about the pros, cons, costs and potential benefits of different tools, practices, and approaches. Each course is limited to 25 participants and takes place over four days during the winter months.

Results

To date, nearly 100 individuals involved in managing 75,000-100,000 irrigated acres in the state have graduated from Colorado Master Irrigator. Two classes of students graduated in 2020 and 2022 in the Republican River Basin (2021 was skipped due to the pandemic), and two classes were held in San Luis Valley's inaugural year in early 2022 due to high levels of interest. In both regions, the course primarily attracts producers that raise major commodity crops (corn, alfalfa, dry beans, potatoes, wheat, etc.). Notably, most Colorado Master Irrigator participants are young (aged 20-45), representing

[18] CWP 6.2, 6.4, 6.5.1, 6.5.2; SPBR BIP 1.9.1 measurable outcomes 1-4, 4.6.2, 5.5.3, 5.4.4, SPBR 5.4

[19] CWP 6.2, 6.4, 6.5.1, 6.5.2; RG BIP 3.0 measurable outcomes 1-4, 4.6.2, 5.5.3, 5.4.4, RG BIP 3.3


2020 Colorado Master Irrigator Graduates, Republican River Basin. Photo by Hannah Moshay

the state's future agricultural leadership. This cohort will steward a major swath of the state's soil, water and energy resources while contending with challenges of water quality and quantity, expensive land and equipment costs, precipitation, and drought due to climate change, and regulatory pressures.

Colorado Master Irrigator participants provide information through intake, mid-course, and exit surveys about their irrigation systems and farm management (e.g., age of irrigation systems and audit status, how many wells and their capacity, crop rotation, use of irrigation management technologies) and about themselves (age, advanced irrigation management interests and motivations/goals related to participating in the program). As part of weekly homework, each participant defines a goal or goals for a field or well, or for their operation related to improving water or energy efficiency and/or conservation. Graduates are also invited to respond to an annual end-of-growing season survey for three years after they graduate, to share progress on their goals and how they use information or connections gained through participating in the program. Together, this data provides insight and understanding about which tools, practices and programs producers are willing to try and are succeeding with – information that is used to refine the master irrigator program curriculum each year and help inform groundwater management districts, NRCS, and state-level water-related programs, agencies, and others.

For their time in the classroom, and if they complete each annual end-of-season survey, each graduate is eligible to receive a participation stipend of $2,000, thanks to a grant from the Colorado Water Conservation Board. Colorado Master Irrigator works with its advisory committee, local sponsors, and state and federal programs to provide

Republican River program	San Luis Valley program
Local hydrology/interstate compact history	Changing hydrology
Soils 101 and residue management	Compact compliance
Regional economics of water conservation	Deep dive into soil health
Irrigation scheduling and weather forecasts	Energy audits
Telemetry	New CRP/NRCS programs
Variable rate and frequency applications	Who's who to help navigate agricultural resources
Irrigation application uniformity	Variable-frequency drives
Maintaining/optimizing well performance	Water budgets
Working with limited-capacity wells	Water supply trends
Using aerial imagery (UAS, Satellite)	Augmentation
Grazing cover crops	Deficit irrigation
Conservation-oriented incentives	Irrigation application efficiency
Well-retirement options	Managing drought/dry production conditions

Table 1: 2022 Colorado Master Irrigator program topics.

$2000 Participant stipends

- $1250 awarded at the end of 2022 Colorado Master Irrigator 4-day program
- $250 for water use/practices reported in 2022, 2023 and 2024

NRCS Targeted Conservation Program
priority ranking when graduates apply for EQIP financial support for approved irrigation water management and soil management plans

Energy audits
(five total, sponsored by local energy co-ops)

- One KC Electric Customer
- One YW Electric Customer
- One Highline Customer
- Two Tri-State

Phytech Package discount (plant sensors)

- 25% discount offered on one field

AquaSpy Kit Discounts (soil moisture sensors)

- Up to $250 off kit purchase

Simplot Grower Solutions

- Four, one-year subscriptions to SmartFarm program

Table 2: Colorado Master Irrigator Republican River Basin 2022 program graduate incentives.

additional incentives, discounts, and opportunities to try tools and subscription programs that provide irrigation decision support and guide producers to keep their systems performing optimally (Table 3).

Future Work

In 2021, with a new chapter in the San Luis Valley, Colorado Master Irrigator began to engage in collaborative, state-wide conversation involving producers, groundwater management district leaders, and state and federal agency staff focused on identifying ways to equip more producers with knowledge, connections, and funding to advance water management and increase conservation and water and energy efficiency. To support ongoing program development and ensure its long-term future, a Colorado Water Conservation Board Water Plan grant was secured to support a state-wide program coordinator and employ a grant writer who will work to establish financial incentives that encourage Colorado Master Irrigator graduates to improve irrigation systems and management on their operations.

As part of this expansion, Colorado Master Irrigator will act as a fiscal agent to support the distribution of grants and funding that may become available from state and other sources to support local groundwater management districts and producers engaged and investing in efforts to reduce consumptive water use and improve irrigation systems and management. Local Colorado Master Irrigator program coordinators and the program's Grant/Funding Coordinator will help draft grant applications and procure reimbursements to support on-farm implementation of conservation-oriented tools and strategies, along with program support to help districts encourage and track progress towards defined conservation targets and goals. This effort has support from Irrigation Innovation Consortium staff based at Colorado State University and CSU Extension staff, regional program advisory committees, and local and regional groundwater management entities.

Discussions stemming from Colorado Master Irrigator, led by the Plains GroundWater Management District, have led the state's Groundwater Commission and Division of Water Resources to consider whether state-level rule changes or other approaches can be used to encourage and support voluntary conservation and efficiency-oriented irrigation management. These are sometimes inhibited due to fear of potential "use it or lose it" consequences for permit holders.[20]

Master Irrigator is modeled on a program launched in the Texas Panhandle in 2016. Inspired and coached by that program, led by the North Plains Groundwater Conservation District, Colorado Master Irrigator has in turn helped guide and support the launch of an Oklahoma Master Irrigator program. These programs are part of a broader multistate group that stretches from California to the Delta region that support programming and local, state, and federal (NRCS) staff involved in advances in irrigation management in groundwater and agriculture-dependent regions.

[20]Case No. 20GW12

Open-source, Satellite-based Evapotranspiration Data to Advance Collaboration and Climate Resilience in the Western U.S.

Robyn Grimm, Ronna Kelly
Environmental Defense Fund, OpenET

Introduction

As farmers and water managers face shrinking water supplies amid droughts in the western US, precise measurement and efficient water use are more important than ever to sustain people, ecosystems, and agricultural economies.

Communities in the western US pay close attention to precipitation – rain and snow being the largest component of the water cycle – to monitor how much water will be available. It is also important to understand how much water is being consumed or used, measured through evapotranspiration (ET). ET is the process by which water evaporates from the land surface and transpires from plants, and it is a key measure of water consumed by crops and other vegetation, which can be used by farmers and water managers to better track water used and water saved, for instance, when farmers change crops or invest in new technologies.

In the western US, ET from irrigated agricultural land accounts for most consumptive water use, ranging from 59% in Texas to 97% in Idaho, with an average of 80% of total water used by people in the region (Dieter et al., 2018). Developing innovative and effective water management strategies is difficult without accurate, consistent information about ET from agricultural lands.

ET data can improve water budgets, advance data-driven irrigation strategies to maximize the "crop per drop" and expand incentive-driven water conservation programs. However, accessing ET data is expensive and difficult. ET is consistently identified as a high-priority data gap or information need in assessments conducted for the US

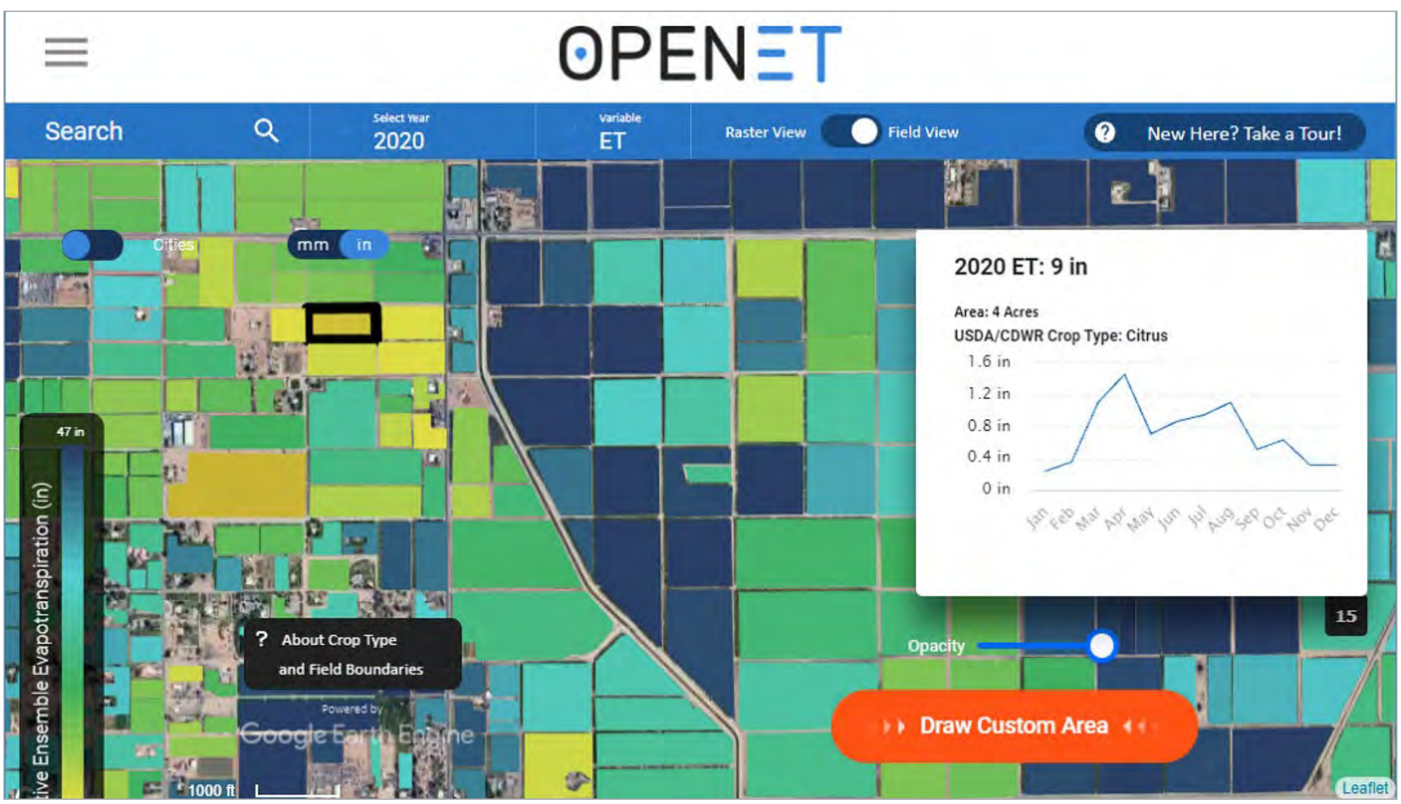

Figure 33: A screenshot of results from the OpenET Data Explorer for a four-acre field of citrus.

Figure 34: This map shows the locations and types of OpenET use cases. Additional information is available at https://openetdata.org/openet-use-cases/.

water resources management community (*Evaluation of Models and Tools for Assessing Groundwater Availability and Sustainability*, 2010; Jenkins, 2021, 2021; National Academies of Sciences, 2021).

OpenET is a nonprofit collaboration that aims to fill this gap by making satellite-based, scientifically rigorous ET data widely accessible to farmers, regulators, and policy makers, enabling better-informed water management and more resilient food systems. The OpenET team launched its online data platform in October 2021, making ET estimates from six established models accessible to the field scale in 17 western states (Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming).

The platform was developed through an unprecedented public-private collaboration involving six ET modeling teams from the US and Brazil, California State University-Monterey Bay, Desert Research Institute, Environmental Defense Fund, Google Earth, Habitat Seven, National Aeronautics and Space Administration (NASA), Stanford University, US Department of Agriculture (USDA), the US Geological Survey (USGS), Universidade Federal do Rio Grande do Sul, University of Idaho, University of Maryland, University of Nebraska-Lincoln, University of Wisconsin, and partners from the agriculture, water resource management and conservation communities. Support comes from a mix of philanthropic and public funding.

To define accuracy across different land cover types, the OpenET team completed the largest intercomparison study of ET data, which included ground-truthing the data with other tools. To demonstrate how OpenET can be used, the team worked with partners on use cases in several states. In California, OpenET is used by a San Joaquin Valley water district to comply with the Sustainable Groundwater Management Act and by farmers in Sacramento-San Joaquin Delta to simplify water use reporting. Oregon water agencies are exploring OpenET to develop budgets for groundwater basins across the state. A groundwater basin in arid eastern

Model Acronym	Model Name	Primary References
ALEXI/DisALEXI	**A**tmosphere-**L**and **Ex**change **I**nverse / **Dis**aggregation of the **A**tmosphere-**L**and **Ex**change **I**nverse	Anderson et al., 2007; Anderson et al., 2018;
eeMETRIC	Google **E**arth **E**ngine implementation of the **M**apping **E**vapo**tr**anspiration at high **R**esolution with **I**nternalized **C**alibration model	Allen et al., 2005; Allen et al., 2007; Allen et al., 2011
geeSEBAL	Google **E**arth **E**ngine implementation of the **S**urface **E**nergy **B**alance **A**lgorithm for **L**and	Bastiaanssen et al., 1998; Laipelt et al., 2021
PT-JPL	**P**riestley-**T**aylor **J**et **P**ropulsion **L**aboratory	Fisher et al., 2008
SIMS	**S**atellite **I**rrigation **M**anagement **S**upport	Melton et al., 2012; Pereira et al., 2020
SSEBop	**Op**erational **S**implified **S**urface **E**nergy **B**alance	Senay et al., 2013; Senay et al., 2018

Figure 35: Models currently included in OpenET.

Oregon is considering OpenET to inform local water management strategies, including the potential for water trading. In Arizona, the Salt River Project is using OpenET to improve its understanding of the connections between forest health, including forest thinning projects to prevent wildfire, and watershed health.

In Colorado, the OpenET platform is being used in a multiyear water conservation pilot project that involves several ranchers. In addition, the Bureau of Reclamation included OpenET in a comparison of satellite-based methods for measuring water consumption to determine which is most appropriate to use in its five-year report on water use and loss for the Upper Colorado River Basin states.

Methods

Advances in the remote sensing of ET have led to multiple approaches to field-scale ET mapping used for local and regional water resource management by US state and federal agencies. In 2017, the OpenET partners – led by NASA, the Desert Research Institute, EDF and Google Earth – came together to build on advances in ET modeling and cloud computing to develop an operational system to generate and distribute ET data at the field scale, using six established, satellite-based approaches for mapping ET.

Primary requirements for including a model in OpenET were its prior use by a state or federal agency, and participation by one or more members of the science team that originally developed the model. This approach – providing data from several models – is designed to inform practitioners about ET model agreement and disagreement, ensure data continuity, and take advantage of the strengths of different ET mapping methods across regions and land cover types.

OpenET relies on publicly available satellite, meteorology, crop type, topography, land use, and soil data as inputs to the ET models. Landsat is the primary satellite dataset used on the OpenET platform, where all models rely on Landsat satellite data to produce data at a spatial resolution of 30m × 30m, along with gridded weather

A panel of early OpenET adopters shares their experience at a user workshop held to solicit feedback from water managers and the agricultural community.

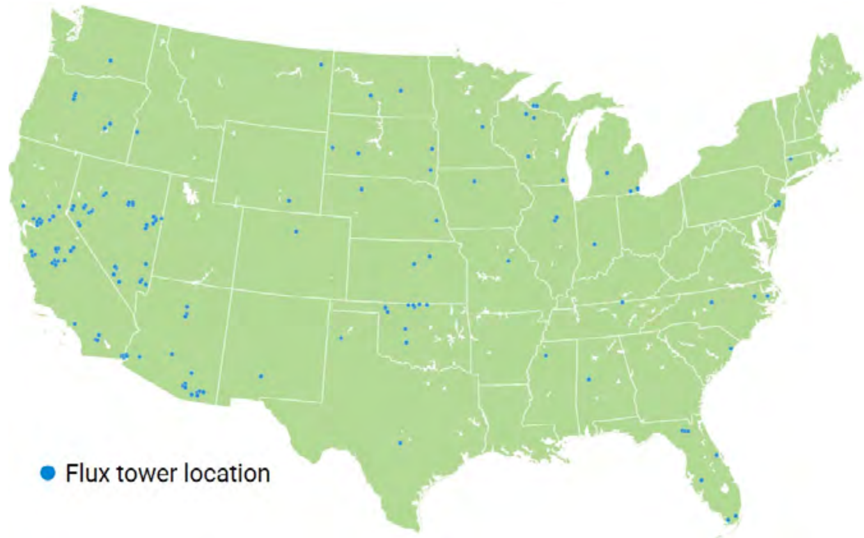

Figure 36: *Intercomparison and accuracy assessment.*

variables, including solar radiation, air temperature, humidity, and wind speed. The Landsat program, a joint effort of NASA and the USGS, provides the longest continuous space-based record of Earth's land surface in existence, dating back to 1972 for optical data and to 1982 for thermal data.

To ensure the platform meets the needs of users, the OpenET team held numerous workshops with water managers and members of the agricultural community to solicit feedback and develop use cases.

The team conducted an extensive intercomparison and accuracy assessment using ground measurements of ET from approximately 140 flux tower sites instrumented with open path eddy covariance systems and four precision weighing lysimeters. These stations are important because they provide in-situ estimates of ET for specific locations with known land use and vegetation types.

All the models were included in the intercomparison study to determine which provide the highest accuracy for different land cover types, regions, and seasons. We used the results of the intercomparison study to calculate a single "ensemble" value from the six models. A simple yet robust approach was chosen, where the single ensemble ET estimate is computed at each time step as the simple arithmetic average after outlier ET estimates are removed. However, to account for the small number of models, a minimum of four was always retained to calculate the single ensemble value. This approach still consistently eliminates outliers while taking advantage of an ensemble of models to improve the accuracy of ET estimates.

Results

The intercomparison study found that the ensemble ET estimate for croplands performed as well as or better than any individual model across most accuracy metrics, with a mean absolute error (MAE) for the growing season of 13.2% (80.3 mm), and a MAE value of 16.6% (15.6 mm) at monthly time steps. The mean bias error is less than 4% for both the growing season and monthly averages, indicating that many of the errors are random, and the overall bias in the OpenET ensemble values is minimal for croplands.

However, from the limited number of cropland in-situ flux stations located in very arid environments, it is evident that some models have a systematic low bias for smaller agricultural areas in arid regions, and the MAD outlier filtering approach does not filter outliers as desired due to the large range in model estimates. This could result in a low bias in the ensemble average. These areas are often indicated by fields with a wide range of ET estimates across the ensemble of ET models.

For natural land cover types, there is a bigger range in the accuracy metrics, but values for slope and bias errors are still reasonable for all land cover types. We did see a positive bias in evergreen and mixed forests, highlighting areas for future research and refinement.

Since the launch, more than 4,200 individual users signed up for free access to the OpenET platform, and the team has held outreach meetings with several groups in the water management community in California, Nevada, and Oregon. In addition to the use cases, we have received

Time Period	Slope	Mean Bias Error)	Mean Absolute Error	Root Mean Squared Error	r-squared	Mean flux tower ET
Water Year: 14 sites with 48 total water years	0.93	-71.6 mm (-7.0%)	91.3 mm (8.9%)	100.5 mm (9.8%)	0.90	1024 mm
Growing Season: 38 sites with 151 growing seasons	1.0	-10.1 mm (-1.7%)	80.3 mm (13.2%)	92.7 mm (15.2%)	0.88	609.5 mm
Monthly: 44 sites with 1,682 total months	0.95	-3.6 mm (-3.9%)	15.6 mm (16.6%)	20.0 mm (21.3%)	0.91	93.7 mm
Daily: 48 sites with 4,913 total Landsat overpass days	0.88	-0.3 mm (-7.4%)	0.8 mm (22.8%)	1. 1 mm (29.7%)	0.81	3.6 mm

Table 3: Accuracy summary for croplands for the OpenET ensemble ET value.

reports of OpenET being used for water management in Kansas and Idaho. In California, a second water district will use OpenET in a new pilot project of an online water accounting platform to help comply with the Sustainable Groundwater Management Act. In Arizona, OpenET is included in a USDA grant application led by Bridgestone Americas to support a crop-switching project that involves a low water use crop called guayule, which produces rubber.

Future Work

An important part of OpenET's mission is to continue advancing the underlying science. The goal is to continue improving the ensemble ET estimates and individual model accuracies over time. Efforts underway include more state and region-specific accuracy assessments and the production of additional training and educational resources for users.

In addition, OpenET will launch an application programming interface (API) later in 2022. The OpenET API will enable users to request data from OpenET via scripted queries and a graphical user interface and will facilitate integration with other applications for irrigation scheduling, farm management, water use reporting, and water management. We are already working on incorporating OpenET data into CropManage, a free online tool for water and nutrient management based on in-depth research and field studies conducted by the University of California Cooperative Extension.

In the future, we hope to expand the geographic coverage of OpenET. The Mississippi River Delta is the next region we expect to cover.

Conclusion

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Changes in hydrologic systems and the effects of climate change make water conservation and management crucial across Colorado and the western United States. Through the utilization of informant interviews with statewide water experts and a complementary stakeholder survey, the following themes were explored:

1. Identification by stakeholders of monitoring gaps in Colorado water management
2. Greatest challenges faced by Colorado water managers across basins and sectors
3. Perceptions of technology usage across Colorado and barriers to technology adoption

Considering these themes, qualitative analysis of informant feedback was completed along with statistical analysis of the survey. These illuminated statewide management gaps related to: (1) improved accuracy and accessibility of groundwater monitoring, (2) streamflow forecasting and improved understanding of Colorado snowpack, (3) increased transparency and ease of water rights transactions and trading, and (4) advanced methods of managing watershed health. Challenges faced by to Colorado managers varied by stakeholder basin and sector but were found to include: (1) population growth and development and the transition of water from agricultural to municipal use, (2) changing hydrology because of extended drought and climate change, and (3) impacts of an intensifying wildfire season on water quality and watershed health. A consistent theme when discussing these challenges was a desire to promote community and statewide collaboration in water management throughout Colorado.

There was strong agreement across sectors and basins that the best way to address these hurdles is to encourage sharing of ideas and solutions across the state. Finally, upon exploration of key considerations expressed by stakeholders for the adoption of novel management technologies, interviewees identified four factors as most important: cost, reliability, accessibility, and security. Stakeholders expressed hesitancy in adopting new technologies if they do not demonstrate resilience in Colorado's harsh climate and rugged conditions. It was also expressed that ease of use and installation encouraged new management measures. Some stakeholders discussed a wariness in some Colorado communities regarding the collection and sharing of data, emphasizing the need for transparency and security in water management solutions.

The Blue Lakes Reservoir near Breckenridge, Colorado, seen from above. Photo by Kat Demaree

These conclusions led to the research on and inclusion of case studies discussing the development and implementation of novel technologies to assist in the future of Colorado water management. Each tool was chosen based on its relevance to the themes that emerged in the informant interviews and survey. Further investigation is needed to develop tools for the digitization of water rights and transactions, however the examples from Deloitte and the Colorado Water Trust demonstrate potential opportunities.

The findings illustrate the importance of qualitative insight and community input into the problems and solutions facing present-day water managers, decision makers, and citizens of Colorado. This report can influence policy surrounding Colorado water management and fuel future research and innovation on these topics, and it is distinct in its effort to bring together the gaps and potential solutions for statewide water management issues, making it relevant across the western United States.

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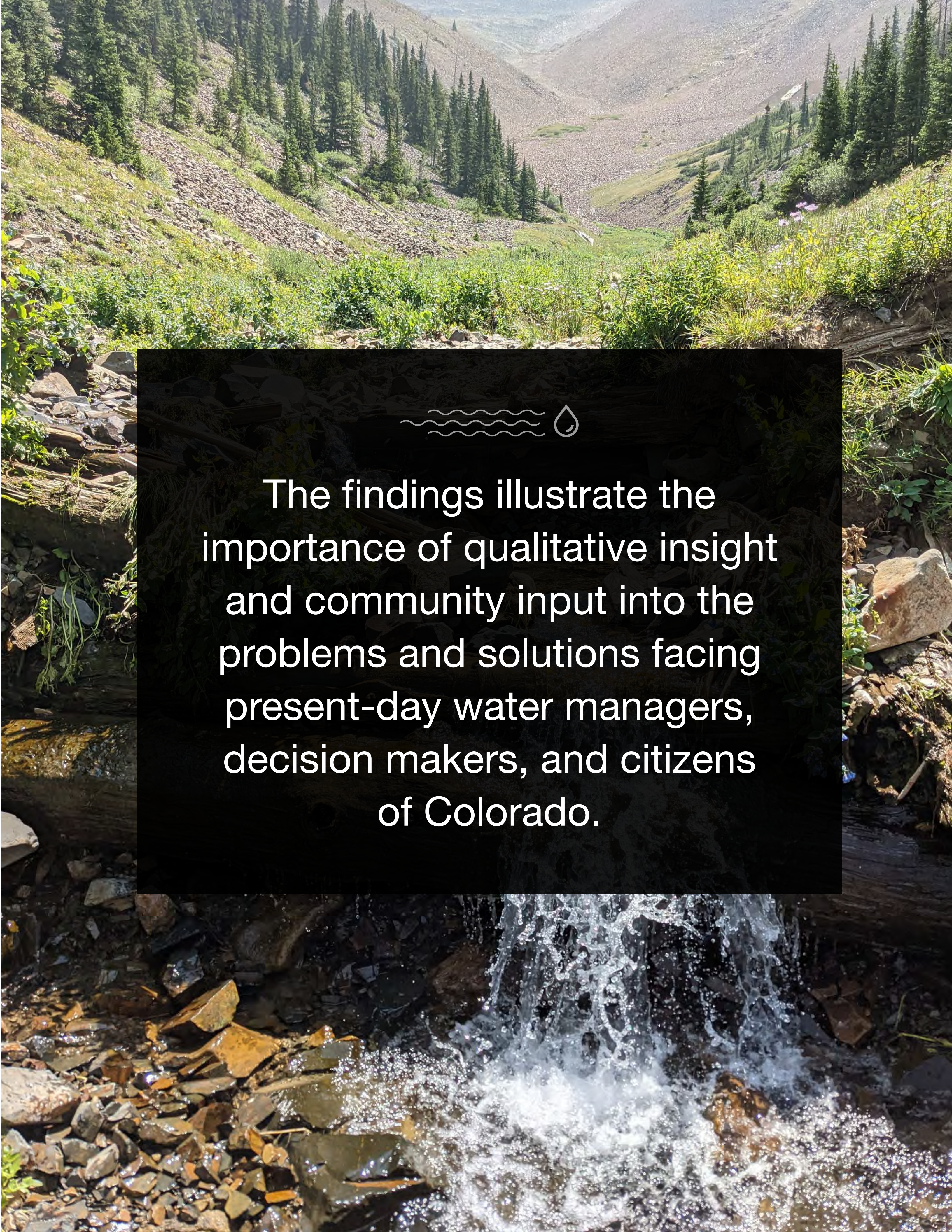

The findings illustrate the importance of qualitative insight and community input into the problems and solutions facing present-day water managers, decision makers, and citizens of Colorado.

Spring 2022

Emerging Technologies *to* Improve Water Resource Management *in* Colorado

Mortenson Center in Global Engineering
UNIVERSITY OF COLORADO **BOULDER**

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