

Real-time irrigation diversion data delivery can benefit adaptive capacity in communal irrigation systems

Lily M. Conrad¹  | Alexander G. Fernald¹  | Marshall A. Taylor²  | Steven J. Guldan³ | Carlos G. Ochoa⁴ 

¹Water Resources Research Institute, New Mexico State University, Las Cruces, New Mexico, USA

²Department of Sociology, New Mexico State University, Las Cruces, New Mexico, USA

³Sustainable Agriculture Science Center at Alcalde, New Mexico State University, Alcalde, New Mexico, USA

⁴Ecohydrology Laboratory, College of Agricultural Sciences, Oregon State University, Oregon, Corvallis, USA

Correspondence

Lily M. Conrad, Water Resources Research Institute, New Mexico State University, Las Cruces, NM, USA.

Email: lily.conrad@deq.idaho.gov

Funding information

College of Agricultural, Consumer and Environmental Sciences, New Mexico State University; New Mexico Legislature, Grant/Award Number: NMWRR12019-2020 and NMWRR12021

Abstract

There is a need to support applied, community-relevant hydrologic research within changing climate, population, and socioeconomic conditions to better inform water policy and management. We hypothesized that providing a rural agricultural community in a semiarid valley with the necessary monitoring tool to meet local water management needs would increase adaptive capacity within the context of long-term drought. Through a community science approach, researchers installed a telemetry monitoring system at participating acequia irrigation diversions that remotely sent water data to a web interface every 15 min. Two surveys distributed before and after web interface access targeted seven adaptive capacity indicators. After the first season of improved data accessibility, the following adaptive capacity indicators significantly increased: information diversity, cognitive social capital, leadership, and proactivity. Rather than focusing on the water savings aspect of real-time monitoring, this paper summarizes a novel water resources study that assessed the social impact of real-time irrigation water delivery monitoring on adaptive capacity. This study suggests that bridging the gap between community need and hydrologic research through community science, sociologic analysis, and stakeholder engagement provides significant benefits for communities facing water management challenges, further supporting problem-driven water resources research.

KEYWORDS

irrigation, drought, monitoring, public participation, water use, acequias

1 | INTRODUCTION

Many basins in the western United States rely on adequate winter snowpack and the slow release of water as temperatures warm to sustain streamflow and meet demand through the dry summer season (Mote et al., 2018). Volume of streamflow is especially vulnerable in these snow-dominated regions due to long-term changes in precipitation and temperature, which impact maximum snow accumulation and runoff timing (Barnett et al., 2005; Clow, 2010). Since water year 1984, winter temperatures have increased significantly, and winter precipitation, maximum snow water equivalent, and snow covered days per decade decreased significantly in the Rio Grande basin (Harpold et al., 2012). In

Research Impact Statement

Real-time web-based monitoring of irrigation diversions implemented through a community science approach helped traditional irrigation communities foster adaptive capacity in long-term drought.

the Upper Rio Grande basin, climate change impacts are projected to decrease snowpack accumulation and create a shift to earlier snowmelt runoff, leaving later portions of the runoff season drier (Chavarria & Gutzler, 2018; Llewellyn & Vaddey, 2013).

The growing awareness of the need to proactively address and mitigate the impacts of climate change resulted in a demand for adaptive capacity assessments at household, community, regional, and national levels (Agrawal, 2010; Fernández-Giménez et al., 2015); yet, current assessment methods are not standardized (Engle, 2011). As a stepping stone of resilience, adaptive capacity is the ability to experiment, learn, and test novel management strategies in response to change, disturbance, or challenges (Armitage, 2005; Eakin et al., 2011; Engle, 2011; Smit & Wandel, 2006) where higher levels of adaptive capacity enable more equitable and flexible water allocation (Fleck, 2016). Despite recent hydro-centric adaptive capacity studies (Douglass-Gallagher & Stuart, 2019; Engle, 2013; Thapa et al., 2016; Varis et al., 2019), measures and characterizations of adaptive capacity vary (i.e., surveys, case studies, statistical modeling, ethnography), are context specific, and findings are not straightforwardly generalizable between different contexts (Engle, 2011). A possible way forward could be first measuring and then characterizing adaptive capacity. Measuring adaptive capacity highlights which management and governance approaches are associated with greater adaptive capacity. Measurement findings inform the subsequent characterization which highlights systems that are or are not implementing approaches that facilitate adaptive capacity (Engle, 2011).

Many researchers argue that the complex nature and variability of water management requires future research that integrates issues relevant to stakeholders to address gaps in knowledge surrounding water management decisions. Appropriately managing water resources at basin or regional scales requires an accurate understanding of user needs, trends in the environment, and the effects of management on water availability (Ellison et al., 2019). Lacking and limited water availability data hinder our understanding of these critical considerations, as well as decision-making for risk assessment, resulting in a demand for more widespread spatial, temporal, and real-time data (Buytaert et al., 2014; Ellison et al., 2019; Paul et al., 2018). The provision of hydrologic data has a direct impact on livelihoods when the need persists and becomes socially relevant (Krueger et al., 2016). Involving stakeholders in water research and management is increasingly encouraged because it provides a platform of deliberation for equitable decisions through social learning, encourages the development of social capital, and legitimizes decisions (Carr, 2015). Buytaert et al. (2014) and Paul et al. (2018) provide a comprehensive overview of recent hydrologic research involving stakeholders but note several limitations, the most prominent one being that nonscientists are limited to gathering information and data rather than including their experiences in the cogeneration of actionable knowledge. Providing relevant, actionable knowledge to a community or population has positive, long-term benefits on water management and use, such as water conservation (Cominola et al., 2021), and assessing the benefits of the generation of actionable knowledge is an area that deserves more attention.

Interdisciplinary water resources research across hydrology and social sciences is gaining momentum but lacks clear integration methods. Seidl and Barthel (2017) surveyed practicing hydrologists on their opinions on incorporating social sciences and social factors into future research. Survey responses indicated that social sciences and humanities are partly or not well integrated into hydrologic research. Most respondents across public sectors (56%), private sectors (79%), and research and education (74%) recognize there is a need to facilitate better integration of social science and hydrologic research (Seidl & Barthel, 2017). Focusing future research objectives on collaborations between hydrology and social sciences will bridge the gap between contextual science and adaptive knowledge by encouraging polycentric governance, cultivating social learning, enabling adaptive management, increasing decision capacity, and building local resilience (Buytaert et al., 2016; Ellison et al., 2019; Gunda et al., 2018; Paul et al., 2018; Ricart et al., 2018; Wehn et al., 2018). Irrigation systems in arid regions are challenged by extended periods of drought and climate variability that have prompted collaborative and dynamic management approaches (Fernald et al., 2015; Guldan et al., 2013). *Acequias* are communal irrigation systems first introduced to the American southwest 200–400 years ago, adapting to environmental, social, governance, and economic challenges throughout the centuries (Gunda et al., 2018). *Acequias* serve as gravity-driven water delivery canals for irrigation purposes as well as local governing organizations in charge of self-organized water allocations (Sabie, 2014). The *mayordomo*, or ditch boss, is responsible for allocating water and overseeing the management of the *acequia*. A few commissioners, or elected officials as a president, secretary, and treasurer, oversee organizing meetings, determining fees, enforcing rules and regulations, resolving disputes, and supporting the *mayordomo*. The *mayordomo* and commissioners work together as the *acequia* leadership or leaders. Finally, *parciantes*, or irrigators, aggregate to form the *acequia* association.

Many *acequia* communities, especially communities dependent on snowmelt runoff, are experiencing challenges related to warming climate, water resource availability, water rights transfer, lack of storage capacity, development, and community structure (Guldan et al., 2013; Sabie et al., 2018). Historically, New Mexico housed up to 1927 active *acequias*, with approximately 640 remaining today (Sabie et al., 2018). More specifically, in the case of the Rio Hondo watershed near Taos, New Mexico, irrigators face increasing residential development, the

expansion of Taos Ski Valley, unpredictable or limited water supplies, warming temperatures, and reduced snow storage stressing current and future water resources (Fernald et al., 2015; Rodríguez, 1987). Water sharing agreements and allocations in acequia irrigation communities along the Rio Hondo are based on water data gathered irregularly by local water managers, resulting in controversy over water measurement and allocation. Increasing socioenvironmental complexity resulted in water managers expressing a need for more available and accessible data for acequia water management and irrigation delivery purposes.

The need to improve scientific understanding of social impacts on water management decisions and concerns (Haefner et al., 2018; Konar et al., 2019; Sanderson et al., 2017; Wesselink et al., 2017) requires an ideal research setting for combining hydrology and social sciences. With such a significant cultural tie to a flood-irrigated agricultural landscape, the communities within acequia systems exhibit complex social connections to local hydrologic phenomena and are an ideal setting for interdisciplinary research. Community commitment and acequia social networks have been linked to adaptive management and resilience in periods of low streamflow as well as high levels of adaptive capacity (Fernald et al., 2012; Gunda et al., 2018). Within each acequia, water allocations are based on community knowledge, a sense of mutualism, and additional reinforcement by water management traditions involving all stakeholders (Gunda et al., 2018). Therefore, water allocation decisions made through sharing agreements are symbolic of communal values and equity, merging themes across hydrology and social sciences.

Initiated in response to a water management need expressed by the Rio Hondo acequias, the main goal of this study was to assess the role of improved data accessibility on adaptive capacity. We hypothesized that increasing the accessibility and availability of objective water information for irrigation purposes would increase adaptive capacity within a rural agricultural community in a semiarid valley. Specific components of adaptive capacity we hypothesized would increase were the following: (1) natural capital, (2) information diversity, (3) knowledge exchange, (4) cognitive social capital, (5) structural social capital, (6) proactivity, (7) and leadership. Through a community science approach, we installed an acequia streamflow data monitoring system with telemetry capabilities and a web interface to meet irrigation water management needs for the Rio Hondo acequias. Community concerns and the coproduction of actionable knowledge drive community science instead of purely theoretical or academic research questions (Carr, 2004; Evans & Guariguata, 2008; Trimble & Berkes, 2013; Wiggins & Crowston, 2011). The acequia monitoring web interface provided a consolidation of real-time water data with simple graphics for participating acequias. This paper fills several gaps in the literature by conducting applied, problem-driven, community science research founded on the coproduction of actionable knowledge, integrating hydrology and social sciences, and providing standardizable and adaptable methods for adaptive capacity assessments.

2 | MATERIALS AND METHODS

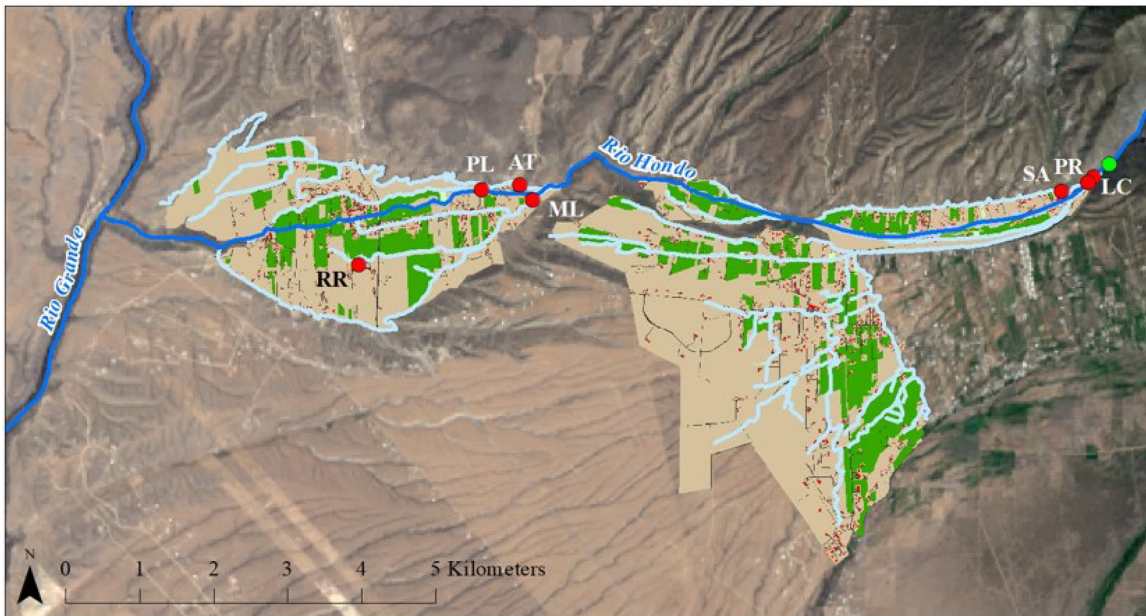
2.1 | Study area

We selected the Rio Hondo watershed as a representative study site due to the presence of an interconnected network of active acequias and community willingness to participate in the research. The Rio Hondo watershed drains an area of approximately 185 km² (Fleming et al., 2014) with an average elevation of 2200m above sea level (Sabie et al., 2018) in Taos County, northern New Mexico, United States (Figure 1). Snowmelt from the Sangre de Cristo Mountains serves as Rio Hondo's primary source of water and drains into the Rio Grande. Located in a semiarid steppe climate, annual precipitation is lower than potential evapotranspiration with hot, dry summers and cold winters. Most precipitation falls during the monsoon season (July–September) with an annual average of 305 mm in Taos, New Mexico. The primary settlements in the Rio Hondo watershed are Valdez and Arroyo Hondo. The Rio Hondo area of interest includes the three communities in the Rio Hondo acequia water sharing agreement: Valdez, Des Montes, and Arroyo Hondo. The Rio Hondo area of interest is comprised of 70% fallow fields, 22% irrigated pasture, 6% roads and structures, 2% riparian vegetation, and dispersed orchards (Cruz et al., 2019; Sabie et al., 2018) (Figure 1). In all, 11 acequias deliver water from the Rio Hondo to irrigate approximately 1161 ha (Fleming et al., 2014). Typical crops grown in the valley are pasture grasses (*Phleum pratense*, *Poa pratensis*, and various *Trifolium* spp.), alfalfa (*Medicago sativa*), fruit orchards (i.e., apple, plum, apricot), grains, and vegetables (Sabu, 2014).

2.2 | Telemetry monitoring system

We established a telemetry monitoring system with a web interface to serve as the nexus between hydrologic information and community water information needs. The telemetry monitoring system included six acequias which divert water from the Rio Hondo (Figure 1): La Cuchilla (LC), Acequia de los Prandos (PR), Acequia de San Antonio (SA), Madre del Llano (ML), Acequia de Atalaya (AT), and Acequia de la Plaza (PL). Each acequia has a streamflow gauging station located downstream of its head gate before any water diversion to crop fields originally constructed and installed for previous research initiatives in the watershed (Cruz et al., 2019) which determined the placement of our telemetry sites. Each gauging station already had a ramp flume (Intermountain Environmental, Inc., Logan, UT, USA), a stilling well, and a metal box for housing equipment. Monitoring equipment from Campbell Scientific, Inc. (CSI) (in Logan, UT, USA) included a pressure transducer model

(a)



(b)

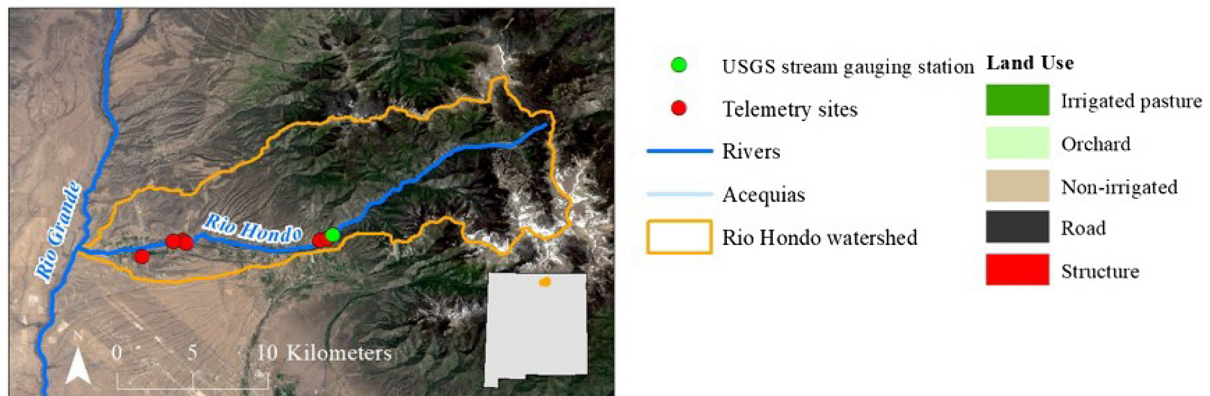


FIGURE 1 Overview maps of the study area showing (a) land use (Sabie et al., 2018) within the Rio Hondo area of interest, Acequia reaches, telemetry site locations, United States Geological Survey (USGS) stream gauging station and (b) monitoring site locations with respect to the entire Rio Hondo watershed in northern New Mexico (inset)

CS451, a conductivity probe model CS547A, and a CR800 data logger to collect streamflow data at each station. Telemetry capabilities enabled remote data transfer and communications at three sites (LC, PR, and SA) through cellular signal (CSI CELL210). At the remaining three sites (ML, AT, and PL), CSI RF451 radios sent information to a nearby relay station (RR). The relay station subsequently communicated the data through a nearby Wi-Fi source with a CSI NL240.

Each station recorded acequia water level, water temperature, and electrical conductivity data every 15 min. The data logger at each station converted stage to streamflow using the manufacturer's equations developed for the corresponding flume size. We verified streamflow values derived from the manufacturer equations with manual streamflow measurements once per week from May 2020 through October 2020 using a portable current meter (Model 2100; Swiffer Instruments, Inc., Seattle, WA, USA) and the velocity-area approach. Once enough flow measurement data were collected, we also developed more accurate, customized rating curves from the manual streamflow measurements for each site to use for future years of data collection and the web interface.

The data were then sent remotely to a web interface designed through CSI's Konect Global Data Service and maintained by New Mexico State University researchers that all interested acequia community members could access. The web interface only displayed data from the previous 15 days; however, stakeholders could be added to an email list to receive automated emails with all data collected by the telemetry monitoring system on a weekly basis. Through a series of community meetings and informal conversations, acequia leaders specified the need for a graphical display to show trends of all parameters over time, instantaneous streamflow values, and a table with daily averages for all parameters. Researchers engaged in conversation with the acequia community members, especially the acequia leaders or water managers, throughout the duration of the study to ensure the web interface display met water management needs.

2.3 | Adaptive capacity assessment

This section will outline the components of our adaptive capacity assessment. We distributed surveys to collect responses from stakeholders in the study area to quantify changes in adaptive capacity before and after improved data accessibility. First, we will present the sampling methodology to explain how we sampled from the population of interest. Second, we will detail the survey design and data analysis specifics.

2.3.1 | Sampling methodology

The population of interest was the Rio Hondo acequia community which spans from hobby gardeners to larger pasture grass operations. The sampling frame included all the acequia leaders and irrigators associated with a Rio Hondo acequia included in the telemetry monitoring. Survey distribution followed a snowball sampling approach. The snowball sampling method is a non-probabilistic approach that relies on social connections within the population to continue distributing the survey and does not generate a random sample (Mayagoitia et al., 2012). This was the best sampling approach for this research due to lack of public information, hesitance to release acequia member contact information, and community openness values. In addition to the inherent constraints and limitations of the snowball sampling approach, the survey distribution period coincided with the beginning of the Coronavirus (COVID-19) pandemic in the United States which limited the researcher's ability to establish contact with survey participants for recruitment and survey completion.

2.3.2 | Survey design and analysis

Researchers distributed two surveys to the Rio Hondo acequia community, the first before and the second after access to telemetry data (December 2019–February 2020 and November 2020–March 2021, respectively) to all possible acequia community contacts. The survey design followed a pretest–posttest design. The pre-test included perspectives from 12 acequia leaders and 18 irrigators ($n = 30$). The post-test included 13 acequia leaders and 17 irrigators ($n = 30$). Respondents could complete the surveys via mail, phone, and online using online survey software (Qualtrics XM Platform, Provo, UT and Seattle, WA, USA). The final paired analysis only included individuals who completed both the pre-test and post-test: 11 acequia leaders and 14 irrigators ($n = 25$).

The survey distributed to acequia community members involved quantitative questions utilizing either Likert, sliding, and binary scales depending survey question phrasing (Table S1) targeting the following adaptive capacity indicators: water management (natural capital), information diversity, knowledge exchange, cognitive social capital, structural social capital, proactivity, leadership, and income diversity (Cox et al., 2010; Fernández-Giménez et al., 2015; Thapa et al., 2016) which were the dependent variables of the analysis (Table 1). The final analysis excluded the income diversity indicator due to the small sample size, incomplete responses, and generally very little reliance on acequias as providing a source of income. The survey questions targeting each specific adaptive capacity indicator may be found in the Supporting Information (Table S1). In the Supporting Information (Table S1), we outline the questions posed in the survey instruments for each adaptive capacity indicator, the question structure (e.g., Likert, sliding, or binary), and the scoring assigned to each answer choice (e.g., if a survey respondent selected 3+ people for all the knowledge exchange sub-questions, 2 points \times 5 sub-questions = 10 points for the respondent's overall knowledge exchange score on the survey). Figure 2 depicts a visual timeline of events that occurred over the course of this study.

Our goal with the data analysis was two-pronged. First, we needed to determine if our selected adaptive capacity indicators could provide insight into and measures of the abstract realm of adaptive capacity. If this were the case, we would then need to quantify the change in the adaptive capacity indicators between pre- and post-web interface observations. To do this, data from the pre-test and post-test each underwent Monte Carlo paired sample t tests ($n = 25$).

Due to our snowball sampling survey data collection approach (i.e., not random sampling), we adopted a randomization inference model (Ludbrook & Dudley, 1998) and reported paired sample t tests with Monte Carlo permutation tests (Ernst, 2004; Manly, 2007; Taylor, 2020). Implementing paired sample t tests with asymptotically derived standard errors and population inference with these survey data would violate the random sampling assumption. Permutation tests are most ideal in the context of random assignment in experimental designs. This is not the case for the present study; however, as Manly notes (2007, p. 180), permutation tests with a data generating mechanism might also be used when neither random sampling nor random assignment can be assumed (see also Taylor, 2020, p. 312). For each paired t test, we first calculated the observed t statistic, randomly sampled one possible permutation of the pre-test adaptive capacity variable, ran the paired t test again, and then calculated the simulated t statistic. We repeated this random sampling (with replacement) of possible permutations for a total of 10,000 simulated t statistics. Since the permutations imposed a random relationship between the observed pre-test and post-test values on any given adaptive capacity indicator, the estimated p value is the probability of getting an observed (“true”) t statistic at least as large as we do under the null hypothesis that the ordering of adaptive capacity values in the pre-test is randomly associated with the ordering of adaptive

TABLE 1 A list of the adaptive capacity indicators targeted by the pre-test and post-test instruments and their descriptions. Please note that adaptive capacity may be delineated in many different ways and there may be overlapping characteristics as many elements are interrelated. We found this breakdown of adaptive capacity indicators and the associated characteristics to be specific enough to obtain necessary insights into adaptive capacity within our study community while broad enough not to trip on overlapping characteristics in our interpretations

Adaptive capacity indicator	Description and characteristics	References
Water management (natural capital)	Water quality or quantity Frequency and diversity of water management practices employed during low-flow	Fernández-Giménez et al. (2015); Thapa et al. (2016)
Information diversity	Enables individuals to learn about new ideas or technologies Diverse sources of information to stay informed	Berkes et al. (2003); Armitage (2005); Baival and Fernández-Giménez (2012); Keskitalo et al. (2011)
Knowledge exchange	The ability to sustain and transfer new and traditional knowledge with others	Berkes et al. (2003); Armitage (2005); Baival and Fernández-Giménez (2012); Keskitalo et al. (2011)
Cognitive social capital	Contributes to greater collective action by instilling trust, reciprocity, and cooperation among individuals Individual's trust and ease with other community members Shared codes, language, and narratives	Fernández-Giménez et al. (2015); Goodman et al. (1998); Nahapiet and Ghoshal (1998)
Structural social capital	Contributes to greater collective action by establishing bonding and linking networks among individuals Interactions within (horizontal) and across (vertical) social positions Network ties and configuration	Wagner and Fernandez-Gimenez (2008); Keskitalo et al. (2011); Brondizio et al. (2009); Nahapiet and Ghoshal (1998)
Proactivity	Ability to interact with others about issues before they worsen Serves as an indication of involvement with collective action (pursuit of shared goals over individual incentives) Used as a proxy for collective action in this and previous studies	Adger (2003); Armitage (2005); Fernández-Giménez et al. (2015)
Leadership	Local leadership able to effectively mobilize community members in response to challenges (e.g., disasters, conflicts)	Armitage (2005); Keskitalo et al. (2011); Thapa et al. (2016)
Income diversity	Enables alternative adaptation options	Fernández-Giménez et al. (2015); Thapa et al. (2016)

capacity values in the post-test under the null of a random data generating mechanism. We report 95% confidence intervals for the right-tailed p values ($\alpha = 0.05$).

In the case of longitudinal data such as these, either a paired t test or repeated-measures ANOVA would be appropriate. However, because our data have only two time points (i.e., pre-test, post-test), the paired t test t statistic and the repeated-measures ANOVA F statistic will provide identical results. The benefit of selecting the paired t test for this analysis is that the t statistic can vary between negative infinity and positive infinity while the F statistic is constrained between 0 and positive infinity, meaning directionality of the effect is easier to establish with the t test.

2.4 | Community engagement approach

Researchers from New Mexico State University—including authors of this paper—have been involved with long-term acequia research focused on hydrologic and social dynamics where community engagement was a key element. Because of this rich history of researchers collaborating with community members, there was already a strong foundation of trust and respect established before this project began. To initiate this study, our team of researchers met with community members individually and in small groups over the course of several months to learn about current challenges facing the Rio Hondo acequias. Following this, we synthesized our notes and created a research plan that would inform community water management based on the challenges described and benefit community science and adaptive capacity research. We then came back to the community and presented our research plan and proposed telemetry sites to the acequia leadership to receive feedback, gauge interest, and discuss feasibility. Thus began this project (Figure 2).

Our team of researchers maintained very close communication with community members throughout the duration of our research. Examples of this included but were not limited to: sending emails and making calls with major updates or issues with the telemetry monitoring

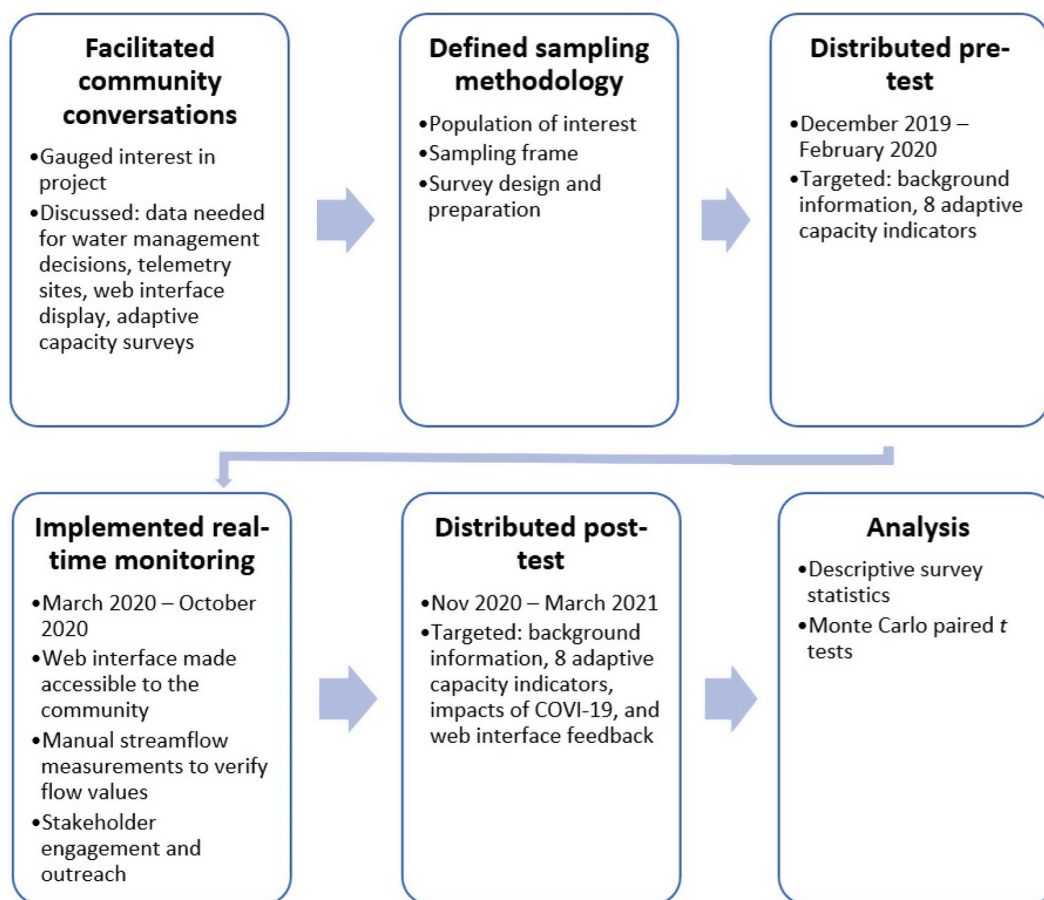


FIGURE 2 A timeline of events that occurred over the course of this study from conceptual community conversations, survey distribution, operationalizing the web interface, and to the final analyses

system, inviting community members into the field to show them the equipment and explain the connections in person, asking the community for help with reaching more people to engage with about the research and monitoring efforts, engaging with community members either face-to-face or over the phone to ask for web interface feedback and satisfaction over the course of the irrigation season. We found that honesty, transparency, and reliable lines of communication were critical for community engagement over the course of our study. The telemetry monitoring network installed for this project is expected to be a long-term resource for the community to better adapt to changing streamflow regimes and for researchers to better understand climate change impacts in the region.

3 | RESULTS

3.1 | Acequia monitoring web interface

For each participating acequia, water managers and users could access the web interface to view graphical, instantaneous, and tabular displays of local water data (Figure 3). Researchers worked closely with community members to design the web interface display and adjusted the display throughout the season as necessary. From post-test feedback of the web interface, 72% of the surveyed individuals were aware of the web interface as a tool, whereas 28% were unaware of the newly implemented tool. Of the individuals who checked the web interface at least once over the irrigation season, 76% of the respondents reported the tool was very to extremely helpful (Figure 4a). Survey respondents (31%) reported the web interface's ability to provide more convenient access to water data as the most helpful attribute (Figure 4b). In addition, the web interface provided more reliable and transparent information, facilitated conversation and collaboration within and between acequias, and allowed for more efficient water allocation and sharing adjustments between acequias (Figure 4b). Overwhelming respondent interest (92%) in continuing this or a similar web-based monitoring tool (Figure 5) further reflects the successful implementation of this web interface for the Rio Hondo irrigators.

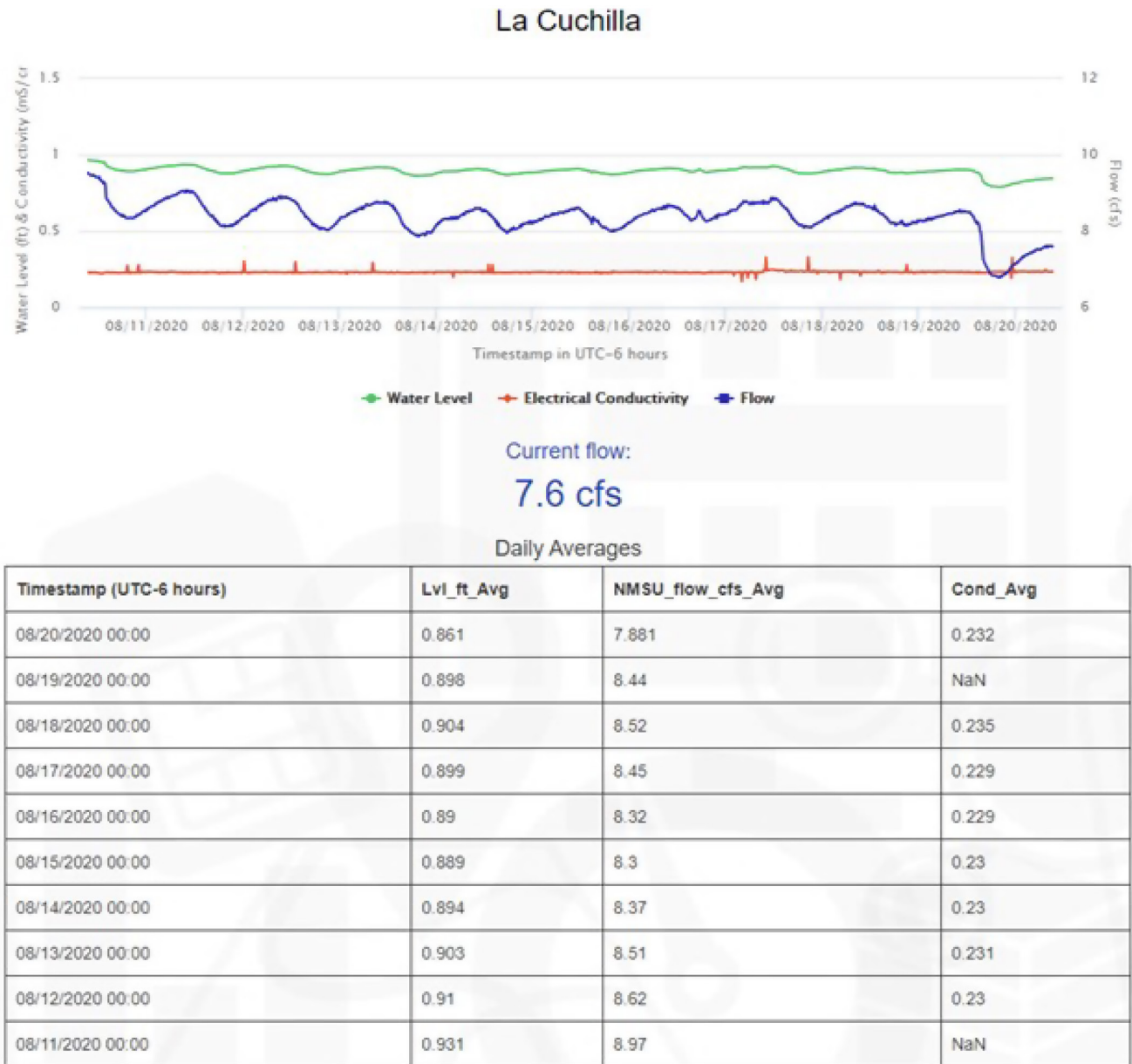


FIGURE 3 This is an example of the water data displayed for each acequia on the web interface and the information community members could view. In this case, La Cuchilla on August 20, 2020. The graphical display visually shows trends of water level (ft), electrical conductivity (mS/cm), and streamflow (cfs) over the previous 10 days. The current flow value in the middle, 7.6 cfs (0.2 m³/s), is the most recent streamflow record which continually updates every 15 min. Finally, the table displays daily averages of stage (Lvl_ft_avg), streamflow (NMSU_flow_cfs_Avg), and electrical conductivity (Cond_Avg) over the past 10 days. This display repeats for each of the six telemetry sites. Community input determined the stage and streamflow units, preferred graphical and tabular displays, and orientation. For international readers, stage values in feet can be divided by 3.281 to convert to meters and streamflow values in cubic feet per second can be divided by 35.315 to convert to cubic meters per second.

3.2 | Adaptive capacity assessment

After one irrigation season of access to real-time irrigation diversion data, four adaptive capacity indicators showed a statistically significant increase ($\alpha = 0.05$) (Table 2).

Information diversity (with a range of 0–5) showed a pre-test mean of 3.40 and a post-test mean of 4.60 ($p = 0.0022$). Cognitive social capital (with a range of 0–26) had a pre-test mean of 13.95 and a post-test mean of 14.86 ($p = 0.0177$). Proactivity (with a range of 0–5) exhibited a pre-test mean of 3.24 and a post-test mean of 3.44 ($p = 0.0004$). Leadership (with a range of 0–16) revealed a pre-test mean of 11.44 and a post-test mean of 13.04 ($p = 0.0070$). These results support our second, fourth, sixth, and seventh hypotheses that information diversity,

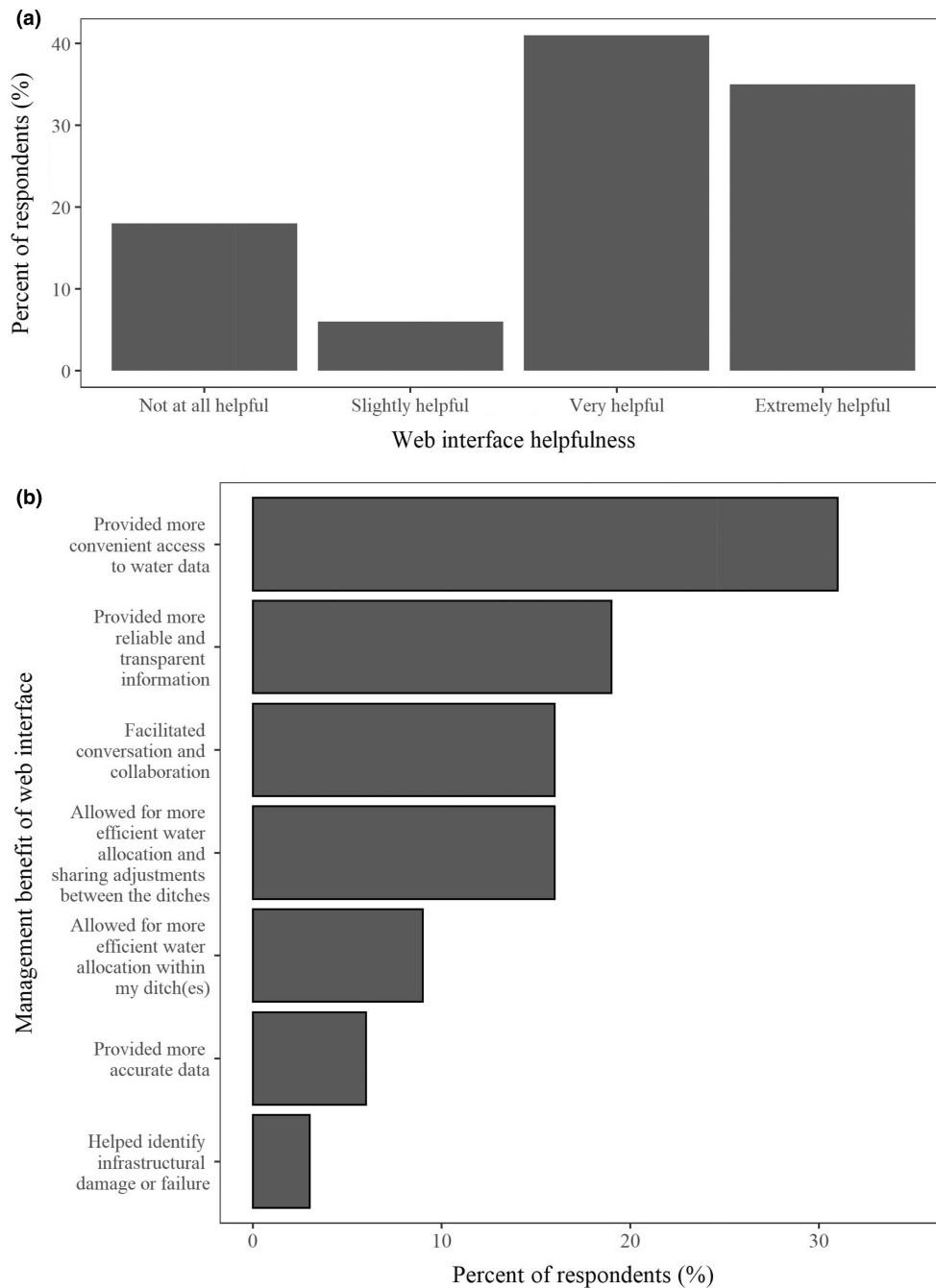


FIGURE 4 A compilation of survey feedback regarding (a) the web interface's general level of helpfulness ($n = 17$), (b) most helpful attributes and added benefits of the web interface ($n = 13$)

cognitive social capital, proactivity, and leadership would significantly increase due to increased data accessibility introduced by the telemetry monitoring system (Table 2).

4 | DISCUSSION

Monitoring systems designed to meet community needs can be successfully implemented in rural communities to increase elements of adaptive capacity to respond to decreasing streamflow trends. Many articles have documented decreasing streamflow trends over the last several decades in the Upper Rio Grande basin region (Chavarria & Gutzler, 2018; Elias et al., 2015; Lehner et al., 2017; Llewellyn & Vaddey, 2013). The survey data in our study supported our hypotheses that information diversity, cognitive social capital, proactivity, and leadership would

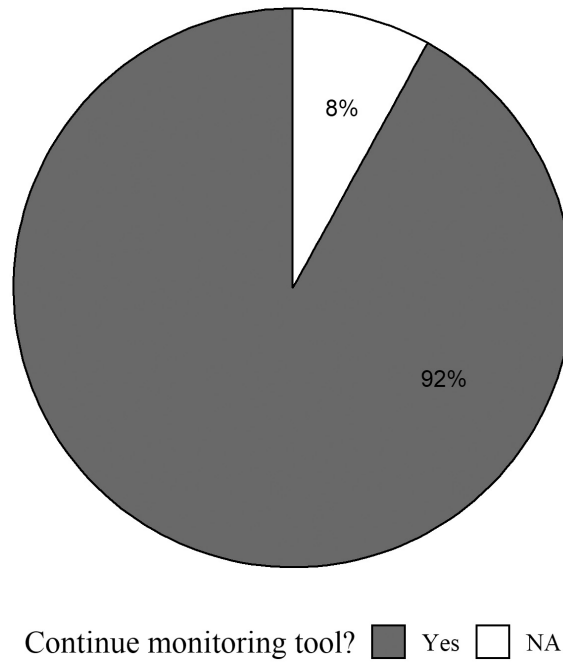


FIGURE 5 When survey respondents were asked about their interest in continuing this or a similar web monitoring tool for future irrigation seasons, 92% indicated that they would like to see this or a similar web-based tool continue into the future ($n = 23$)

TABLE 2 Comparison of each adaptive capacity indicator between the pre-test and post-test ($n = 25$). Monte Carlo paired sample t tests assessed the differences and underwent 10,000 permutations. The t statistic, p value, and 95% confidence interval are reported for each adaptive capacity indicator. Upper-tail p values are reported. Details regarding the score ranges are found in [Table S1](#).

Indicator (score range)	Pre-test mean	Post-test mean	t	p	95% CI
Water management (0–48)	14.40	17.04	1.162	0.4650	(0.4552, 0.4748)
Information diversity (0–8)	3.40	4.60	4.157	0.0022 ^a	(0.0014, 0.0033)
Knowledge exchange (0–10)	5.92	5.52	–0.499	0.814	(0.8061, 0.8215)
Cognitive social capital (0–26)	13.95	14.86	0.722	0.0177 ^a	(0.0152, 0.0205)
Structural social capital (0–10)	3.00	3.00	0.000	1.000	(0.9996, 1.0000)
Proactivity (0–5)	3.24	3.44	1.000	0.0004 ^a	(0.0001, 0.0010)
Leadership (0–16)	11.44	13.04	2.157	0.0070 ^a	(0.0055, 0.0088)

^aSignificant differences are highlighted by p values with an asterisk when $\alpha = 0.05$.

increase within a rural agricultural community when exposed to a telemetry monitoring system. These four significant indicator variables thematically coincide with helpful aspects of the web interface gleaned from the post-test. The significant increase in the information diversity indicator is particularly noteworthy since the introduction of the web interface would specifically impact this indicator. Designed to serve as another source of information, we expected the web interface to diversify information sources water managers and irrigators reference. This is further supported by two of the most helpful attributes and added benefits reported of the web interface: more convenient, reliable, and transparent access to water information ([Figure 4b](#)). It is evident that the web interface benefitted the community ([Figure 5](#)), and its introduction and use were detected as a positive impact on adaptive capacity ([Figure 6](#)).

Other major benefits of the web interface indicated by survey responses included facilitation of conversation and collaboration, and more efficient water allocation and sharing adjustments between acequias ([Figure 4b](#)). Both benefits may have created ripples that impacted proactivity, leadership, and cognitive social capital. The ability to make water allocation decisions more efficiently through greater ease of

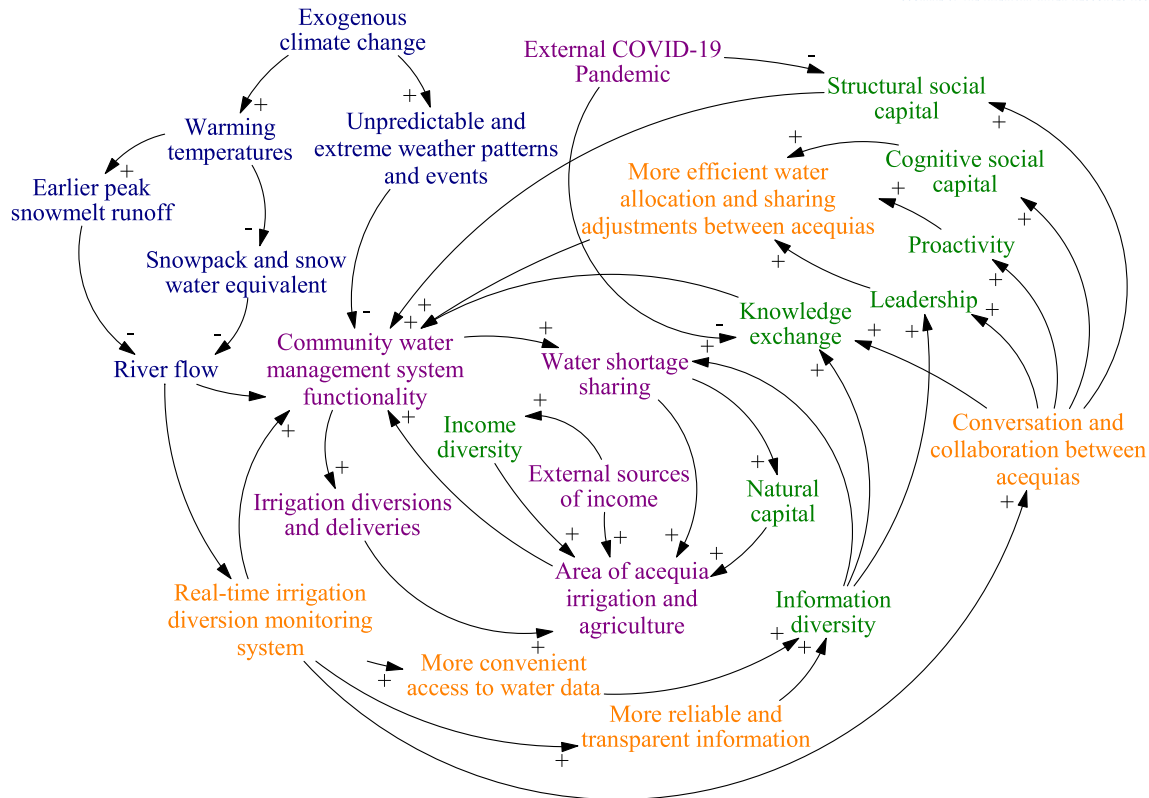


FIGURE 6 Causal loop diagram demonstrating relationships and interactions between hydrologic variables (blue), socioeconomic and Acequia water management elements (purple), beneficial aspects of the real-time monitoring web interface reported in our surveys (orange), and adaptive capacity indicators (green)

collaboration and trust would help acequia leaders plan, mobilize others, and adjust earlier (Figure 6). Therefore, the implementation of this web interface as a water management tool indicates preliminary evidence that providing more convenient, reliable, and transparent water information benefits several social aspects of communal water management.

Including these eight adaptive capacity indicators (see green variables in Figure 6) provides a holistic view of how information is absorbed, disseminated, and used to inform management decisions within a community and were selected from an in-depth literature review of adaptive capacity indicators (Table 1). Arguably, from the stance of applied and community science, knowing how information is used by managers and decision makers is more critical than creating the tool that generates the information. The adaptive capacity indicators we target with our research helped us quantify and visualize the different pathways along which information can be used and distributed within the Rio Hondo acequia community (Figure 6), helping to explain the observed impacts and benefits to water management and water management systems detected in our surveys.

A potential confounding variable must be noted. This research attempted to measure and characterize the impacts of a telemetry monitoring system on adaptive capacity. During the 2020 irrigation season, the COVID-19 pandemic occurred, which was out of the researchers' control. On the post-test, 68% of respondents indicated that they felt COVID-19 greatly impacted their irrigation season, mainly because individuals could not attend or organize regular meetings to discuss water allocations, many individuals are members of vulnerable populations and avoided others. The stress of COVID-19 will confound the impact of introducing the telemetry system; however, the occurrence of the pandemic will ultimately benefit the measurement of adaptive capacity by introducing adverse circumstances that make any adaptive capacity that much more apparent (Engle, 2011, 2013).

COVID-19 likely dampened the results of the knowledge exchange, structural social capital, and water management indicators, impacting their lack of statistical significance. A majority of respondents (68%) reported an inability to interact with others due to social distancing restrictions and precautions with the pandemic, which could have directly impacted knowledge exchange by closing avenues of communication with others. This may have also impacted structural social capital by limiting the help individuals could receive (i.e., government agencies or acequia leaders could have been more difficult to contact). Finally, respondents reported that they were not able to receive as much irrigation water as in previous seasons. This may be a combined effect of drought (i.e., less water available) and the COVID-19 pandemic social restrictions (i.e., fewer water allocation meetings were held and attended), impacting if, which, and who could receive irrigation water or implement water management practices.

This study took place over a short period of time and is based on a small sample size ($n = 25$) which inherently limits our ability to make interpretations. For example, our results could not be expanded to other irrigation communities very definitively and do not show evidence

of trends or changes to adaptive capacity within this community over time. Results of this study would be more robust with a larger sample size paired with long-term attention. Unfortunately, a larger sample size was unrealistic due to COVID-19 pandemic social, political, and institutional restrictions. However, this article is the beginning of long-term, real-time irrigation delivery monitoring in the Rio Hondo Valley and paves the way for future work exploring and seeking to refine our knowledge at the intersection of hydrologic and social sciences in this region.

One of the challenges of measuring and assessing adaptive capacity is that findings are not easily generalizable. Similarly, water management problems and solutions are also not easily generalizable, especially among small agricultural valleys given hydrologic and water policy variability. However, this framework of community science and survey-based assessments of social indicators has great potential for application with contextual modifications to other agricultural areas, especially in drought and climate-vulnerable regions. Localized water monitoring systems designed to meet community needs increase certain aspects of adaptive capacity; these systems and monitoring tools have undeniable positive impacts on the communities involved, although the specific impacts might vary from basin to basin. These water resource monitoring systems will also help local irrigation leaders and irrigators use water more efficiently, enable water managers to have access to a localized database, and inform changes to future water allocation policy and sharing agreements that may ultimately increase resilience. Findings from this study could help inform a socio-hydrologic model to predict the impact of more widespread water data accessibility or water data delivery technologies on sustainable water management across arid and semiarid regions.

Similar studies also concluded that providing irrigation districts and communities with real-time water data allows stakeholders to make effective water management decisions and changes during times of low flow (Ellison et al., 2019) as well as improve water conservation efforts (Cominola et al., 2021). Real-time monitoring initiatives are particularly relevant to sustainable water management in regions experiencing widespread and long-term drought causing downstream or marginalized water users to rely on groundwater more heavily and consequentially (Fuchs et al., 2019). During these times of drought and stressed surface water resources, there is a need to provide real-time data to help inform more efficient and equitable surface water allocations while they are available. This paper contributes to the lack of literature supporting localized water monitoring and impact assessment of these systems on the social aspect of irrigation communities and water management. More research that quantifies the social benefits and impacts of data-delivery tools for water management is needed in both urban and rural settings to further determine when implementation of such tools would be most appropriate. In the case of this research, the Rio Hondo acequia community had wanted a telemetry monitoring system since the early-mid 2000s, so it was a welcomed addition by the time this study occurred. What would the social benefits look like in a community with a different historical context and need for a web-based interface? What would the social and adaptive capacity benefits look like in a more urban environment? What are the demands for web-based tools for water quantity versus water quality management concerns and would there be any differences in changes to or impacts on adaptive capacity?

The emergence and development of robust, affordable, and low maintenance equipment provide greater opportunities for future research to incorporate community involvement and more widespread telemetry capabilities (Buytaert et al., 2014; Paul et al., 2018). Future telemetry monitoring and data accessibility objectives have the potential to complement and lead to larger scale innovative policy, legislative initiatives, and interagency collaborations (e.g., New Mexico Water Data Initiative, Open and Transparent Water Data Platform for California, Western States Water Council Water Data Exchange). Continued development of telemetry equipment will likely lead to affordable or more cost-effective products which will encourage additional applications of monitoring networks at community scales, further supporting the advancement of our understanding of water availability, community science, and water data accessibility.

While data needs from decision makers vary depending on water management challenges, the underlying message is that access to data helps water managers and is a valuable resource for resilience. An international panel of water management experts indicated that while every type of data is important, river flow data were consistently reported as the most important, and that access to data is critical for planning under uncertainty, policy implementation, and conflict resolution (Ward et al., 2019). Evaluation of data platform case studies in California demonstrated that when used appropriately, access to data can facilitate more data-centric management approaches and improve decision-making capacity (Moran et al., 2020). In addition, Dutch water managers reported that access to high-resolution spatial data, products that display data in a digestible manner, and tools to facilitate communication with stakeholders would benefit management and decision-making (Pezij et al., 2019). Ultimately, lack of data contributes to uncertainty and will impact risk perception which is a critical component of human decision-making processes (Hyun et al., 2019). In an era of increasing hydrologic complexity and changes, future hydrologic research must include key environmental and social drivers to better support water management. Not only will this better inform science and expand methods across disciplines, forming multilevel and interdisciplinary partnerships has potential to better inform water policy and facilitate on-the-ground improvements for the future of all water resources.

5 | CONCLUSIONS

This study demonstrated a successful community science approach for designing and installing a real-time monitoring system to better inform water management within a rural agricultural valley. Researchers and community members successfully combined perspectives and experiences to create a web interface with water quantity and quality data at participating irrigation diversions for use within acequia networks.

After the first season of web interface availability, post-test results suggested significant increases in information diversity, cognitive social capital, proactivity, and leadership. These elements of adaptive capacity are critical for facilitating cooperation and communication within decision making frameworks, adaptive management to better address annual and seasonal variability, and long-term community resilience within water-stressed regions.

This research not only benefitted the community by addressing water management concerns, but also begins to fill the gaps within peer-reviewed, hydrologic literature. The literature is missing (1) examples of applied, problem-driven, community science research founded on the coproduction of actionable knowledge, (2) clear integration methods across hydrologic and social sciences, and (3) standardizable and adaptable methods for adaptive capacity assessments. This paper helps fill all three gaps by demonstrating successful collaborations with stakeholders, with social scientists, and providing a survey template that can be easily adapted for future hydro-centric adaptive capacity assessments to evaluate the social impacts of management solutions. These are all qualities of research that increase understanding and cultivate resilience of highly stressed basins as climate change gains momentum.

AUTHOR CONTRIBUTIONS

Lily M. Conrad: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, visualization, writing – original draft, writing – review and editing. **Alexander G. Fernald:** Conceptualization; funding acquisition; investigation; methodology; supervision; writing – review and editing. **Marshall A. Taylor:** Conceptualization; formal analysis; methodology; resources; supervision; visualization; writing – review and editing. **Steven J. Guldán:** Resources; supervision; writing – review and editing. **Carlos G. Ochoa:** Formal analysis; methodology; resources; supervision; writing – review and editing.

ACKNOWLEDGMENTS

The authors declare no conflicts of interest. This research was funded by the state of New Mexico Legislature through special appropriations made to the New Mexico Water Resources Research Institute Community Hydrology Program NMWRRI2019-2020, state appropriations NMWRRI2021, and New Mexico State University's College of Agricultural, Consumer and Environmental Sciences. We are grateful for the involvement of the Rio Hondo acequia community in this research and would like to thank the acequia community for their contributions, feedback, and support.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Anonymized and aggregated data (Conrad et al., 2021) used for the adaptive capacity analysis in this study can be openly and freely accessed within the New Mexico Water Resources Research Institute's Data Set repository at the following link: <https://nmwrri.nmsu.edu/ds-001/>.

ORCID

Lily M. Conrad  <https://orcid.org/0000-0001-5596-4753>

Alexander G. Fernald  <https://orcid.org/0000-0003-0299-6705>

Marshall A. Taylor  <https://orcid.org/0000-0002-7440-0723>

Carlos G. Ochoa  <https://orcid.org/0000-0002-4958-919X>

REFERENCES

- Adger, N.W. 2003. "Social Capital, Collective Action, and Adaptation to Climate Change." *Economic Geography* 79(4): 387–404. <https://doi.org/10.1126/science.11.277.620>.
- Agrawal, A. 2010. "The Role of Local Institutions in Adaptation to Climate Change." In *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World*, edited by R. Mearns and A. Norton, 173–78. Washington, DC: The World Bank. <https://openknowledge.worldbank.org/bitstream/handle/10986/28274/691280WPOP11290utions0in0adaptation.pdf?sequence=1>.
- Armitage, D. 2005. "Adaptive Capacity and Community-Based Natural Resource Management." *Environmental Management* 35(6): 703–15. <https://doi.org/10.1007/s00267-004-0076-z>.
- Baival, B., and M.E. Fernández-Giménez. 2012. "Meaningful Learning for Resilience-Building among Mongolian Pastoralists." *Nomadic Peoples* 16(2): 53–77. <https://doi.org/10.3167/np.2012.160205>.
- Barnett, T.P., J.C. Adam, and D.P. Lettenmaier. 2005. "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions." *Nature* 438(7066): 303–09. <https://doi.org/10.1038/nature04141>.
- Berkes, F., J. Colding, and C. Folke. 2003. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge, UK: Cambridge University Press. <https://doi.org/10.1017/cbo9780511541957.003>.
- Brondizio, E.S., E. Ostrom, and O.R. Young. 2009. "Connectivity and the Governance of Multilevel Social-Ecological Systems: The Role of Social Capital." *Annual Review of Environment and Resources* 34: 253–78. <https://doi.org/10.1146/annurev.enviro.020708.100707>.

- Buytaert, W., A. Dewulf, B. De Bièvre, J. Clark, and D.M. Hannah. 2016. "Citizen Science for Water Resources Management: Toward Polycentric Monitoring and Governance?" *Journal of Water Resources Planning and Management* 142(4): 01816002. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000641](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000641).
- Buytaert, W., Z. Zulkafli, S. Grainger, L. Acosta, T.C. Alemie, J. Bastiaensen, B. De Bièvre, et al. 2014. "Citizen Science in Hydrology and Water Resources: Opportunities for Knowledge Generation, Ecosystem Service Management, and Sustainable Development." *Frontiers in Earth Science* 2(26): 1–21. <https://doi.org/10.3389/feart.2014.00026>.
- Carr, A.J.L. 2004. "Why Do We All Need Community Science?" *Society and Natural Resources* 17: 841–49. <https://doi.org/10.1080/08941920490493846>.
- Carr, G. 2015. "Stakeholder and Public Participation in River Basin Management—An Introduction." *WIREs Water* 2(4): 393–405. <https://doi.org/10.1002/wat2.1086>.
- Chavarria, S.B., and D.S. Gutzler. 2018. "Observed Changes in Climate and Streamflow in the Upper Rio Grande Basin." *Journal of the American Water Resources Association* 54(3): 644–59. <https://doi.org/10.1111/1752-1688.12640>.
- Clow, D.W. 2010. "Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming." *Journal of Climate* 23(9): 2293–306. <https://doi.org/10.1175/2009JCLI2951.1>.
- Cominola, A., M. Giuliani, A. Castelletti, P. Fraternali, S.L.H. Gonzalez, J.C.G. Herrero, J. Novak, and A.E. Rizzoli. 2021. "Long-Term Water Conservation Is Fostered by Smart Meter-Based Feedback and Digital User Engagement." *npj Clean Water* 4(29): 1–10. <https://doi.org/10.1038/s41545-021-00119-0>.
- Conrad, L.M., A.G. Fernald, M.A. Taylor, S.J. Guldán, and C.G. Ochoa. 2021. "Real-Time Irrigation Diversion Data Delivery Can Benefit Adaptive Capacity in Community Irrigation Systems: Data Set." New Mexico Water Resources Research Institute—Data Sets. <https://nmwrri.nmsu.edu/ds-001/>.
- Cox, M., G. Arnold, and S.V. Tomás. 2010. "A Review of Design Principles for Community-Based Natural Resource Management." *Ecology and Society* 15(4): 38. <https://doi.org/10.5751/ES-03704-150438>.
- Cruz, J.J., A.G. Fernald, D.M. VanLeeuwen, S.J. Guldán, and C.G. Ochoa. 2019. "River-ditch Flow Statistical Relationships in a Traditionally Irrigated Valley near Taos, New Mexico." *Journal of Contemporary Water Research & Education* 168: 49–65. <https://doi.org/10.1111/j.1936-704x.2019.03320.x>.
- Douglass-Gallagher, E., and D. Stuart. 2019. "Crop Growers' Adaptive Capacity to Climate Change: A Situated Study of Agriculture in Arizona's Verde Valley." *Environmental Management* 63: 94–109. <https://doi.org/10.1007/s00267-018-1114-6>.
- Eakin, H., S. Eriksen, P.O. Eikeland, and C. Øyen. 2011. "Public Sector Reform and Governance for Adaptation: Implications of New Public Management for Adaptive Capacity in Mexico and Norway." *Environmental Management* 47: 338–51. <https://doi.org/10.1007/s00267-010-9605-0>.
- Elias, E.H., A. Rango, C.M. Steele, J.F. Mejia, and R. Smith. 2015. "Assessing Climate Change Impacts on Water Availability of Snowmelt-Dominated Basins of the Upper Rio Grande Basin." *Journal of Hydrology: Regional Studies* 3: 525–46. <https://doi.org/10.1016/j.ejrh.2015.04.004>.
- Ellison, J.C., P.J. Smethurst, B.M. Morrison, D. Keast, A. Almeida, P. Taylor, Q. Bai, D.J. Penton, and H. Yu. 2019. "Real-Time River Monitoring Supports Community Management of Low-Flow Periods." *Journal of Hydrology* 572: 839–50. <https://doi.org/10.1016/j.jhydrol.2019.03.035>.
- Engle, N.L. 2011. "Adaptive Capacity and Its Assessment." *Global Environmental Change* 21(2): 647–56. <https://doi.org/10.1016/j.gloenvcha.2011.01.019>.
- Engle, N.L. 2013. "The Role of Drought Preparedness in Building and Mobilizing Adaptive Capacity in States and Their Community Water Systems." *Climatic Change* 118: 291–306. <https://doi.org/10.1007/s10584-012-0657-4>.
- Ernst, M.D. 2004. "Permutation Methods: A Basis for Exact Inference." *Statistical Science* 19(4): 676–85. <https://doi.org/10.1214/088342304000000396>.
- Evans, K., and M.R. Guariguata. 2008. *Participatory Monitoring in Tropical Forest Management*. Center for International Forestry Research. <https://doi.org/10.4135/9781446294406.n266>.
- Fernald, A., S. Guldán, K. Boykin, A. Cibils, M. Gonzales, B. Hurd, S. Lopez, et al. 2015. "Linked Hydrologic and Social Systems That Support Resilience of Traditional Irrigation Communities." *Hydrology and Earth System Sciences* 19: 293–307. <https://doi.org/10.5194/hess-19-293-2015>.
- Fernald, A., V. Tidwell, J. Rivera, S. Rodríguez, S. Guldán, C. Steele, C. Ochoa, et al. 2012. "Modeling Sustainability of Water, Environment, Livelihood, and Culture in Traditional Irrigation Communities and Their Linked Watersheds." *Sustainability* 4: 2998–3022. <https://doi.org/10.3390/su4112998>.
- Fernández-Giménez, M.E., B. Baival, B. Batbuyan, and T. Ulambayar. 2015. "Lessons from the Dzud: Community-Based Rangeland Management Increases the Adaptive Capacity of Mongolian Herders to Winter Disasters." *World Development* 68(1): 48–65. <https://doi.org/10.1016/j.worlddev.2014.11.015>.
- Fleck, J. 2016. *Water is for Fighting over: And Other Myths about Water in the West*. Washington, DC: Island Press.
- Fleming, W.M., J.A. Rivera, A. Miller, and M. Piccarello. 2014. "Ecosystem Services of Traditional Irrigation Systems in Northern New Mexico, USA." *International Journal of Biodiversity Science, Ecosystem Services and Management* 10(4): 343–50. <https://doi.org/10.1080/21513732.2014.977953>.
- Fuchs, E.H., J.P. King, and K.C. Carroll. 2019. "Quantifying Disconnection of Groundwater from Managed-Ephemeral Surface Water during Drought and Conjunctive Agricultural Use." *Water Resources Research* 55(7): 5871–90. <https://doi.org/10.1029/2019WR024941>.
- Goodman, R.M., M.A. Speers, K. McLeroy, S. Fawcett, M. Kegler, E. Parker, et al. 1998. "Identifying and Defining the Dimensions of Community Capacity to Provide a Basis for Measurement." *Health Education and Behaviour* 25(3): 258–78.
- Guldán, S.J., A.G. Fernald, C.G. Ochoa, and V.C. Tidwell. 2013. "Collaborative Community Hydrology Research in Northern New Mexico." *Journal of Contemporary Water Research & Education* 152(1): 49–54. <https://doi.org/10.1111/j.1936-704x.2013.03167.x>.
- Gunda, T., B.L. Turner, and V.C. Tidwell. 2018. "The Influential Role of Sociocultural Feedbacks on Community-Managed Irrigation System Behaviors during Times of Water Stress." *Water Resources Research* 54: 2697–714. <https://doi.org/10.1002/2017WR021223>.
- Haefner, M., D. Jackson-Smith, and C.G. Flint. 2018. "Social Position Influencing the Water Perception Gap between Local Leaders and Constituents in a Socio-Hydrological System." *Water Resources Research* 54(2): 663–79. <https://doi.org/10.1002/2017WR021456>.
- Harpold, A., P. Brooks, S. Rajagopal, I. Heidbuchel, A. Jardine, and C. Stielstra. 2012. "Changes in Snowpack Accumulation and Ablation in the Intermountain West." *Water Resources Research* 48(11): 1–11. <https://doi.org/10.1029/2012WR011949>.
- Hyun, J.Y., S.Y. Huang, Y.C.E. Yang, V. Tidwell, and J. Macknick. 2019. "Using a Coupled Agent-Based Modeling Approach to Analyze the Role of Risk Perception in Water Management Decisions." *Hydrology and Earth System Sciences* 23(5): 2261–78. <https://doi.org/10.5194/hess-23-2261-2019>.
- Keskitalo, E.C.H., H. Dannevig, G.K. Hovelsrud, J.J. West, and Å.G. Swartling. 2011. "Adaptive Capacity Determinants in Developed States: Examples from the Nordic Countries and Russia." *Regional Environmental Change* 11(3): 579–92. <https://doi.org/10.1007/s10113-010-0182-9>.
- Konar, M., M. Garcia, M.R. Sanderson, D.J. Yu, and M. Sivapalan. 2019. "Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human—Water Systems." *Water Resources Research* 55: 874–87. <https://doi.org/10.1029/2018WR024088>.

- Krueger, T., C. Maynard, G. Carr, A. Bruns, E.N. Mueller, and S. Lane. 2016. "A Transdisciplinary Account of Water Research." *WIREs Water* 3(3): 369–89. <https://doi.org/10.1002/wat2.1132>.
- Lehner, F., E.R. Wahl, A.W. Wood, D.B. Blatchford, and D. Llewellyn. 2017. "Assessing Recent Declines in Upper Rio Grande Runoff Efficiency from a Paleoclimate Perspective." *Geophysical Research Letters* 44: 4124–33. <https://doi.org/10.1002/2017GL073253>.
- Llewellyn, D., and S. Vaddey. 2013. "West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment." U.S. Department of Interior, Bureau of Reclamation, Upper Colorado Regions, Albuquerque Area Office. <http://www.usbr.gov/WaterSMART/wcra/reports/urgia.html>.
- Ludbrook, J., and H. Dudley. 1998. "Why Permutation Tests Are Superior to t and F Tests in Biomedical Research." *The American Statistician* 52(2): 127–32. <https://doi.org/10.1080/00031305.1998.10480551>.
- Manly, B.R.J. 2007. *Randomization, Bootstrap and Monte Carlo Methods in Biology*, 3rd ed. Boca Raton, FL: Taylor & Francis Group.
- Mayagoitia, L., B. Hurd, J. Rivera, and S. Guldán. 2012. "Rural Community Perspectives on Preparedness and Adaptation to Climate-Change and Demographic Pressure." *Journal of Contemporary Water Research & Education* 147: 49–62. <https://doi.org/10.1111/j.1936-704x.2012.03102.x>.
- Moran, T., A. Saracino, Z. Sugg, B. Thompson, and J. Martinez. 2020. "Evaluating the Use of Data Platforms for Water Management Decisions: Final Report Submitted to the S.D. Bechtel, Jr. Foundation." Water in the West. Stanford Digital Repository. <https://purl.stanford.edu/cb612zf3515>.
- Mote, P.W., S. Li, D.P. Lettenmaier, M. Xiao, and R. Engel. 2018. "Dramatic Declines in Snowpack in the Western US." *Climate and Atmospheric Science* 1(1): 1–6. <https://doi.org/10.1038/s41612-018-0012-1>.
- Nahapiet, J., and S. Ghoshal. 1998. "Social Capital, Intellectual Capital, and the Organizational Advantage." *Academy of Management Review* 23(2): 242–66.
- Paul, J.D., W. Buytaert, S. Allen, J.A. Ballesteros-Cánovas, J. Bhusal, K. Cieslik, J. Clark, et al. 2018. "Citizen Science for Hydrological Risk Reduction and Resilience Building." *WIREs Water* 5(1): e1262. <https://doi.org/10.1002/wat2.1262>.
- Pezij, M., D.C.M. Augustijn, D.M.D. Hendriks, and S.J.M.H. Hulscher. 2019. "The Role of Evidence-Based Information in Regional Operational Water Management in The Netherlands." *Environmental Science and Policy* 93: 75–82. <https://doi.org/10.1016/j.envsci.2018.12.025>.
- Ricart, S., A. Rico, N. Kirk, F. Bülow, A. Ribas-Palom, and D. Pavón. 2018. "How to Improve Water Governance in Multifunctional Irrigation Systems? Balancing Stakeholder Engagement in Hydrosocial Territories." *International Journal of Water Resources Development* 0627: 1–34. <https://doi.org/10.1080/07900627.2018.1447911>.
- Rodríguez, S. 1987. "The Impact of the Ski Industry on the Rio Hondo Watershed." *Annals of Tourism Research* 14(1): 88–103.
- Sabie, R.P., A. Fernald, and M.R. Gay. 2018. "Estimating Land Cover for Three Acequia -Irrigated Valleys in New Mexico Using Historical Aerial Imagery between 1935 and 2014." *The Southwestern Geographer* 21: 36–56.
- Sabu, S. 2014. "Modeling Acequia Water Use in the Rio Hondo Watershed." MS thesis, University of New Mexico. http://digitalrepository.unm.edu/wr_sp%0Ahttp://digitalrepository.unm.edu/wr_sp.
- Sanderson, M.R., J.S. Bergtold, J.L. Heier Stamm, M.M. Caldas, and S.M. Ramsey. 2017. "Bringing the 'Social' into Sociohydrology: Conservation Policy Support in the Central Great Plains of Kansas, USA." *Water Resources Research* 53(8): 6725–43. <https://doi.org/10.1002/2017WR020659>.
- Seidl, R., and R. Barthel. 2017. "Linking Scientific Disciplines: Hydrology and Social Sciences." *Journal of Hydrology* 550: 441–52. <https://doi.org/10.1016/j.jhydrol.2017.05.008>.
- Smit, B., and J. Wandel. 2006. "Adaptation, Adaptive Capacity and Vulnerability." *Global Environmental Change* 16(3): 282–92. <https://doi.org/10.1016/j.gloenvcha.2006.03.008>.
- Taylor, M.A. 2020. "Visualization Strategies for Regression Estimates with Randomization Inference." *Stata Journal* 20(2): 309–35. <https://doi.org/10.1177/1536867X20930999>.
- Thapa, B., C. Scott, P. Wester, and R. Varady. 2016. "Towards Characterizing the Adaptive Capacity of Farmer-Managed Irrigation Systems: Learnings from Nepal." *Current Opinion in Environmental Sustainability* 21: 37–44. <https://doi.org/10.1016/j.cosust.2016.10.005>.
- Trimble, M., and F. Berkes. 2013. "Participatory Research towards Co-Management: Lessons from Artisanal Fisheries in Coastal Uruguay." *Journal of Environmental Management* 128: 768–78. <https://doi.org/10.1016/j.jenvman.2013.06.032>.
- Varis, O., M. Taka, and M. Kummu. 2019. "The Planet's Stressed River Basins: Too Much Pressure or Too Little Adaptive Capacity?" *Earth's Future* 7(10): 1118–35. <https://doi.org/10.1029/2019EF001239>.
- Wagner, C.L., and M.E. Fernandez-Gimenez. 2008. "Does Community-Based Collaborative Resource Management Increase Social Capital?" *Society & Natural Resources* 21(4): 324–44.
- Ward, S., D.S. Borden, A. Kabo-Bah, A.N. Fatawu, and X.F. Mwinkom. 2019. "Water Resources Data, Models and Decisions: International Expert Opinion on Knowledge Management for an Uncertain but Resilient Future." *Journal of Hydroinformatics* 21: 32–44. <https://doi.org/10.2166/hydro.2018.104>.
- Wehn, U., K. Collins, K. Anema, L. Basco-Carrera, and A. Lerebours. 2018. "Stakeholder Engagement in Water Governance as Social Learning: Lessons from Practice." *Water International* 43(1): 34–59. <https://doi.org/10.1080/02508060.2018.1403083>.
- Wesselink, A., M. Kooy, and J. Warner. 2017. "Socio-Hydrology and Hydrosocial Analysis: Toward Dialogues across Disciplines." *WIREs Water* 4(2): e1196. <https://doi.org/10.1002/wat2.1196>.
- Wiggins, A., and K. Crowston. 2011. "From Conservation to Crowdsourcing: A Typology of Citizen Science." In 44th Hawaii International Conference on System Sciences, Kauai, HI.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Conrad, Lily M., Alexander G. Fernald, Marshall A. Taylor, Steven J. Guldán and Carlos G. Ochoa. 2023. "Real-time irrigation diversion data delivery can benefit adaptive capacity in communal irrigation systems." *JAWRA Journal of the American Water Resources Association* 00 (0): 1–15. <https://doi.org/10.1111/1752-1688.13100>.