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SCIENCE AND DECISION MAKING: WATER MANAGEMENT AND TREE-RING DATA IN THE WESTERN UNITED STATES[1]

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ABSTRACT: Growing populations, limited resources, and sustained drought are placing increased pressure on already over-allocated water supplies in the western United States, prompting some water managers to seek out and utilize new forms of climate data in their planning efforts. One source of information that is now being considered by water resource management is extended hydrologic records from tree-ring data. Scientists with the Western Water Assessment (WWA) have been providing reconstructions of streamflow (i.e., paleoclimate data) to water managers in Colorado and other western states (Arizona, New Mexico, and Wyoming), and presenting technical workshops explaining the applications of tree-ring data for water management for the past eight years. Little is known, however, about what has resulted from these engagements between scientists and water managers. Using in-depth interviews and a survey questionnaire, we attempt to address this lack of information by examining the outcomes of the interactions between WWA scientists and western water managers to better understand how paleoclimate data has been translated to water resource management. This assessment includes an analysis of what prompts water managers to seek out tree-ring data, how paleoclimate data are utilized by water managers in both quantitative and qualitative ways, and how tree-ring data are interpreted in the context of organization mandates and histories. We situate this study within a framework that examines the coproduction of science and policy, where scientists and resource managers collectively define and examine research and planning needs, the activities of which are embedded within wider social and political contexts. These findings have broader applications for understanding science-policy interactions related to climate and climate change in resource management, and point to the potential benefits of reflexive interactions of scientists and decision makers.

(KEY TERMS: tree-rings; paleohydrology; water management; coproduction.)

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INTRODUCTION: EVALUATING SCIENCE-POLICY INTERACTIONS IN THE WESTERN UNITED STATES

Growing populations, limited resources, and sustained drought have placed increased pressure on already over-allocated water resources throughout the western United States (Fulp, 2005). As a result, some water managers have begun to seek out and utilize paleoclimate information to better understand the effects that climate variability may have on water supplies and system reliability (Woodhouse and Lukas, 2006). A plethora of potentially useful data for

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water managers does exist, but this scientific information must be made accessible and relevant for decision makers in order for it to be useful in water planning. This also requires that climate scientists, resource managers, and decision makers are effectively working together to connect scientific knowledge to planning and policy in water management. Interactions and partnerships between scientists and decision makers, however, are increasingly recognized as a process that is much more complex than simply passing information from science "producers" to science "users" (e.g., Jacobs and Pulwarty, 2003; Vogel *et al.*, 2007). Rather, effective science-policy interactions must be understood as multidirectional, requiring participation from many experts with different knowledge backgrounds and outcome goals.

To better understand what makes science-policy partnerships more or less effective, we conducted an assessment of collaborations from 2000 to 2007 between paleoclimatologists from the Western Water Assessment (WWA) and water providers in Arizona, Colorado, New Mexico, and Wyoming to determine if and how tree-ring based reconstructions of hydrology have been useful and applicable to water resource planning and management. Partnerships between scientists and management personnel, along with a series of technical workshops, have been the mechanisms for the translation of scientific results into information for water resource applications in the efforts we examine here. Interviews were used to assess the outcomes of ongoing and established research partnerships with three water utilities in Colorado, and survey information was elicited from the entire population of attendees from seven workshops conducted in four western states to determine if and how scientific information presented in the technical workshops has been incorporated into water resource planning.

In the following sections, we first provide an overview of the key challenges to the integration of science and decision making, and then we describe the *coproduction of science and policy* as a framework for assessing interactions between scientists and resource managers. A short introduction to tree-ring based reconstructions of streamflow and the history of their application to water management follows. We then describe the research questions and methods used to assess the use of reconstructions of streamflow by water management agencies, targeting the factors and events that have prompted water managers to seek out climate-related information, the ways that tree-ring data are interpreted in the organizational context of water supply agencies, and issues of credibility and acceptance of tree-ring data. The results are organized into four main topics (corresponding to four research questions): (1) why water managers seek out paleoclimate data, (2) the use of paleoclimate data, (3) the importance of institutional characteristics and water users, and (4) data challenges and considerations. Finally, we advocate science-policy models that promote interactive, iterative, and reflexive partnerships between scientists and decision makers, while also considering the larger social context within which climate data are both produced and used in resource management.

INTEGRATION OF SCIENCE AND DECISION MAKING: KEY CHALLENGES AND OPPORTUNITIES

During the past decade, researchers have begun to examine what barriers exist in the translation of science to water management and policy. This research has documented that the "accessibility, credibility, understandability, relevance, and timing" of research (Pagano *et al.*, 2001, p. 1148) can affect the ability of decision makers to determine how, and what type, of climate data may be useful for managing water resources. More specifically, scientists must be able to communicate and share information with decision makers and planners at appropriate temporal and spatial scales for management purposes, while water management agencies must have the capacity, knowledge, and willingness to appropriately incorporate scientific information into decision making (Gamble *et al.*, 2003).

With respect to the production of scientific knowledge, researchers must also understand that "better science" does not necessarily lead to better management and decision making (Tribbia and Moser, 2008; McNie, 2007). Instead, gaps may exist between what data decision makers are aware of, their knowledge about how to use that data, and what information may actually be necessary to address a particular management concern. At the same time, differences in background, professional training, and organizational mandates often places emphasis on different outcome goals for scientists and decision makers, producing significant barriers for meaningful and sustained interactions between researchers and resource managers (Janse, 2008; White *et al.*, 2008). Social practice and institutional norms can also affect the creation and utilization of scientific knowledge, including the influence of priorities and procedures of scientific funding institutions on research activities and the preference for technological solutions to environmental concerns among the resource management community (Jasanoff, 1990).

To examine and address many of these issues, conceptual frameworks have been developed to better understand how science is used in decision making and to improve the integration of scientific information in resource management. Fundamentally, this approach begins from the standpoint that "science" and "policy" exist not as separate spheres of knowledge and practice, but instead, they are *coproduced* through engagements of researchers, decision makers, and the public (Lemos and Morehouse, 2005). Coproduction refers to the "collaborative process of knowledge production that involves multiple disciplines and stakeholders of other sectors of society" (Pohl, 2008, p. 47), and the process of interactive and iterative "stakeholder" involvement procedures that collectively shape research agendas with both scientists and policy makers (Lemos and Morehouse, 2005).

Most importantly, the coproduction of science and policy approach places emphasis on the interactive, and often blurry, relationship between society and scientific expertise in resource management. As Vogel *et al.*, 2007, p. 351 state:

> Interestingly, when scientists and practitioners begin working together…both the science and the practice change, and sometimes in unexpected or unintended ways. For example, practitioners and policy makers become more than mere recipients of scientific knowledge but begin to help configure research agendas…Such outcomes can, however, blur the "traditional" roles of scientist and practitioners, as the producer, user, and brokering roles become more fluid and less compartmentalized. Knowledge thus flows in many directions and the distinction between "pure" and "applied" or Modes I and II science can no longer be clearly made.

As the above quote shows, it is increasingly being accepted that there is no "linear process" of delivering scientific information to decision makers, nor a definite distinction between the practices of science and policy (Vogel *et al.*, 2007; White *et al.*, 2008). Instead, in science-policy engagements there is "an actual re-shaping of both groups' perceptions, behavior, and agendas that occurs as a function of their interaction" (Lemos and Morehouse, 2005, p. 61), leading to more integrated and sustained interactions between producers and users of scientific information. If an interactive research process is in place, useful integration of scientific information into water resource planning may be achieved.

We use this coproduction framework in our assessment and discussion of the partnerships between paleoclimate researchers and water managers in the western U.S. paying close attention to how science and policy are (or are not) integrated in these efforts and what social and technical factors influence the use of scientific information. Although the emphasis of this paper is primarily an assessment of how science has influenced the practice of water planning, input from water managers to scientists was central to the formation of partnerships between water providers and WWA researchers during the study period, including what types of scientific data were created for water resource applications (Woodhouse and Lukas, 2006). Without the influence and input of water managers in shaping the scientists' research and delivery of information, these science-policy partnerships would not have occurred.

A BRIEF OVERVIEW OF TREE-RING DATA AND WATER RESOURCE MANAGEMENT

Gaged streamflow records are the basis for water resource management where surface water is the primary water supply. In the western U.S., very few gage records are 100 years or longer, and even the longest records contain a limited number of sustained severe droughts, the events that are most challenging to water management. Recent drought conditions in the western U.S. have made it increasingly clear that the range of variability in the gage records may not be fully representative of true long-term variability. Information on long-term natural hydrologic variability over multiple centuries can be obtained from tree rings in moisture-sensitive trees (e.g., tree species whose ring widths correlate well with variations in moisture availability), offering a proxy method to determine streamflow over periods much longer than the available gage records (also referred to as "paleoclimate data" in this paper). The close association between water-year streamflow and annual tree growth, linked by the regional climate, is particularly strong in the southwestern and intermountain western U.S. making it possible to create high quality reconstructions of annual streamflow for gages such as on the mainstem Colorado River, its upper and lower basin tributaries (Stockton and Jacoby, 1976; Smith and Stockton, 1981; Meko and Graybill, 1995; Hidalgo *et al.*, 2000; Woodhouse *et al.*, 2006: Meko *et al.*, 2007), the South Platte River (Woodhouse and Lukas, 2006), and the Sacramento River (Meko *et al.*, 2001).

Increased availability and awareness of tree-ring data during the past decade has prompted a growing number of water managers to seek out tree-ring data for use in a variety of applications, ranging from general assessments of long-term hydrologic variability to numerical inputs into water supply models (Woodhouse and Lukas, 2006). Although the number of water managers using tree-ring data, and to some extent, the ways they are using the tree-ring data, has increased in the past several years, the application of tree-ring data to resource management is not new: the use of these data in water resource management extends back to the 1930s in the western U.S. (see Table 1).

While this brief overview of the history of tree-ring applications for water resources documents the usefulness of tree-ring data to water management, these applications have been relatively isolated (Woodhouse and Lukas, 2006). Increased demand on water supplies due to population growth and new recreational and environmental uses, along with a decrease in supply resulting from persistent drought conditions since about 1999, have converged throughout many parts of the western U.S. during the past decade. This has resulted in an increase in research on the applications of tree-ring data in resource management and greater attention to the adequacy and reliability of water supplies for both municipal and rural water agencies and providers. This paper documents efforts to introduce these data to water managers, and is the first evaluation of the outcomes of these efforts to utilize tree-ring data in water management.

WWA RESEARCHERS AND WATER MANAGERS IN THE WESTERN U.S.: ESTABLISHED AND EMERGING COLLABORATIONS

Researchers from the WWA, a joint program of the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado (including the second and third authors of this paper) found that increased pressure on western U.S. water resources and growing interest in the long-term frequency and severity of drought conditions, were conducive to the introduction and acceptance of new sources of scientific information to water managers. WWA is one of nine NOAA funded Regional Integrated Sciences and Assessment (RISA) programs that have undertaken this effort of engaging decision makers in the production and delivery of science. Starting in 2000, WWA scientists developed several partnerships with Colorado Front Range water managers to collaboratively investigate ways that tree-ring data, including streamflow reconstructions, could be incorporated into water resource management. This also included the creation of specific streamflow reconstructions in the watersheds of water providers. Collaborations with three "established research partners" are the subjects for the in-depth interviews in this assessment project.

TABLE 1. Brief Overview of Applications of Tree-Ring Data to Water Resource Management.

Hardman and Reil (1936)	Truckee River, possible applications to water resource management; agricultural regions of the Truckee River Basin.
Schulman (1942)	Report for the Los Angeles Bureau of Power and Light, assessment of reliable power generation from the Colorado River.
Potts (1962)	For Denver Water Board, annual S. Platte flow, droughts for estimating future storage requirements.
Earle and Fritts (1986) and Meko *et al.* (2001)	Sacramento River reconstructions for the California Department of Water Resources.
Smith and Stockton (1981)	Salt and Verde Rivers reconstructions for the U.S. Army Corps of Engineers.
Young (1995)	Hydrologic, economic, social impacts of Colorado River drought.

Based on the positive outcomes of these initial partnerships and broader interest within the larger community (including local and state water planners, municipal water engineers, consultants, and other water-related agency management), WWA researchers began to share the results of this work with the larger community through a series of technical workshops in 2006. The main goals of these workshops were to explain the methodologies for creating streamflow reconstructions from tree-rings and explore how these reconstructions could be used in water resource. Water managers, decision makers, and climate scientists also gave brief presentations on their experiences incorporating the tree-ring information in resource management, planning, and policy. Seven of these workshops were held in 2006 and 2007 in Boulder, Alamosa, and Durango, Colorado; Cheyenne, Wyoming; Albuquerque, New Mexico; and two in Tucson, Arizona. During the workshops, discussions between scientists and water managers helped participants collectively define and understand challenges of water management in the region and how tree-ring data could be used to address those challenges.

The workshops were accompanied by the development of a web resource, TreeFlow, to provide access to the tree-ring data and information about applications of the data. Feedback received in surveys completed at the conclusion of each workshop indicated that water managers found the training and information about applications useful, but no formal follow-up or post-workshop evaluation was performed at that time. In early 2008, survey data were collected from participants in these workshops as part of this assessment project. The results of this independent evaluation (from both interviews and surveys) are reported and analyzed here.

It should be noted that the workshop survey respondents are probably biased in a positive manner toward using paleoclimate data and other climate information in water management, relative to the entire population of water practitioners. The way the invitation lists for the workshops were assembled from existing contacts and networks, and the choice of invitees to attend or not, will likely tend to select individuals already interested in, and inclined to see positive value in, the paleoclimate data. So we make no claim that the survey respondents are representative of the water community at large in their attitudes toward, and use of, the paleoclimate data.

Although the results of this evaluation are applicable throughout the western U.S. because many states face similar water management issues in the region, interview and survey respondents were only from the following states: Arizona, Colorado, New Mexico, and Wyoming. Together, the partnerships between WWA researchers and water utilities in Colorado, along with the workshop that began thereafter, occurred from 2000 to 2008, and serve as the study period for this evaluation.

RESEARCH QUESTIONS AND METHODS

The fundamental goal of this project is to evaluate the outcomes of interactions between WWA scientists and water managers in the western U.S., including how water managers and utility directors are using tree-ring data in hydrologic models of water supply, resource planning, and decision making. Four specific research questions guided this project:

1. What motivates the acceptance and use of scientific information for planning in water resource management?
2. How have tree-ring data been used by water managers, and has this influenced organizational procedures or plans related to climate variability and uncertainty?
3. What is the relationship between institutional characteristics of water supply organizations and the use of tree-ring data in water resource management?
4. What data challenges still exist in the incorporation of tree-ring data in water management?

Data collected regarding these questions have allowed us to better consider the coproduction of scientific knowledge for decision making, including (1) why tree-ring information becomes relevant for resource planning, (2) how tree-ring data is actually used in water resource management and the influence of this information on water management plans and assessments of water supplies, (3) what institutional factors influence the way tree-ring data is used in water management and drought planning, and (4) the challenges that still exist in using tree-ring data in water management. Given the increased pressures on water supplies throughout the western U.S., finding ways to improve communication and interactions between climate scientists and water managers has the potential to help address many pressing concerns related to water supply in the region.

Research Phase One: Interviews With Established Research Partners

Four semistructured interviews were conducted with nine individuals associated with three different water utilities in Colorado during January 2008 (see Table 2 for summary of interviews). Each interview was approximately 1 hour long, consisting of open-ended interview questions designed to elicit information regarding the integration of tree-ring data into water management by each organization, the institutional context within which tree-ring data have been used, and each organization's general satisfaction with the tree-ring data and other information they were provided by WWA researchers. Qualitative analysis was performed on the interviews to produce a

TABLE 2. Summary of Interview Participants.

Water Provider	Number of Interviews	Comments
Organization A	One group interview with three water managers/engineers	Private water utility serving a large urban area.
Organization B	One group interview with two water engineers from consulting firms and one interview with a water supply manager	City-owned water utility serving a mid-sized urban area.
Organization C	One group interview with three water managers/engineers	Publically owned water conservation district, which is currently experiencing a transition from agricultural to urban water uses. A water board determines how much of each contractee's water quota will be delivered each year based on snow pack, runoff, and estimated diversions.

general summary of each individual organization's background and use of tree-ring data and to decipher general topics or themes that occurred in multiple interviews. Although the number of utilities included in this evaluation is small ($n = 3$), it represents the entire population of water utilities that have had sustained interactions (over a period of several years) with WWA researchers to generate tree-ring reconstructions of streamflow for gages specific to those utilities, and apply them to water planning.

All of the water providers we interviewed are located in Colorado's Front Range, a semiarid region where snow-fed surface water is the main water supply. Furthermore, these three water utilities represent a range of organizational characteristics for water providers in the western U.S. We use pseudonyms for these utilities (e.g., Organization "A") to maintain the confidentiality of interviewees. This research design was chosen to allow interviewees to speak openly about their collaborations with scientists, without concern that their statements would be attributed to them or their organization.

Research Phase Two: Surveys of Technical Workshop Participants

We also evaluated the outcomes of seven technical workshops for water managers conducted by WWA researchers during 2006 and 2007. A written survey, administered via the internet, was distributed to all previous workshop participants to determine if and how they have utilized the paleoclimatic information provided in the workshops. The survey was sent to 71 individuals, from a wide variety of public and private water entities. The response rate for the internet survey was 40% ($n = 29$); one response was subsequently removed from the survey due to inconsistent responses to several questions, leaving a total of 28 responses (39% of those contacted) which were tabulated and analyzed. It is possible that there is a bias in the survey responses because the workshop participants who have had more interactions with the researchers, and have been using the tree-ring data, may have been more likely to respond to the survey (all responses were anonymous, so we cannot test for this bias). So the survey responses may overstate the positive outcomes of the workshop and use of the tree-ring data, but do serve as an important indicator of how paleoclimate data have been used by water managers.

The workshop survey population offers a much larger and more diverse set of responses than was obtained from the interviews. The relationship between the researchers and most of these individuals and organizations has not extended beyond the contact at the workshop they attended. The survey questions were designed to elicit basic background information on workshop participants, if and how tree-ring data have been integrated into the operations or decision making of the organizations, what information from the workshops has been most or least useful, and what other paleoclimatic data might be of use. Table 3 contains a summary of the occupational background of survey respondents, to provide information about the segment of the water management community that provided responses to the survey questions. The majority of workshop participants self-identify as being in water planning or operations (56 and 41%, respectively), followed by research, consulting, and municipal government.

Both methods, interviews and surveys, were designed to address all four stated research questions, and thus, examples from both interviews and surveys are used in the following results sections. The full interview questions and survey questions/responses have been provided as Appendix S1-S3 (see Supporting Information). Only the portions of the interviews and surveys that most directly and clearly address the specific research are specifically discussed as part of this paper.

RESULTS (1): WHY WATER MANAGERS SEEK OUT TREE-RING DATA

Both the interview and survey data provide insight into what has prompted water managers to seek out paleoclimate data and information. The most prominent motivating factor that was specifically mentioned by interview and survey respondents to questions about why they choose to seek out tree-ring data was the occurrence and persistence of an extreme event – drought. Dry conditions began around 1999 or 2000 in many western states and persisted for several years, with extreme meteorological and hydrological drought in 2002 (often referred to as

TABLE 3. Survey Responses to the Question "In What Area(s) Do You Work?" (respondents could select more than one answer).

Planning	56%
Operations	41%
Research	26%
Water conservation district	15%
Water conservancy district	0%
Private consulting	26%
City government	26%
County/state government	15%
Federal government	16%

the "2002 drought" in Colorado). Organization C, for example, began to use tree-ring data in water resource planning after the 2002 drought drastically reduced the amount of water they were able to provide to contracted water users. Historically, Organization C provides at least 50% of individual water quotas to users, though in 2002 they were only able to provide 30%, a level unprecedented in their history as a water conservation district. In response to a question about why they began collaborating with WWA researchers on tree-ring based streamflow reconstructions, an engineer from Organization C stated:

> "We hadn't seen anything like that [the 2002 drought]…So we were contemplating a 30% quota, which was just unheard of and a lot of us here were really pretty worried about 30% of a full allotment…We were water supply limited for the first time." (January 16, 2008, personal communication)

Droughts and low flows were very instrumental in motivating Organization A, B, and C's interest in collaborating with WWA researchers to reconstruct streamflows over longer time periods than had been available through the gaged record.

Through survey responses, we did find that drought was not the only factor motivating water managers to consult paleoclimate data in planning efforts. The survey respondents were allowed to provide an open-ended response to the question "What initially prompted your interest in tree-rings or the use of tree-ring data?" The answers were wide-ranging, but frequently referred to the need to better forecast variability and/or assess the reliability of water supplies, the desire to improve planning for future water supplies, and uncertainties related to the potential frequency and severity of sustained drought conditions over longer time scales. Other responses included exposure to paleoclimate data in their own research or studies (e.g., graduate research projects), media exposure to climate data, or desire to acquire additional knowledge of paleoclimate data for personal or professional use. Importantly, our interview and survey responses indicate that there is wide interest in paleoclimate data among water managers for many applications, meaning that there are many potential entry points for scientists to make paleoclimate data relevant for water management.

RESULTS (2): HOW WATER MANAGERS USE TREE-RING DATA

Interviews and survey data show that paleoclimate data are used in both quantitative and qualitative assessments. Table 4 shows that 14% of survey respondents have begun to use tree-ring data in their work when they had not being doing so before, and an additional 14% of respondents that were already using tree-ring data now recognize additional applications of tree-ring data. Almost all workshop attendees (96%) agreed that the workshops provided them with a better understanding of how streamflows are reconstructed from tree-rings, while more than 70% have a better understanding of the range of natural variability that exists in streamflows from the reconstructions. A large portion of survey respondents (68%) recognize the potential usefulness of tree-ring data, a reflection of the understanding for applications of climate data they gained at the workshops. Importantly, the interaction of scientists and decision makers during the workshops appears to have facilitated communications on the applications of tree-rings for water management, while also increasing the credibility of tree-rings for use in water resources planning (71% of survey respondents indicated that "tree-ring data are more credible to me and/or my organization"). Only a small number of the survey respondents (7%) have not used the information from the workshops.

TABLE 4. Survey Responses to the Question "What Outcomes Have Resulted From Your Participation in the Tree-Ring Technical Workshops?" (respondents could select more than one answer).

I have a better understanding of how streamflows are reconstructed from tree-rings	96%
I have a better understanding of the range of natural variability in streamflow	71%
I have a better understanding of how streamflow reconstructions can be used in water management	79%
Tree-ring data are more credible to me and/or my organization	71%
I realize the potential usefulness of tree-ring data to my organization	68%
I now use tree-ring data in my work	14%
I was already using tree-ring data, but now recognize additional applications	14%
I have not used the information I received [learned] at the workshop	7%

TABLE 5. Survey Responses to the Question "How Have Tree-Ring Data Been Used by You, Your Organization, or Organizations That You Consult For?" (respondents could select more than one answer).

To broaden understanding of hydrologic variability	75%
To educate users/public	46%
To educate board and other decision makers	50%
As input into a water system model or other model	25%
For quantitative analysis, but not in a modeling environment	14%
To inform planning and decision making	54%
I have not used tree-rings in my organization	18%

One of the most revealing results of the survey (Table 5) was that more than half of the respondents (54%) have used the tree-ring data to inform planning and decision making. Furthermore, approximately 50% of respondents have used the information they learned in the workshops to educate their boards, decision makers, and/or publics, while up to one-quarter of workshop participants are using tree-ring data in some form of quantitative analysis (e.g., water models). Less than 20% of the respondents have not used tree-ring data in their own organization (Table 5).

Quantitative Use of Tree-Ring Data

All three water utilities that we interviewed are using tree-ring reconstructions of streamflow in a quantitative environment, incorporating the data into water system models. This allows these water providers to gain a better understanding of their system's reliability over a wider range of hydrologic variability, and assess the performance of drought management plans to accommodate those fluctuations. Organization A, for example, was using a 45-year instrumental record [1947-1991] and the 1950s drought *without* use restrictions as a worst-case scenario for water supply modeling and planning, prior to the acquisition of tree-ring data. The incorporation of streamflow reconstructions into Organization A's hydrologic model, however, revealed that the worst drought in the 360-year tree-ring record (in the 1840s) *could* have been accommodated by current drought management plans if severe use restrictions had been implemented. The importance of this finding is that Organization A's system performed through the 1950s without water use restrictions, but could only get through the 1840s with restrictions. As a result, Organization A is now considering any changes that need to be made in their system and/or operations to get through a 1840s drought without use restrictions. Organization B also integrated the reconstructed flows into their water supply system model to assess their ability to meet demands under a broader range of conditions that presented in the gage record, and to develop a city drought plan with conservation thresholds.

Water managers at Organization C have also used data from tree-ring reconstructions to quantitatively assess water quotas that the organization would have set over the entire paleo streamflow record, under their current quota-setting guidelines. They were surprised to find that quotas lower than 50% of contracted water allotments (their lowest historical allotment prior to 2002) were not nearly as unusual as they assumed from the single occurrence (2002) of a below 50% allotment in approximately 50 years of system operation. This finding held a very important implication for Organization C's water allotees, who generally believed that they would always receive at least 50% of their water allotment, even in drought years. Organization C also has plans to use tree-ring data to construct a more sophisticated "quota-chronology" model over the entire paleo record to help identify "trigger-points" for their drought plan. They will be able to present the output from this model to water users to provide a better picture of what their water quotas might be under certain conditions. A water engineer from Organization C stated:

> So, I did this little study, just to kind of look at – it wasn't very sophisticated. It just kind of ran through our project under some different quota-setting methodologies and I guess the result out of that study is that the 30% quotas really aren't that unusual when you have a longer time period to look at, based on the way that we set quotas at that time. We had a few public meetings just to knock on people's doors and say, "oh, by the way, you know that 50% you thought you might get, it's going to be 30%!" (January 16, 2008, personal communication)

Quantitative assessments of water supplies using paleoclimate data are providing important information about drought frequency and severity to water suppliers in the western U.S. How these insights will be incorporated into planning efforts and future water models, however, is still being considered and evaluated by many of these organizations.

Qualitative Use of Tree-Ring Data

As shown in Table 4, a large proportion of survey respondents (approximately 50%) have used the tree-ring information to educate water boards and/or publics about the range of hydrological variability and frequency and severity of droughts. This is also the case with the water utilities we interviewed. Tree-ring data have been used to educate Organization A's board about longer records of streamflow variability and to update drought plans. Organization A's board was happy to see that a longer record of streamflows from the tree-ring record could have been accommodated using current drought plans, and the tree-ring record also gave the water board a better sense of the frequency of drought and restriction events. A water manager from Organization A describes their process of using the tree-ring information for education of their high-level decision makers in the following statement:

> So we took them [the board] through part of the planning process to re-educate or educate them on

> what our planning approach was – the 1950s drought, without restrictions, what we learned from using the tree-rings – and we got a really positive favorable response that made them feel a lot better to see a longer hydrological period. (January 14, 2008, personal communication)

Furthermore, all three organizations and a high proportion of survey respondents (75%) indicated that the tree-ring record was important for gaining a better understanding of hydrologic variability – including the sequences, spells, and persistence of drought (Table 5). Specifically, the tree-ring record has shown many of these water utilities that using the 1950s drought – or another 20th Century drought as the worst-case scenario – may not be adequate for testing water system reliability. The tree-ring record has also helped define breadth of uncertainty and helps place some bounds on expectations for the future, based on the past. These responses seem to indicate that the credibility of tree-rings for use in water management is increasing with better understanding of how these records are produced by scientists.

RESULTS (3): IMPORTANCE OF INSTITUTIONAL CONTEXT AND USER CONSTITUENCIES

Interviews with the three Colorado water utilities also indicated that organizational structure and history greatly affect how tree-ring data are incorporated into planning and operations.

Organization B, for example, is located in an area with several climate research centers and has established relationships with climate scientists. Consultants that work with Organization B were interested in obtaining a better understanding of the magnitude of drought variability even before drought conditions of the 2000s, so they sought out tree-ring data to lengthen the time domain of water system models. A model using tree-ring reconstructions was used to help develop Organization B's 2003 drought plan, which has been embraced by the city council and wider community that they serve (historically a very environmentally active community). Furthermore, Organization B is now in the process of using tree-ring data in conjunction with climate change model output in the next phase of planning. A consultant working for Organization B describes the initial motivation to seek out tree-ring data in the following statement:

> And so, we had a limitation – an analytical problem in terms of only being able to look at the same historical trace [gaged flow record] over and over again. And people have done recombinations, you can do synthesized hydrology traces based on that, but early on I remember reading about the tree ring data that Stockton and Jacoby had done on the Colorado River Basin [in 1976]… and based on that they had cast some doubt as to…"gee, we might actually be having a relatively wet century here"…The next thing they [Organization B's City Council] saw is the drought plan in 2003…at that time, they heard about tree rings and they were fascinated. (January 15, 2008, personal communication)

Conversely, Organization C, a water provider with a more conservative approach to climate change than Organization B, would like to gain a more complete understanding of the tree-ring record as a way to begin assessing the impacts that variability beyond that seen in the gaged record (i.e., over past centuries) may have on their water supply. Organization C is also concerned with the perceptions of their water customers about climate change, so they are very cautious about including paleoclimate data in their current assessments of water supplies. This is primarily because they do not want to create fear that water supplies will decrease in the future and create the possibility that their water users – who currently buy and sell shares of delivery rights in an open market – would "hoard" water.

Survey respondents indicated that there are also social and technical barriers to the use of paleoclimate information (Table 6). Most frequently, these concerns about the use of tree-ring data are related to the perception of tree-ring data by stakeholders (37%) or difficulty incorporating tree-ring data into water models or decision making (30%). A smaller portion of individuals believe tree-ring data is still too uncertain/not credible (22%) or feel that the observed record is sufficient for their needs (15%).

Overall, the survey and interviews point to the important influence of social and political factors on how paleoclimate data are incorporated into water management (particularly aspects of water

TABLE 6. Survey Responses to the Question "Do You or Individuals in Your Organization Have Any of the Following Concerns That Might Limit the Use of Tree-Ring Data?" (respondents could select more than one answer).

Tree-ring data are too uncertain/not credible	22%
Stakeholders/public may not accept/understand use of tree-ring data	37%
Observed/gaged record is sufficient for our planning needs	15%
It is difficult to use tree-ring data in qualitative or quantitative assessments with gage data	22%
It is difficult to incorporate information related to tree-ring data into decision making	30%
None of the above	37%

management related to water supplies and drought management). Just because managers understand the utility and applications of tree-ring data to their work does not necessarily guarantee that they will use it.

RESULTS (4): DATA CHALLENGES AND CONSIDERATIONS

Both interviewees and survey respondents indicated that using tree-ring information in decision making and planning can pose some distinct challenges, including the need for both spatial and temporal disaggregation of the tree-ring data to use it in modeling. Of survey respondents, 22% agreed with the statement: "It is difficult to use tree-ring data in qualitative or quantitative assessments with gage data" (Table 6). Organization A developed an "analog method" to disaggregate the annual reconstructed flow values for their water supply model requiring daily inputs at 450 nodes, matching each year in the reconstruction with a similar year in their model period. Engineers from Organization A, however, indicated that "giant leaps" – i.e., assumptions about the spatial and temporal representativeness of the "analog" data – have to be made in this procedure. One engineer from Organization A said:

> So there's like 450 nodes that we have daily data for, so, using the tree-ring data unfortunately you have to make giant leaps…absolutely giant leaps…so what we did was we…we just went back and found the closest year in the '47 to '91 data that we had, so the year 1680 might have been closest to 1950. And so we used the daily data for 1950 for all the east slope nodes. So, it's a huge leap. (January 14, 2008, personal communication)

Organization A also indicated that they are interested in working with paleoclimate researchers to create ensemble reconstructions of streamflow to obtain a better understanding of the uncertainty of tree-ring records, particularly around extreme low-flow years. This might allow them to get a better sense of the firm yield (the maximum yield deliverable without failure during the gage period, Archfield and Vogel, 2005) of their water system using the tree-ring records. Organization B, however, indicated that the most important factor to them in using tree-ring data, or any climate data, for drought planning is how well the parameters of the water model, and in particular water rights, are specified. They were less concerned with creating new or better streamflow reconstructions and were more interested in creating new applications of tree-ring data, such as analyses that combine past climate variability from tree-rings and projected future climate changes.

Concerns about public perceptions of the use of climate data in planning procedures poses other data concerns for water managers that wish to use tree-ring data in their planning efforts. Although Organization A has developed a strategy for disaggregating the tree-ring data spatially and temporally to provide the necessary input into their water system model, they are still using the 1950s drought for planning, in part because of Environmental Impact Statement (EIS) process requirements. They said that using tree-ring data in their water model might open the organization up to questions about how they determine their water supplies during public review procedures, which are derived from streamflow reconstructions. A water engineer from Organization A said:

> Even if we have everything worked out on a [model] run and we are comfortable with it and have confidence in it, you can't really use that model run so easily for an EIS process because people go "well what happened in October of 1634…why in November this did this happen." (January 14, 2008, personal communication)

As a result, it appears that "data accuracy" in tree-ring applications means different things to different water providers. Some organizations want better reconstruction model skill (e.g., a reconstruction that captures low flows better), while other organizations are satisfied with the reconstruction quality and are more interested in using the data in better water supply models (e.g., a model that handles complex water rights). In any case, acquiring and using tree-ring data has prompted that the organizations more closely examine their drought plans and consider a wider range of variability than is present in the instrumental record.

DISCUSSION OF RESULTS AND CONCLUDING REMARKS

Paleoclimate researchers and water utilities in the western U.S. have embarked upon collaborative and productive partnerships for integrating tree-ring data into water management efforts. The science-policy engagements that we report on here took the form of specific research collaborations between scientists and water providers (e.g., creating specific streamflow reconstructions in consultation with a water utility) and the form of a more general workshop format where researchers and resource managers shared information and experiences related to the integration of paleoclimate data and water resource planning. Our findings show that deliberate and reflexive interactions between scientists and resource managers can improve the accessibility, understanding, and utilization of paleoclimate data in water management, while also providing important feedback to scientists about how their information can be made most relevant to decision makers. We also found that these engagements of scientists and decision makers do, in fact, increase the credibility of tree-ring data within individual organizations, though significant social and institutional barriers may still exist within the water utility itself, or among the utility's users, with respect to incorporation of paleoclimatic data into water planning efforts.

We did find that paleoclimate data can be made relevant to water resource management through many types of applications, from water model inputs to educational information on drought severity. Perhaps most significantly, our evaluation of partnerships between paleoclimate scientists and water managers reveals that these collaborations *do* change the practice of water management in many ways: in quantitative ways such as the inclusion of paleoclimate data in water models, and also qualitative ways including the use of tree-ring information in educational outreach to water utility boards and publics. All of the interviewed research partners and most of the workshop participants who responded to our survey state that they have a better understanding of the range of hydrological variability they may reasonably expect. This improved understanding has been integrated into water models, drought planning efforts, and educational outreach to utility directors and water users. The three water utilities we interviewed for this project have all re-examined their established practice of using the 1950s drought as the worst-case scenario, and they are beginning to incorporate paleoclimate data and streamflow reconstructions into drought management efforts and water supply models to address the finding that more severe droughts have occurred in the past.

This evaluation also reveals many aspects of science-policy interactions that can pose difficulty in meaningful integration of decision making and scientific research efforts. We found that the institutional context and history of a water utility impacts the approach to incorporating paleoclimate data into water management. In the case where there is a history of use of paleoclimate data and information, water utilities have been able to aggressively pursue integration of paleoclimate information into resource planning. Conversely, other water managers have indicated that steps still need to be taken to make paleoclimate data more credible to their publics and board members. This is evidence that interactions between scientists and resource managers occur in complex social and political contexts that must be acknowledged and accounted for in effective partnerships.

Furthermore, our assessment demonstrates the usefulness of the coproduction framework for understanding and evaluating science-policy partnerships. Because environmental policies and planning efforts have important outcomes for the management of ecosystems and natural resources, it is essential that we know why decision makers consider and use scientific information, how it is communicated by scientists to decision makers (and vice versa), and what policies and planning procedures result. By recognizing that science and resource management exist not as separate spheres of practice, but instead are actively coproduced, science-policy partnerships can lead to better water management practice. Going beyond the "delivery" of scientific information, to recognizing its coproduction, can allow scientists and water managers to engage in conversations about planning and research practice. Through active engagement in the coproduction of science and policy, research scientists are afforded the opportunity to help with policy considerations, while resource managers can help define and create scientific research agendas. Furthermore, the role of society, as part of the science-policy engagement should be given more attention in future interactions between managers and research scientists. Given the complexity and severity of the environmental problems facing the western U.S. and other parts of the country, we think these interactions are both necessary and timely. The lessons learned in this work are also broadly applicable to other scientific fields, and are relevant to planning for adaptation to climate change and its impacts on water resources.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. List of interview questions.

Appendix S2. Brief description of interview questions and methods.

Appendix S3. List of survey questions and responses.

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