The Critical Role of Communities of Practice and Peer Learning in Scaling Hydroclimatic Information Adoption

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ABSTRACT

Significant effort has been put into advancing the use and usability of information products to support adaptation to drought and climate variability, particularly for the water supply sector. Evidence and experience show that advancing the usability of information through processes such as coproduction is time consuming for both providers and users of information. One challenge for boundary organizations and researchers interested in enhancing the usability of their information is how such processes might ''scale'' to all the potential organizations and individual managers that might possibly be able to benefit from improved climate information. This paper examines information use preferences and practices specifically among managers of small water systems in the Upper Colorado River basin, with an eye toward identifying new opportunities to effectively scale information usability and uptake among all water managers—regardless of location or capacity—in a resource-constrained world. We find that boundary organizations and other usable science efforts would benefit from capitalizing on the communities of practice that bind water managers together. Specifically, strategic engagement with larger, well-respected water systems as early adopters, supporting dissemination of successes and experiences with new information products among a broader community of water managers, and increasing well-respected water systems' capacity to engage directly with rural systems may all serve as useful strategies to promote widespread distribution, access, and adoption of information.

1. Introduction

Water is a critical and scarce resource across the western United States, and its sustainable and equitable management is one of the region's most important and challenging tasks of the twenty-first century. For example, in the Southwest region of the United States, seasonal runoff of snowpack is shifting earlier into the year (Barnett et al. 2008), more precipitation is falling as rain instead of snow (Pierce et al. 2008; Barnett et al. 2008; Li et al. 2017), and evapotranspiration rates are increasing and resulting in reduced soil moisture and surface water (Dettinger et al. 2015; Udall and Overpeck 2017). These changes are resulting in overall lower streamflow volumes and decreased availability of water supply for critical uses in the later summer and fall months (Barnett et al. 2005; Mote 2006).

The adoption of new hydrologic and climatic information by water managers dealing with existing climate variability and longer-term changes in water supply is seen as a major opportunity for building adaptive capacity to these changes (Kirchhoff 2013). We know a great deal about the factors that shape the use of hydroclimatic information (hereafter referred to as ''information'') among decision-makers more generally, and among water managers specifically [see Kirchhoff (2013) for a detailed review of determinants of information use for water managers]. These factors include those related to the characteristics of the information itself and how it is produced (e.g., Cash and Moser 2000; Cash et al. 2003; Bales et al. 2004; Lemos and Morehouse 2005; Dow et al. 2009;

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Kalafatis et al. 2015) as well as factors related to the institutional and social forces that shape adoption (e.g., Pagano et al. 2001; Rayner et al. 2005; Lemos 2008; Kirchhoff et al. 2013). ''Usable science,'' therefore, can be thought of as relevant science that is produced in a timely way to support near-term decision-making, as compared with basic research, which does not have the goal of being immediately relevant to a societal decisions (Dilling and Lemos 2011).

In pursuit of usable science, emphasis has been placed on coproduction (Lemos and Morehouse 2005; Beier et al. 2017), the ''process of producing usable, or actionable, science through collaboration between scientists and those who use science to make policy and management decisions'' (Meadow et al. 2015, p. 179). Coproduction as a process has at its heart a focus on connecting researchers and practitioners (those making decisions outside the research community) to develop research agendas or decision-support information and tools, prioritizing the needs of practitioners, maintaining iterative and ongoing connections over time, and building trust between researchers and practitioners (Ferguson et al. 2014). It is recognized that coproduction does not typically emerge automatically but must instead be fostered and deliberately incentivized (Lemos and Morehouse 2005; Dilling and Lemos 2011).

One of the challenges commonly associated with coproduction is its high transaction cost and the demand on staff time and resources that iterative interaction and trust-building with scientists requires (Lemos and Morehouse 2005; Dilling and Lemos 2011; Lemos et al. 2012). The intensive nature of coproduction therefore can result in selective engagement by information providers with larger-scale, higher-capacity decision-making organizations located in populated, urban areas (Kirchhoff 2013). Organizations that lack the capacity to engage, whether because of smaller staff sizes or remoteness from providers of new information can be left out of picture. Even those practitioner organizations who do participate can suffer ''stakeholder fatigue'' from constantly being asked to participate in research workshops (Lemos et al. 2018). Effectively ''scaling up'' the reach of new information and tools to all potential practitioners who could benefit remains a major challenge.

There are a number of strategies that have been used to promote interaction between researchers and practitioners to encourage coproduction (Dilling and Lemos 2011; Meadow et al. 2015). One prominent model is the ''boundary organization,'' which facilitates the translation of information, interaction and exchange, and mutual understanding between producers and practitioners (Kirchhoff et al. 2015; McNie 2007). Though boundary organizations have been shown to improve information usability and uptake, the traditional boundary organization model, which is centered around a single organization, is also resource-intensive and difficult to scale (Lemos et al. 2012). One proposed solution is the use of *boundary chains* (Kirchhoff et al. 2015; Lemos et al. 2014), which involves linking multiple boundary organizations together through a chain of relationships that serve to capitalize on the existing social capital of smaller, localized boundary organizations and more efficiently connect resource-constrained university-based boundary organizations with end users (e.g., water managers). Another solution is the idea of leveraging and bolstering existing knowledge networks as a means of scaling information adoption (Bidwell et al. 2013).

In contrast to these models that focus on how to better link the research communities to end users of information, *communities of practice* have been identified as a more informal and fluid model of knowledge sharing centered on the testing, application and learning that comes from the experience of ''solving recurring issues held in common'' (Kalafatis et al. 2015, p. 32). Communities of practice are defined as networks of actors fundamentally bound together by a shared social identity (Wenger 2000), in which ''shared values and practices are reinforced'' (Pelling et al. 2008, p. 870). Kalafatis et al. (2015) find evidence of practitioner networks among the water management community as a critical venue for tailoring, interpreting, and improving the usability of information products. While much scholarship has focused on coproduction and the role of boundary organizations in recent years (Kirchhoff et al. 2013; Lemos et al. 2018), there has arguably been less focus on how communities of practice might play a role in addressing the challenge of providing usable science to a wider group of practitioners.

Within any given community of practice, the theory of *diffusion of innovation* provides a promising construct through which to think about *how* learning occurs. Diffusion of innovation theory focuses on the roles that different members of a group of potential adopters play in facilitating the diffusion of a social, technological, or scientific innovation (in this case, hydroclimatic information products) across existing networks (Rogers 1995). Specifically, *innovators* play an important role in absorbing the risk and uncertainty of trying something new, while *early adopters* play a critical role in normalizing the innovation and providing advice and information to others about the innovation. The *early* and *late majority* adopt the innovation once it has been fully normalized by *innovators* and *early adopters* (Rogers 1995).

The dynamics of the diffusion of innovation have been studied in multiple contexts, including agriculture (Padel 2001), forestry (Reed 2007), and water management (Callahan et al. 1999; Pagano et al. 2001; Lemos 2008). Within the water management context specifically, earlier studies of adoption of seasonal climate forecasts (SCFs) by water managers conclude that piloting SCFs in actual water management systems through demonstration projects, and documenting project successes among early adopters, are potential strategies for building confidence and encouraging widespread adoption of SCFs among water managers (Callahan et al. 1999; Pagano et al. 2001). Lemos (2008) also explores how institutional factors influence risk tolerance among water managers to innovate and adopt new information use practices, and points to the central role that relative decision flexibility plays in diffusion of innovation dynamics in the water management context.

In light of the challenges for coproduction processes and boundary organizations to effectively ''scale up'' and reach all of the constituencies that could potentially benefit from new information in a changing a variable climate, we sought out to investigate how smaller, more remote water providers in our region, the U.S. state of Colorado, might access and use new sources of information. We studied water management decision making within the snowpack-driven river basins of Colorado's Western Slope (the portion of the state west of the continental divide). These systems commonly deal with wide variability in precipitation and snowpack from year to year and are run with a much smaller staff than a typical large urban water utility. In this paper, we examine three distinct aspects of the decision and information use context of five rural water providers: 1) the factors that motivate or constrain managers to change the way they use information; 2) managers' existing knowledge networks (i.e., the various channels through which new information is obtained), and information sources; and 3) the aspects of information sources that influence their likelihood of adoption. This research was also motivated by the potential need to support adoption of new hydroclimatic information products by a wide range of water managers in the future, given recent federal investment in decision-support tools such as the National Integrated Drought Information System (NIDIS) Upper Colorado River basin Drought Early Warning System.

We first describe our research methods (section 2) and study area (section 3). Next, we present our results: we describe the factors identified by interviewees that enable or constrain information adoption, summarize interviewees' current knowledge networks, and characterize aspects of their information sources that influence adoption choices (section 4). Finally, we provide insights and recommendations for those interested in providing usable science to smaller water systems (sections 5 and 6).

2. Methods

We used a comparative case study design (Yin 2014) to characterize decision contexts for information use among five Western Slope water systems. A comparative study allowed us to identify themes that emerge across multiple units of analysis (water system organizations) and for a broader understanding of decision contexts for information use, beyond what a single case study design could offer (Yin 2014). We selected cases that reflect the large variation in water systems found across the largely rural Western Slope region (see next section for description of cases selected). Our goal was to build theoretical knowledge about advancing drought information use in rural, resource-constrained systems tied to mountainous, snowmelt-driven river basins, rather than to draw conclusions generalizable to other empirical contexts. Therefore, we did not randomize the selection process but rather strategically selected systems that represent the heterogeneity of systems across the region. We had assistance in identifying possible entities to interview from the Colorado River District and other contacts of Western Water Assessment throughout the region.

The data used in this study were collected through a combination of in-person, semistructured interviews (Schensul et al. 1999) (n = 14; 2–4 interviewees per organization) with key staff in the winter and spring of 2017 and an in-depth document review, which allowed for triangulation of self-reported information from interviewees. Our criterion for selecting participants was that the individuals had to play some role in operational decision-making related to water supply and drought management. Snowball sampling (Bernard 2000) was used to identify additional interviewees at each organization, based on recommendations by the original contacts made at each entity. We interviewed every individual recommended by our initial contacts at each organization. Though we only interviewed 14 managers in total across these five systems, due to the small nature of these organizations those 14 individuals included nearly every key staff member responsible for decision-making related to water supply. Our relatively small sample of interviewees therefore captured the views of the central decision-makers at each organization.

Interview questions focused on the following themes: key concerns in managing water supply, characterizing annual decision making processes, information used to make decisions, and preferences and barriers related to information use. The interview protocol was pretested with two water systems outside of our study area, and we made revisions to interview prompts based on tester feedback.

We also requested key internal documents from interviewees of each of the five systems; among the 30 documents shared by the study participants, we identified and reviewed a subset of relevant documents ($n = 24$) that specifically described internal decision structures related to water supply management, drought monitoring, drought response, or information use as a way of triangulating and/or supplementing descriptions of decision structures provided by interviewees (a detailed description of water managers' decision structures related to drought can be found in section 4). These included internal water supply planning memos, drought response plans, forecast reports, and reservoir operations plans.

Interviews were manually transcribed, and interview transcripts and entity documents were coded by the lead author using the qualitative coding software NVivo (Bazeley and Jackson 2013). Codes were developed based on emergent themes from the interview and document data as well as from relevant literature on information use and usability. Such themes include primary versus secondary information use, value of information, information sources, and factors influencing information adoption. By basing the initial development of codes on key literature reviewed, we were able to quickly focus in on relevant a priori coding categories that were directly tied to our research questions. Emergent coding categories allowed us to systematically capture themes unanticipated from the literature.

3. Case description

a. *Colorado Western Slope*

This study focuses on Colorado's Western Slope region, which encompasses much of the Upper Colorado River basin (UCRB). The main water supply for the UCRB originates in the headwaters region (Livneh et al. 2015) where the hydrology can be categorized as snowmelt dominated, with complex topography (Livneh et al. 2014). Other snowmelt-dominated systems in the western United States include the Columbia, the California/Sierra Nevada systems, the Rio Grande, and a wide range of systems exist internationally—an estimated 1/6 of the world's population rely on snowmelt for water supply (Barnett et al. 2008). The overarching issue faced by these systems is that there is a heavy reliance on annual snow runoff for water supply due to the relatively small capacity of human-made reservoirs (Mote 2006), making accurate information about changing snowpack conditions critical to water resource management. The principal economic sectors across the Western Slope include ranching, irrigated agriculture, natural resource development, recreation, tourism, and mining. As stated in the Colorado Climate Change Vulnerability Study (Gordon and Ojima 2015), "virtually every aspect of Colorado's economy is tied to water." This is especially true for the economy and culture of the Western Slope. Water on the Western Slope is needed for a wide variety of uses, including municipal, industrial, recreation (e.g., rafting, fishing), irrigated agriculture, and ecological flow needs, for example, for endangered species. Much of the water originating from the Western Slope is allocated for use elsewhere, either via the Colorado River to meet water demands of other states downstream, or routed through transmountain diversions that bring water to the more populous and agriculturally intensive areas of eastern Colorado. Future water demand is expected to triple across the Western Slope, with the majority of that demand coming from the municipal and industrial sectors (Gordon and Ojima 2015; Fig. 1).

b. *Cases: Five water systems*

We selected five water systems across Colorado's rural Western Slope region to examine in this comparative case study. The authors' home institution Western Water Assessment (WWA) is a university-based boundary organization and information provider located along the more urban, populated Front Range region of the state. We strategically selected five Western Slope water systems that are relatively remote in relation to WWA's main hub along the Front Range region. We also selected systems from across distinct subbasins throughout the Western Slope region. Local water systems across the Western Slope include municipal utilities, regional retail water suppliers, wholesale water suppliers (such as water conservancy districts), and ditch companies. The amount of storage available to these entities is also varied, with some entities managing and benefiting from large federal reservoirs, and some entities depending solely on snowpack as their form of storage. While they are all part of the Colorado River basin, their specific subbasins face varied levels of drought risk as well as varied user demands, ranging from large-scale agriculture to outdoor irrigation at high-end resorts to residential indoor uses among growing town populations (Table 1).

4. Results

a. *Organizational factors: Capacity, experience with drought, and generational turnover*

The most widely identified determinant of information adoption among the interviewees was organizational

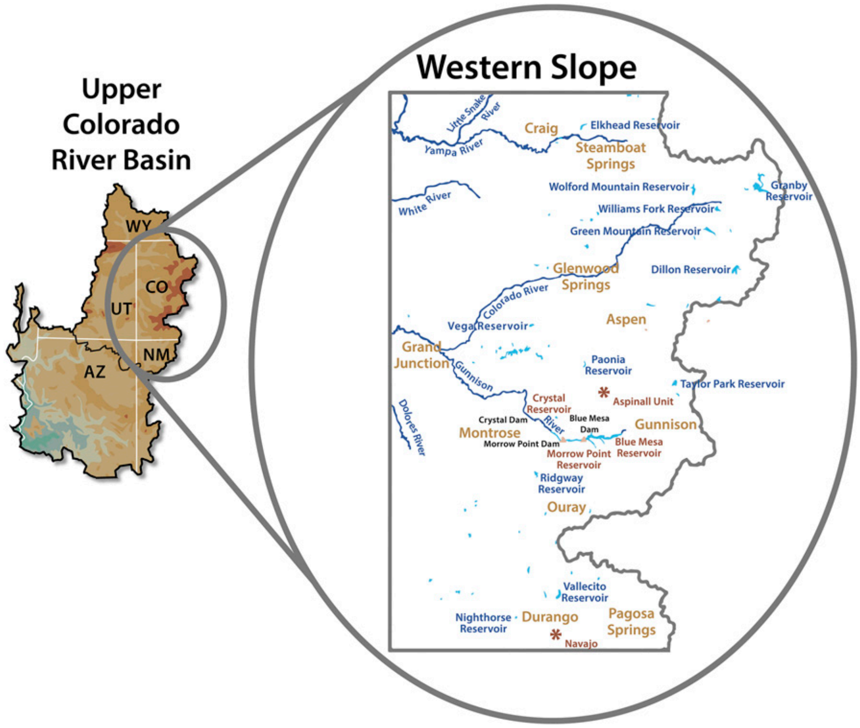

FIG. 1. Map of Western Slope region of Colorado (Source: Adapted from Colorado River District map).

capacity, including both staff resources and technical expertise. Several managers mentioned that, as part of small organizations, they and their colleagues face "manpower constraints" (case 1) and generally lack "the ability to fund staff that monitors all of this" (case 4) as well as the "time or energy to be able to . . . do a full review of what people are . . . looking at" (case 1). In addition to simply having the staff resources to monitor for new products, some managers specifically mentioned a lack of technical expertise to "have a new statistical model built up" from new products and data (case 1) or conduct their own forecasting (case 3). Managers at one system use consultants to make up for the lack of in-house expertise, but one manager expressed that it "can be a hindrance sometimes" (case 5). Additionally, even if staff have the technical expertise to interpret products effectively, they may be "wearing so many hats" that they cannot dedicated time to assessing, interpreting, and working with new products.

Some managers actively compare themselves to the larger organizations in the region that are seen as possessing an ideal level of capacity and technical expertise to keep up with emerging products:

TABLE 1. Summary of selected cases by attribute [1 acre foot (af) ≈ 1233.5 m^3].

Organization type	Business type	Customer use	Storage	Total water/people served
Water conservancy district	Wholesale	Irrigation Augmentation	Total reservoir storage: 44 000 af	26 000 af in annual contracts
Water conservancy district	Retail	Domestic use	Total reservoir storage: 11 960 af	33 000 accounts 80 000 people 10 000 af yr^{-1}
Water conservancy district	Wholesale	Irrigation Augmentation	Total reservoir storage: 108 087 af	1857 af in augmentation 106 230 af available for irrigation (amount used varies year to year)
Municipality	Retail	Domestic use Irrigation	No storage	3500 accounts 2000 af yr^{-1}
Municipality	Retail	Domestic use Irrigation	No storage	10 000 people 3377 af yr^{-1}

> Denver Water, for example, has a much more concentrated ability to dial into this stuff on a daily basis. They're sophisticated, they've got managers and forecasters that we simply cannot afford (case 3).

> If you look at the Front Range, you get that intensity, those large organizations that are very, very well staffed, very well skilled, and so forth. And you look on the Western Slope, there's no one organization that can come even close (case 5).

Another common contextual factor that played a role in determining adoption of new information products was the type of experience managers had in the past with product adoption. For one system (case 1), managers had relied on CBRFC forecasts for several years to manage their reservoir, but over time found them insufficiently accurate to support reservoir management decision-making. These same managers were ultimately motivated by a recent experience with an extreme event to change the way they were using information to drive decision-making, an action they had wanted to take but had not yet gotten around to. Shortly after the drought of 2012, managers at the system shifted from an external forecast product provided by the CBRFC and developed their own probabilistic forecast model based entirely on SWE inputs. As explained in an internal memo about the adoption of the new tool, ''The proposed system is more conservative than relying upon early season forecasts, but it almost guarantees that demands will be met even in the event of a busted official forecast'' (case 1).

For another system (case 2), the 2002 drought had significant negative impacts within their subbasin, but due to their own drought risk mitigation investments prior to the drought, their system was not impacted and they did not impose any use restrictions among their customers. However, the managers at that system were still driven to change their information use practices and begin ''participating a heck of a lot more'' in regional water supply condition discussions such as the Colorado Climate Center's NIDIS Drought Early Warning System, not because of their own sense of vulnerability but because they were ''getting a lot of heat'' from local and regional stakeholders that they had not done enough to support drought recovery for the region.

The last contextual factor that was raised among the interviewees was staff turnover among water management staff. Staff turnover in some cases was viewed as a positive event that opened up opportunity for needed change. For example, a manager at one system (case 1) attributed the development of a new reservoir management operational tool to staff turnover in the mid-2000s. After starting as the new district engineer, he had ''a different expectation of the science that could be used'' to manage the reservoir. According to this individual, the previous manager's approach was simply to be ''wrong half of the time.'' A manager at another system (case 4) attributed being better prepared for drought now than in the past due to having ''newer employees'' that ''have a bunch of different contacts'' and ''are well versed with looking at forecasts and using technology.'' However, staff turnover can also pose challenges to maintaining continuity and institutional knowledge about how to best use information in the context of a system's particular operations: managers at case 5 expressed concern over the imminent retirement of a senior staff member, who played a key role for many years in interpreting hydroclimatic information for decision-making.

b. Determinants of information use: Intrinsic factors: Scale, skill, and understandability

Scale was the most widely mentioned criteria for prioritizing and adopting information products. As one manager put it, every ''little pocket of the mountain'' has distinct ''nuances'' that are not captured by regional information, making ''localized data'' essential for decision making (case 5). There is a clear need for data that ''best represents the direct source of inflow'' for any given system (case 1); local information ''is actually much more relevant to [their] problems'' (case 4); especially because it can capture institutional factors that affect water availability, for example, ''the subtleties of how the river gets administered'' (case 5). One manager mentioned ''local'' as making the difference between using a product to directly influence a decision versus using it for general background and context: ''The more localized, the more likely I would use it. And that's why most of these tools that are qualitative [i.e. at too large a scale], we just say they're qualitative. Because they aren't local enough to necessarily be meaningful'' (case 5).

For managers who depend on inflow forecasts to manage reservoirs (cases 1 and 3), *skill* is also of critical importance. Concern about predictive skill of Colorado basin River Forecast Center (CBRFC) forecasts for their area drove one group of managers (case 2) to develop their own SWE-based forecast model (case 2), while another manager at a different system (case 3) values the skill of CBRFC forecasts as their indicator for decision-making so much that they support additional snowpack data collection needed to improve the accuracy of inflow forecasts.

Understandability in terms of the scientific inputs and assumptions going into a new information product was also mentioned by one manager as a key factor in determining whether he would adopt it in his decision-making. According to this interviewee, lack of transparency prevents managers from figuring out the embedded parameters of a product, which means they continue to rely on existing tools (case 5).

c. Information dissemination: Knowledge networks and influence of information sources

1) Current knowledge networks

Managers primarily accessed information products directly from agency websites and portals, such as NRCS for snowpack data, USGS for streamflow data, and NOAA for temperature and precipitation forecasts. Only one manager regularly participated in university-based boundary activities such as the Western Water Assessment Climate Dashboard and the Colorado Climate Center Drought Early Warning System webinar; the other 13 interviewees were either vaguely familiar with the platforms but never participated or had never heard of them.

When asked about their typical channels for information outside of their main sources, interviewees mentioned a number of professional organizations, such as American Water Works Association (case 2) and Colorado Water Congress (case 2), as well as agencies that play a critical role in managing larger reservoirs and coordinating water users throughout the Western Slope, such as the Bureau of Reclamation Western Colorado Office (case 1), and the Colorado River District (cases 4 and 5). A few managers mentioned ''keeping in touch with peers and other communities'' (case 4) and checking in with ''other utilities in the valley'' (case 5).

Rather than looking to these organizations and peers specifically for learning about new information products, managers instead rely on these industry peers for their interpretation of emerging drought conditions based on those peers' own preferred information products. For example, one manager relied on one particular individual at the Colorado River District to interpret drought conditions on an annual basis, in lieu of looking directly at drought information products such as the CBRFC streamflow forecasts:

> [Staff member at Colorado River District], in the spring time period, he's in daily communication with the River Forecast Center on what they're expecting. And he gives us the big picture of what's happening everywhere, on the West Slope. . .I do not know how he does it. Basically you get him on the line, you just say, what's happening this year, do you see anything that's out of the ordinary (case 5).

Another manager explained that, though the Bureau of Reclamation's drought predictions are not directly relevant to his own water system, he still thinks ''they do an amazing job in terms of tracking things'' based on ''the information available to them'' and finds value in paying attention to them in terms of getting ''a general sense of how we're looking compared to the rest of the state'' (case 1).

2) Credibility of information sources

Some managers (cases 1–3) mentioned the importance of how an information product is disseminated to them. One manager was more likely to use a new information product if he heard about it from ''an agency I'm familiar with'' (case 3), that is, through their existing knowledge networks. One manager specifically emphasized the importance of hearing about a product from a person or organization with hands-on experience managing large-scale systems:

> If we heard from someone who had been trying in practice, you bet, if I talked to the River basin Forecast Center who does this kind of stuff for huge scale reservoirs and operations, that have many moving parts and considerations, you bet I'm going to listen to those guys (case 1).

Another manager similarly placed value on sources of information having hands-on management experience; he explained that, though they hear about information products from state government entities such as the Colorado Water Conservation Board (CWCB), he believed it to be a downside that ''they've never operated a water system'' (case 2).

In addition to the dissemination process, one manager specifically mentioned the importance of how a product is tested and proven to give better results, specifically emphasizing the desire to see products piloted within actual water systems before adopting it into his own system:

> What we really trust is when someone shows up and says, hey look, we started looking into, whatever parameter, and it has actually given us better results . . . if someone can come to me with that, that they had an idea, and they tested it, and they saw some positive results, you bet, we're going to look into that (case 1).

5. Discussion

a. Communities of practice and the role of peers in diffusion of information adoption

Our findings suggest that water management knowledge networks across the region may be more insulated from boundary organizations and activities than presumed by the coproduction and information adoption literature (but see Kirchhoff 2013). Indeed, our interviewees heard about new information from a narrow range of sources, which for the most part drew heavily from their professional networks or directly from agencies that produce products widely established as industry standard [e.g., USGS streamflow, Natural Resources Conservation Service (NRCS) snowpack data]. Interviewees' information sources largely did not include translational information platforms implemented by the primary boundary organizations in the region (the Climate Dashboard implemented by the Western Water Assessment or the NIDIS Upper Colorado River basin Drought Early Warning System implemented by the Colorado Climate Center), suggesting that these traditional boundary organization efforts may be reaching a finite circle of decision-makers (Kirchhoff 2013).

Moreover, interviewees' criteria for adopting new information products, aside from the universal values of "fit" such as scale, skill, and understandability, were generally focused on the information source and the degree of trust in that source—specifically, our interviewees trusted sources who have significant hands-on water management experience over other types of sources and are often times organizations with a dual role of both providing information to regional water managers and managing water resources themselves (e.g., Colorado River District, Bureau of Reclamation). Our results confirms the essential role that *communities of practice* play in translating information for decision-making in the water sector (Kalafatis et al. 2015; Lackstrom et al. 2014; Cravens 2018), similar to the role that national peer learning networks such as the Water Utility Climate Alliance play in cultivating peer learning among larger municipal water suppliers throughout the United States (Water Utility Climate Alliance 2016). Moreover, our results suggest that these managers may actually be so embedded within and reliant on their community of practice that, in some cases, interaction with boundary activities and information providers may not occur among most of the members of their immediate practitioner networks.

Beyond highlighting the critical role of communities of practice, our results illuminate the varied roles that industry peers play in normalizing information adoption, as characterized by diffusion of innovation theory (Rogers 1995). For one system, managers strongly valued being able to see a product tested and proven predictive for another system first, in order to be willing to adopt it. This is reminiscent of recommendations from earlier studies on promoting SCF use (Callahan et al. 1999; Pagano et al. 2001) and also aligns with the essential role described by Rogers (1995) of innovators in absorbing the initial risk of innovation, demonstrating success, and of encouraging adoption by early adopters who are aware of the need for change and willing to change after the initial risk is taken by others. In some cases, managers relied on industry peers not as sources of information products but rather as sources of tailored assessments of local conditions. In those cases, managers trusted the assessments and interpretations by their peers on face value without needing to personally look at the information products supporting those interpretations. For these managers, complete normalization of a new information product—to the extent that the product is already thoroughly integrated into local assessments of drought conditions made by trusted industry peers throughout their community of practice—is essential to their adoption, following the adoption behavior prescribed by Rogers (1995) to *early* and *late majority* groups. While studies have shown that some decision-makers are more likely to emulate peers at organizations of a similar scale to their own (Kalafatis and Lemos 2017), we find that our interviewees—those who behave as either *early adopters* or the *majority*—tend rather to look to peers at organizations *larger* than their own. Indeed, having the capacity to absorb risk is essential to a manager's willingness to innovate before their peers (Rogers 1995). This fact holds important implications for how the decision-support community can effectively promote the adoption of new information products among water managers and their peers.

b. *Implications for alternative strategies to advancing information use*

Our findings suggest a number of key takeaways for the usable science community. First, as has been previously identified, we find that scale, skill, and understandability of an information product are important factors that influence managers' ability and willingness to adopt a product, regardless of organizational scale. For example, we confirm that managers perceive the scale of information products as critically important, with smaller-scale information—reflecting their specific geography and management needs—seen as essential to usability. Producers of operational hydroclimatic forecasts are putting significant effort into generating more local information that is also skillful (IPCC 2012) and should continue to do so; in the meantime, boundary organizations should continue to work with managers to help them understand when information that is less local may actually be more accurate, and how to use what is available. In addition, the constraining or enabling effect that previous experience with innovation can have (Lemos 2008; Pagano et al. 2001) was also validated by one of our cases (case 1) in which a negative past experience with using an external forecast product led managers to stop using external forecast products and develop their own internal model based entirely on snowpack monitoring data.

Events such as staff turnover and occurrence of hydroclimatic extremes (e.g., drought) also appear to provide windows of opportunity that decision-support providers can capitalize on to promote new products (Bolson and Broad 2013; Rayner et al. 2005; O'Connor et al. 2005, Feldman and Ingram 2009; Kirchhoff et al. 2013). There is also a clear need for low-cost, individualized tailoring services to making information products available and usable among resource-constrained water organizations (Jacobs and Pulwarty 2003). The boundary chain model (Lemos et al. 2014), which focuses on leveraging existing networks and social capital of trusted, localized boundary organizations, still ultimately places the emphasis on the translational function of boundary spanning entities and still assumes a basic capacity and motivation among end users to engage in a coproductive process. Certainly, boundary objects such as assessment reports, web portals, and webinars, assume a certain degree of capacity and connectedness on the part of end users, even with robust marketing efforts. These approaches may be missing the mark in the case of water systems that have not previously, do not currently, and may not ever, engage in boundary processes.

Given the reality that 1) we are operating in a resource-constrained world in which individualized tailoring services cannot be available to every water manager and 2) many rural water managers are insulated from boundary and coproduction processes (even webinars and dashboards), our findings point to new possibilities for conceptualizing—and ultimately scaling—information adoption. Rather than looking exclusively or even primarily to boundary organizations to do the ''scaling up'' of knowledge innovation to the very local scale; instead, communities of practice may offer an alternative, more effective solution. Leaders within a given water community of practice may be essential nodes where knowledge is taken up, tried, tested, and reported on within the broader group of practitioners. The most elusive of qualities that underpins successful information use, trust in the product and the source, is likely to be highest when the entity promoting the information has used it in practice and suffers the same risk for a wrong call.

Water managers' communities of practice also serve as an arena for replication and normalization of new practices, as perpetuated by the *diffusion of innovation* dynamic as well as serving as a venue for highly individualized information tailoring (Kalafatis et al. 2015). This dynamic offers important insights into how the usable science community might capitalize on water managers' tendencies to emulate their peers (Lemos 2008). Managers have a tendency to accept their peers' assessments of drought conditions and prefer to see products proven predictive in other systems first. Information providers and boundary organizations may consider selectively engaging with respected higher capacity water systems in the region with the innovative leanings necessary to act as early adopters (Rogers 1995) and work with those systems to pilot, demonstrate, and integrate new products (Callahan et al. 1999; Pagano et al. 2001).

In addition, boundary organizations can seek opportunities to support the documentation and dissemination of successes and lessons from those experiences to the wider community of practice, leveraging existing professional information channels (Lackstrom et al. 2014). Adoption of products proven successful in systems managed by respected industry leaders, or direct use of drought condition assessments from industry peers, is likely to have a much lower transaction cost for managers in terms of the vetting and trust-building process required for direct use of a new product. Products proven predictive and useful elsewhere may also be low-hanging fruit solutions welcomed by ''one man show'' managers at risk of or undergoing staff turnover and shifts in institutional memory. Having trust in the early adopters of a new product may go a long way in motivating managers to work against the constraints they face and find a solution to integrating the product into their own decision-making. Boundary organizations and decision-support providers stand to deepen their impact by deploying resources to support experimentation and innovation by higher capacity water systems and dissemination of successes and lessons learned by industry peers (see Table 2 for a summary of key considerations and potential opportunities for decision-support providers).

c. *Directions for future research*

Though our findings are a small sample of rural water providers, this study suggests important insights and raises useful questions for guiding future research and efforts to scale information adoption. Additional research is needed on a broader sample of lower capacity water managers to determine whether the promise of leveraging communities of practice might bear out on a wider basis. In addition, there is a need for richer empirical descriptions of communities of practice within the water management industry and of demonstration projects for new climate information products.

TABLE 2. Key findings and considerations for boundary organizations and the science translation community.

Key finding	Considerations for boundary organizations, information providers, and funders
Scale, skill, and understandability are critical determinants of information adoption	Producers of operational hydroclimatic forecasts should continue to put significant effort into improving these characteristics of products
Staff changes and extreme events provide windows of opportunity for information adoption	Information providers and boundary organizations can strategically engage with water systems during key staff turnover moments and specifically connect new staff with trusted peers who are well connected with various decision-support resources throughout the region
Water managers face human capacity constraints that limit their ability to consider or look for new information beyond what they already know and to tailor new information to make it usable for their own systems	Decision-support organizations with funding capacity (CWCB, NIDIS) may consider funding or subsidizing low-cost, individualized information-tailoring services to make information products available and usable among resource-constrained water organizations
Water managers more likely to adopt new information if their peers, especially larger organizations, adopt a product first	Information providers and boundary organizations can selectively engage with respected, higher-capacity water systems in the region to support experimentation and adoption of new products
Water managers are more likely to adopt a new information product if they hear about it from a trusted peer within their community of practice	Information providers and boundary organizations can work with early-adopter water systems to document successes and lessons from experimentation and use of new products and disseminate those successes through existing professional knowledge networks
Water managers directly depend on trusted organizations that have a dual role focused on both hands-on water management and information dissemination; managers often depend on individuals in these organizations to obtain their personal, localized assessments of conditions	Decision-support organizations with funding capacity (CWCB, NIDIS) may consider providing direct funding to larger-scale water systems to enhance their capacity to directly support and work with local water systems

Regional boundary organizations and knowledge producers would benefit from conducting in-depth social network analyses of water management professionals on a regional basis to understand how diffusion of new, innovative practices works in contemporary water management. Last, longitudinal evaluations of the effects of demonstration projects on replication across professional networks would provide needed insight into the validity of this alternative information dissemination model compared to traditional boundary activities such as interpretation and tailoring.

6. Conclusions

Significant effort has been put into advancing the use and usability of information products to support adaptation to drought and climate variability, particularly for the water supply sector. This effort is warranted, as risks associated with drought and water scarcity are increasing across the western United States with population growth, changes to the volume and timing of snowpack runoff, and increased competition for different types of water uses.

Usable science researchers to date have placed an emphasis on understanding various determinants that shape water managers' readiness to take up information. Previous work has focused on factors related to the information products themselves and to managers' decision contexts and institutional constraints, with an eye toward improving the interactive coproduction processes of boundary organizations and translational agencies.

Our findings illuminate a missing piece of the usable science puzzle and help to answer the question of how to effectively scale information usability and uptake in a world in which resources available to support usable science efforts are highly limited. By looking specifically at rural water systems, we discover new insights that can help shape efforts to scale information usability across different types of users, not only among managers of smaller rural systems.

We find that scaling usability in the water management sector may in fact require thinking beyond an emphasis on producer–user interaction and translation, and toward a greater focus on capitalizing on water managers' professional community of practice. Boundary organizations and translational agencies must continue to do the important work of engaging with users to produce usable information products; however, they may be wise to also explore new strategies and resources to support experimentation and adoption of new information products by higher-capacity water systems, facilitate the dissemination of their successes and experiences to the broader community of practice within the water management sector, and bolster the ability of higher capacity water systems to directly engage with rural water managers.

As these rural systems grapple with a changing environment and increasing demand pressures, our ability to find new ground for advancing the use and usability of scientific knowledge to support improved water management outcomes becomes all the more urgent.

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