WESTERN WATER ASSESSMENT
WHITE PAPER

The Colorado Basin River Forecast Center and the Decision Making Process

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Western Water Assessment

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Introduction and background

The National Oceanic and Atmospheric Administration's National Weather Service (NOAA/NWS) operates a network of thirteen River Forecast Centers (RFCs) across the country with the intended purpose of providing water management entities, emergency managers, and others with forecasts of streamflow and volumetric water supply at timescales ranging from hourly to seasonal. These predictions, along with others from entities such as the US Department of Agriculture's Natural Resources Conservation Service (NRCS) in western snow-dominated areas, are designed to provide actionable information that will improve the outcome of a host of decisions relating to issues such as reservoir management, drought restrictions, and flood preparations. NOAA/NWS has made significant investments in developing improved forecasting methods and forecast verification.

Despite these continued technical advances, recent research demonstrates that potential users of forecasts do not always rely on available forecast information in decision making (Werner et al. 2013). Barriers to forecast use have been characterized broadly as technical, financial, legal, cognitive and institutional (Pulwarty and Redmond 1997), and can include political pressure, legal and policy constraints, issues with infrastructure and natural and managed water supply, as well as a lack of scientific background or awareness of forecast availability (Werner et al. 2013).

In an attempt to further understand this disconnect, we developed a study, with input from the Colorado Basin River Forecast Center (CBRFC), to investigate characteristics of the users or potential users of CBRFC forecasts (hereafter referred to as "stakeholders") and their decision making contexts. Previous work has suggested that decision context is an important determinant of how usable information is to decision makers, in addition to the characteristics of information itself such as skill, timing, and accessibility (Dilling and Lemos 2011). Furthermore, water managers who have experienced past weather and climate events such as drought, flood, extreme temperature or precipitation events, etc., are more likely to feel at risk to such events in the future and therefore use forecasts (O'Connor et al. 2005). Accordingly, this study focused specifically on the decision context of CBRFC stakeholders in order to learn:

- Who are CBRFC's main stakeholders, and what roles do they play in water management?
- What weather and climate events have these stakeholders experienced in the past, what do they see as their most important risks now and in the future, and what kind of strategies have they used in the past and plan to use in the future to reduce the impacts of these events?
- What kinds of decisions do they make, what information do they use to make decisions, where do they obtain that information, and what role does that information play in their decision making processes?

In addition, we leveraged this effort to analyze the utility of a use-inspired scientific project developed by our colleagues at the Western Water Assessment Regional Integrated Sciences and Assessments Program (WWA). That effort was aimed at quantifying the contribution of watershed changes—specifically, tree death due to bark beetle infestation along with desert dust deposition on snowpack ("dust on snow"). We investigated whether stakeholders are concerned about these changes and whether improved forecast skill based on the outcome of this project could help to improve stakeholder decision making. Thus we posed an additional set of research questions:

- Are stakeholders aware of and concerned about the impact of dust on snow and bark beetle infestations on streamflow and streamflow forecasts? Would they like information about these impacts? If so, what form should that information take to be usable to them? If forecast skill could be improved by incorporating watershed change information, would that improve stakeholder decision making?

Methodology

We reviewed the literature on decision making and use of information in addition to examining papers discussing previous surveys that focused on use of weather and climate forecasts. We then developed an online survey in consultation with the CBRFC. Three municipal water managers pretested the survey and their comments were incorporated into the final version.

In an attempt to obtain survey responses from both current and potential users of CBRFC forecasts, we drew from lists of attendees at the CBRFC annual stakeholder forum[1] and Colorado River Forecasting Service (CRFS) technical committee meetings, as well as lists of NWS personnel, managers of reservoirs within the CBRFC's forecast area,[2] emergency managers in the region, and a 2013 roster of water organizations compiled by the Bureau of Reclamation for the Upper Colorado region. [3] The CBRFC Hydrologist-in-Charge sent an email to the organization's established stakeholders explaining the purpose of the survey and encouraging them to participate. The survey was then distributed to a total of 142 stakeholders via email through Survey Monkey in June and July 2013. Full or partial responses were received from 69 of those stakeholders (a response rate of 49%). The survey is reproduced in full in Appendix A.

The next step of the project was a qualitative study that sought to add depth to the survey responses through interviews of survey respondents. Twenty-nine survey respondents had responded "yes" to a survey question asking whether they would be willing to participate in a follow-up interview. All 29 were contacted by email and invited to participate in an interview. Eleven of these respondents agreed to be interviewed[4] and were interviewed by telephone in April and May 2014. The interview questions are reproduced in full in Appendix B.

The following sections describe our findings from the survey and interviews.

Characterization of stakeholders

Survey respondents worked for federal (36.5%), state (6%), regional and municipal water agencies (22.5%), water conservancy districts (19%), flood control and irrigation districts (8%), energy-related organizations (3%), and organizations providing either research, consulting, or work on policy issues (5%). Survey respondents were located in Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming. This includes the CBRFC forecast area as well as areas that rely on Colorado water.

1 CBRFC interactions with its stakeholders include holding an annual stakeholder forum at which CBRFC forecasters try to gain a better understanding of stakeholder needs while improving stakeholder understanding of CBRFC products.

2 The list of reservoirs is found at http://www.cbrfc.noaa.gov/gmap/list/list.php?type=damcrit.

3 The current version of the roster is found at https://www.usbr.gov/uc/water/users/roster.pdf.

4 Two additional survey respondents indicated they would be willing to be interviewed but because they did not think they could provide useful information they were not interviewed.

The 11 interviewees represent three water conservancy districts, water providers for major urban areas serving a total of over 20 million customers (Denver and surrounding suburbs, Salt Lake City, southern California including L.A.), a project that delivers water from the Colorado River to Central Arizona including Phoenix and Tucson, a federal hydropower marketing administration, two state water agencies, and a consulting firm that works with water managers. The interviewee organizations are listed in Table 1.

Table 1. Interviewee organizations.

Interviewee organizations
Central Arizona Project
Central Utah Water Conservancy District
Colorado Water Conservation Board
Denver Water
Dolores Water Conservancy District
Riverside Technology, Inc.
Salt Lake City Department of Public Utilities
Upper Yampa Water Conservancy District
Western Area Power Administration
Wyoming State Engineer's Office

The missions of the interviewee organizations involved with water management generally include some combination of protection, development, distribution, conservation and management of water supplies and water rights. In addition, the mission of the Western Area Power Administration involves marketing and delivery of clean, renewable, reliable, cost-based federal hydroelectric power and related services, and the mission of Riverside Technology, Inc. is to apply the best science in terms of snow and water supply hydrology for clients to support their decision making.

The interviewees have occupied their current positions on average 9 years. They are responsible for the following functions and decisions: managing reservoir operations/deciding to release/deliver water, managing facilities maintenance, modeling hydrology and water demands, estimating the amount of available hydropower based on runoff forecasts and the cost of power purchases, assuring state compliance with Colorado River compacts, tracking and evaluating the agency's portfolio of water rights, preparing data for research projects, managing Colorado River resources and developing programs including transfers, agriculture fallow, interstate exchanges, and international programs, overseeing water quality, meteorological and hydrological consulting, protecting water rights for instream flow, making sure treatment plants have water to treat, deciding whether to install and fund stream gages, and making decisions about capital maintenance projects.

Around half of all survey respondents worked in managerial jobs with titles such as manager, superintendent, coordinator, supervisor, chief, president, and/or director. Engineers represented around another 17% of survey respondents, hydrologists 16%, and the remainder chose meteorologist, water resource specialist/planner, scientist/researcher or climatologist as their job title. Forty-six percent of survey respondents identified their affiliation as either Municipal and Industrial (M&I) water management (19%) or "other water management" (27%). In addition, the twenty percent that selected "other" as their affiliation listed water management functions including M&I and agricultural water supplier; municipal water/wastewater system; state government - water rights and oversight of interstate compacts and decrees; reservoir water management; water conservancy district/M&I, industrial, agricultural, environmental and recreational water storage; and M&I, agriculture, recreation, hydropower, and fish and wildlife water management; hydrologic modeling and reservoir operations. This leads us to conclude that up to two-thirds of survey respondents are affiliated in some way with water management. The remainder of survey respondents identified their affiliation as government forecaster (14%), emergency management/flood control (8%), agriculture (5%), and the remainder at 3% or less were scattered among energy, water treatment and research.

The service areas of survey respondents are primarily Colorado, the Colorado River Basin, and Utah, as would be expected of current or potential CBRFC forecast users. Table 2 shows the service areas of survey respondents.

Table 2. Service areas of survey respondents.

States	
Arizona, including municipalities and counties within the state	18%
California, including municipalities and counties within the state	5%
Colorado, including municipalities and counties within the state	34%
Idaho, including municipalities and counties within the state	3%
Nevada, including municipalities and counties within the state	8%
New Mexico, including municipalities and counties within the state	8%
Utah, including municipalities and counties within the state	23%
Wyoming, including municipalities and counties within the state	8%
Regions	
Colorado River Basin	31%
Southwest region (Arizona, New Mexico, Colorado, Utah)	13%
Western U.S.	13%
U.S.-Mexico border	3%
National	3%
Global	2%
n=62, respondents could select all answers that applied	

A list of the rivers that supply water to survey respondents' organizations is included in Appendix C.

Characteristics of M&I water management respondents' systems

Those survey respondents who identified "M&I water management" as their affiliation provided the following information about their water systems:

Their systems ranged in size from 1,000 clients participating in a well augmentation program to 19 million people.

The percentage of their water that comes from groundwater, surface water, or "other" is shown in Table 3.

Table 3. Source of water supply of M&I Water Management survey respondents.

	Groundwater	Surface water	Other[5]
Respondent 1	100%	0	0
Respondent 2	10%	90%	0
Respondent 3	25%	75%	0
Respondent 4	0	100%	0
Respondent 5	100%	0	0
Respondent 6	0	100%	0
Respondent 7	20%	60%	20%
Respondent 8	25%	75%	0
Respondent 9	9%	43%	48%
Respondent 10	40%	60%	0
Respondent 11	16%	68%	16%

The percentage of their water that goes toward industrial/commercial, municipal/residential, agricultural, or other uses is shown in Table 4 .

Table 4. Uses of water supply, M&I Water Management survey respondents.

Respondent	Industrial commercial	Municipal/residential	Agricultural	Other[5]
Respondent 1	25%	75%	0	0
Respondent 2	20%	72%	0	8%
Respondent 3	35%	60%	5%	0
Respondent 4	30%	70%	0	0
Respondent 5	0	100%	0	0
Respondent 6	23%	77%	0	0
Respondent 7	25%	70%	5%	0
Respondent 8	30%	45%	25%	0
Respondent 9	3%	87%	1%	9%
Respondent 10	50%	50%	0	0
Respondent 11	20%	65%	15%	0

5 The survey did not ask for an explanation of "other" answers.

The decision making context of CBRFC stakeholders

We sought to use survey results to better characterize the context in which CBRFC stakeholders make decisions, including their perceptions of risk. As noted above, previous research has found that having experienced certain weather and climate events in the past can influence water managers' perceptions of future risk and their use of forecasts (O'Connor et al. 2005). Thus the survey asked about experiences with a variety of different weather events affecting water management.

Table 5 displays the percentage of survey respondents who have experienced various events in the past 10 years (also shown in Figure 1), and the problems that the events caused. The biggest problem caused by floods and wildfire was unanticipated expenses. For unusually high temperatures the biggest problem was both unanticipated expenses and assuring system reliability which were experienced by slightly more than half of survey respondents experiencing this event. For the remaining events, the largest problem was assuring system reliability. The event that caused lost revenue most often is drought.

Table 5. Events experienced by and problems caused for survey respondents.

		Problems Caused by Event		
Event	**% who have experienced event in past 10 years**	**% who experienced lost revenue from event**	**% who experienced unanticipated expenses from event**	**% who experienced difficulty assuring system reliability from event**
Drought	95%	**52%**	52%	**61%**
Floods	79%	29%	**71%**	49%
Wildfire	69%	32%	**86%**	32%
Unusually high temperatures	69%	21%	**53%**	**53%**
Unusual change in timing of snow melt/snow melt peak flow	61%	13%	33%	**83%**
Unusual change in melt season runoff volumes	53%	33%	29%	**81%**
Unusual change in annual runoff volumes	47%	33%	29%	**79%**
Unusual change in magnitude of snow melt peak flow	47%	9%	41%	**68%**
Unusual change in timing of snow accumulation	44%	16%	21%	**79%**
Unusual change in summer and fall baseflow	24%	27%	20%	**80%**
Unusual change in monsoon season flow	24%	0	44%	**67%**
n=62 (2nd column), n=49 (3rd, 4th, 5th columns), respondents could select all answers that applied				

Figure 1. Events experienced by survey respondents.

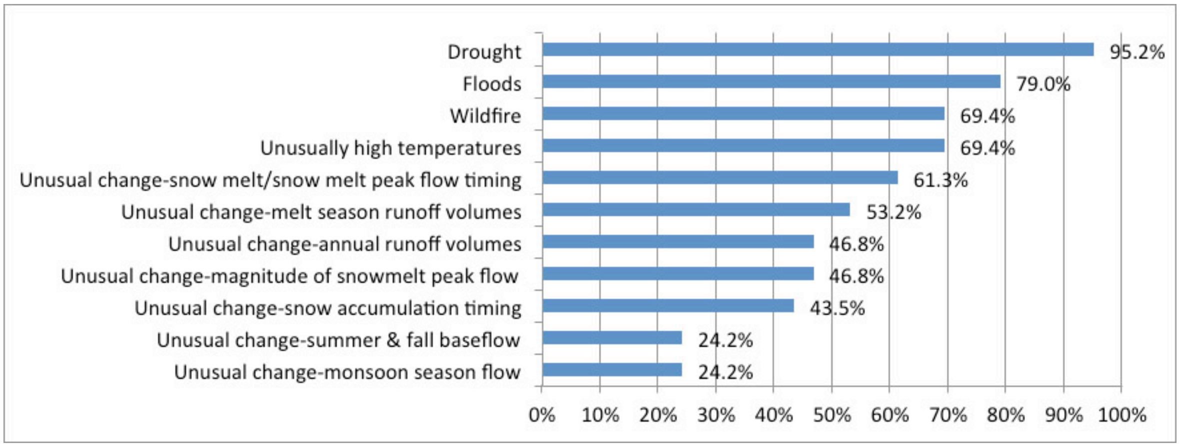


Table 6 displays the events that at least half of all survey respondents have experienced broken down by the organization's geographic service area (shown by state as well as the Colorado River Basin)[6]. Drought is the one event that has been experienced most consistently across the region.

Table 6. Events experienced by service area.

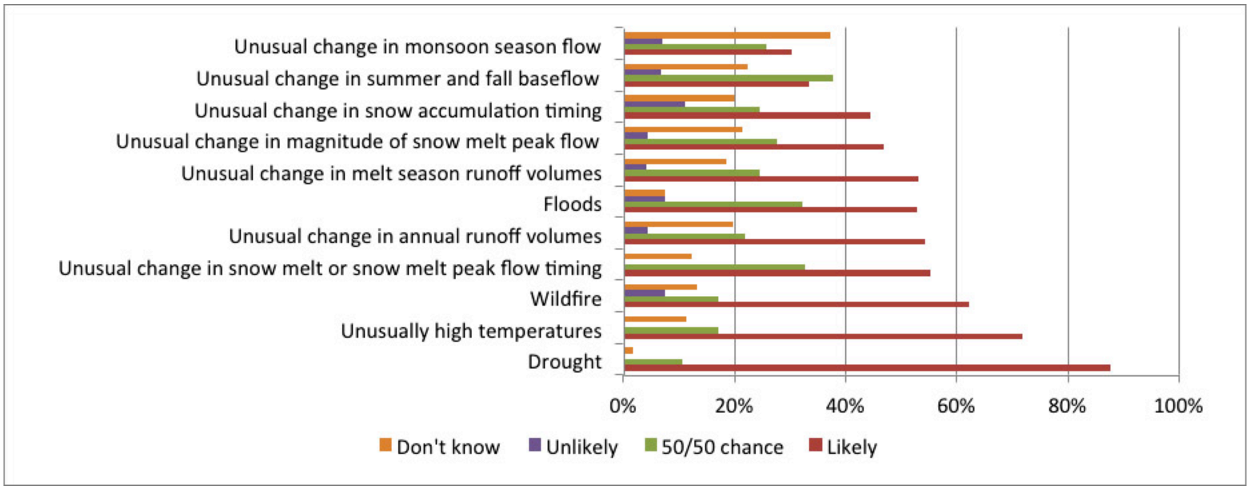
	Service area					
Event experienced	**Arizona N=11**	**Colorado N=21**	**New Mexico N=5**	**Utah N=14**	**Wyoming N=5**	**CO River Basin N=19**
Drought	100%	100%	100%	93%	100%	100%
Floods	100%	62%	80%	93%	80%	68%
Unusually high temperature	91%	76%	80%	64%	60%	84%
Wildfire	82%	67%	60%	79%	80%	58%
Unusual change in timing of snow melt/snow melt peak flow	55%	81%	60%	71%	60%	68%
Unusual change in melt season runoff volumes	55%	67%	100%	71%	60%	63%

Figure 2 shows survey respondents' perception of the likelihood of experiencing impacts from these same events in the next 5-10 years. The highest percentage of survey respondents answering this question felt they were likely to experience drought impacts: almost 100% of survey respondents think it is likely (88%) or there is a 50/50 chance (11%) of experiencing future drought impacts. This response could be explained by the fact that over 95% of survey respondents had experienced drought in the past (see Table 5 and Figure 1), supporting the results of O'Connor et al. (2005) that water managers who experienced problems in the past are likely to expect to experience them in the future. Slightly more survey respondents (72%)

6 Additional service areas identified by survey respondents -- Southwest region (Arizona, New Mexico, Colorado, Utah), Western U.S., National, U.S. Mexico border, Global, Other (mainly California and Nevada) – are not included in Tables 6 or 7 because they cover a much broader area and thus are not as useful in identifying geographic perceptions of risk. The "other" category could not be broken down by state.

felt they are likely to experience future impacts from unusually high temperatures compared to the percentage who had experienced unusually high temperatures in the past (69.4%), possibly reflecting an awareness of projections that the region is expected to become significantly warmer in the future (see, e.g., Lukas et al. 2014; Overpeck et al. 2013). Far fewer respondents thought it was likely they would experience future impacts from floods (53%) compared to those who had experienced floods in the past (79%) in the past. However, another 32% thought there was a 50/50 chance of experiencing impacts from floods in the future. These findings indicate there could be greater uncertainty about future precipitation trends and flood impacts than about future drought or unusually high temperatures, which is consistent with two recent reports about climate and extreme events in the region (Lukas et al. 2014 p. 1; Overpeck et al 2013 p. 127). Other events that more than half of survey respondents felt they were likely to experience in the future include wildfire, unusual change in snow melt or snow melt peak flow timing, unusual change in annual runoff volumes and unusual change in melt season runoff volumes, at levels more or less similar to those who had experienced these events in the past and, again, with a fair amount of uncertainty.

Figure 2. Perception of likelihood of experiencing future impacts from events.



n=57; respondents could select all answers that applied

The perception that the five events shown in Table 6 are *likely* to cause future impacts are broken down by service areas[7] in Table 7 below:

7 Again, we did not include additional service areas identified by survey respondents -- Southwest region (Arizona, New Mexico, Colorado, Utah), Western U.S., National, U.S. Mexico border, Global, Other (please specify) -- in this table because they cover a much broader area and thus are not as useful in identifying geographic perceptions of risk.

Table 7. Events survey respondents felt are "likely" to cause future impacts by service area.

	Service area					
Event likely to cause future impacts	Arizona N=11	Colorado N=19	New Mexico N=5	Utah N=13	Wyoming N=5	CO River Basin N=17
Drought	100%	74%	80%	92%	100%	94%
Floods	55%	44%	60%	54%	60%	38%
Unusually high temperature	91%	61%	80%	92%	80%	88%
Wildfire	73%	59%	80%	69%	100%	56%
Unusual change in timing of snow melt/ snow melt peak flow	50%	56%	60%	50%	60%	69%
Unusual change in melt season runoff volumes	55%	59%	60%	50%	50%	67%

Survey respondents were next asked to choose from a list which mechanisms they used in the past to reduce the impacts from these events. Table 8 indicates the percentage of survey respondents that have used each of these mechanisms in the past, followed by how effective those who used the mechanism found it to be. The most frequently used mechanisms were increased use of CBRFC forecasts[8] followed by increased use of other weather/climate forecasts and instituting a water conservation program. The options are listed in descending order of percentage of use.

Table 8. Mechanisms used by survey respondents in the past and their effectiveness.

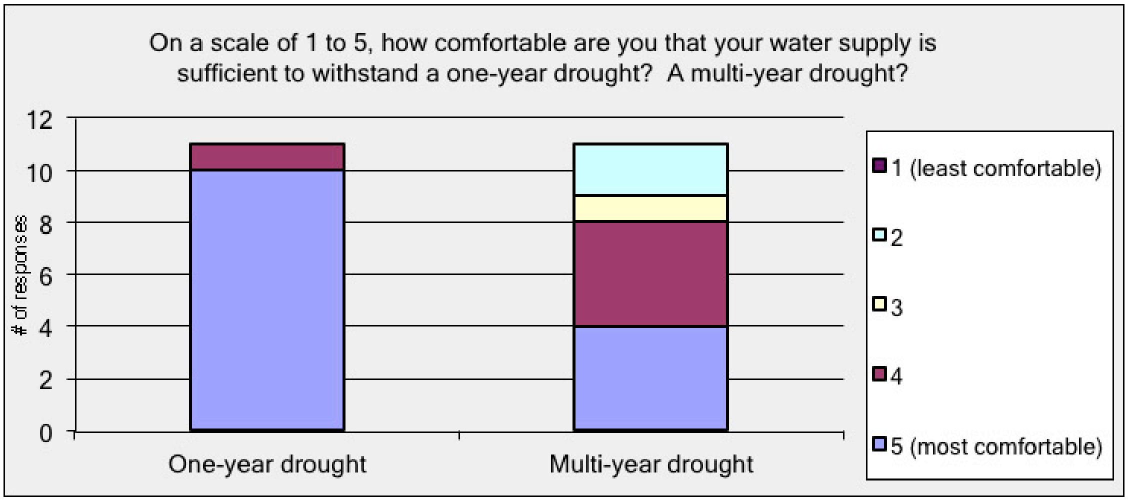
	% who used this mechanism	% labeling this mechanisms very effective	% labeling this mechanism somewhat effective	% labeling this mechanism not at all effective
Increased use of CBRFC forecasts	75%	44%	56%	0%
Increased use of other weather or climate forecasts	71%	29%	69%	2%
Instituted water conservation program	50%	52%	48%	0%
Developed drought plan	45%	36%	59%	5%
Trained personnel	43%	48%	52%	0%
Developed emergency management plan	34%	27%	60%	13%
Increased storage	32%	67%	33%	0%
Transbasin diversion	25%	67%	33%	0%
Purchased water rights or shares	25%	54%	31%	15%
Instituted water budget/raised water rates/imposed surcharge	25%	33%	67%	0%

8 We speculate that this finding may reflect the fact that a high percentage of survey respondents are already engaged with CBRFC as stakeholders and thus more likely to be using their forecasts than water managers and other entities that are not so engaged.

Instituted outdoor water restrictions	21%	73%	27%	0%
Changed staffing level	21%	40%	60%	0%
Increased groundwater pumping capacity	18%	75%	25%	0%
Leased alternative water source/ used water bank	18%	40%	60%	0%
Instituted warning system	16%	63%	38%	0%
Instituted conjunctive use of groundwater and surface water	14%	86%	14%	0%
Other[9]	9%	50%	50%	0%
Built levees	5%	50%	50%	0%
Adopted floodplain zoning	5%	40%	60%	0%
Applied for disaster assistance	4%	100%	0%	0%
Built flood control dam	2%	100%	0%	0%
Evacuated residents	2%			
n=56 (2nd column), 52 (3rd, 4th, 5th columns), Respondents could select all answers that applied				

Those survey respondents who chose M&I water management as their affiliation were asked how comfortable they were, on a scale of 1 to 5, that their system could withstand a 1-year drought and a multi-year drought. As shown in Figure 3, almost all were most comfortable that their system could withstand a 1-year drought, but less than half were as comfortable they could withstand a multi-year drought.

Figure 3. Drought vulnerability perception of M&I survey respondents.



Interviewees have reduced the impacts from weather and climate challenges in the past using a variety of strategies.[10] As described by one interviewee, the conventional approach of water

9 "Other" responses were: 1) built debris trapping structures for wildfire mitigation and burn area restoration, also considering special water assessments to pay for mitigation expenses; 2) sent letter to residents in the flood plain during risk of inundation; 3) tiered water rate structure, twice annual leak detection program, alert customers when leaks are detected by meter system; 4) provide information on these things.

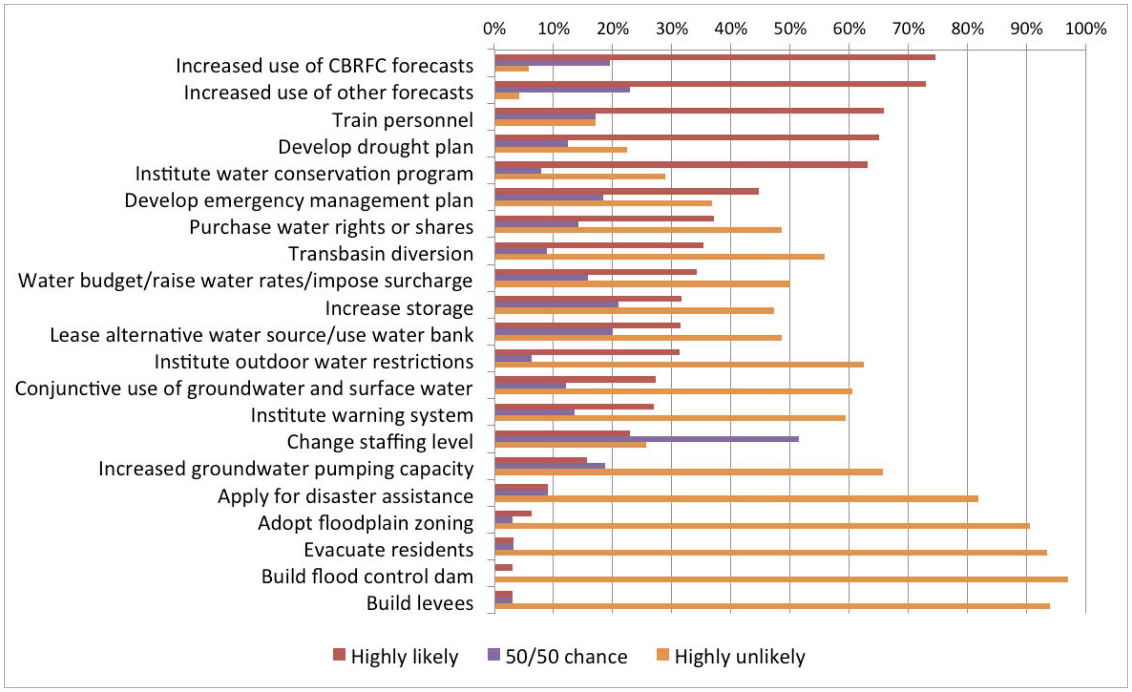
10 Unlike survey respondents who were asked to choose from a list of coping mechanisms, the interviewees were allowed to name any strategies.

managers has been to have enough reservoir storage capacity to guarantee a good water supply going into drought, then draw down reservoirs during drought and wait for wetter weather to return and refill the reservoirs. During high water years, the flood risk downstream is lowered by drawing down reservoirs prior to runoff to have space in the reservoir to capture the peak flow. Other strategies depend on the organization in question and could include improved modeling and forecasting, proportionally reducing allocations (without shorting senior rights), temporary loans and leases to keep fisheries going and keep water in streams during drought, communicating with customers, adjusting budgets, and billing changes. One interviewee changed its contracts with customers so that it can alter the amount of power delivered and have customers take on more of the cost of purchases during droughts. Finally, one organization participated on a statewide drought committee that makes recommendations to the governor.

Two interviewees measure the effectiveness of their strategies by whether reservoirs filled and water supply needs were met while flooding was avoided.

The most likely future mechanisms of survey respondents, with over 60% saying it was highly likely they would use each of the following, were increased use of CBRFC (75%) and other forecasts (73%), training personnel (66%), developing drought plans (65%) and instituting water conservation programs (63%). The least likely future mechanisms, with over half of respondents highly unlikely to adopt them, include transbasin diversions, outdoor water restrictions, increased groundwater pumping capacity, conjunctive use of groundwater and surface water, instituting a warning system, applying for disaster assistance, adopting floodplain zoning, evacuating residents, and building flood control dams or levees.[11]

Figure 4. Likelihood that survey respondents will use selected mechanisms in the future.



n= 52; respondents could select all answers that applied

11 These responses may reflect the mechanisms that the respondents' organizations have authority to institute instead of an assessment of the effectiveness of the mechanism. For example, 100% of respondents who instituted outdoor watering restrictions found them either "very effective" or "somewhat effective", yet only 31% of survey respondents thought it "highly likely" they would use this coping mechanism in the future. Some of the survey respondents may not have the authority to institute outdoor watering restrictions.

Interviewees were asked about strategies for reducing the impacts from future weather and climate challenges.[12] Three interviewees indicated they did not plan to make any changes. Reasons included the perception that the status quo was working and that state and federal water law and rules limit their organization's choice of strategies.

The remaining interviewees are considering a variety of strategies. Several mentioned changes in or improvements to monitoring and forecasts, including helping fund a SNOTEL[13] site or snow course, tracking Colorado River Basin studies that are looking at paleohydrology and climate change, and continuing to rely on streamflow forecasts from the CBRFC, Missouri Basin RFC and NRCS. Some interviewee organizations have started to take steps to include climate change considerations in their decision making by, for example, updating models to incorporate climate change in their assumptions, hiring a consultant to model the impact of climate change on water availability, developing a decision support system that would allow the organization to run different scenarios, taking sea level rise into account when designing projects and trying to gain a better understanding of vulnerability to climate change. Four interviewees plan to use conservation as a future strategy, and three plan to increase reservoir storage. Other strategies include desalination plants, weather augmentation (cloud seeding), aquifer storage and recovery, water reuse, long-term investment in watershed protection, and a better understanding of water demand.

In response to an open-ended question about top concerns, survey respondents most often listed climate variability and change-related issues as top concerns. The general topics mentioned most frequently by survey respondents were:

Top short-term (next few years) concerns:

1. Climate variability/change including extreme events and drought
2. Water supply/demand balance issues
3. Budget issues
4. Wildfire

Top long-term (10-20 years) concerns:

1. Climate variability/change including extreme events and drought
2. Water supply/demand balance issues
3. Colorado River Compact issues
4. Population growth issues

The interviewees indicated that their organizations face a number of short- and long-term challenges, many of which (though not all) are weather- or climate-related. Four interviewees mentioned drought as a significant short-term challenge while two thought flooding would be a significant short-term challenge. A commonly expressed short-term challenge was maximizing and managing the organization's finite water supply to meet multiple demands including agricultural and environmental demands in the face of population growth. Other short-term challenges included protection of water rights, trying to make decisions given forecast

12 Unlike survey respondents who were asked to choose from a list of coping mechanisms, the interviewees were allowed to name any strategies.

13 SNOTEL (short for snow telemetry) is an automated system that collects snowpack and related climatic data in the western U.S. and Alaska. It includes manually measured snow courses and automated SNOTEL stations operated by the Natural Resources Conservation Service (NRCS). http://www.wcc.nrcs.usda.gov/snotel/SNOTEL_brochure.pdf.

uncertainty, predicting the amount and rate of runoff to optimally manage reservoirs, and the impacts of energy development.

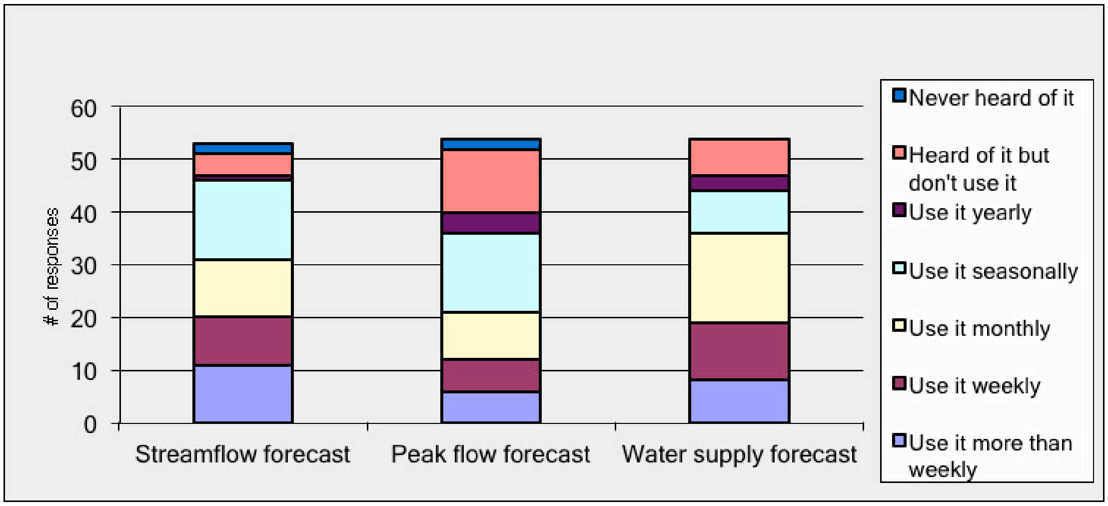
Several interviewees mentioned significant short- and long-term challenges due to potential reductions in Colorado River allocations under the Bureau of Reclamation's 2007 Interim Guidelines once Lake Mead drops below 1075 feet.[14] One interviewee felt it was almost inevitable that the Colorado River will go to a "Tier 1 shortage" by 2017. Another interviewee noted that the combined problems of over-allocation of the Colorado River, drought, declines in Colorado River flows projected by climate models, and declines in Lakes Powell and Mead means we are "living off borrowed time from big reservoirs." Some interviewees mentioned that it would be a significant challenge to protect their customers in light of these anticipated reductions.

Other long-term challenges mentioned by interviewees include future uncertainty regarding climate change and its impacts, maintaining the organization's financial strength, infrastructure issues (aging, physical security in light of vandalism/terrorism threats), the need to replace retiring long-term staff as well as document their years of institutional memory and knowledge, inadequate storage to provide for the long-term needs of customers and from future growth in energy development and agricultural acreage, uncertainty about the success of various programs, uncertainty about changes in water quality standards and having to adapt to changes in the electricity industry.

Use of forecasts from CBRFC and other entities

Most survey respondents have heard of and use streamflow, peak flow, and water supply forecasts produced by the CBRFC.[15] Of the three, the peak flow forecast is used the least frequently even though most respondents had heard of it.

Figure 5. Use of CBRFC forecasts by survey respondents.



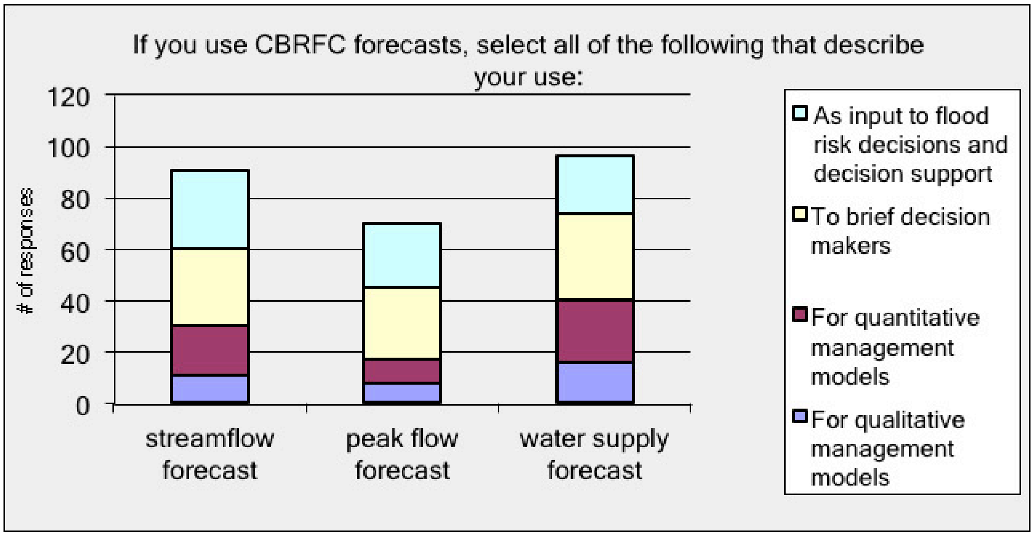
n=54; respondents could select only one response for each type of forecast

14 Record of Decision, Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement (November 2007), http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf.

15 Thirty-six percent of survey respondents are required by legal or policy obligations (contracts, rules, statutes, agreements, etc.) to use CBRFC forecasts in making decisions.

As shown in Figure 6 below, given a choice of four uses, survey respondents indicated that CBRFC forecasts were most often used to brief decision makers and as input to flood risk decisions and decision support.

Figure 6. Types of uses of CBRFC forecasts by survey respondents.



n= 48; respondents could select all answers that applied

Survey respondents find CBRFC forecasts useful for a variety of decisions, primarily related to reservoir operations (timing and volume of releases, power generation, releases for environmental benefits, recreational flows, public notifications). They are also useful for flood-related decisions (near-term river flooding, flood control, purchasing flood insurance), as well as warnings (for floods, high flows, emergency management), forecasts (flood forecasts, Water Supply Outlooks and Forecasts, coordination with NRCS forecasts, second opinion to in-house forecast), for drought planning, declarations and disaster assistance, water and power purchases, Colorado River Compact issues, scheduling maintenance, flows through tunnels, and timing of field work.

These responses were largely reiterated in the interviews. Several interviewees rely on the forecasts to manage reservoirs. Two entities use Ensemble Streamflow Prediction (ESP) traces[16], and one of those organizations uses these traces to develop strategies for setting outflow with the objective to fill its reservoir and avoid downstream flooding. CBRFC forecasts are also used to assess the probability of hitting triggers on Lake Mead under the 2007 Interim Guidelines and then to decide what kind of response is appropriate if a shortage is declared. The CBRFC snow conditions map[17] is used to track accumulating snowpack in the Upper Colorado Basin, which helps determine upcoming streamflow and thus provides an idea of how supply will look in the upcoming season. CBRFC runoff forecasts are also used by the Bureau of Reclamation in their models to decide how to operate reservoirs, the results of which are fed into power system models to determine the best way to release water and how much power to purchase. CBRFC forecasts are used by several organizations to update their boards or for information and public messaging. Another organization uses the forecasts to decide where to conduct fieldwork as

16 ESP (Ensemble Streamflow Prediction), a component of the National Weather Service's River Forecast System, "uses the current hydrologic model states as initial conditions and drives the model using historical temperature and precipitation" to produce probabilistic forecasts (Werner et al. 2004).

17 The map is located at http://www.cbrfc.noaa.gov/lmap/lmap.php?interface=snow.

well as where to focus on protecting water rights for the state. One interviewee couples CBRFC forecasts with operating plans to create decision tools or models. Another interviewee no longer relies on the CBRFC mean forecast for decision making because of problems experienced in the past due to the small size of its reservoir but instead has developed its own analysis using SNOTEL information.

The characteristics of CBRFC forecasts and decision support from the CBRFC

Interviewees praised CBRFC's decision support. Several mentioned that CBRFC is always trying to improve its forecasts. As one interviewee put it, "CBRFC is always trying to advance the forecasting science, constantly looking at improvements, has a nice development/deployment cycle, testing and deciding whether to incorporate into operations." Interviewees specifically liked that CBRFC runs models continuously to see future trends; prepares specific forecasts for agencies and provides other customized forecasts; frequently updates its forecasts (twice a week and more frequently if requested); bases its forecasts on current conditions; provides a hydrograph rather than just a volumetric forecast so users can look at several scenarios for runoff amount and timing which helps manage for extremes; compares the current water year to prior water years as well as the long term average so a user can contrast how the current season compares to prior seasons and the long-term; provides data that are easily transferable, understandable and applicable to user needs; improves the accuracy of its forecasts, especially with new technology such as satellite images; and provides forecasts in real time data.

Features of the CBRFC website that interviewees valued include the water supply links, including the data for reservoirs, streamflow predictions, and snowpack data; and the graphic information about how the forecast is likely changing day to day. They like that information is readily available and accessible online. One interviewee likes the updated format of the website. However, another interviewee observed that, while the website is very complete, he "doesn't want to search for stuff" so instead of using the website this interviewee asks CBRFC staff to identify the specific products needed. Interviewees also like the monthly webinars and annual stakeholder meetings.

Interviewees described CBRFC customer service as very responsive to their needs. They feel that CBRFC makes clear its mission is focused on meeting customer needs. Some noted that CBRFC strives to achieve this mission by constantly asking for feedback which occurs formally at their annual meeting as well as informally-the lines are always open; that its good about soliciting that kind of information—"what's useful, where can we improve;" that its staff talk to users in between meetings and actively work to learn what they need and to customize products. As one interviewee put it, "we tell them 'we want this' and they send us the link to the exact thing we need and if they don't have it, they will develop it." Interviewees described CBRFC as one of the most open, helpful agencies they've ever worked with. They did not think its customer focus was common in other agencies. One interviewee specifically mentioned that interactions with Ashley [a hydrologist with CBRFC] have been excellent, and CBRFC has helped that organization understand the basis for its forecasts. Finally, an interviewee noted that CBRFC is more advanced and transparent than other RFCs, its staff is really responsive to questions such as what went into forecast and how good are models historically, and it will provide forecast information in different formats.

Barriers to forecast use and suggestions for improvement

The largest barrier to survey respondents using CBRFC forecasts was difficulty determining the quality of the forecasts:

Table 9. Limitations to use of CBRFC forecasts.

Limitations to use of CBRFC forecasts.	
Difficulty determining quality of CBRFC forecasts[18]	41%
Other (please specify)[19]	27%
Difficulty knowing which CBRFC forecasts are useful	22%
Inaccuracy of CBRFC forecasts	22%
Lack of familiarity with CBRFC forecasts	22%
My organization's operating procedures	19%
Conflict between CBRFC forecasts and other forecasts I use	19%
Difficulty interpreting CBRFC forecasts	16%
Conflict between CBRFC forecasts & non-forecast factors	8%
Conflict between CBRFC forecasts & our organization's internal tools	5%
Legal constraints	3%
n= 37, respondents could select all answers that applied	

Survey respondents who do not use CBRFC forecasts stated that the following would have to change for them to begin using the forecasts: 1) include the Rio Grande basin;[20] 2) improve the web page maps to handle southern Arizona better;[21] 3) for users of Internet Explorer 8 repair webpages to render properly, especially map interfaces; 4) forecast for flash flooding

Interviewees were asked if there was a level of forecast skill they expected from CBRFC. Their responses indicate that many may have answered the question in terms of forecast accuracy instead of skill.[22] Several didn't have a specific level other than "the more accurate the better." Further, there seemed to be some uncertainty about how to measure forecast skill. One interviewee acknowledged that he doesn't understand skill enough to comment on it. Others suggested a metric but seemed uncertain about it, as illustrated by these two comments: "I would think that the level of forecast skill is the measure of the percentage of time that the forecast is 80% correct. Perhaps percent of time is not the correct metric, I'm not sure of that. I don't know if there's one metric that can be more helpful." "If CBRFC gets close 75% of time…though not really sure where that cutoff will be." One interviewee suggested a metric of "accurate every year +/- 5-10%" but acknowledged that was not very realistic. Another indicated that the level of skill has gotten a lot better and he expects it to keep improving. He and others acknowledged that forecast reliability declines with longer lead time, and that long-range weather forecasting capabilities are beyond current skill levels and there is no technology right now to improve that skill. His hope is that satellite and remote sensing technology can help. Another interviewee

18 The survey question used the term "quality" broadly without defining it. It could have been interpreted by survey respondents to mean either skill or accuracy or both.

19 "Other" reasons include: 1) do not apply to Rio Grande basin; 2) flash floods aren't forecastable;3) conflict between CBRFC forecasts and our organization's unique internal tools; 4) I'm new at this, I need to learn more about the capabilities of the system; 5) slow webpage; 6) organization does its own forecasting for the locations of interest but appreciates the ability to compare its model output with the CBRFC's independent forecast at the same location.

20 CBRFC indicates that this is handled by a different RFC (West Gulf RFC), but that the water supply forecasts for that basin are available on the CBRFC web page.

21 CBRFC indicates it is fixing this problem.

22 Forecast skill measures how the forecast improved on persistence or climatology.

was hopeful that re-forecasts being evaluated in the CBRFC/NOAA-SARP project may increase forecasting skill. Finally, one interviewee suggested that having forecasts through the end of the upcoming water year was a reasonable expectation that would retain the same level of skill. More important to interviewees than meeting a minimum level of skill or accuracy is that CBRFC explains forecast uncertainty so that interviewees can understand and explain it to their customers and not represent forecasts as more accurate or skillful than they are. Interviewees agreed that CBRFC does a good job explaining uncertainties as well as the median, 50% and 90% projections.

Interviewees had several suggestions for improvements to CBRFC forecasts or additional information they would like, some of which may be beyond current capabilities:[23] 1) greater use of satellite data and remote sensing information/technology of snow covered area that is incorporated into models; 2) incorporating advanced data assimilation techniques*; 3) better understanding of model reliability and skill; 4) using numerical weather prediction models in probabilistic forecast as future climate scenarios as opposed to historic weather information*; 5) better long-range monsoon forecast; 6) better quality of information upstream from Flaming Gorge*; 7) based on results of the CBRFC and NOAA-SARP's co-project regarding the Parleys Watershed System using the re-forecasting techniques, and running those data through the hydrology models, for future forecasting of the reservoir management*; 8) show snowpack as percent of average (rather than percent of median) like they did in the past (runoff and precipitation are still shown as percent of average)[24] ; 9) have the same runoff percentages (currently 10, 30, 50, 70, 90) and peak flow percentages (currently 10, 25, 50, 75, 90); 10) have CBRFC work together with the NRCS again to put out a forecast (as one interviewee put it, "it's very confusing who's doing what"); 11) provide a forecast beyond 5-7 days on actual river flows; and 12) visuals showing big synoptic storm tracks. However, one interviewee observed that water managers already have too much information and are overwhelmed by it.

Other forecasts and Information used in decision making

Survey respondents used a variety of other products in addition to CBRFC forecasts in decision making, most often the U.S. Drought Monitor, U.S. Seasonal Drought Outlook, Climate Prediction Center Precipitation Products, and CBRFC Forecast Briefings:

Table 10. Other information used by survey respondents in decision making.

Product	% of survey respondents using
U.S. Drought Monitor	67%
U.S. Seasonal Drought Outlook	65%
Climate Prediction Center Precipitation Products	63%
CBRFC Forecast Briefings	63%
Climate Prediction Center Temperature Products	55%
NRCS State Basin Outlook Reports	53%
Climate Prediction Center (CPC) ENSO Update	41%
Surface Water Supply Index (SWSI)	37%

23 Those suggestions that are already under development are indicated with an asterisk.
24 CBRFC indicates this is still available.

Multivariate ENSO Index	35%
Palmer Drought Severity Index (PDSI)	29%
Western Regional Climate Center	29%
Western Water Assessment (WWA) Intermountain West Climate Dashboard	28%
Information from Colorado's Statewide Water Availability Task Force	24%
SWCast (Klaus Wolter)	24%
Standardized Precipitation Index (SPI)	22%
Climate Assessment for the Southwest (CLIMAS) Southwest Climate Outlook	20%
NIDIS Weekly Drought Webinars	20%
U.S. Hazards Assessment	16%
IRI ENSO Information	14%
Other (please specify)[25]	10%
Denver Water Water Watch Report	6%
Vegetation Drought Response Index (VegDri)	4%
Crop Moisture Index (CMI)	4%
n=51, respondents could select all answers that applied	

In addition to CBRFC forecasts and the information listed above, interviewees rely on data from state water resources agencies, SNOTEL sites, Salt Lake City Public Utilities snow courses, national digital forecast database for temperature and precipitation, SNODAS near-term snow forecast products[26], Missouri Basin and other RFCs, Northern Water, Bureau of Reclamation's 24 month study, in-house forecasts and data[27], and USGS data. Two interviewees mentioned the Colorado Dust-On-Snow (CODOS) program.[28] One stated that his organization actively supports the program, and another mentioned that CODOS creates maps showing where dust layers have been deposited over time which helps identify whether melting will accelerate.

Interviewees used the non-CBRFC forecasts for several reasons. Some thought that more information leads to better results. They note that the information is available and may be useful, and while there is some duplication, each forecasting agency has a unique role and skill set. For example, the state water resources agency knows the status of streams at a much more granular scale than CBRFC. The CPC long range forecasts are the "gold standard" for long term dry/wet, cool/warm forecasts which are separate from what CBRFC provides. The National Integrated Drought Information System (NIDIS) is more focused on drought and low flow while CBRFC is more of a resource for flood conditions and water supply. Further, water management agencies don't have staff or expertise to do their own forecasts and would rather rely on experts. Finally, NRCS has a lengthy track record.

25 "Other" responses were: 1) NRCS SNOTEL sites (http://www.wcc.nrcs.usda.gov/snow); 2) NWS Weather Prediction Center (WPC) Quantitative Precipitation Forecasts (http://www.wpc.ncep.noaa.gov/qpf/qpf2.shtml), Jet Stream Maps, Northern Water's Water Supply Index, Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) precipitation data (http://www.cocorahs.org), SC ACIS, Snow Alarm (http://snowalarm.com/models.php); 3) related webinars.

26 http://nsidc.org/data/docs/noaa/g02158_snodas_snow_cover_model

27 Thirty-eight percent of survey respondents generate internal forecasts and 49% rely on their internally generated forecasts or metrics in making decisions.

28 Colorado Dust-on-Snow program, http://www.codos.org/#codos.

All interviewees plan to rely on this non-CBRFC forecast information in the future for a variety of reasons including the possibility of advancements and interesting ways of applying forecasts, the need for any good inputs to improve decision support systems they're trying to build, expected future data enhancements from the technology that is under development, and the need for coping mechanisms for future increases in drought intensity and potentially critical scenarios on Lake Mead.

Interviewees also rely on the following non-weather and climate information in making decisions: budget; amount of water in storage; personal experience/gut instinct of people who have lived in the area for many years; on-the-ground, direct observation; operational constraints—physical or political limitations to decisions; projections of water demand; estimates of electricity prices and trends; datasets of water supply and water availability; and Bureau of Reclamation criteria for federal projects.

Interviewees indicated that the amount of weight they give to CBRFC forecasts when making decisions relative to other information depends on several factors, including the type of decision, the time of year and geographical location. Reservoir operators rely heavily on CBRFC forecasts since those forecasts are considered accepted input. The Bureau of Reclamation is legally required to use CBRFC forecasts in its 24 month operating report. Even water managers who are not legally required to use CBRFC forecasts still do so since it would be difficult to explain to stakeholders why they did not use CBRFC forecasts if their decisions turned out to be wrong. One interviewee whose agency relies heavily on the 24-month Bureau of Reclamation study quantified the weight given to CBRFC forecasts as "between a little and 50/50, not a lot." Several interviewees give greater weight to CBRFC forecasts the closer it gets to snowmelt season. One decision maker indicated CBRFC forecasts are weighted "80%" closer to runoff but only "40%" in April. Earlier in the season one interviewee relies on his organization's own regression analysis. Geographical location was a factor in how much weight two interviewees give to CBRFC forecasts. For one, the forecasts are weighted heavily for inflows into Flaming Gorge and operations downstream because they do a good job but less weight is given to CBRFC forecasts upstream. For another, the weight depends on how close you are to critical elevations. However, this decision maker noted that his organization makes decisions about investing in multi-million dollar projects, so even if not much weight is given to the forecast, it's on a big decision so the forecast has an impact.

Mountain pine beetle and dust on snow

An ongoing WWA research project has been examining the impacts on snowmelt of dust on snow and bark beetle infestations. Deems et al. (2013) found that, depending on severity, dust can shift peak snowmelt up to 6 weeks earlier and reduce annual flow volume up to 6% compared to pre-disturbance conditions. A later simulation of catchment-scale impacts from dust and beetle disturbances found that beetle infestations increased annual water yield between 8 and 13 percent, dust deposition in the same catchments caused snowmelt to occur earlier, and the two disturbances appeared to have little interactive effect (Livneh et al. 2015).

This project sought to analyze the potential for the WWA research to be usable in the CBFRC context, specifically, how such information can improve stakeholder decision making. To explore these issues we first asked survey respondents about their awareness of and concern about the potential of mountain pine beetle (MPB)[29] infestations and dust on snow to affect streamflow

29 The survey used the term "mountain pine beetle" but the problem extends to other types of beetles, so the generic term "bark beetle" is more appropriate.

and streamflow forecasts. We found that 47% of survey respondents were very aware and 36% were somewhat aware (total of 83%) of the potential for MPB to affect streamflow. They learned of the problem mainly through word of mouth or conferences; 36% learned of it from WWA. A total of 19% of survey respondents were very concerned and 45% were somewhat concerned (total of 64%) about the impact of MPB on streamflow. Another 19% were very concerned and 41.5% were somewhat concerned (total of 60.5%) about the impact on streamflow forecasts.

We further found that 74% of survey respondents were very aware and 15% were somewhat aware (total of 89%) of the potential for dust on snow to affect streamflow. As with MPB, they learned mainly through word of mouth or conferences; 38% learned from WWA. A total of 28% of survey respondents were very concerned and 51% were somewhat concerned (total of 79%) about the impact of dust on snow on streamflow, while 21% were very concerned and 53% were somewhat concerned (total of 74%) about the impact of dust on snow on streamflow forecasts.

Interviewees were asked if they had noticed any impacts to their operations and decision making from dust on snow and/or bark beetles. While several were aware of the scientific findings concerning dust and beetle impacts, only one interviewee attributed observed changes in runoff in his area to dust. Since dust has already had impacts within the forecast area, other interviewees may not have made the connection between impacts they experienced and dust. Another interviewee did not see the timing of melt from dust as a big issue for his organization—noting "it's going to melt eventually," as long as supplies arrive[30]. One interviewee did not notice any direct impacts, but acknowledged his organization could be affected if dust is taken into account by the Bureau of Reclamation in making water releases. Another interviewee noted that bark beetles have killed some trees in that organization's watershed but due to the diverse age class and diversity of tree species, the forests in that area haven't been completely devastated by the beetles. One thought the beetles had peaked in his area and were declining.

Several interviewees nevertheless expressed concern about future potential impacts. One mentioned studies concluding that a 5% reduction in runoff from dust would mean less water, which could put his agency more at risk for cutbacks and require that it spend more money on water programs because of dust. Another interviewee thinks dust and/or beetle impacts are going to become critical since earlier runoff has implications for the irrigation season and snowpack throughout the year. One specifically wanted to know of impacts from dust to both snowmelt timing and volume decreases so his organization doesn't overestimate inflow and draw down its reservoir so they can't refill it. Timing is important to this organization because it wants space in reservoirs when the peak hits. It operates its system first for water supply, but if opportunities arise it tries to operate for environment enhancement or recreation or to reduce flood risk as well.

Interviewees were asked what information about the hydrologic impacts from dust on snow and bark beetle infestations would be useful to them and whether it could be incorporated into products they currently use. Three interviewees did not think the information would be useful at this time or felt they had more important concerns. Although one was aware of the scientific information about dust and beetles, he did not think this information would have any practical impact on operations since nothing could be done about it. He was more concerned about the impact to reservoirs from forest fires than in changes in the rate or timing of runoff. Another interviewee was not aware of any impacts to operations from dust or beetles, but said, "If we see major operational things in future, we'll worry." A third interviewee felt that it was perhaps too

30 This interviewee did not mention the potential impact to flow volume from dust or beetles.

early for information on these phenomena to be useful: “I think it will become more important and pressing if climate change impacts were more felt to a greater degree. Down the road, it may have a larger impact. The more information the better to try to improve the water supply forecast. At the same time, maybe it’s not quite the right timing yet.” However, this interviewee did think that building the information into the forecast or even better showing it separately on a CBRFC map would be a good idea because climate change is happening even more quickly than anticipated. It was unclear to this interviewee how the information could be incorporated into a model.

The remaining interviewees are interested in obtaining information about dust and/or beetle impacts. The interviewee who has firsthand experience of dust accelerating runoff knows it affects CBRFC shorter-term outlooks at his site and feels information about it should be incorporated into those forecasts. Knowing the short-term impact of dust would be relevant to decisions especially around rafting releases. Several other interviewees would like CBRFC to incorporate the impacts of dust (both volume and timing) and beetles into streamflow and water supply forecasts and ESP traces, with some acknowledging that this might have to wait until “the science gets there.” It was suggested that WWA work with CBRFC to incorporate dust and bark beetle research into forecasts. Another suggestion was to provide a basin-wide estimate of how much dust affects runoff annually, what are potential options for reducing dust, how much is anthropogenic or potentially controllable, what would costs be (cost/benefit analysis), and other impacts from mitigating dust. This interviewee would like a quantification of the individual impacts of weather modification, tamarisk removal, dust and beetles on water supply which would help identify actions that could have the biggest impact. One observed that, on the Colorado River, dust has the biggest impact on peak forecasts, and there needs to be better information to understand the impact and what it means when peaks are higher than expected. Another area of interest was the impact of dust and beetles on water quality. Finally, one interviewee wanted more research on how beetles would affect operations and for what period of time, whether the beetle situation is temporary or permanent, and whether there are mitigation options or “we have to live with it”?

When asked how best to disseminate the dust or beetle information some interviewees would prefer to have the information incorporated into forecasts rather than shown separately. Their organizations lack capacity to adjust forecasts if the information is provided separately, which could be a widespread problem. The information could be incorporated into CBRFC streamflow forecasts and short-term outlooks and then yields from years without impacts could be compared to years with impacts by, for example, adding a line on the same graph or a layer on a map where you can zoom in to different areas to see how this year’s impacts compare to an average year, the previous year, and a high impact year, as well as how the average is changing. Other interviewees would prefer to have the information shown separately in addition to or instead of being incorporated into forecasts but again the emphasis was on being able to determine whether impacts are normal for that year. One interviewee thought the answer was to “just make it known that it’s a factor however you do it”. Another suggested that it would be helpful to have access to an online time lapse camera that would allow users to see what day dust is evident since most dust events are followed by snow events. This interviewee would know some melt accelerator is going to occur by being able to watch snow melt until dust is visible.

Some concern was expressed that new websites for dust and beetle impacts should not be created without a good reason. The Colorado Dust-On-Snow program website already provides quite a bit of information.[31] One interviewee thought the focus should be on existing technologies,

31 See the Colorado Dust-On-Snow program website at http://www.codos.org/#codos.

incorporating information into what we have, and building on history. In order to educate users one interviewee suggested that WWA facilitate a "Forecasting 101" series that would discuss dust on snow and bark beetle impacts. Finally, one interviewee suggested that researchers should seek input from the Colorado Basin States Biannual Technical Meeting about how studies should be done, then after presenting their findings ask the group how best to provide the information. The agenda for this group is set by Don Osler (Upper Basin) and Colby Pellegrino (Lower Basin).

Finally, interviewees were asked what kind of time horizon they would like (i.e., daily/weekly/seasonal) for the dust and beetle information. Two felt that timing would depend on the type of information being provided. For example, with bark beetle there might be more seasonal effects (you won't see it come and go), while with dust one would need more frequent information. If a dust layer is exposed, receiving information weekly would be desirable. One of these interviewees would like a daily update for snowpack, precipitation and how runoff is likely changing. Other interviewees mentioned wanting the information out one or two weeks, depending on skill. Extending long term weather trends is helpful for volumetric. Two interviewees felt the current frequency of CBRFC and Bureau of Reclamation forecasts and time horizons are about right. Other interviewees were interested in longer-term information but acknowledged that is not currently feasible. Finally, one interviewee "wants it texted to me as it's happening but that's not a reality".

Summary of findings

This study was intended to answer several questions. We briefly summarize our findings below.

1. Who are CBRFC's main stakeholders, and what role do they play in water management?

- Most survey respondents work for federal, state, regional or municipal water agencies and water conservancy districts located in Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming.
- Well over half of survey respondents are affiliated with water management.
- Interviewees represent conservancy districts, water providers for major urban areas, a federal hydropower marketing administration, two state-level water agencies, and a consulting firm.
- Interviewees are involved with reservoir management, facilities maintenance, modeling, estimating available hydropower, assuring state compliance with Colorado River compacts, tracking and evaluating water rights, preparing data for research projects, managing Colorado River resources, overseeing water quality, protecting water rights for instream flow, making sure treatment plants have water to treat, and deciding whether to install and fund stream gages.

2. What weather and climate problems have these stakeholders experienced in the past, what do they see as their most important risks now and in the future, and what kind of coping strategies do they use?

- Most survey respondents have experienced primarily drought but also floods, unusually high temperatures, wildfire and unusual change in snowmelt timing and runoff volume.

- Survey respondents mainly expect to experience drought, unusually high temperatures and wildfire in the next 5-10 years.

- The top short and long-term overall challenges for survey respondents are climate variability/ change including extreme events and drought and water supply/demand balance issues. Other top short-term concerns are budget issues and wildfire, while other top long-term concerns are Colorado River Compact issues and population growth.

- Drought and flooding, as well as maximizing and managing the organization's finite water supply to meet multiple demands, are top short-term concerns of interviewees while climate change is more of a long-term concern. The potential reduction in Colorado River allocations under the Bureau of Reclamation's 2007 Interim Guidelines is both a short and long-term concern for several interviewees.

- Survey respondents largely reduced the impacts from these events in the past through use of CBRFC and other forecasts. The most likely future mechanisms of survey respondents to reduce impacts are increased use of CBRFC and other forecasts, training personnel, developing drought plans and instituting water conservation programs.

- Interviewees have reduced impacts from events in the past through reservoir management, improved modeling and forecasting, proportionally reducing allocations, temporary loans and leases to keep fisheries going and keep water in streams during drought, communicating with customers, adjusting budgets, and billing changes. Future mechanisms for interviewees include monitoring and forecasting, incorporating climate change considerations in their decision making, conservation, increasing reservoir storage, desalination, weather augmentation, aquifer storage and recovery, water reuse, long-term investment in watershed protection, and a better understanding of water demand.

3. What kinds of decisions do stakeholders make, what information do they use to make decisions, where do they obtain that information and what role does that information play in their decision making processes?

- Most survey respondents had heard of and use CBRFC peak flow, streamflow and water supply forecasts.

- CBRFC forecasts are useful to survey respondents and interviewees for a variety of decisions, primarily related to reservoir operations but also flood-related decisions, warnings, forecasts, for drought declarations and disaster assistance, water and power purchases, Colorado River Compact issues, scheduling maintenance, flows through tunnels, timing of field work, to update boards, and for public messaging.

- At least half of survey respondents use the following other forecast products in making decisions: U.S. Drought Monitor, U.S. Seasonal Drought Outlook, Climate Prediction Center Precipitation Products, CBRFC Forecast Briefings, Climate Prediction Center Temperature Products and NRCS State Basin Outlook Reports.

- In the future, interviewees are likely to continue using forecasts other than those produced by CBRFC. The forecasts often provide information that is not included in CBRFC forecasts.

- The weight interviewees give to CBRFC forecasts when making decisions relative to other information depends on several factors, including the type of decision, the time of year and geographical location. Reservoir operators may rely most heavily on CBRFC forecasts since those forecasts are considered accepted input and, in some cases, are required by law or policy.

4. Are stakeholders aware of and concerned about the impact of dust on snow and bark beetle infestations on streamflow and streamflow forecasts? Would they like information about these impacts? If so, what form should that information take to be usable to them? If forecast skill could be improved by incorporating watershed change information, would that improve stakeholder decision making?

- Most survey respondents are aware of and concerned about the impact of bark beetles and dust on snow on both streamflow and streamflow forecasts, though somewhat more concerned about dust on snow impacts.

- Interviewees generally are aware of the scientific findings in this area but only one attributed impacts that his organization has already experienced to dust.

- Several interviewees are concerned about future potential impacts from beetles and dust and would like information about impacts either incorporated directly into CBRFC forecasts or displayed separately or both, as well as seeing how the current impacts compare to those in previous years as well as average and high years.

- For some interviewees it is difficult to sort through all of the information that is already available.

Conclusions and Implications Moving Forward

CBRFC forecasts are likely to be used for a variety of water management and other decisions in the future. They are the most cited mechanism among this group of stakeholders for reducing the impacts from present and future weather and climate-related events such as drought, floods, wildfire, unusually high temperatures and unusual changes in snowmelt timing, which survey respondents expect will recur in the future.

Both survey respondents and interviewees are mostly aware of and concerned about the impact of bark beetles and dust on snow on streamflow and streamflow forecasts, though only one interviewee attributed impacts that his organization had already experienced to dust on snow. Some interviewees observed that dust and beetle information will become more important and pressing in the future when climate change impacts are felt to a greater degree, which raises the research question to what extent will responding to dust and beetle impacts “use up” the adaptive capacity that is available for responding to other climate change impacts.

Most interviewees would like to see information about beetles and dust on snow either incorporated into existing CBRFC forecasts or displayed separately, with an indication of how the current year compares to past years and the average for dust. Additional research could identify the optimal method of providing this information to maximize its usability by decision makers.

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Appendix A

The Colorado Basin River Forecast Center (CBRFC) is one of 13 National Weather Service (NWS) River Forecast Centers which are located within major river basins throughout the U.S. The National Weather Service is a component of the National Oceanic and Atmospheric Administration (NOAA), an Operating Unit of the U.S. Department of Commerce. The NWS's mission is to "provide weather, water, and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy." The mission of the RFCs is to produce the Nation's river, flood and water supply forecasts in support of saving lives and property and to enhance the economy and environment of the country. The CBRFC generates streamflow forecasts across the Colorado Basin and Utah.

The Western Water Assessment (WWA) is collaborating with the CBRFC to improve forecasts and their application to stakeholder decision making processes. To accomplish that goal the WWA is conducting this survey among stakeholders of the CBRFC to 1) assess the current use of CBRFC products in decision making, and 2) understand the vulnerabilities and coping strategies of stakeholders in order to better tailor CBRFC products to reducing those

vulnerabilities. "CBRFC stakeholders" include people who have attended a CBRFC stakeholder meeting or otherwise have interacted with the CBRFC or who could use CBRFC forecasts in their decision making processes.

We greatly appreciate your time and effort in completing this survey. All information obtained from the survey will help provide feedback to both the CBRFC and WWA for input into ongoing and future efforts to improve forecast products.

Please contact Bobbie Klein (bklein@colorado.edu) if you have any questions.

The following page is a consent form. We want you to understand what you are being asked to do and what risks and benefits are associated with the study. This form should help you decide whether to participate in this survey.

*1. Please read the following material that explains this research study. Clicking yes below will indicate that you have been informed about the study and that you want to participate. We want you to understand what you are being asked to do and what risks and benefits—if any—are associated with the study. This should help you decide whether or not you want to participate in the study.

You are being asked to take part in a research project conducted by Bobbie Klein, Managing Director of the Center for Science and Technology Policy Research at the University of Colorado at Boulder, 488 UCB, Boulder, CO 80309-488.

This project is under the direction of Professor Lisa Dilling, Department of Environmental Studies and Center for Science and Technology Policy Research, 488 UCB. Bobbie Klein can be reached at 303-735-3751 or bklein@colorado.edu. Professor Dilling can be reached at 303-735-3678.

If you agree to take part in this study, you will be asked to complete an online survey that will last approximately 20 minutes. The survey can be accessed from any location where you have internet access and can be taken at any time up until one month after the survey start date.

There are no foreseeable risks or discomforts for participating in this study. You may not receive any direct benefit from taking part in this study. However, by participating in this study subjects can help to inform the research community and the CBRFC about their use of CBRFC products in decision making, as well as their vulnerabilities in order to better tailor CBRFC products to reducing those vulnerabilities. Data that we collect can be used to inform and direct future research and products.

Funding for this study is being provided by the Western Water Assessment.

You have the right to withdraw your consent or stop participating at any time. You have the right to refuse to answer any question(s) or refuse to participate in any procedure for any reason. Refusing to participate in this study will not result in any penalty or loss of benefits to which you are otherwise entitled.

We will make every effort to maintain the privacy of your responses. Only the primary researchers will have access to the data and information about participation will not be shared with others including the superiors or coworkers of participating employees. No identifying information will be used when results are published.

Other than the researchers, only regulatory agencies such as the Office of Human Research Protections and the University of Colorado at Boulder Institutional Review may see your individual data as part of routine audits.

If you have questions regarding your rights as a participant, any concerns regarding this project or any dissatisfaction with any aspect of this study, you may report them confidentially to the Institutional Review Board, 3100 Marine Street, Rm A15, 563 UCB,

(303) 735-3702.

AUTHORIZATION

I have read this information about the study or it was read to me. I know the possible risks and benefits. I know that being in this study is voluntary. I choose to be in this study. I know that I can withdraw at any time.

- Yes, I agree to the above consent form.
- No, I don't agree to the above consent form

Section 1. Background information about stakeholders

2. What organization do you work for?

3. What is your job title?

5

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4. Which of the following best describes your affiliation. Please select only one:

- Agriculture
- Emergency management/flood control
- Energy
- Forestry & Ecosystem Management
- Government forecaster
- M&I Water Management
- Other Water Management
- Public Interest and Education
- Ranching
- Research
- Tourism and Recreation
- Water Treatment
- Wildlife and Fisheries Management
- Other (please specify)

Section 1.A. Information about municipal water systems

5. How many people does your system serve?

6. What percentage of your water comes from the following sources (total=100%):

Groundwater

Surface Water

Other

7. What percentage of your water goes to the following uses (total=100%). If you need to explain your answer please use the box at the end of this survey:

Industrial/commercial

Municipal/residential

Agriculture

Other

8. On a scale of 1 to 5, how comfortable are you that your water supply is sufficient to withstand a one-year drought? A multi-year drought?

	1 (least comfortable)	2	3	4	5 (most comfortable)
One-year drought					
Multi-year drought					

If you would like to explain your answer, please do so here (optional):

9. Please identify your organization's service area. Select all that apply.

- Arizona, including municipalities and counties within the state
- Colorado, including municipalities and counties within the state
- New Mexico, including municipalities and counties within the state
- Utah, including municipalities and counties within the state
- Wyoming, including municipalities and counties within the state
- Southwest region (Arizona, New Mexico, Colorado, Utah)
- Colorado River Basin
- Western U.S.
- National
- U.S.-Mexico border
- Global
- Other (please specify)

10. If applicable, please identify the source(s) of water for your water supply (for example, Colorado River):

Section 2. Vulnerability

11. Please check all of the following events that your system has experienced in the past 10 years:

- Drought
- Floods
- Unusually high temperatures
- Wildfire
- Unusual change in timing of snow melt or snow melt peak flow
- Unusual change in monsoon season flow
- Unusual change in magnitude of snow melt peak flow
- Unusual change in timing of snow accumulation
- Unusual change in summer and fall baseflow
- Unusual change in melt season runoff volumes
- Unusual change in annual runoff volumes
- None of the above
- Not applicable
- Other (please specify)

12. For each of the following events your system experienced in the past 10 years, what problems did they cause?

	Lost revenue	Unanticipated expenses	Difficulty assuring system reliability
Drought			
Floods			
Unusually high temperatures			
Wildfire			
Unusual change in timing of snow melt or snow melt peak flow			
Unusual change in monsoon season flow			
Unusual change in magnitude of snow melt peak flow			
Unusual change in timing of snow accumulation			
Unusual change in summer and fall baseflow			
Unusual change in melt season runoff volumes			
Unusual change in annual runoff volumes			
Other			

13. What do you think is the likelihood that your system will experience impacts from the following events in the next 5-10 years?

	Unlikely	50/50 chance	Likely	Don't know
Drought				
Floods				
Unusually high temperatures				
Wildfire				
Unusual change in timing of snow melt or snow melt peak flow				
Unusual change in monsoon season flow				
Unusual change in magnitude of snow melt peak flow				
Unusual change in timing of snow accumulation				
Unusual change in summer and fall baseflow				
Unusual change in melt season runoff volumes				
Unusual change in annual runoff volumes				
Other				

14. The following question lists several potential mechanisms for coping with variation in weather and climate. Please select each mechanism that your organization has used in the past 10 years.

- Increased use of CBRFC forecasts
- Increased use of other weather or climate forecasts
- Instituted outdoor water restrictions
- Instituted water conservation program
- Instituted water budget/raised water rates/imposed surcharge
- Purchased water rights or shares
- Leased alternative water source/used water bank
- Increased storage
- Increased groundwater pumping capacity
- Transbasin diversion
- Instituted conjunctive use of groundwater and surface water
- Built flood control dam
- Built levees
- Instituted warning system
- Adopted floodplain zoning
- Developed emergency management plan
- Developed drought plan
- Applied for disaster assistance
- Evacuated residents
- Trained personnel
- Changed staffing level
- None of the above
- Other (please specify)

15. For each coping mechanism that your organization used in the past 10 years, please rate its effectiveness.

	Very effective	Somewhat effective	Not at all effective	Did not use
Increased use of CBRFC forecasts				
Increased use of other weather or climate forecasts				
Instituted outdoor water restrictions				
Instituted water conservation program				
Instituted water budget/raised water rates/imposed surcharge				
Purchased water rights or shares				
Leased alternative water source/used water bank				
Increased storage				
Increased groundwater pumping capacity				
Transbasin diversion				
Instituted conjunctive use of groundwater and surface water				
Built flood control dam				
Built levees				
Instituted warning system				
Adopted floodplain zoning				
Developed emergency management plan				
Developed drought plan				
Applied for disaster assistance				
Evacuated residents				
Trained personnel				
Changed staffing level				
Other				

16. For each of the following potential coping mechanisms please indicate how likely it is that your organization will use it to cope with future weather and climate variations:

	Highly likely	50/50 chance	Highly unlikely
Increased use of CBRFC forecasts			
Increased use of other weather or climate forecasts			
Institute outdoor water restrictions			
Institute water conservation program			
Institute water budget/raise water rates/impose surcharge			
Purchase water rights or shares			
Lease alternative water source/use water bank			
Increase storage			
Increased groundwater pumping capacity			
Transbasin diversion			
Institute conjunctive use of groundwater and surface water			
Build flood control dam			
Build levees			
Institute warning system			
Adopt floodplain zoning			
Develop emergency management plan			
Develop drought plan			
Apply for disaster assistance			
Evacuate residents			
Train personnel			
Change staffing level			

The following 2 questions ask you to list your organization's top concern(s) with respect to fulfilling its mission within different time frames. Examples of concerns could include legal issues with the Colorado River Compact, environmental concerns, population growth, increase in weather/climate extremes, fire impacts to water sources, changes to water rights administration, or water supply/demand imbalance. Please be as specific as possible.

17. Please list your organization's top short-term concern(s) (concerns arising roughly within the next few years) with respect to fulfilling its mission.

1.

2.

3.

18. Please list your organization's top long-term concern(s) (concerns arising within the next 10-20 years) with respect to fulfilling its mission.

1.

2.

3.

Section 3. Decision-making and use of forecasts

The following series of questions relates to 3 forecasts produced by the Colorado Basin River Forecast Center (CBRFC): streamflowforecasts, peakflowforecasts, and watersupplyforecasts (click on the forecast name if you would like to view the forecast webpage).

19. Please indicate your familiarity with and use of CBRFC streamflow, peak flow, and water supply forecasts:

	Never heard of it	Heard of it but don't use it	Use it yearly	Use it seasonally	Use it monthly	Use it weekly	Use it more than weekly
Streamflow forecast							
Peak flow forecast							
Water supply forecast							

20. If you use CBRFC forecasts, select all of the following that describe your use:

	As input to flood risk decisions and decision support	To brief decision makers	For quantitative management models	For qualitative management models
streamflow forecast				
peak flow forecast				
water supply forecast				

21. CBRFC forecasts are useful in making the following decisions:

22. Do any legal or policy obligations (contracts, rules, statutes, agreements, etc.) require you to use CBRFC forecasts in making decisions?

- Yes
- No

23. Please describe the legal or policy obligations that require you to use CBRFC forecasts.

24. Please check all of the following factors that limit your use of CBRFC forecasts:

- Legal constraints (contracts, rules, statutes, agreements, etc.)
- My organization's operating procedures
- Difficulty interpreting CBRFC forecasts
- Difficulty knowing which CBRFC forecasts are useful
- Difficulty determining the quality of CBRFC forecasts
- Concern about or experience with an inaccurate CBRFC forecast
- Lack of familiarity with CBRFC forecasts
- Conflict between CBRFC forecasts and other forecasts I use
- Conflict between CBRFC forecasts and other non-forecast factors that influence my decisions
- Conflict between CBRFC forecasts and our organization's unique internal tools
- Other (please specify)

25. If you do not currently use CBRFC forecasts for decision making, what if anything would have to change for you to begin using them? If you would never use CBRFC forecasts for decision making please answer "no changes."

5

6

26. Please select all of the following products and summaries that you use in decision making:

- U.S.DroughtMonitor
- U.S.SeasonalDroughtOutlook
- U.S.HazardsAssessment
- PalmerDroughtSeverityIndex(PDSI)
- SurfaceWaterSupplyIndex(SWSI)
- StandardizedPrecipitationIndex(SPI)
- VegetationDroughtResponseIndex(VegDri)
- CropMoistureIndex(CMI)
- TheWesternWaterAssessment(WWA)IntermountainWestClimateDashboard
- ClimateAssessmentfortheSouthwest(CLIMAS)SouthwestClimateOutlook
- ClimatePredictionCenterPrecipitationProducts
- ClimatePredictionCenterTemperatureProducts
- NRCSStateBasinOutlookReports
- MultivariateENSOIndex
- ClimatePredictionCenter(CPC)ENSOUpdate
- DenverWaterWaterWatchReport
- CBRFCForecastBriefings
- NIDISWeeklyDroughtWebinars
- InformationfromColorado'sStatewideWaterAvailabilityTaskForce
- WesternRegionalClimateCenter
- IRIENSOInformation
- SWCast(KlausWolter)
- Other (please specify)

27. Does your organization generate forecasts internally?

- Yes
- No

28. Do you rely on your organization's internally generated forecasts or metrics in making decisions?

- Yes
- No

29. Are you aware of the potential for mountain pine beetle infestations to affect streamflow?

- Yes, very aware
- Somewhat aware
- No, not aware

30. Where did you learn about the potential for mountain pine beetle infestations to affect streamflow (check all that apply)?

- Newspaper
- Television
- Colleague/word of mouth
- Western Water Assessment event or publication
- Other water organization such as AWWA event or publication
- Conference
- Journal article
- Listserv

Other (please specify)

31. Are you aware of the potential for dust deposition on snow to affect streamflow?

- Yes, very aware
- Somewhat aware
- No, not aware

32. Where did you learn about the potential for dust deposition on snow to affect streamflow (check all that apply)?

- Newspaper
- Television
- Colleague/word of mouth
- Western Water Assessment event or publication
- Other water organization such as AWWA event or publication
- Conference
- Journal article
- Listserv

Other (please specify)

33. How concerned are you about the impact of mountain pine beetle infestations on streamflow?

- Very concerned
- Somewhat concerned
- Not concerned
- Don't know

34. How concerned are you that mountain pine beetle infestations will affect the accuracy of streamflow forecasts?

- Very concerned
- Somewhat concerned
- Not concerned
- Don't know

35. How concerned are you about the impact of dust deposition on snow on streamflow?

- Very concerned
- Somewhat concerned
- Not concerned
- Don't know

36. How concerned are you that dust deposition on snow will affect the accuracy of streamflow forecasts?

- Very concerned
- Somewhat concerned
- Not concerned
- Don't know

37. Please provide any additional comments that are relevant to this survey, including explanation of any of your previous answers if you wish.

38. If you would be willing to participate in a follow-up interview please provide your contact information:

Email address

Te

Appendix B

Interview Questions

1. What is your current position at your organization?

2. How long have you held this position, or any related positions, at your organization? Can we identify your organization in the project report?

3. What are your main job responsibilities?

4. Can you briefly state the obligations or duties (mission) and goals of your organization?
   a. What do you do in your position to achieve these goals?
   b. What decisions do you make or contribute to?

5. What do you see as your organization's most significant challenges (weather and non-weather/climate-related) over both the short term (1-2 years) and the long term (5+ years)?

6. Focusing on weather and climate challenges,
   a. How have you already dealt with these challenges in the past?
   b. What strategies do you think will be most effective in meeting those challenges in the future?
   c. How do you determine if a strategy has been effective?

7. Turning to use of CBRFC forecasts,
   a. How do you currently use CBRFC forecasts in your decision making process?
   b. What do you value about CBRFC forecasts?
   c. What would make you more likely to rely on CBRFC forecasts in the future?
   d. Do you have a level of forecast skill that you expect from CBRFC?
   e. If so, how do you check that the forecasts are meeting or not meeting your expectations?
   f. What information would you like to have from CBRFC that you currently don't receive?

8. Turning to other information,
   a. Do you rely on or consult other forecasts besides the CBRFC's in making decisions?
   b. Why do you currently use these forecasts?
   c. If you expect to rely on these forecasts in the future, please explain why.
   d. Do you rely on or consult non-forecast information in making these decisions?
   e. What other forecasts, scientific information, or other information would you like to have?
   f. How much weight do you give to CBRFC forecasts in making these decisions compared to other types of information?

9. The Western Water Assessment is collaborating with CBRFC on a project that is looking at the combined impacts of bark beetle infestations and dust deposition on snow to better understand snow accumulation and melt in the Upper Colorado River Basin with the goal of

improving CBRFC forecasts.

a. How might dust on snow/bark beetle impacts affect decisions you make or your operations?

b. What information about dust on snow and bark beetle infestations would be useful to you?

c. Are there products or tools you currently use that could incorporate dust on snow/beetle information or that might be affected by it?

d. Where would you like that information to be made available (examples: incorporated into CBRFC forecast, shown separately on CBRFC website as map, etc.).

e. What time horizon for this information would be most useful, i.e. daily/weekly/seasonal, and what are the lead times for your decisions?

Appendix C

Water sources (rivers) listed by survey respondents

Animas River (listed by 2 respondents)

Arkansas River

Bear River and Bear River Basin

Big Cottonwood Creek

Big Thompson River

Blanco River

Blue River Alluvium

Colorado River and Colorado River Basin (listed by 20 respondents)

Dolores River (listed by 3 respondents)

Drainages feeding the Duchesne, Strawberry

Florida River (listed by 2 respondents)

Fraser River

Great Basin

Green and Great Salt Lakes basins

Gunnison River (listed by 3 respondents)

Imported San Juan-Chama

Little Navajo River

Mancos River

Navajo River

Pine River

Sacramento River

San Juan River (listed by 2 respondents)

Santa Clara River (listed by 2 respondents)

South Platte River (listed by 4 respondents)

Tonto Creek

Upper Colorado River (listed by 4 respondents)

Upper Santa Fe River watershed

Verde River

Virgin River (listed by 2 respondents)

Wasatch Front Streams

Weber River

Willow Creek

Yampa River and tributaries