on loba

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 elds for a total of 11 years conducting groundwater monitoring, groundwater ow 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

Federal of cials 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

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

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

highlighting basin-speci c 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 bene ts of more ef cient irrigation systems. Several studies have explored the impact of drought on farmers and demonstrated how drought experience in uences 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 aridi cation’ (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 scienti c efforts to improve management practices and strategies are areas of increasing focus, prompted by recent droughts of record. Improvements in irrigation ef ciency 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 elds. 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

declining water levels at Lake Powell and Lake Mead have resulted in signi cant 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 fer 2022).1bi(. moDl)]TJ EMC /P <</Lang (en-US)/MCID 691 >>B70tl <<vpoMimlleges

of nominal classi cations. 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

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 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 gures 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 nd 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.

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

Metrics

Additionally, the survey tool investigated water monitoring metrics and data gaps in Colorado water. A prede ned 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 ve 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 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 Satis ed”, “Somewhat Satis ed”, “Somewhat Unsatis ed”, or “Highly Unsatis ed”. Each rating was given an associated

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 identi ed 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

What are the greatest barriers to implementing a technology?

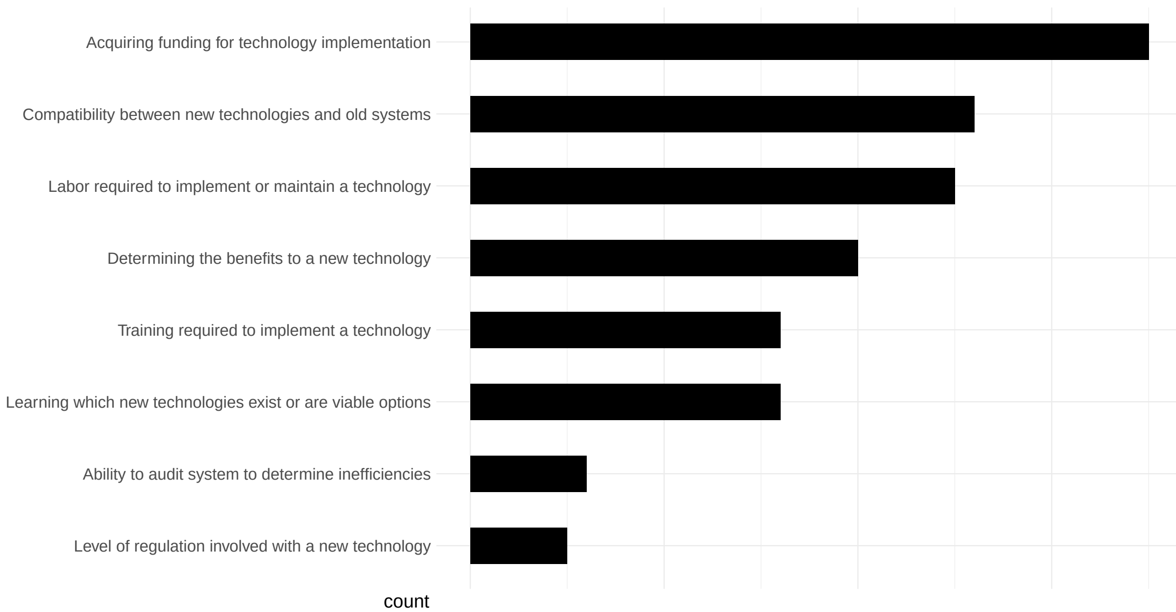
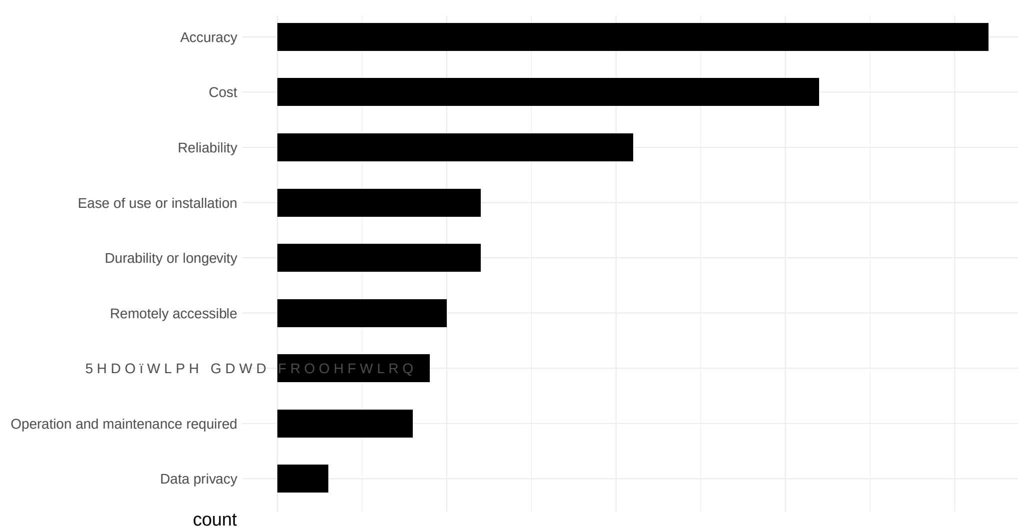


Figure 14: Factors and barriers to technology adoption reported as the total number of times each item was selected. Respondents were asked to select as many items as were applicable. Top panel: Frequency of total responses for each potential barrier to technology implementation. Bottom panel: Frequency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

Which factors are most important when choosing 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, 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 identi ed across Colorado:

- Water availability from snowpack and stream ow prediction
- Ease of data access and understanding of water rights and transactions
- Monitoring groundwater and subsurface soil moisture
- Impacts of wild re 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 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 rBasins, primarilSfT/MCr

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 con ned 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 de ned 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 uidity, transparency, and effectiveness in water transactions (Richter, 2016).

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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 stream flow 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.

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 ef ciency.

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 good management, bene ts for regulators also exist, as transactions will become more ef cient 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 ef ciency 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 bene ts to hardware sensors: quality control of water and chemical levels, quantity measurements, identi cation of waste points (leaks, non-revenue water), monitoring wear/tear or condition of equipment, etc. These bene ts 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 bene ts to water users over time are likely to outweigh these, given the alternative is less data or unreliable, manual readings.

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 ooding 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 stream ow 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 s ObP <u44der in the snpack)nt acroslarge rienve[(bioonaost)]TJ EMC /P << ewater sensorcouploved witant

The combination of near-real- or real-time data inputs with software designed to encourage more sustainable water use has many bene ts. 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.

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 bene ts from such work may outweigh the initial regulatory burden. Through improvements in ef ciency, transparency and security, water users and the state may see the bene ts 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.

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.

Case Study Legend

Figure 19: Visualization of water accounting data.

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:

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

Division 2 accounting speci es that 22.2 CFS was native stream ow 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 speci c 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 ows 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 ef cient 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

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 speci c treatments.

Methods

Timely, high-resolution, broad-area aerial imagery is critical to enabling environmental analysis and effective deployment of watershed treatment methodologies. Aerial

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

Aridi cation in the western United States is jeopardizing water security and drastically increasing water stress for communities and agricultural producers, while incentivizing the im25ementation ofm the im32ementation ofbeultang aMG(Resour)n Solano SuJ ainabilncrGSA).ID 2811 >>BDC 0.428 en-U

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 tting coef cients to individual predictor variables (e.g., stream ow, evapotranspiration, soil moisture, temperature, precipitation, estimated yield from in-situ sensors, and groundwater level) with groundwater abstraction from groundwater abstraction was veri ed with observed measurements fromactie 0.42e8.120n.2 (ounab. The skill of)]TJ EMC /P <</Lang (en-US)/MCID 2913 >>BDC T* [(each pr)18 (location of groundwater abstraction and make it possible to consider h.2 differinces in aquifer medium (i.e., sand versus loam), differinces in borehole scriened interval ipiths, and differinces in borehole use (i.e., agriculture versus domestic) can be used to select a more accurate groundwater abstraction predictor variable.

Figure 25: Data obta2e8d from Solano County groundwater project.

Results

groundwater abstraction, while at high ows (>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 ef cient energy use at higher yields. Since Well 11 typically experienced ows 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 spbtiple-13o expand n111 ang5

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 lters, 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 eld 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

CASE
STUDY

Improved Snowpack Monitoring with Airborne Snow Observatories

Jeffrey Deems
Airborne Snow Observatories, Inc.

Taylor Winchell
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 quanti ed, 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

CASE
STUDY

Colorado Ungauged Stream ow Prediction

Stephanie Kampf, Abb

Figure 32: Predicted vs. observed mean annual stream ow 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 stream ow 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 in uence on stream ow, and future monitoring locations could be selected more strategically

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

CASE
STUDY

Colorado Master Irrigator

Amy Kremen
Colorado State University, Irrigation Innovation Consortium

Introduction

Colorado Master Irrigator is a non-pro t 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 ef ciency. 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 bene ts (water, labor, other savings) of making changes or upgrades can be dif cult 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 eld 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 inef ciencies 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, management, aceeds miinevel ofn 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 de nes a goal or goals for a eld or well, or for their operation related to improving water or energy ef ciency 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 re ne 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 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

CASE STUDY

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 ef cient 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 dif cult 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 dif cult. ET is consistently identi ed 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 eld of citrus.

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,

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 wild re, 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 ve-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 eld-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 eld 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.

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

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. Identi cation 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

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The ndings 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.

Mortenson