Colorado River: Building a Science Agenda
Final Workshop Report

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TOP LEFT: *Aerial View of Lake Mead and Hoover Dam water intake towers, as seen from the Arizona side of Hoover Dam, 2017. Mario Roberto Durán Ortiz*

TOP RIGHT: The confluence of the Little Colorado River with the Colorado River provides an important addition of sediment to the river, 2017. Tara Lohan

BOTTOM LEFT: USGS scientist tracks the time-of-arrival of the pulse flow on March 24, 2014. Eloise Kendy

BOTTOM RIGHT: An endangered humpback chub swims through the Colorado River, 2012. Arizona Game and Fish

PI: Katharine Jacobs
Director, Center for Climate Adaptation Science and Solutions
Professor, Department of Soil, Water and Environmental Science
University of Arizona
Tucson, Arizona

Colorado River: Building a Science Agenda
Summary of Workshop
Hosted by the Institute of the Environment
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Section I
Executive Summary

The Colorado River has often been called the lifeblood of the Southwestern United States. The river provides a partial water supply for nearly 40 million people in the seven Basin States and Mexico. It is a highly managed system that has been transformed by engineering and increasingly through climate change. With storage levels in its two largest reservoirs, Lakes Mead and Powell, at levels that threaten to trigger shortages in the Lower Basin, and recurring droughts in tributaries throughout the Upper Basin and in the Southwest, sustainability of resources – hydrological, ecological, and environmental – is threatened.

A workshop, "Colorado River: Building a Science Agenda," was held at the University of Arizona October 10-12 2017. The purpose was to gather leading physical and social scientists from multiple disciplines whose work touches on various aspects of the Colorado River in order to assess the state of scientific knowledge in several issue areas that had not been fully addressed previously, and identify the future research necessary to close the most salient and decision-relevant gaps in scientific knowledge. The workshop was designed to encourage a truly interdisciplinary conversation to inform the development of a science agenda that is much broader and more comprehensive than those of previous studies, especially at the intersection of social and physical science issues. The evolution of basin-wide research is described in **Section II.**

The overall objective was to evaluate the river from a systems perspective that acknowledges the interconnected nature of resources and processes throughout the physical basin and service area. Participants engaged in a series of panel discussions, plenary sessions, and small group breakout sessions and identified where existing knowledge could support better management of the river, and where additional scientific investments are required. Content of these sessions is summarized in **Section III.**

In breakout sessions on the final day of the workshop, participants distilled a list of topics that had emerged over the previous two days into **four overarching themes for further research**:

- Building an Integrated Approach to Basic Science Research in the Colorado Basin
- Anticipating Future Colorado River Challenges: Science of Crises and Tipping Points
- Holistic Management of Integrated Systems at Landscape Scales
- Creating Adaptive, Resilient and Just Institutions

These themes had significant support within the group of workshop participants as a whole, and are elucidated in the Conclusions section of this report, **Section IV**, where priority topics within each theme are also identified.

Section II
Workshop Background

The Colorado River provides a partial water supply for nearly 40 million people in the seven Basin States and Mexico. It is a source of irrigation water for 5.5 million acres, and its dams generate hydroelectric power that supports the economy of the Southwest. The river, and the basin it drains, is also a tremendous environmental and cultural asset, featuring seven National Wildlife Refuges, four National Recreation Areas, and eleven National Parks. One study estimated that the river is responsible for $1.4 trillion/year of economic activity (James et al., 2014). Yet the Colorado is imperiled by a range of stresses, including increasing demand, over-allocation of water rights, and climate change. The water levels in its major reservoirs are now at an all-time low since the time they were first filled. The combined loss of surface and groundwater reserves creates great uncertainty and risk for water managers and users.

Largely due to the potential for a management crisis, and consistent with the SECURE Water Act, the U.S. Department of the Interior's Bureau of Reclamation, in conjunction with the seven Colorado River Basin states, completed a detailed review of basin conditions in 2012. The Colorado River Basin Water Supply and Demand Study (hereafter "Basin Study") showed persistent shortages in 2060 of millions of acre-feet per year. Our workshop, entitled "Colorado River: Building a Science Agenda," acknowledges this report and builds upon that outstanding effort and its follow-on activities. We seek to identify priority areas for interdisciplinary science research in the Colorado Basin and to form a strategic research agenda supporting integrated management of water and a wide range of water-related issues throughout the Basin.

Participants were urged to consider the state of knowledge in a variety of areas and identify science priorities for filling knowledge gaps. This required addressing many topics that go beyond what was addressed in the Basin Study, including the full range of plausible future flow reductions, groundwater impacts, flood management, ecological impacts, water quality, potential changes to governance processes, and climate change vulnerability across coupled human-environmental systems.

Moreover, participants were encouraged to think across disciplinary lines to consider the interactions of climate, hydrology, ecology, and human-environmental systems throughout the Basin and to identify gaps in knowledge pertaining to their interrelationships and synergies. This led to the identification of several integrated topical areas emphasizing the interdependent nature of the Basin's challenges, such as: implications of climate variability and long-term trends on water availability and flood risk in the Colorado River; impacts of future changes on environmental services, ecosystems and species; the ability to characterize and address uncertainty in ways that are meaningful to Colorado River management; and the influence of secondary impacts and cascading effects, including how climate may affect changes in Basin water demand. A common theme was the need to evaluate the river from a systems perspective that acknowledges the interconnected nature of resources and both natural and managerial processes throughout the physical basin and service area.

The workshop focused on identifying where existing knowledge can support better management of the river, and where additional scientific investments are required. The workshop was envisioned as the scientific foundation for further conversations and subsequent workshops that will include a wide range of affected decision-makers, natural resource managers, and NGOs. These collective efforts are intended to ensure that the full range of risks and opportunities inherent in managing water in the Colorado Basin are considered and future science efforts produce information and tools that are *relevant to* real-world decision contexts. Ultimately the goal is to promote sustainability of water resources, communities, and ecosystems throughout the Basin.

Section III
Meeting Report

Most sessions at the workshop were held in plenary, with attendees participating in at least one of several topical panels outlined below. The summaries below capture the most salient points from each session presented by the panelists/presenters and in the discussions that ensued. They are not a verbatim transcript of the conversation.

A. INTRODUCTORY SESSION

1: INTRODUCTION

Co-hosts Kathy Jacobs (University of Arizona) and Doug Kenney (University of Colorado) welcomed participants and introduced the purpose of the workshop: to identify priorities for interdisciplinary science research in the Colorado River Basin in the face of transformative change, recognizing the importance of both fundamental research and applied science that connects to management solutions.

The workshop is viewed as an opportunity for scholars to meet and think through interdisciplinary challenges and talk about science gaps and issues, without political or institutional constraints. Follow-on activities are being planned to expand stakeholder representation in this effort and to consider stakeholder input to the final workshop report.

2: DISCUSSION OF STAKEHOLDER PRIORITIES, INTENDED OUTCOMES, AND OPPORTUNITIES

(Bailey Kennett, University of Arizona)

In anticipation of the workshop, 18 stakeholders were interviewed from across the Basin to build a basic understanding of the science needs that they perceive to be of greatest urgency. The stakeholders represented a wide diversity of fields, associations, and views (including U.S. and Mexico federal agencies, all basin states [represented through state agencies or water providers], tribal communities, agriculture, and environmental NGOs). The list was compiled from an original list of 173 organizations represented in the 2012 Basin Study as well as groups that provided substantial comment on that report. Interviews of 20 minutes to an hour were conducted with 17 of the stakeholders. The intention was for all workshop participants to start with a general idea of what are the looming issues as perceived by key stakeholders without any expectation that these represent the full range of issues and perspectives, or that the findings were statistically significant. A list of preliminary themes for discussion, based on these interviews, was produced and is summarized in **Appendix C.**

Interviewees were asked in advance to consider the following questions:

- what key physical or social science research is missing or incomplete in our current state of knowledge on the Colorado River?
- what physical and social science concepts or topic areas are well understood but not well integrated into Colorado River management?
- what are the most pressing Colorado River science needs related to: a) climate variability and change; b) environmental and instream impacts; and c) managing climate change vulnerabilities across coupled human-environment systems?

The topics that multiple stakeholders mentioned were:

- Effects of temperature on hydrologic processes
- Opportunities to utilize remote sensing data to improve understanding of soil moisture, ET, and water demands

- Evaluation of social response to pulse flows in Mexico
- Need for improved data and monitoring coordination with Comisión Nacional del Agua (CONAGUA) in border region
- Groundwater management in Delta region; overall institutional support for restoration work.
- Non-native species management (endangered Upper Basin fish)
- Achieve consensus on, then sustain, an ecological monitoring regime to help understand and adapt to future impacts
- Impacts from spring floods and reduced late season baseflow on stream morphology, sediment impacts to habitats, migration, food webs, ecosystem services
- Explore possibility of alternative water rights frameworks
- Effectively engage with agricultural community to build resilience
- Basin-specific strategies for framing/communicating climate change to decision-makers and public
- Dust-on-snow mitigation strategies
- Salton Sea mitigation water; need neutral research on proposed strategies (e.g., Sea of Cortez pipeline, transfers)
- Assumptions about the need for adaptation should better account for expected (autonomous) adaptations by water managers (who are always adapting to a variety of changing conditions)

3: COLORADO RIVER BASIN STUDY OVERVIEW, REGIONAL ISSUES, AND UPDATES/WAYS FORWARD SCIENCE NEEDS

(Jim Prairie and Carly Jerla, U.S. Bureau of Reclamation and the Center for Advanced Decision Support for Water and Environmental Systems, University of Colorado)

Jerla began the joint presentation by reviewing highlights of Reclamation actions pertaining to the Colorado River for 1999-2017. 2000 is viewed as the start of the "current" drought in the Colorado River Basin, with the percent capacity in Lakes Powell and Mead dropping from nearly full to around 50% in the first 5 years. The Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operation of Lake Powell and Lake Mead ("Interim Guidelines"), adopted in 2007, were the first of several efforts to address the operations of Lakes Powell and Mead during drought and low reservoir conditions.

Two very low years of inflow in Mead and Powell in 2012 and 2013 initiated discussions of the Drought Contingency Program (DCP) to try to avoid hitting the target levels in Lake Mead that trigger shortages. A related pilot program was established in 2014 to fund conservation projects throughout the Basin, thus far resulting in 100,000 acre-feet of storage conserved in the Lower Basin that is not allocated to specific users.

Currently, both the Lower and Upper Basins are engaged in DCP negotiations. These efforts dovetail with Minute 323, an implementation agreement associated with the 1944 U.S.-Mexico treaty, which extends certain components of 2012's Minute 319 (which specified how Mexico would address shortage and deliveries during high and low reservoir periods) through 2026. Minute 323 also addresses ongoing issues of salinity and the All-American canal, quadruples restoration of habitat acreage in Mexico, and implements a binational water scarcity agreement if the Lower Basin states approve their DCPs. The risk of Lake Mead reaching critically low elevations (1,025 feet) is now assumed to be 50% by 2026. The DCPs are intended to reduce this risk. Renegotiation of the Interim Guidelines is required by 2026.

Reclamation's 2012 Colorado River Basin Study used the best-available science and extensive scenario planning to provide a sound technical foundation for future studies, but there were several topics, including groundwater issues, that were set aside for a variety of reasons. Some of the outstanding issues were addressed in its subsequent "Moving Forward" effort, which concluded in 2015. "Moving Forward" convened stakeholder groups in three areas: M&I conservation; agricultural conservation; and environmental and recreational flows, and its three reports speak to future actions/opportunities, some of which relate to developing a science agenda. The Ten Tribes Partnership was also expected to wrap up and issue its tribal water use report later in 2017. The report will focus on opportunities for Tribes to use their allocations as well as to participate in broader water management solutions across the Basin.

Jim Prairie described ongoing Reclamation research activities, including the activities of the Colorado River Hydrology Workgroup, which seeks and identifies actionable science within a 1- to 3-year timeframe, improved operations and planning data and methods, and the best available and cost-effective projects. Many of these efforts can be traced back to Appendix U of the 2007 Interim Guidelines, which reviewed science and methods for incorporating climate change into Reclamation's Basin planning studies.

The Southern Nevada Water Authority (SNWA) Hydrology Research Symposium in May 2017 reviewed science needs for the Colorado River Basin and involved stakeholders (states, feds, academics, NGOs, tribes) and researchers. While it did not address policy, it did examine implications of climate variability and change in understanding future water supplies and sought opportunities to leverage available funding. Its report will be released in late 2017 and will include a spreadsheet of science gaps that identifies which entities are working on what topics.

A variety of research topics are currently under investigation at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES), with most focused on efforts that can be integrated into Reclamation's planning, decision-making, and management processes. Some current projects include: updating reservoir evaporation coefficients; using remote sensing to better estimate agricultural consumptive use in the Upper Basin (UB); improving streamflow forecasts; understanding and integrating the fifth Coupled Model Intercomparison Project (CMIP5) data in Basin studies of future climate and hydrology; and multi-objective evolutionary algorithms (MOEA). CADSWES is also updating reservoir evaporation coefficients with changing temperatures and preparing for a formal review of the 2007 guidelines no later than 2020.

B. PANEL PLENARY SESSIONS

For the panel sessions, motivating questions were:

1) What science exists that is not currently being used, and why? What can be done to support enhanced use of existing knowledge?

2) What are the critical gaps in knowledge that need to be filled? What are the highest priority science needs, given our current state of knowledge and the potential for progress?

Session 4 (Panel): CLIMATE VARIABILITY AND EXTREMES: FLOODS AND DROUGHT ISSUES

(Julie Vano, National Center for Atmospheric Research, moderator; Vic Baker, University of Arizona; Dan Cayan, University of California, San Diego; Dennis Lettenmaier, University of California, Los Angeles; Jonathan Overpeck, University of Michigan; Brad Udall, Colorado State University; Jim Prairie, Bureau of Reclamation and University of Colorado; Connie Woodhouse, University of Arizona; and Martyn Clark, National Center for Atmospheric Research)

What are the implications of climate variability and long-term trends on water availability and flood risk in the Colorado River? What is the full range of plausible future flow reductions for the river? This topic area provided a basis for discussions of the implications of climate variability and long-term trends on both water availability and flood risk on the main stem and major tributaries, and on environmental services, ecosystems, and species. Panelists were asked to identify/summarize the research issues that they are most concerned about:

Floods and droughts
Probabilistic analysis, using a very short record, has been used to assess flooding risk for current water management, while the paleorecord for floods has not been sufficiently studied. Also, extremes of floods and droughts have been studied in the paleorecord separately but not in conjunction or with rapid transitions from one to another. What are the frequencies of occurrence and background conditions affecting outcomes, including the role of temperatures in exacerbating drought? What are the effects of warming on Lower Basin flows?

The most extreme events produce disasters and dominate impacts. Taleb (2010) talked about the degradation of predictability and how "black swan" events – which are unpredictable, have extreme impacts, and inspire *ex post facto* explanations – are dominating social systems and management. Attempts to reduce uncertainties need to acknowledge the randomness in the system as well as our lack of understanding of unknown but knowable topics. By understanding past flood events we can learn about the potential for much greater events than those in the instrumental record. There's a great certainty introduced by the past: what has happened, can happen again.

Regarding drought, the paleorecord could provide a glimpse of the future, but needs to be considered in the context of a warmer atmosphere holding more moisture. We know that megadroughts have also occurred in the Basin, and we think they had much warmer temps than the global average—a local temperature anomaly. What caused those anomalies?

Regional temperature changes are especially critical in the headwaters and create feedbacks that impact vegetation through higher growth rates, longer seasons, and more evapotranspiration. Independent of precipitation, a shift may occur in the severity-duration of higher temperatures, resulting in more dust in the atmosphere and more tree mortality.

For potential megadroughts, the operational option of storing more water in reservoirs only works if floods are minor. In fact, there is an advantage of lower reservoir levels during floods, which is in conflict with operational objectives for water supply. But for big floods, it is essential to protect the dam, not the water supply. Until we can predict dynamics of these floods, Lake Powell levels must be kept low enough to accommodate probable maximum floods (which have already been exceeded twice in the historic period) and store water elsewhere.

Dynamics of Change
We see declining snowpack, earlier runoff, and changes in snow in lower elevations in response to climate change. However, understanding is poor about how changes in seasonality affect changes in evapotranspiration or how snowpack changes resonate throughout the water cycle. Land surface models, which include feedback mechanisms, give inconsistent predictions. Aggregate changes are understood but process descriptions are very poorly developed. Temperature and streamflow studies have weak underpinnings and lack understanding of the hydrologic processes that are responsible. Current models don't adequately represent dynamics of change. We may have estimates of soil conditions and use them to describe landscape conditions, but we should be interested in dynamics and feedbacks. How does the landscape itself change over time due to hydrologic changes, and how does this landscape change influence the water cycle?

The Colorado Basin's hydrology is uniquely influenced by the extent that summer precipitation can dominate it. There is extreme spatial variability; 75% of runoff is from 25% of the Basin, but it is hard to predict summer runoff based on snowpack alone. Annual runoff (as opposed to seasonal) is more important in the Colorado Basin than elsewhere in the West because of its large reservoirs that hold up to four years of water supply. Winter warming in the West changes the timing of streamflow but (generally) not the amount. That said, the underlying processes have been inadequately addressed. Changed albedo because of earlier snowmelt may have a big impact; the additional evaporation due to higher temperatures may be "stealing" water that was previously being supplied as runoff in the warm season.

Global climate model (GCM) outputs generated by CMIP5 vs. CMIP3[1] models vary considerably. Disposition of the wetter events and heaviest events in the more recent generation of models may be key to this. There are fewer chances of precipitation and more dry days because of Hadley cell expansion toward the poles, along with occasional competition from heavy precipitation events from a generally wetter atmosphere. Are flooding events becoming larger, and more frequent, or are they just happening in different places, due to shifts of Hadley cells?

Predictability (Signposting)

It may not be possible to predict an exact event, but it may be possible to recognize that conditions that herald the onset of particular conditions are occurring, putting people and water managers on notice. What does the paleorecord tell us about thresholds that activate actions temporally or spatially? Which areas of the Colorado Basin are more vulnerable to drought or floods?

Causative elements may be related to a shifting Hadley cell (moving warmer, drier conditions further from the equator). Paleorecords could help explain this and help determine precursors of events by allowing us to look at the record spatially and with higher resolution.

Is our forecasting skill getting less accurate at timescales that fit planning and management needs because of climate change? How does a manager respond to a prediction of higher extremes but uncertainty in terms of timing or direction? Can we condition our projections toward some parts of the range? These are critical questions from a water management perspective.

Climate science has not been successful in predicting precipitation. However, runoff is very sensitive to precipitation and failure to predict it means we need to learn more about *how* to predict it as well as to understand other hydrologic variables such as sublimation and ET in a changing climate. The direct loss of snowpack to the atmosphere may be accelerated by a warm or moist atmosphere. If forecasting isn't reliable, we could share signposts with water managers, e.g., in critical locations such as the San Juan Mountains of Colorado and New Mexico, where GCMs are showing 70% more precipitation than historical records, and even a 5% change in precipitation generates a 10% change in runoff.

Models that don't have useful skill in anticipating conditions should be thrown out rather than being averaged in with other models that do a better job. In climate downscaling, take what we believe to be true from the GCMs and climate models and don't use precipitation information we don't have confidence in. Even raw GCMs can be helpful in improving projections on hydrologic initial conditions such as snowpack and soil moisture.

The more we learn about uncertainty, the better our true understanding of the system is revealed, even though this often results in larger model spread and the perception that we are losing ground in predicting future

[1] CMIP stands for Coupled Model Intercomparison Project, an effort to understand differences in projections across a multitude of global climate models.

conditions. This speaks to the importance of translating science and clearly messaging what we do know and the nature of the uncertainty.

Key messages:

- Put effort into research focused on resilience in the face of “black swans” (unexpected large-impact events).
- There is a lot of easy science that can be done on temperature impacts, directed to managers.
- Improve understanding of losses in the system, e.g., from sublimation. New measuring techniques for bulk water storage can test models at an integrated scale.
- Extract from the science where there is reasonable skill (e.g., temperature); otherwise default to historic observations. We don’t have a change signal with precipitation. Scientists should be clearer about what information should not be used and which models should be thrown out.
- Understanding underlying processes and their interaction across time scales is very important. For the long-term, move beyond thinking that properties define processes to focus on how processes define properties. Understand the slower dynamics of change and their feedbacks into interannual and seasonal variability. For the shorter term, develop predictive capability on temperature in the climate and seasonal forecasts.
- How can we combine and consider situations under which you’d get both drought and a tendency for more intense storms?
- We need a balance between “informational science” that can be used now by management, and more fundamental research that helps us understand systems in the long term and is a process of continual discovery. Some modeling is not at all useful for management, but helps scientists learn over time.
- A holistic framework could help identify which uncertainties (and certainties) are more important than others. What is the relative contribution of the range of different influences on this system? Can this be incorporated into a matrix for stakeholder use?

Session 5 (Panel): CHANNEL MORPHOLOGY, SEDIMENT, HABITAT, AND RECREATION ISSUES
(Karl Flessa, University of Arizona, moderator; Vic Baker, University of Arizona; Bonnie Colby, University of Arizona; Will Graf, University of South Carolina; Pat Shafroth, U.S. Geological Survey; Ellen Wohl, Colorado State University; Jack Schmidt, Utah State University)

Increased erosion, transport, and deposition of sediment result from ecological disturbances like floods and wildfire as well as more intense precipitation influence a river’s flow regime, quality, and physical characteristics. All of these impacts are predicted to become more intense with climate change. Altered geomorphology and nutrient transport not only impact aquatic and terrestrial habitats, but the structure and productivity of floodplains, beaches, and estuaries. Sediment transport in the Colorado River system is researched and monitored through the Glen Canyon Dam Adaptive Management Program and USGS’s Grand Canyon Monitoring and Research Center (GCMRC), among other efforts.

In analyzing and applying strategies from across the Basin, what can be learned about the specialized physical processes that occur on the upper surfaces of deltas in the Colorado River system (at the headwaters of the reservoirs and the Colorado River Delta), where ecosystem interactions are critical?

The panelists considered the Colorado River Basin to include its “service area,” i.e., those areas to which the river’s water is delivered, not only where it flows. The Basin extends beyond the watershed itself to include southern California, central New Mexico, Colorado’s Front Range, and so on. The southern portion of the Basin – Mexico, in particular – faces more of a threat from declining precipitation than the northern portion, for example, so it is important to consider the broader scope of the Colorado system and not just the natural watershed. Another key message: “It’s a river.” The river is not simply a system of conveyances and reservoirs for delivering water and power. The river’s other components, including ecosystems and ecosystem services, are also important. River management should include management of all its ecosystem services and values.

Cross-Cutting Themes: *Integration of existing knowledge, generation of new knowledge and incorporating river science into river management* (Flessa, Graf, Baker, Schmidt)

What has been learned about Colorado River Basin forces and processes is not being adequately or skillfully communicated to decision-makers at the highest levels. Basin-scale approaches, venues, and formats are needed for sharing the considerable knowledge already gained about restoration or other aspects of river science. Integration and coordination must be a priority; what has been learned in the Delta can be useful in the Multi-Species Conservation Program, for example. The river is a managed system but it must be managed on a basin-wide scale for environmental services. We need to be mindful of the river as a living and connected organism, not a thing merely to be engineered or an engineering problem to be solved. In light of the impending renegotiation of the Interim Guidelines, climate science and river science need to inform river management.

At the same time, the complexity of the system needs to be better communicated to managers and stakeholders; there are many interacting variables. NGOs and stakeholders get frustrated when data are presented only in a fragmented yet precise way rather than through a contextualized, integrated, and multi-dimensional lens.

The concept of ecological drought, as described recently by Crausbay et al. (2017), illustrates that what shapes and influences environmental resources is the interaction of natural processes and human activities. We need to integrate the anthropogenic part with natural systems.

Sediment and the riparian zone (Wohl, Shafroth, Schmidt, Graf)
We’re very aware that the water flow regime has been altered. We have data on water volumes/flows, but no real records for sediment discharge, which is equally important. What is the basin-wide sediment budget of the river and its tributaries? How can we modify the flow regime from dams to create desired channel configurations? The river is gradually becoming more simplified and less heterogeneous, which decreases our ability to maintain native fish, for example. How can a more natural channel be engineered below Hoover Dam? What happens to sediment once mobilized, as in flash floods? It will be difficult and expensive to determine a sediment budget at the basin scale, but perhaps this is where funding should be targeted for remote sensing so we can get an approximation of it.

How do/will changes in vegetation affect channel and riparian zone geomorphology and habitats?
Changes to riparian vegetation and plant communities are often driven by fluvial disturbances and by water availability. Many changes in the upland vegetation are from wildfire, and transformation can be rapid. The recent paper by Joel Sankey et al. (2017) on projected changes in fire frequency and severity and impacts to erosion and sedimentation is highly relevant. Physical processes provide a template for vegetation growth, but there are feedbacks in the system. For example, to control tamarisk, a biological control beetle was released into the Upper Basin in the mid-2000s. It is now moving quickly into Lower Basin and Rio Grande and hybridizing. Where and how and will tamarisk dieback be replaced by other vegetation, and how will it affect bank erosion?

GCMRC has been encouraged to develop an ecosystem model of the Colorado River in the Grand Canyon. King and colleagues in South Africa developed a model for the Okavango system (King and Brown 2010; King et al. 2014) which included response curves for 1700 variables. When they didn’t have data, they used a best guess.

The work resulted in three scenarios for development along the river system and showed system changes under each. King's concept of "development space" as defined by stakeholders – the zone of acceptable change, or amount of ecosystem services stakeholders are willing to lose in a given scenario – proved to be a powerful communication tool. Could we do this for the Colorado River?

Humans optimize designs for the river for the moment. But it's a river, and follows the laws of nature as well as the decisions of people. Human values will not be same in the next 10 or 50 years. The design lifetime of dams is 50 to 100 years. There may be opportunities to reassess what we are doing. We have an analysis and decision support system that discounts the future (particularly through standard cost-benefit analysis).

Ecosystem services and their valuation (Colby, Graf, Flessa)
The role of economic sciences in river management has evolved. Early dams only required very basic cost/benefit analysis but with the environmental movement, more is demanded in the equation, to assess the balance of human uses vs. free-flowing river values. Economics is a tool for evaluating the way that river changes resonate throughout the economy (e.g., through jobs, recreational willingness to pay, property values), but non-market values (such as the cultural value of pulse flows; existence values) also need to be assessed, documented, and communicated in a way that decision makers can use.

The river provides a broad range of ecosystem services to society, both within and beyond the basin. How can these be best quantified or monetized? How can the beneficiaries of the services support river restoration, especially if such restoration diminishes the supply of water and power?

Environmental justice is an issue embedded in economic sciences relating to the river. Economic studies of recreational water use often focus on those with enough money to do those activities; willingness to pay is implicit in most studies. Environmental, recreational, and non-use values can also be hard to communicate to decision makers who are skeptical of their credibility.

"Hydrologic colonialism" is Graf's term (1999) for costs in one area or sector leading to benefits elsewhere. For example, the costs of development of hydropower are borne by people who live in the Basin, but many of the benefits are transferred elsewhere. A geographic model of costs and benefits would be beneficial. There is a time component to the environmental justice issues: benefits are gained now, costs often come later (as with fish ladders added to the Snake River, which ultimately cost more than the dams that made them necessary). Many environmental consequences of Colorado River diversions are exported to Mexico. How does one cost out environmental justice over time, with respect to tribes, endangered species, etc.? They were not part of the equation when the dams were built.

An example of non-use values: The Minute 319 pulse flow in the Delta made a huge symbolic impact in relationships between U.S. and Mexican decision-makers. It also was very important to local communities. However, it set up a tension between those who want pulse flows and those who want base flows.

Upper Basin
Many of the panelists expressed concerns focused on the Lower Basin. Which issues also affect the Upper Basin (defined here as above Lake Powell) or are strictly Upper Basin issues? The world's largest oil shale and tar shale reserves are in the Upper Basin on BLM lands, including under the Yampa River. What are the implications of developing these reserves from a water and sediment perspective? The Yampa is not a small river; it provides a lot of water and sediment and is the last most natural tributary of the Colorado. There are many proposals for

extreme development in the area and frackers on the Front Range have the ability to pay 10 times as much for water as cities and other interests.

Session 6 (Panel): ENVIRONMENTAL/BIOLOGICAL ISSUES (INCLUDING WATER QUALITY)
(Cliff Dahm, University of New Mexico (moderator); Kevin Bestgen, Colorado State University; Bob Hall, University of Montana; Mark Stone, University of New Mexico; Dave Kreamer, University of Nevada, Las Vegas; and Pat Shafroth, U.S. Geological Survey)

Impacts from climate change and other human activities influence the flow and quality of Colorado River water, as well as species, habitats, and ecological systems directly and indirectly dependent on the river. While the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin (1988) and the Lower Colorado River Multi-Species Conservation Program (2005) have made significant environmental gains, evolving conditions present new challenges and research questions. What is the long-term prognosis for habitat recovery, especially of native Colorado River fishes, and what trade-offs are needed to improve long-term conditions? There is a need to address multiple water quality issues, including increased salinity under reduced streamflows, pesticides, heavy metals, and movement of groundwater plumes of toxic substances.

The panelists were asked to consider the following issues: salinity; chemical pollution; species biodiversity and health; non-native species management; streamflow and flow impacts; and science communication.

Native and Non-native Fish
Fish health in the Colorado Basin is on a decidedly negative trajectory: of 35 native fish species, three are extinct and 23 are threatened or endangered. Managers need simple and specific information to dial flows for the persistence of native fish. The Upper Basin has the most active preservation projects. How climate changes the hydrology of the basins in the northern portion of the Basin is important. Upper Basin recovery programs sunset in 2023; species are supposed to be recovered by then, but are all declining. More time is needed; the problems are big, long-term, and shifting.

How can existing species conservation programs in the Lower and Upper Basins be made more effective? More stakeholder interaction and interest in delta recovery programs is resulting from Minutes 319 and 323. What science exists that isn't being used? Competing management objectives result in misplaced priorities. The Lower Basin recovery program is more of a checklist. Goals are insufficiently focused on stocking fish; recruitment, natural recovery, and applied science should be higher on the agenda. Every population of razorback sucker has gone extinct except those in hatcheries.

We need to be more strategic about what we try to recover and where; we can't recover everything, everywhere or shape "designer flows" everywhere or deal with invasive species everywhere.

We need better tools and focused funding for ongoing management of non-native, invasive species. Native species are quickly being eradicated and states need to be able to coordinate with federal agencies and have areas set aside to exclude non-natives.

Movement of Water and Sediment through the System
From the headwaters to the delta, we need to map and understand the movement of water and sediment. How are they influenced by the management infrastructure and climate variability and change?

- In the *headwaters*, the driver of concern is the impact of increased temperatures, both gradual (snowpack changes, yield changes, sediment patterns) and sudden (heat waves, etc.)

- In the *tributaries*, more water storage is increasingly important to be able to deal with extremes, but the tributaries are particularly vulnerable to flood events. Social justice issues are particularly acute in the tributaries because those who are tied to the water source are detached from where water management decisions are being made and a resilience perspective is especially important.
- For the *mainstem*, interesting research is being done on adaptive capacity and socioecological perspectives. Minute 319 resulted in adaptive capacity and social infrastructure successes. We are hitting benchmarks on acreage but not on species recovery, which does not bode well when climate change is added to the mix.
- *The Delta* shows the most profound divergence from what the environmental system used to be and is a now a completely novel ecosystem. What ecological objectives are feasible now and what do we want the delta system to look like, given a limited water supply and tradeoffs between human and ecological systems? Where, when, and how much water do you want to deliver?

Riparian Vegetation
Invasive plants such as saltcedar (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia* L.) have been competing with the previously dominant willow-and-cottonwood riparian vegetation for decades. Floods and droughts have an easy and clear connection to riparian dynamics; the streamflow regime and its interaction with sediment ultimately determine the surfaces on which plants grow. Increased temperatures, reduced surface flows and declining alluvial water tables all stress or kill cottonwoods, as we have seen in the Bill Williams River. Do we need to focus preservation on particular areas? Should there be signposting for trouble ahead from a basin-wide perspective? What monitoring or instrumentation is needed? Can we integrate what we know about flow regimes and cottonwood regeneration? Previous tamarisk reduction efforts were mechanical or chemical and localized, while beetles are more extensive. What is sustainable in terms of replacement vegetation?

We should assess and map where in the Basin key conditions exist for regeneration of species and the most likely locations of their demise. Where in the Basin do we have fluvial disturbances and drought in the context of cottonwood populations? Where are conditions right for regeneration at the basin scale? The middle Rio Grande in central New Mexico has dominant age classes of cottonwoods from the 1920s and 1940s that are quite vulnerable and are without substantial regeneration since the 1940s. Natural selection and adaptive capacity may help us deal with drought. Tom Whitham and colleagues (2012, 2010) at Northern Arizona University looked at cottonwood genetics and relationship to restoration. Some genotypes might be more resilient and better suited to conservation in the context of warming and drought.

Springs
Groundwater-dependent ecosystems need to be addressed; the areal percentage of an actual stream is only a very small component of the landscape, and surface flows are often less important than subsurface flows in supporting vegetation. Springs are important in rural areas for consumption as well as for their environmental and cultural values. They are important to many Native American cultures and sustain highly localized endangered species. Spatially intermittent streams and rivers commonly have perennial segments linked to springs, with the flow in the intermittent segments linked to precipitation events. But despite their importance, springs are often ignored by researchers. Only 10% of springs are thought to be mapped or named. In the Grand Canyon, of the 4,162 sampling events on springs done since the 1950s, maximum contaminant level (MCL) exceedance was seldom recorded. Arsenic was not measured in 93% of the springs, but when measured, it exceeded standards 53% of the time. There are not only significant data gaps but perceptual gaps; the focus is on surface water (mainly the mainstem) and on mobile species.

Water Temperatures and Intermittency

Dams substantially impact ecological processes downstream, disrupting flows of water, sediment, nutrients, and temperatures, as well as migration corridors. As reservoir levels drop, the water becomes warmer and resulting hotspots can impact food webs. Across the Basin, how does algal production change with temperature? How will nitrogen and phosphorus loading affect stream ecology downstream (noting that more intense precipitation can exacerbate these issues)? Nutrient changes may be more significant than temperatures and amount of light.

Hydro-peaking alters invertebrate populations significantly below dams, and this resonates through the system (Kennedy et al. 2016). Daily fluctuations in water flows below dams affect biodiversity; altering flows could result in an assemblage of aquatic invertebrates that better represent past populations. How does altering the flow of organic matter in the river change what can reside there? Organic matter has been ignored in mineral sediment budgets (it is burned off in such studies) and needs instead to be retained and measured so that carbon dynamics in rivers can be better understood.

Intermittent streams are increasing in prevalence, yet of the 15,000 USGS gauges in the United States, only around 1,000 are on intermittent streams and only 300 of those are active. There is little information on the flow dynamics but it affects the sediment balance (Datry, Bonada and Boulton, 2017). We have something to learn from Australia's Murray Darling Basin regarding swings between extreme wet and dry: after megadrought, a return to wet conditions mobilized a huge amount of organic matter and over 2,000 kilometers of the river system became hypoxic and inhospitable to the ecosystem (Dahm et al. 2015).

Fires and Water Quality

Fires, which are increasing in areal distribution and intensity in the West, also mobilize ash and debris in the stream system, to the detriment of both the environment and the operation of the built system. The 2011 Las Conchas Fire in New Mexico was hot and fast; a high percentage (30-40%) of the burn scar was high intensity. Continuous monitoring there showed a mobilization of black carbon and ash starting from the small tributaries to the mainstem of the Rio Grande, resulting in a huge stretch of anoxia and hypoxia in the mainstem over 50 miles in length and a shut-down of the Albuquerque/Rio Grande drinking water treatment system (Dahm et al. 2015). Dynamics of many processes can be best understood only through continuous real-time sensing, which should be a priority. More and better sensors are needed to monitor chemicals like nitrate, ammonium, and phosphate. Do flow engineering structures make anoxia worse because channelization can deliver water and sediment downstream more effectively? Or does the altered turbulence increase re-aeration that reduces anoxia and hypoxia? Channelization and pooling did increase anoxia in the Rio Grande after recent major fire events.

Novel Ecosystems

Reforestation has been occurring in many areas since the 1980s because of sediment buildup and has resulted in novel ecosystems in unexpected places. A good outcome of this workshop could be the development of a meaningful theoretical framework for managing novel ecosystems. We need to especially focus on novel *aquatic and riparian* ecosystems, which have largely been overlooked although there are some very novel ecosystems below dams. This is also true for the inflow regions of reservoirs where sediments are deposited and novel riparian plant communities have been established. Should the baseline be a return to past conditions or are we to start fresh? Do we manage to an ideal or a historical precedent or to a condition or dynamic that is likely to be sustainable in the context of altered flow and sediment regimes?

Session 7 (Panel):
CULTURAL, INSTITUTIONAL AND LEGAL ISSUES
(Doug Kenney, University of Colorado, moderator; Dustin Garrick, Oxford University; Sharon Megdal, University of Arizona; Dan McCool, University of Utah; Larry MacDonnell, University of Colorado; and Jason Robison, University of Wyoming)

As the water balance in the already over-allocated Colorado River Basin becomes more vulnerable, pressures on and between water users is likely to increase, while management institutions and existing legal frameworks will be pressed to cope with changing conditions. A static institutional response is not a realistic premise. We need to identify and analyze options for changing the rules of management. In order to prepare for these stresses, it will be important to understand – to the best of our ability – the tradeoffs and implications (cultural, institutional, legal, economic) that can be expected in the future. What institutional, cultural, and legal barriers and capacity limitations constrain our ability to inform decision-making for Colorado River management? And further, can we manage the watershed in an integrated way that accounts for extreme events, urban development, and environmental needs?

The Colorado River is seen as a model of governance by many, which is surprising, because others consider it litigious, inflexible, and lacking transparency in both process and leadership. What is our model? How do we operate and make decisions? How can the Law of the River be made more adaptive to improve preparations for rapidly changing natural and human environments?

Conflict Resolution under Extreme Scarcity
Long-term megadroughts and megafloods as evidenced in the geological record are even more likely now, as are gaps between supply and demand. How will people behave politically under conditions of extreme scarcity? How will Colorado Basin and water institutions respond to the first Lower Basin shortage declaration? Now is the time to design decision-making and conflict resolution structures that function under extreme conditions and can respond to unprecedented challenges. New models of collaborative processes to deal with such situations must be more fair and inclusive than in the past; environmental justice must be designed into the system to a greater degree than has occurred in the past.

Comparative analysis can help to transfer lessons in disaster management and crisis management from other basins around the world. Garrick (2015) used comparative analysis, both quantitative and qualitative, to examine the response to the end of the millennium drought in Australia's Murray Darling Basin. The basin was in rapid transition and many of its challenges can be traced back to decisions made in that crisis. Much could be learned about the implications of a Lower Basin shortage based on that experience.

Tipping points are of particular interest. Where does the system break? The Interim Guidelines can't hold up if Udall and Overpeck (2017) are correct; the system can't withstand the level of shortage that they anticipate. Each shortage level at Lake Mead represents a tipping point that will have political ramifications, for example, the loss of hydropower. In Arizona, the Central Arizona Groundwater Replenishment District's ability to access stored groundwater supplies is another tipping point, which could lead to major dislocations if that water can't be recovered. The tendency in such situations is reactive and is likely to exacerbate vulnerability. Centralizing decision-making around technical planning, as they did (with unsuccessful outcomes) in the Murray Darling Basin, reminds us of the importance of maintaining local capacity and coordination and of developing inclusive models of conflict resolution processes.

Changes to the Law of the River
How rigid are our current institutional mechanisms? The Law of the River has been amended in multiple ways over time—for example, we are on the 323rd amendment of the 1944 treaty. But is the system sufficiently flexible? The pace and scope of challenges are going to pick up dramatically with a changing climate and the continued evolution of water management practices, such as the conversion of tribal water rights from "paper rights" to "wet water" and the potential for actual development. Institutional arrangements that are adequate for responding to a steady trickle of incremental perturbations may be woefully inadequate to deal with the cumulative impact of such changes, and with the special challenges of major, "black swan" events. By developing new procedures now, we can enhance our capacity for resiliency.

Empowering and Supporting Tribes
How might governance be improved to empower Colorado Basin tribes to promote and respond to cultural, social, and economic aspects of their self-determination? Research strands within this topic could be:

1) Domestic intra-tribal research, with a focus on individual Basin tribes. A key subject is capacity and capacity-building to engage in water governance (legal, technical) essential for internal organization and external relations: a) How do tribes differ in the respective levels of their capacities to engage? b) What are their self-expressed priorities for water management? c) What key capacity-building resources do they say they need to manage their water?
2) Domestic intertribal research on technical, legal, and political intertribal relations: a) What is the current extent of cooperation and what forms does it take? b) What are basin tribes saying about the effectiveness of this cooperation? What views do they express on how to measure improvement and inclusivity? c) Parity – how can existing governance programs and processes allow tribes to work on a par with state and local governments? What does inclusivity look like? d) What are their views on enhancing governance and opportunities to enhance collaborative governance?
3) Comparative analysis of Indigenous responses -- How are similarly situated tribes outside the Basin dealing with these issues, managing rivers, and with what institutional structures?

Science Informing Decision-making
How can science inform decision-making? How do you go from research on collaborative processes to actually influencing and improving management deliberations? In order to understand these processes and their degree of resilience, it is important to consider the autonomy of decision-making, inclusivity, dependence on outside resources, and who has control of the final product. Often, the biggest barrier in the application of research is the people factor, including limited stakeholder capacity to engage meaningfully in policy, regulatory, and economic debates, and limited understanding of extremely complex suboptimal choices. In addition, to what degree are adaptive learning/adaptive management principles included? Also, how can we optimize federal agency investment in governance as well as engineering?

Governance research could shed light on a variety of evolving policy areas. One example is transboundary water-sharing protocols, which are not well developed at the state, tribal, and international levels. Effective governance research involves multiple iterations with stakeholders to define research questions and to assess the realistic decision space for possible reforms; this type of user-driven research is not typically consistent with NSF-defined research programs, but is essential if we are to effectively use science to help meet the coming challenges in the Basin.

Session 8 (Panel):
VULNERABILITIES ACROSS COUPLED HUMAN-ENVIRONMENT SYSTEM ISSUES (MANAGING RISK AND UNCERTAINTY)
(Bonnie Colby, University of Arizona, moderator; Dustin Garrick, Oxford University; Holly Hartmann, consultant; Dick Norgaard, University of California Berkeley; and Reagan Waskom, Colorado State University)

The 2009 SECURE Water Act that initiated the 2012 Basin Study documented a need to synthesize climate change impacts, groundwater impacts, flood management criteria, water demand forecasts, ecological restoration, and water quality impacts, among other topics, but a complete vulnerability assessment of the full human-environmental system is still lacking. How will potential changes in coupled human-environmental systems stress key resources (e.g., water storage, instream flows, groundwater reserves, energy systems) and processes (e.g., water management, infrastructure, socioeconomic conditions, environmental services) in the Colorado River Basin service area? Are forecasts of water supply shortfalls based on good science that considers current and anticipated demographic patterns, water conservation trends, and environmental needs?

Coupled Approach Failures
A coupled human-environmental systems approach is an important idea but isn't being used to the extent it should by the scientific community, and thus is not affecting policy thinking. In most cases, it is difficult to adequately tell complex stories in a way that influences thinking and decision-making. For example, natural systems modeling is not being used by the scientific community in the Sacramento-San Joaquin Delta, and engineering solutions are being proposed without benefit of a coupled-systems approach. Historical events have defined the problem as fish vs. flows, but the issues are much more complicated. In such cases, how can this institutional inertia be overcome?

Coupled Approach Successes
The Great Lakes Research Lab is a model for an entity that effectively incorporates science into decision-making and can respond quickly to changing issues and demands and diverse stakeholder needs. Institutions and individuals are increasingly adopting systems thinking. Climate outlooks, given their probabilistic nature, should be used as training tools in adaptation; each varies by skill, location, season, and performance attributes and each provides an opportunity to practice and evaluate adaptation. The effectiveness of different management alternatives can be evaluated across different scales and under different climate conditions. The most promising alternatives can be examined in terms of cost/effectiveness. Similarly, Carpe Diem West's Healthy Headwaters initiative allowed water utilities to broaden their focus to consider land-use trends and threats as well as issues of justice and inclusion. Identifying and cultivating networks of decision-makers who are especially amenable to taking in and implementing research (early adopters) is a more effective way of getting science used than by identifying communities of practice.

Governance Capacity
Capacity is a key concept; we need improved ability to understand governance deficits in the Basin that would affect the ability of the Basin to adjust. How well-matched are the institutions and challenges? What are appropriate scales for building capacity? How does one reconcile tradeoffs/winners/losers? We can build on recent advances in social-ecological systems thinking to deconstruct complex basins into component parts so as to better understand how the actors are changing and where deficits may lie.

Rivers offer an outstanding opportunity to consider linkages across boundaries and borders. Look at commonalities of the Colorado River and Rio Grande, whose allocations are controlled by the same treaty; there is great potential for broadening U.S. and Mexican perspectives.

Agricultural Vulnerability and System Reliability

As the primary user of water in the Colorado River service area, the future of agriculture is particularly salient in shaping possible river futures. The agricultural infrastructure is aging fast, yet water decision-makers rely heavily on agricultural water in times of drought or shortage. Some key agricultural research needs/questions include:

1) What options exist to improve quantification of consumptive use and return flows, from local to watershed scales, in a consistent way across the Basin states?
2) How do irrigation efficiency measures influence the hydrologic cycle? What fraction of return flows actually make it back to the rivers? And what are the larger systemic impacts, both pro and con?
3) How can conserved water be shepherded to targeted reservoirs or river reaches before it is consumed by other water users?
4) How might alternative transfer methods (ATMs) (market-based mechanisms to incentivize water savings and transfers) protect agricultural viability while addressing urban water needs?
5) What is the proper role of market mechanisms, and what legal/institutional challenges (e.g., "use it or lose it") are instrumental in shaping options?
6) Do efforts to modernize agricultural infrastructure provide opportunities to improve conservation and water management?

The federal government and particularly the U.S. Department of Agriculture farm programs have a role to play in sustainability. So far subsidies for agricultural efficiency haven't translated into more water in the river but into more crops. Reclamation and USDA should cooperate more and at a bigger scale. The current focus is at the congressional district level (e.g., for the EQUIP program), instead of the basin scale. The need to evolve agricultural practices to reflect changing hydrologic and demographic conditions is not fully understood or appreciated. The USDA/Farm Bill could be very influential by offering incentives that affect overall agricultural water use, and that strategically shape the evolving relationship between farms and cities.

Water Banks and Markets

Water banks and market transfers are becoming more active and prevalent. Informal transactions often provide new ways of making water available, but are they optimal? Are these possible evasions of state change-of-use-procedures the best approach to distribute money, water, and risks? Intentionally created surplus water (ICS) can currently only be retrieved by the contractors who generate it; it can't be sold. Liberalization of this rule could be useful. Is it possible to scale up from current pilot programs?

Water markets are not really collaborative but competitive, unless regulated to avoid negative outcomes (i.e., third party externalities). How can and should markets evolve at various scales? In the Murray Darling Basin, many years were spent developing dynamic market mechanisms but they were dependent on effective governance that didn't materialize. Can we improve markets before a crisis?

Session 9 (Panel): TRIBUTARIES, DELTA, AND GROUNDWATER ISSUES

(Jeff Mount, Public Policy Institute of California (moderator); Karl Flessa, University of Arizona; Kathy Jacobs, University of Arizona; Dave Kreamer, University of Nevada, Las Vegas; and Pat Shafroth, U.S. Geological Survey)

Tributaries

The mainstem of the Colorado Basin is fed by dozens of small creeks and larger tributaries emerging in the headwaters of the Upper Basin. Surface runoff and groundwater is managed in these tributaries—principally for agriculture and by private land owners. What are the major policy issues that need to be addressed regarding tributaries and how might better science and monitoring help address them?

Two principal groundwater- related challenges are that groundwater is inadequately monitored and managed throughout the Basin and that surface water and groundwater are generally not managed conjunctively. One notable exception is found in Colorado, where tributary groundwater is tightly incorporated into the surface water management system. Leadership from the very top federal levels – including both USDA and DOI – has not prioritized considering groundwater in the broader Colorado River Basin water management. Institutional issues (including states' rights) impede dealing with groundwater in a broader context; this is a particular concern in that groundwater is a major source of supply during drought. Given that groundwater pumping increases precisely as surface flows and the potential for hydropower decline, there is an energy/water nexus issue that also requires attention.

In the Upper Basin, some relatively undisturbed tributaries provide valuable insights into the characteristics of naturally functioning systems. These can be laboratories for learning. Some of the undeveloped tributaries there can be a useful reference for baseline conditions and may prove useful for tracking shifts in hydrologic and biologic conditions due to climate change. Many stakeholder and watershed groups present in these tributary systems function very well, creating additional opportunities.

Lower Basin tributaries and springs are often groundwater-dependent. Many perennial rivers and streams are converting to intermittent and ephemeral streams due to increasing evaporative losses as the region warms and groundwater recharge declines. The shift in perennial systems can be exacerbated by water management activities. Many Lower Basin tributaries are also influenced by large sediment loads that impact channel and riparian ecosystems and have the potential to increase local flood risk. There are some good small-scale restoration projects in progress in the Lower Basin on tributaries that don't reach the mainstem, but there is no regional approach to addressing ecological conditions in tributaries.

Groundwater and Aquifer Storage and Recovery

Since the start of the current century, demand for Colorado River water has consistently outstripped supplies from natural streamflow, a situation that has only been possible because of drawing down reserves in Lakes Mead and Powell. This reservoir storage depletion has been paired with a corresponding – largely invisible but potentially significant – unsustainable decline in groundwater storage. Projections and analysis of streamflow reductions or increased demands for Colorado River water must also inform how these changes impact groundwater reserves. This includes identifying research gaps that must be filled to more comprehensively evaluate groundwater/surface water interactions in natural and managed systems. Given the long-term climate trends, assessments are needed of the impacts on groundwater as an alternative supply, and the implications for recharge, flow regimes, groundwater-dependent ecosystems, and management. Additionally, studies are needed that examine how groundwater pumping is affected by a combination of increased drought and decreased hydro-power availability.

For mainstem and tributary reservoirs there is a delicate balance between flood control and water storage. Conjunctive use programs that shift reservoir water to groundwater storage is an opportunity to improve flood performance of reservoirs and reduce losses to evaporation. The Lower Basin states are doing aquifer storage but the full capacity for useful storage and recovery is unknown. There are exceptions in Arizona, where it is clear that there is a lot of capacity. Aquifer storage and recovery (ASR) for Las Vegas has reached the point where no more can be added, so Nevada began banking in Arizona and California.

Basin-scale management of groundwater will involve closing a number of important data gaps. This includes basin recharge and pumping information, and solid information on losses (and recovery) of water from surface reservoirs due to seepage (e.g., losses to the Navajo Sandstone in Lake Powell). Groundwater quality is also an important data gap, with poor quality affecting many rural and tribal communities. This includes increasing the number of groundwater monitoring wells that track water quality. For example, in the Grand Canyon Canyon, only 12 monitoring wells cover a roughly 100 x 120 square-mile area. Groundwater contamination (e.g., from uranium) is an issue in many of the region's wells and springs.

Aquifer storage, including banking and trading, may be an important hedge against future water scarcity in the Upper and Lower Basin. It will likely involve complex management challenges that balance storage on an intrastate and an interstate basis, along with consequences for other water users. Much more assessment of the opportunities and constraints of groundwater banking is needed.

The resilience of the aquifer storage system will depend on whether the water is recoverable. For example, the question of whether stored groundwater will be there when it is needed is a concern in some areas of Arizona. Throughout the Basin, a reduction in surface water flows has historically meant switching to groundwater pumping. In Arizona, this is done in the context of the Groundwater Management Act, at least within the Active Management Areas. In some unregulated areas, overdrafts are increasing rapidly. Groundwater will inevitably be used if there's a shortage on the CAP. Expanded groundwater use could have cascading effects on power systems (due to higher demand) and groundwater prices. These impacts might cascade differently through the system in the Upper and Lower Basins.

Data gaps relating to groundwater include surface water losses from seepage from reservoirs, e.g., losses to Navajo sandstone. Groundwater is also poorly monitored in the Grand Canyon area, with only about 12 monitoring wells in a 100 x 120 square-mile area. Groundwater contamination (e.g., from uranium) is also poorly monitored.

Colorado Delta

Signed in 2012, Minute 319 (an amendment to the 1944 U.S.-Mexico Water Treaty) delivered a 105,000 acre-feet pulse flow of water to the Colorado River Delta in the spring of 2014, as well as 52,500 acre-feet of base flow. In addition to CONAGUA and U.S. Bureau of Reclamation, a number of non-profit organizations were involved in pulse flow negotiations, as well as follow-up monitoring and restoration work. Minute 323 was signed in October 2017 to extend this work to 2026, when the Interim Guidelines expire. To successfully implement Minute 323, a new research agenda will be needed. This includes identifying problems or challenges inherent in current international agreements with Mexico and how collaborations can be strengthened to improve monitoring, flow deliveries, restoration work, and maximize social benefits on both sides of the border.

Minute 323 is not framed as an experiment as 319 was, but as implementation of restoration. No pulse flows are planned, but base flows sent to targeted areas are planned. In these communities, they are farming nature, creating simulated natural systems; that's how restoration is proceeding. The U.S. share of environmental water does not come from Lake Mead but from irrigation efficiencies in Mexico and the water that would otherwise be lost through seepage (amounting to 23,333 acre-feet per year). Environmental groups were hoping for 45,000 acre-feet of savings and now are scaling back some of their plans. The U.S., Mexico, and NGOs are sharing costs of increasing efficiency. The estuary is now a restoration target as a result of Minute 323. NGO restoration groups have targeted acreage they will restore, and are determining density, abundance, and other goals to get to 80% restoration.

In terms of the major scientific uncertainties that science could address to help delta management, the low-hanging fruit has been wisely picked by the NGOs already, so restoration will only get harder and opportunities fewer. Also there will never be enough water in the estuary to bring it back to its former glory.

Between 1983 and the 2014 pulse flow, there were some major flows to the Colorado Delta due to big discharges from lower tributaries. One possibility for improving restoration is to take advantage of natural wet years in the Salt-Gila system to provide more realistic "pulse flows" than the current regulated approach.

Salton Sea

The Salton Sea remains one of the greater challenges in the Basin, although many in the Basin view this as "California's problem." California has committed to managing the Sea to reduce the potential for air pollution associated with dust and to conserve wetland and open water habitat for migratory birds. Most of this work is occurring in California, without taking a full-system integrated look at options and assessing the impacts of these actions on Basin water supply and energy management. In some ways the Salton Sea is a linchpin to a number of issues, and the ultimate interdisciplinary challenge, whether the focus is the Drought Contingency Plan, migratory bird habitat, water supply, air quality, salinity, the energy/water nexus, or environmental justice. All of the places where the Colorado River provides water should be incorporated into a basin-wide agenda.

C. FINAL PLENARY SESSION

OVERLAP WITH STAKEHOLDER SUGGESTIONS

Bailey Kennett was asked to identify the areas of overlap between the issues that she heard from stakeholders during her interviews and those brought up by the scientists in this conversation. Some of the themes where there is significant overlap are:

- Temperatures – the importance of changing temperatures affecting a wide array of management and water supply considerations
- Flooding – the need to consider more thoroughly the potential impacts of large floods, not just drought
- Strategies for communicating risk – ways to help managers understand and prioritize among the many issues that they face
- Holistic watershed framing – both the scientists and the stakeholders acknowledged the need to think about linkages between systems and the need to express these issues more holistically
- Agricultural viability – there is interest in practical recommendations that keep farmers producing, and being prepared for expected changes, while participating in conservation efforts and drought contingency plans
- Salinity management issues – interest in options and constraints for salinity management
- Capacity building – this was an issue raised in several contexts, but in particular the need to build capacity among those who have historically not had an opportunity to influence water management decisions

Section IV
Conclusions: Overarching Themes/Priorities

> "Problem-based study is difficult, but there are opportunities to work across fields and disciplines; integrating the conversation this way can provide true breakthroughs."
> – Participant Bob Hall

Workshop participants agreed that a science agenda for Colorado Basin research must be highly interdisciplinary and forward-looking, and recognize the importance of both fundamental research and applied science and management solutions. A recurring sentiment was the need to identify big problems and grand visions for change: "Science may be incremental, but not all change is." Incremental changes are insufficient to address Basin challenges, and both institutionally and scientifically it is important to think outside the norms. The academic community is well-positioned to bring transformative change to the table. At the same time, the importance of carry-through from science to application was noted, with findings adapted to the scale of management decisions. Too much science doesn't make it to the endpoint where it is actually tested and used.

The following four interdisciplinary themes for future research emerged from suggestions made in the workshop breakout sessions and in the final plenary discussion session.

(1) **Building an Integrated Approach to Basic Science Research in the Colorado Basin**
The Colorado River Basin can be considered a living laboratory for testing the effects of climate dynamics on land and water resources, with implications for other rivers in the U.S. West and internationally. This first theme focuses on understanding the multiple dimensions, processes, and drivers of change at work in the Basin. This is fundamentally different from simply observing the changes that are taking place. By testing sensitivity to climate variations, such as temperature and precipitation in association with other dynamics such as changes in wildfire and land use, we can understand more about feedback loops. (An example of a feedback loop is less surface water reducing groundwater recharge at the same time that people pump more groundwater to make up for lost surface water supplies).

There is also a need to think about the drivers of change using a more system-wide perspective, at multiple scales, so that the implications of change can be better understood from the headwaters to the Delta. This foundational research can subsequently inform the models that are currently used to anticipate possible future conditions. Improved understanding is critically important in the context of the intense human and biological dependence on constrained resources, interstate and international shortage-sharing efforts, and the increased potential for transformational landscape change. Within this theme, the group agreed that priorities were:

- *Temperature*: Temperature drives the hydrologic cycle, and there is increasing evidence that warmer temperatures are having dramatic impacts on snowpack and runoff, but also on stream chemistry and riparian and aquatic ecology. Managers and scientists alike continue to be surprised by the cumulative impacts of increasing temperatures on a variety of hydrologic variables, including evapotranspiration and sublimation (loss of snowpack directly to water vapor rather than through melting). There has been less attention to the direct and indirect effects of temperature on habitat and biodiversity, but understanding these issues is critical to successful conservation efforts.
- *Process-based Understanding of Change*: How (and why) do Basin conditions change? For example, scientists are not sure why the most recent global climate modeling (Coupled Model Inter-comparison Project 5, or CMIP 5) indicates that the West will be wetter than previous efforts (CMIP 3). Is this primarily because of changes in intense precipitation? Also, what are the multiple factors influencing snowpack and snowmelt that are not yet fully incorporated into modeling efforts (including dust on snow, changes to rain-on-snow timing, albedo and water loss, effects of canopy

cover and shade on snowmelt)? Finally, can we arrive at a more process-based understanding of the intersections of groundwater and surface water systems in the Basin in the context of climate change, and what are the implications for current and future seasonal flows and riparian and aquatic ecosystems in the Basin?

- *Scientific Foundations and Baseline Data*: Improved monitoring of groundwater, surface water, sediment flows, return flows (runoff from agriculture, for example, that returns to a stream or aquifer), consumptive use, and system losses would greatly improve the capacity to understand the impacts of alternative management practices and also improve modeling efforts. A particularly difficult monitoring and projection challenge is understanding current and future water demand across the basin states using consistent assumptions. There is also the potential for new technologies and remote sensing to revolutionize monitoring efforts, and these opportunities need to be explored. All of these efforts would be useful in establishing realistic and useful baselines against which to measure change.

(2) **Anticipating Future Colorado River Challenges: Science of Crises and Tipping Points**
Identify and explore the full spectrum of possible extreme events, feedbacks, and tipping points that can overwhelm physical and institutional systems, and the potential for mitigating the associated risks. Failure to consider low-probability, high-consequence events could have devastating consequences, but these events are difficult to study because of their rarity. Yet we do have information, mostly through tree ring data, about past multi-decadal droughts and more intense flooding than has been seen in the instrumental record, and climate change could mean even more extreme events. Being prepared for crises requires examining our institutions and developing conflict-reducing institutional processes for dealing with crises. We must also examine fundamental assumptions about how our decisions may either reduce or exacerbate risk.
Priority areas for inclusion are:

- *Drought/Flood Interface*: One topic that has not received significant attention is the potential to move quickly from serious drought conditions to extreme flooding, yet such turnarounds have occurred in the past. Understanding probabilities (based on historic and projected conditions), causation, impacts, and management implications that are associated with rapid swings between wet and dry extremes could be very useful to water managers.
- *Black Swans:* Consider what can be discovered from the past about other "black swan" events – which are rare, unpredictable, have extreme impacts, and inspire *ex post facto* explanations – but which dominate social systems and management. Looking beyond the historical record can inform us about potentially catastrophic events: how often they occurred in the past, their future probabilities, and how climate change might affect those probabilities. How can we recognize the signposts (threshold precursors and vulnerable geographic locations), causation, potential impacts (to infrastructure, food supply and agriculture, threatened or endangered species, etc.) so as to develop mitigating management options?
- *Institutional Performance in Extreme Events*: The degree to which extreme events are devastating or manageable to people is largely related to our institutional capacity to prepare and respond. Comparative studies of river basin governance regimes to identify opportunities, constraints, and useful lessons, including better understanding of forcing factors of existing regulations in place in the Basin today, e.g., the Clean Water Act, ESA, and the Law of the River.
- *Transformative Change in Coupled Human/Natural Systems*: What are the threshold events that might overwhelm human and natural systems in the Colorado Basin, and what are our options for anticipating, recognizing, and managing risk before it is too late? What are the step changes that might be required in our management systems to deal with crossing tipping points in human and natural systems?

(3) **Holistic Management of Integrated Systems at Landscape Scales**
Develop tools and methods to compare and assess system drivers of notably different types to determine relative risks, cumulative impacts, and feedback relationships at large scales. Stressors in this context could include climatic changes, water management/use decisions, ecological processes such as competition and predation, and land cover modifications. Review how shifting climatic conditions over long timescales can modify landscape properties and runoff patterns, and the impacts and feedback loops associated with this transition. Priority areas are:

- *Coordinated Sediment, Water Management and Habitat Restoration*: Incorporate sediment/erosion management and fire concerns into water management and environmental frameworks.
- *Groundwater Assessment*: Assessment of groundwater reserves, surface water/groundwater connections (including springs), opportunities for storing water underground in aquifers, along with later recovery of water, and the role of institutions and institutional change in managing groundwater sustainably in a changing climate.
- *Projecting adaptive behavior for improved scenario planning*: What are the expected management responses to change in the absence of explicit preparation for climate change? While natural resource managers and decision-makers have always worked to respond to changing conditions and limit risk, projections for future trends frequently assume no such actions. This baseline needs to be explored/established prior to additional or innovative climate adaptation efforts.
- *Implications of Alternative Management Schemes* across multiple sectors and expanded geographic areas: In managing Salton Sea issues, for example, the full range of issues and options must be considered concurrently and holistically, including wildlife habitat, water quality and supply, recreation, health impacts, international treaties, social justice, energy, and agriculture.
- *Signposts*: Identification of indicators (signposts) of change in physical, ecological, social and political systems that can be useful for adaptive management.

(4) **Science for Adaptive, Resilient and Just Institutions**
Despite the best intentions of water managers, historical approaches to managing the Colorado River have focused primarily on water supply issues and engineering solutions. In a more perfect world, a systems-based approach to management would be advisable that respects both ecological systems and social systems (cultures, institutions, etc.) and treats them in a more integrated way (for example, valuing the concepts of "ecosystem services", or "traditional knowledge", or "existence value" in decision processes related to river-based assets). In addition, we need to think more broadly about the possible roles of each of the water-using sectors in the basin in achieving societal values. That said, many water users cannot currently engage effectively in river policy and management, and significant capacity-building is required in order to allow true engagement. Research needs associated with this theme include:

- *Justice and Equity*: Characterize how shifting physical conditions influence the distribution of costs, benefits, risks and opportunities among sectors, stakeholder groups, tribes, regions, generations, and other distinct parties, and the options for mitigating those impacts through collaborative, inclusive processes.
- *Comparative Governance*: Conduct comparative studies of river basin governance regimes to identify opportunities, constraints, and lessons useful in assessing institutional performance and informing institutional change in the Basin.
- *Outcome-Oriented Environmental Management*: Assess progress in environmental restoration and management programs in light of shifting values, climatic/environmental conditions, and markets. Identify options for establishing realistic environmental goals that are consistent with these

analyses, and programs designed for implementation (e.g., Endangered Species Act). Identify lessons that are useful in an outcome-oriented management approach that can be shared across the basin.

- *Agricultural Stewardship:* Explore possible agricultural sector futures and roles, including institutional factors, challenges, and opportunities. (For example, the current Agricultural Act of 2014 expires at the end of FY 2018 and a renewal of the Farm Bill could be used as a vehicle to shape those outcomes, including identification of legal constraints, measurements of consumptive use, and community economics). Identify strategies and implementation tools for desired outcomes.
- *Integrated Lessons*: Identify what has been learned in species preservation and recovery efforts across the Basin, including in the Delta, as well as feasible objectives and trade-offs between human and ecological systems.
- *Institutional Development and the Social Science of Capacity Building:* Examine the underlying issues and barriers to broader engagement in science and governance processes, and design solutions to address them. Build tools, training programs and efforts to empower stakeholders to better use science and research products and to participate more fully in resource management decisions.

The group recognizes that some of these topics could be combined and/or resorted in future proposals, but all of these ideas had significant resonance within the group.

Section V
Next Steps

Follow-on activities are being planned to expand stakeholder representation in this effort and to include stakeholder input in a subsequent report to NSF that will be broadly shared.

Workshop organizers will convene water managers and stakeholder representatives (representing a broad range of interests) in April of 2018 to respond to the findings of this science report and discuss strategies for refining and moving forward with the research topics identified in this initial workshop. Representatives will include those who were interviewed, but also a much larger and more diverse array of participants.

Additional workshops have been proposed (but are not yet funded) that would engage stakeholders to, for example: 1) discuss how elements of integrated water resources management, adaptive management and other frameworks could be employed to address challenges in the Basin's coupled natural-human system; 2) further review and compare experiences from other river basins that could offer lessons for the evolution of the Colorado River management; 3) expand tribal engagement in these topics and 4) consider legal and economic strategies to address anticipated challenges.

Workshop organizers will develop a short white paper for broader distribution that explains and outlines the work and recommendations of this initial NSF-supported workshop. This paper will be shared with subsequent workshop attendees and other interested parties.

Participants will have ongoing opportunities to review and comment on this and subsequent documents that are produced in conjunction with this process.

APPENDIX A: PARTICIPANTS

NAME	INSTITUTION
Baker, Vic	University of Arizona
Bestgen, Kevin	Colorado State University
Caine, Nel	University of Colorado (ret.)
Cayan, Daniel	University of California, San Diego
Clark, Martyn	National Center for Atmospheric Research
Colby, Bonnie	University of Arizona
Dahm, Cliff	University of New Mexico
Flessa, Karl	University of Arizona
Garrick, Dustin	Oxford University
Graf, Will	University of South Carolina
Hall, Robert	University of Montana
Hartmann, Holly	Holly C. Hartmann Consulting
Jacobs, Kathy	University of Arizona
Jerla, Carly	U.S. Bureau of Reclamation
Kenney, Doug	University of Colorado
Kreamer, Dave	University of Nevada, Las Vegas
Lettenmaier, Dennis	University of California, Los Angeles
MacDonnell, Larry	University of Colorado
McCool, Daniel	University of Utah
Megdal, Sharon	University of Arizona
Mount, Jeff	Public Policy Institute of California
Norgaard, Richard	University of California, Berkeley
Overpeck, Jonathan	University of Michigan
Prairie, James	U.S. Bureau of Reclamation
Robison, Jason	University of Wyoming
Schmidt, Jack	Utah State University
Shafroth, Pat	U.S. Geological Survey
Stone, Mark	University of New Mexico
Udall, Brad	Colorado State University
Vano, Julie	National Center for Atmospheric Research
Waskom, Reagan	Colorado State University
Wohl, Ellen	Colorado State University
Woodhouse, Connie	University of Arizona

STAFF SUPPORT, University of Arizona
Mary Black, Arin Haverland, Bailey Kennett

APPENDIX B: WORKSHOP AGENDA

Colorado River: Building a Science Agenda
Oct. 10-12, 2017
ENR2 Building, Room S215, University of Arizona

(Panel and discussion leaders are marked in **bold** below.)

TUESDAY, OCTOBER 10: Room S215, ENR2

Pre-workshop	Light lunch provided at ENR2 for early arrivals and organizers.
1:00 – 1:30 PM	PURPOSE OF WORKSHOP, INTRODUCTIONS, EXPECTATIONS Kathy Jacobs and Doug Kenney
1:30 – 2:15 PM	DISCUSSION OF STAKEHOLDERS PRIORITIES, INTENDED OUTCOMES AND OPPORTUNITIES: EXPECTED PATH FORWARD Bailey Kennett, Kathy Jacobs and Doug Kenney
2:15 – 3:30 PM	COLORADO RIVER BASIN STUDY OVERVIEW, REGIONAL ISSUES, AND UPDATES / WAYS FORWARD SCIENCE NEEDS Jim Prairie and Carly Jerla
3:30 – 4:00 PM	BREAK
4:00 – 5:30 PM	CLIMATE VARIABILITY AND EXTREMES: FLOODS AND DROUGHT ISSUES [Panel: Vic Baker, Dan Cayan, Dennis Lettenmeier, Jonathan Overpeck, Brad Udall, Julie **Vano**, Jim Prairie, Connie Woodhouse, Martyn Clark]
5:30 – 6:00 PM	RECEPTION AT ENRB2, Executive Conf. Rm. (rooftop)
6:00 – 7:30 PM	HOSTED DINNER AT ENRB2

WEDESDAY, OCTOBER 11, Rm. S215, ENR2

8:30 –9:00 AM	CONTINENTAL BREAKFAST
9:00 – 10:00	CHANNEL MORPHOLOGY, SEDIMENT, HABITAT AND RECREATION ISSUES [Panel: Vic Baker, Bonnie Colby, **Karl Flessa**, Will Graf, Pat Shafroth, Ellen Wohl, Jack Schmidt]
10:00 – 10:15	BREAK
10:15 – 11:45	ENVIRONMENTAL /BIOLOGICAL ISSUES (INCLUDES WATER QUALITY) [Panel: **Clifford Dahm**, Kevin Bestgen, Bob Hall, Mark Stone, Dave Kreamer, Pat Shafroth]
11:45 – 12:30	LUNCH BREAK ONSITE

12:30 – 1:30 PM	CULTURAL, INSTITUTIONAL AND LEGAL ISSUES [Panel: Dustin Garrick, Sharon Megdal, Dan McCool, Larry MacDonnell, Jason Robison, **Doug Kenney)**
1:30 – 2:30	VULNERABILITIES ACROSS COUPLED HUMAN-ENVIRONMENT SYSTEMS ISSUES (MANAGING RISK AND UNCERTAINTY) [Panel: **Bonnie Colby**, Dustin Garrick, Holly Hartmann, Richard Norgaard, Reagan Wascom]
2:30 – 2:45	BREAK
2:45 – 3:45	TRIBUTARIES, DELTA AND GROUNDWATER ISSUES [Panel: Karl Flessa, Kathy Jacobs, Dave Kreamer, **Jeff Mount,** Pat Shafroth]
3:45	GO TO BUS
4:00	DEPART FOR ARIZONA SONORA DESERT MUSEUM (ASDM) BY BUS
4:30 – 8:00	RECEPTION & DINNER AT ASDM

THURSDAY, OCTOBER 12, Rm. S215, ENR2

8:30 – 9:00	CONTINENTAL BREAKFAST
9:00 – 9:30	DISCUSSION OF CRITERIA FOR PRIORITIZING SCIENCE NEEDS Kathy Jacobs and Doug Kenney
9:30 – 10:30	BREAKOUT DISCUSSIONS OF PRIORITY INTERDISCIPLINARY SCIENCE NEEDS TO SUPPORT MANAGEMENT DECISIONS [Breakout Session leaders: **Kenney, Jacobs, Vano, Hartmann**]
10:30 – 11:00	BREAK
11:00 – 12:30	REPORT BACK AND DISCUSSION OF SCIENCE NEEDS AND PRIORITIES
12:30 – 1:00 PM	DISTRIBUTE BOX LUNCHES; DISCUSS PATH FORWARD
1:00 – 2:00	BREAK
2:00 – 4:00	ADVISORS MEET TO DISCUSS CONCLUSIONS AND NEXT STEPS, **ECR, Rm. 604**

APPENDIX C: STAKEHOLDER ISSUES DOCUMENT

Preliminary Themes for Discussion

Document Structure

A preliminary document was made available to attendees in advance of the workshop, organized by themes that were drawn from a combination of a) a series of interviews with various practitioners, scientists, and decision makers conducted in July and August 2017; b) review of primary source documents and peer-reviewed articles, and c) input from various workshop advisory board members and participants. Under each theme is a discussion prompt, a laundry list of issues that have come up in interviews and conversations, and a preliminary list of relevant readings, all of which are included in this report's much-expanded bibliography. Workshop participants were asked for input on both the issues and readings.

To establish the issues list, a series of 18 interviews were conducted by the University of Arizona research team. In these interviews, conversations with water managers, environmental interests, and other stakeholders in the basin states were focused on their perceptions of gaps in the scientific foundation for sound decision-making. The people interviewed were nominated by our advisory committee to provide input into our conversations, given that only people with academic affiliations were invited to this workshop. The intent here was NOT to exclude stakeholder perspectives but rather to limit the amount of basin water management politics that has dominated many previous conversations. The stakeholders who were interviewed, along with many others, will have an opportunity to provide substantial input to the research recommendations through review of the report generated at this workshop and in a subsequent meeting that will focus squarely on their interests and perspectives.

I: Climate Projections, Hydrologic Forecasting & Extreme Events

Discussion Prompt

What are the implications of climate variability and long-term trends on water availability and flood risk in the Colorado River? What is the full range of plausible future flow reductions for the river? This topic area provides a basis for later discussion of the implications of climate variability and long-term trends on both water availability and flood risk on the main stem and major tributaries, and on environmental services, ecosystems, and species.

Reclamation's 2012 Colorado River Basin Water Supply and Demand Study ("Basin Study") focused on an average future Colorado River runoff decline of 9% by 2060, while reductions identified by researchers range from a 6 to 45 percent decline by 2050 and current century stream flows are around 20 percent lower than last century. Reductions in flow will be driven by increasing temperatures and the resulting impacts on hydrologic processes. Given these projections and a likelihood of more extreme events, including floods, droughts and extreme heat, how can researchers help managers incorporate a broad suite of supply scenarios in their strategic planning?

Talking Points and Stakeholder Concerns[*]

Hydrological Forecasting Improvements and Needs

- Updated flow projections, using CMIP-5 dataset and adjusted for temperature increases in the Basin, especially as re-negotiations for 2007 Interim Guidelines approach.*
- Improved techniques for mid-term streamflow modeling (2- to 10-year forecasts)
- Snow modeling:
    - Better snowpack modeling and snowmelt forecasting*; hi-resolution imaging has been shown to improve streamflow forecasts. Also need a consistent measurement of snow coverage to use as basis for improved river management.
    - Examine precipitation-to-runoff ratio of high-efficiency watersheds; they occupy narrow elevation bands and particular orientations that accumulate snow well, allowing them to translate snow into streamflow better than other watersheds. What are their physical parameters and why are they efficient? With climate change, will they become more or less efficient?
    - Impacts from altered snowmelt: spring floods; reduced late-season baseflow*; landscape response to earlier snowmelt
    - Impacts of high temperatures on snowpack, e.g. sublimation
- Improved understanding of water lost to transpiration (significant amount in Upper Basin). As vegetation changes with climate change, how will transpiration be impacted?
- More confidence in reconstructed flows of Lower Basin tributaries, particularly those between Lake Powell and Lake Mead. To what extent will flows be affected by climate change?

Climate Projection Needs

- Better understanding of regional historical climate, and a scientific process for selecting appropriate periods of record for climate analyses rather than relying on earliest dates in instrument record
- Considering temperature and precipitation projections in fundamentally different ways or with different levels of confidence
- Updated information about evaporation from Lake Mead and Lake Powell
- As storm tracks change, how will dust-on-snow be impacted?
- Localized climate downscaling, particularly for Upper Basin
- Role of individual tributaries in mainstem flows past and future

High Intensity Flood Events

- Need more confidence in monsoon projections and expected impacts from climate change, especially in the Southwest, and focused on particular tributary inflows
- Potential for extreme precipitation and flooding on the Colorado, esp. Upper Basin
- Need a better understanding of Infrastructure impacts, especially potential for dam failure
    - Current infrastructure isn't designed to route extreme flood events; need to explore and exercise response to catastrophic scenarios that could involve impacts to major

[*] indicates at least three stakeholders expressed this concern in pre-workshop interviews.

infrastructure, including dams, as well as impacts to cultural assets and recreation, and other social impacts.*

- Erosion, sedimentation, loss of storage capacity in reservoirs, and ecosystem impacts of flooding

Severe Drought & Extreme Heat

- Basin-wide, what happens to the system as temperatures continue to escalate, beyond initial estimates?*
- Need to improve understanding of how precipitation, snowpack, and runoff respond to temperature increases and their impacts on evaporation and evapotranspiration.
- Consideration of altered drought-tolerance threshold for crops and native vegetation
- Impacts to water quality, ecosystems, and recreation
- Multi-decadal drought risk

Support & Communication Issues and Needs

- Risk communication, especially for flood events; how to effectively communicate risk under "normal" conditions as well as extreme conditions*
- Guidance for water managers on applying climate and hydrology forecasts; water managers across the basin draw from many different sources, which may reflect the high degree of uncertainty and/or unexplained differences in projections among the scientific community
- Guidance and support for Reclamation in utilizing new, continually evolving climate data
    - A stronger scientific consensus on Basin-appropriate GCMs and downscaled data and methods could encourage more regular updates for hydrology model
- Guidance on adaptation planning, considering local constraints*; approaches for agencies to plan for climate change/water supply impacts are inconsistent
- Remote sensing data needs to be better utilized to improve understanding of soil moisture, ET, water demands*

II. Groundwater

Discussion Prompt

Since the start of the current century, demand for Colorado River water has consistently outstripped supplies from natural streamflow, a situation that has only been allowed to persist by drawing down reserves in Lakes Mead and Powell. This reservoir storage depletion has been paired with a corresponding – largely invisible but potentially massive – decline in groundwater storage. Projections and analysis of streamflow reductions or increased demands for Colorado River water must also inform how these changes impact groundwater reserves. What research gaps must be filled to more comprehensively evaluate groundwater/surface water interactions in natural and managed systems? Given the long-term climate trends, what are the impacts on groundwater as a backup or alternative supply, and the implications for recharge, flow regime, groundwater-dependent ecosystems, and management? How is groundwater pumping affected by a combination of increased drought, and decreased hydro-power availability?

Talking Points and Stakeholder Concerns

Groundwater Impacts along River Corridor

- Stream & riparian impacts of overdraft

- Consumptive uses and losses, especially to groundwater infiltration, for Lower Basin tributaries and agricultural users
- Better understanding of riparian and root zone vegetation and impacts on recharge, versus mountain block recharge, is needed to improve understanding about net recharge

- Reservoir bank storage
  - Is water stored in banks "lost to the system"? How to quantify this storage?
  - Should stored water be accounted for when quantifying Lake Mead and Powell levels?

Groundwater-Surface Water Connection

- Need a better understanding of this connection at the US-Mexico border*
  - Better metering and monitoring on both sides of the border to predict and evaluate impacts from overdraft. A greater understanding may allow us to reduce pumping in both US and Mexico at certain times of the year.
  - Better understanding of groundwater migration at the border region

Support & Communication

- A better groundwater governance structure could improve water management at the border
- Groundwater banking is a flexible management strategy that should be further explored and implemented across the basin*
- Groundwater measuring and monitoring, and data collection, could be improved in all the basin states, on the U.S.-Mexico border, within each of the tributary watersheds, and in the Delta

III. Colorado River Delta

Discussion Prompt

Signed in 2012, Minute 319 (an addition to the 1944 U.S.-Mexico Water Treaty) delivered a 105,000 acre-foot pulse flow of water to the Colorado Delta in the spring of 2014, as well as 52,500 acre-feet of base flow. In addition to CONAGUA and U.S. Bureau of Reclamation, a number of non-profit organizations were involved in pulse flow negotiations, as well as follow-up monitoring and restoration work. As Minute 319 expired in 2017, negotiations were being finalized for follow-up legislation, Minute 323, which was signed on Sept. 21, 2017.
What further research is needed to set a course for continued restoration success in the Colorado River Delta? What problems or challenges are inherent in current international agreements with Mexico and how can collaborations be strengthened to improve monitoring, flow deliveries, restoration work, and maximize social benefits on both sides of the border?

Talking Points and Stakeholder Concerns

Reduced Freshwater Flows

- What are the impacts from changes in spring floods/peak runoff and reduced late-season baseflow to ecosystems, agriculture, and fisheries?

Restoration Efforts

- Restoration should be research-based, not political or ad hoc
  - A theoretical framework is needed to develop strategies and adapt to changing conditions

    - Consider natural variability: physical, chemical, and biological processes as well as the influence of human activities
    - Restoration should not aim to "re-create" the past, but rather incorporate our understanding of anticipated future conditions
- How to measure success of restoration? What are the criteria?
    - Coordinate work in the Delta with other restoration work in the Basin?
- How to optimize existing flows?* Should there be more careful or focused targeting of restoration sites?*
- Need for a regional assessment of ecosystem health and risk factors
    - Work being done through Minute 319 and by NGOs is currently focused on the narrow riparian corridor – important, but this habitat is highly affected by regional groundwater depletion (for agricultural use), on which there is little to no focus.
        - CONAGUA could be very instrumental in facilitating regional groundwater management with regional farmers and irrigation districts. Its collection of regional groundwater data is integral to restoration planning. With data, a binational team could collaboratively develop a model to illustrate the relationship between the corridor and water management practices in the larger delta region.
        - Leakage from irrigation canals is an important source of recharge water that keeps restoration sites viable

Delta Surface Processes: Natural and Economic Sciences

- Need improved understanding and theoretical explanation of the behavior of channel forms, sediment redistributions, and connections with biological systems on dynamic delta surfaces.
- Create a convincing approach to monetizing the value of delta surfaces and particularly their habitats.

Pulse Flow and Baseflows

- Change in future deliveries needed to meet environmental need?
    - Minute 319 monitoring revealed that less than 10% of pulse flow got to the targeted restoration site; need more targeted water deliveries to achieve restoration goals.
    - Minute 323 does not separate "pulse flows" from "baseflow"; together they are called "environmental flow." Although not written into Minute 323, more targeted "mini pulse flows" are recognized as important for social reasons.
- Need research to illustrate the social response to the Minute 319's pulse flow and Minute 323's more targeted "mini pulse flows"*
    - Better understanding could ensure that flows are delivered at a time and location that maximizes community benefit*
    - Evaluations of the social benefits are important in building continued support for pulse flows and overall delta restoration
- Need an ecological baseline
    - Current monitoring is less significant without a historical baseline
    - Baseline should include extreme conditions (droughts and floods) to the extent such records are available

    - What is projected future ecological condition? Is there only one, or a set of future conditions?
- Need for improved understanding and monitoring of baseflow deliveries
    - Monitoring and information about hydrologic response was gathered for Minute 319 pulse flows, but not for baseflow – which will be the primary delivery method moving forward. Need for installation and monitoring of discharge meters at approximately 15 flow delivery sites.

Support & Communication

- How can scenario planning help with understanding a range of possible futures?
- Need for increased institutional support and collaboration involving Reclamation and CONAGUA
    - River restoration should be supported as an integral part of hydrological science
- Need for better collaboration with CONAGUA*
    - Was highly involved in Min 319 negotiations and pulse flow monitoring, but participation has been limited with recent turnover
    - Invite Mexican representatives to follow-up stakeholder workshop

IV. Water Quality & Ecology

Discussion Prompt

Impacts from climate change and other human activities influence the flow and quality of Colorado River water, as well as species, habitats, and ecological systems directly and indirectly dependent on the river. While the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin (1988) and the Lower Colorado River Multi-Species Conservation Program (2005) have made significant environmental gains, evolving conditions present new challenges and research questions.

What is the long-term prognosis for habitat recovery, especially of native Colorado River fishes, and what trade-offs are needed to improve it? There is a need to address multiple water quality issues, including increased salinity under reduced streamflows, pesticides, heavy metals, and movement of groundwater plumes of toxic substances due to increased pumpage.

Talking Points and Stakeholder Concerns

Water Quality

- Need for further research on chemical pollution and its impacts, particularly in the Lower Basin
- Salinity
    - Are there ways to manage salinity further upstream than has been done in the past?
    - Return flows will be harder and more expensive to dilute with decreased streamflow.
- Need research on economically productive water quality improvements
    - Example: In El Paso, a private company purchases brackish desalination byproduct and refines it for use in manufacturing and agricultural processes, while returning a higher quality water to the system

Species Health & Biodiversity

- Biodiversity
    - Poor biodiversity baseline, especially in watershed outside of mainstem

    - Consider biodiversity loss outside of mainstem and reservoirs; tributaries, wetlands, and cienegas experience significant loss
- Endangered species management
    - Need awareness of whether endangered species are viable under future climate conditions, and whether management techniques are worthwhile and efficient. If research indicates a species will not be viable under future conditions, what are the Endangered Species Act (ESA) implications?
- Non-native species management
    - Non-native fish in Upper Basin threaten four endangered species*.
    - Need research on population control measures for species such as Quagga mussels in Lake Mead
    - How will reduced abundance of tamarisk/saltcedar associated with biological control affect future trajectories of riparian vegetation and associated restoration planning and implementation?
- Salton Sea salinity
    - Appear to be at hypersaline tipping-point for fish breeding, only finding tilapia
        - Cascading impacts to migratory bird habitat and Pacific Flyway

Impacts from Reduced Flows, Changes in Seasonality, & Ecological Disturbances

- Changes in water chemistry/quality
    - Higher water temperatures, both in-stream and in reservoirs; what are the impacts to aquatic habitat/species and to water treatment?*
    - Higher chemical concentrations, including increases in Lower Basin selenium, endocrine disruptors, and contaminants of emerging concern (CECs).
    - Higher effluent concentrations require additional treatment.
    - Greater organic material, from flood events, wildfires, and bark beetles
    - Lower oxygen levels and increased algal blooms, with new species of cyanobacteria
- Breeding, spawning, and nursery habitats impacted by spring floods and reduced late season baseflow, affecting:*
    - fish migration patterns
    - aquatic and riparian food webs
    - changes in stream morphology
    - ecosystem services, including commercial fisheries and recreational fishing

Support & Communication

- Increase public education about introduction of non-native species
    - Impacts and potential alternative species (for recreation)
- Achieve consensus on and sustain a monitoring regime, to help understand and adapt to future ecological impacts.*

V. Fluvial Geomorphology

Discussion Prompt

Increased erosion, transport, and deposition of sediment that result from ecological disturbances like flood and wildfire as well as more intense precipitation influence a river's flow regime, quality, and physical characteristics.   All of these impacts are predicted to become

more intense with climate change. Altered geomorphology and nutrient transport impact aquatic and terrestrial habitats, as well as the structure and productivity of floodplains, beaches, and estuaries. Sediment transport in the Colorado River system is researched and monitored through the Glen Canyon Dam Adaptive Management Program and USGS' Grand Canyon Monitoring and Research Center, among other efforts.
In analyzing and applying strategies from across the Basin, what can be learned about the specialized physical processes that occur on the upper surfaces of deltas in the Colorado River system (at the headwaters of the reservoirs and the Colorado River Delta), where ecosystem interactions are critical?

Talking Points and Stakeholder Concerns

Flow Regimes

- Better understanding of flow regimes for tributaries
- Impacts of forest loss (bark beetle, wildfire) on runoff and flow regimes
- How will reduced abundance of tamarisk/saltcedar associated with biological control condition fluvial processes such as bank erosion, channel widening, and levee development as well as vegetation geomorphic feedbacks?

Environmental Flows

- Local-level environmental flow specifications are needed throughout Basin, including tributaries; restoration and flow protection happen locally, but data isn't scaled to that level.
- Aside from a specific flow requirement number, are there indicators that tell us what a healthy river looks like?

River Channel Impacts from Ecological Disturbances or Altered Flows

- Channel and bank erosion from increased spring floods
    - Increased sediment transport & deposition
- How can spatial heterogeneity and associated ecosystem functions be re-created and maintained in the lower, alluvial portions of the Colorado River (between Davis and Imperial Dams, or Davis Dam and the border, for example)?

Floodplain and Riparian Impacts of Reduced Flows

- Disconnect of terrestrial and aquatic ecosystems
    - Food web impacts
    - Predominance of non-native riparian vegetation
    - Species loss, especially in riparian areas that are dependent on subsurface groundwater or surface flows
- Infrastructure (municipal, residential, agricultural)
    - Insufficient water intakes for utilities (eg Southern Nevada Water Authority
    - Regulatory issues with wastewater and stormwater discharge?
    - Inaccessible boat launches
- Ecosystem services: impacts to fisheries, recreation

Support & Communication

- Colorado River management should be more integrated with forestry groups/natural resources management/land use planning activities
- There is a need for sustainable funding support for continuous monitoring of the fine sediment, and resultant flux, of the Colorado River and its major tributaries.

VI. Human Dimension

Discussion Prompt

As the water balance in the already over-allocated Colorado River Basin becomes more vulnerable, pressures on and between water users is likely to increase, while management institutions and existing legal frameworks will be pressed to cope with changing conditions. In order to prepare for these stresses, it will be important to understand – to the best of our ability – the tradeoffs and implications (cultural, institution, legal, economic) that can be expected in the future. What institutional, cultural, and legal barriers and capacity limitations constrain our ability to help inform decision-making for Colorado River management? And further, can we manage the watershed in an integrated way that accounts for extreme events, urban development, and environmental needs?

Talking Points and Stakeholder Concerns

Cultural Issues

- Transition of land and water from agricultural to urban uses
- Integration of tribal perspectives into river management
    - Tribal elders must be consulted and have a seat at river management discussions.
    - Tribal communities often value water differently than other Western water users; incorporation of these values could affect assumptions about water demand, as well as water allocations/transactions.
- Meeting expectations of wilderness supporters, recreation (rafting, hiking, camping, fishing, boating/marina and hunting) communities
- Building a common language and "safe space" for a broad range of stakeholders to have meaningful input into river management issues

Institutional Issues

- Drought Contingency Plan / DCP+ discussions
- Intrastate shortage and use allocations
- Hydropower operations
- Salton Sea issues are often disconnected from Colorado River management/planning discussions, yet upstream impacts trickle down
- Reduced yields from Colorado tributaries may further impact an over-allocated Colorado River
- Groundwater-surface water regulatory issues

Renegotiation of Interim Shortage Guidelines

- Consider outcomes to river ecosystems between reservoirs, not just river flows in the face of sustained drought.

- River science research should be integrated with water resource engineering so a wide range of outcomes are evaluated for river management that look at implications to water supply reliability and to river ecosystem rehabilitation as a joint optimization problem.
- How accurate and relevant are water demand forecasts?

Legal Issues

- ESA – is it broken? Can the system be managed in a way that achieves objectives?
- Water transfers – different rules in different states, regions…under what conditions should they be allowed?
- Quantity and quality and timing of deliveries to Mexico (both surface and groundwater)
- Quantity and quality of deliveries to tribes:
    - Adjudications of Colorado River water rights for Basin tribes are crucial in effectively managing basin supplies, especially amidst conversations about shortage sharing and transfers. Important to remember that it takes time, money, and resources (to construct infrastructure, etc.) to translate a paper water right to actual wet water, to properly recognize sovereign entities and cultural priorities
- Delivery of Salton Sea mitigation water (as provided in Quantification Settlement Agreement (2003)) expires in 2017*
- Need to explore the possibility of an alternate water rights framework; need intrastate and interstate policies and priorities. Can we envision new laws to better manage the river, without being limited by state or national boundaries?
    - If the Law of the River were to be modified in the future, tribal water rights would need to be used as a baseline.

Characterizing and Addressing Uncertainty in the Context of Colorado River Management

- Sources of uncertainty, both human and natural
- Characterizing and managing uncertainty, explaining uncertainty, incorporating it into decision processes
- Predictive capacity at different time frames into the future
- Decision-making and uncertainty: moving beyond uncertainty to action

Agriculture

- Recognition of the value of agriculture and food security* has improved slightly since CA drought, but more work is needed.*
- Cultural and institutional strategies need to be identified for managing ag-urban transfers (primarily a concern for ag districts with junior priority; e.g., Western Slope CO), including guidance on conditions under which transfers are acceptable.
- At a large scale, how to socialize/incentivize farmers to use less water after decades of use-it-or-lose-it mentality?

Science Communication

- Science communication to farming community
    - Need to effectively engage and collaborate with agricultural community so as to build resilience to climate change and promote food security.*

- Progressive/younger farmers can be targets for irrigation technologies, adaptation efforts, conservation partnerships.
- Interest in evolving research related to new technologies and management strategies that promote agricultural efficiency. This includes: ag to urban conservation programs; on-farm conservation; seasonal fallowing (crops that reduce year-round yield and water use, but still keep farms producing); modified or adapted crops with higher salt tolerance; opportunities for drainwater re-use; and specific and economically viable crop & farm management recommendations under assumptions of overall less waterDefining environmental flow requirements involves many ecological variables but water managers/providers don't necessarily want that level of detail

- Need a broad assessment about healthy rivers' needs, produced in a way that's approachable for water managers. Evaluations may require inclusion of economic and social benefits.*
- Basin-specific research on effective climate change framing and communication strategies, for decision-makers and the public.*
- When engaging stakeholders/public, need to incorporate sociological context – what is their cultural and economic relationship with water and water use?
- How to effectively market and deploy conservation technology to change behavior, such as encouraging direct potable reuse?
- Help people in the arid West understand basic risks to water supply and encourage them to support policy changes their leaders are trying to enact
- Social sciences can assist in furthering an understanding and acceptance of the concept of multiple benefits and resilience. For example, we can use metrics that value resilience to more appropriately price water.

Funding and Economic Evaluations

- Need more consensus on data collection, methods and results of economic evaluations before they're accepted and adopted by water managers
- Production of social/economic evaluations of resources within a service area for water providers and specific communities
- Difficulties and logistics of creating long-term funding streams to improve management of the River – for communities, agriculture, ecosystems, and river health

VII. Vulnerabilities across Coupled Human-Environmental Systems

Discussion Prompt

The 2009 SECURE Water Act that initiated the 2012 Basin Study documented a need to synthesize climate change impacts, groundwater impacts, flood management criteria, water demand forecasts, ecological restoration, and water quality impacts, but a complete vulnerability assessment of the full human-environmental system is still lacking. How will potential changes in coupled human-environmental systems stress key resources (e.g., water storage, instream flows, groundwater reserves, energy systems) and processes (e.g., water management, infrastructure, socioeconomic conditions, environmental services) in the Colorado River Basin service area including the seven basin states and Mexico? Are forecasts of water supply shortfalls based on good science that considers current and anticipated human population trends and projections, water conservation trends, and environmental needs?

Talking Points and Stakeholder Concerns

Stresses to Key Resources

- Water supplies or storage
    - Dust-on-snow (often from over-grazing, off-road vehicles, ash from wilfire) requires more research to determine effective mitigation strategies because it enhances melting*
    - Improved understanding of likely water supply benefits vs. ecosystem/headwater impacts from constructing new high-elevation reservoirs. As a contentious issue, this hasn't been discussed – need neutral research.
    - A new program is needed to measure reservoir evaporation and seepage into the bedrock surrounding the large reservoirs. Such measurements are lacking at Lake Powell since the mid-1970s. Measurements could help determine best strategies of where water should be stored in the river network to minimize losses.
    - Regular monitoring of reservoir sedimentation in the large (and small?) reservoirs is needed.
- Ecosystems & instream flows
    - How to manage or delay equalization releases from Glen Canyon Dam in a way that is more compatible with downstream Grand Canyon ecosystem?
    - Minutes 319 and 323 stipulate lining irrigation canals in the delta in Mexico to save water for restoration. However, leakage is an important source of water that keeps delta restoration sites viable (and is also critical to groundwater recharge in some areas).
    - Will occasional years of unusually warm reservoir releases cause: a) a short-term impact on the Grand Canyon ecosystem that would be readily reversed when cold summer releases resume, or b) an irreversible ecosystem shift from what has prevailed since the 1970s? If b), is there an ecosystem science recommendation on whether an ecosystem shift is acceptable or should be avoided at all costs?
- Groundwater reserves
    - How to sustainably manage groundwater reserves, as reliance on this non-renewable supply intensifies with decreasing surface water availability?
    - How to facilitate artificial recharge in times of surplus, and management/ institutional/economic schemes that support recovery of stored water

Stresses to Key Processes

- Water management
    - Need to better understand and address demand management as a tool for the Upper Basin to meet its obligations to the Lower Basin.*
    - Better utilize remote sensing data for understanding consumptive use.* With ground-based monitoring for verification, remote sensing can allow single points to be extrapolated into broad-based consumptive use value. This is especially important in the

    - Upper Basin, where demands aren't quantified from reservoir releases, and is of particular use in irrigated agriculture and for natural vegetation.
    - Assumptions and projections should better account for expected adaptations by water managers.* Given that water management agencies continually adapt, what is the real chance of shortage?
- Decision-making and management
    - "Watershed" perspective is not given sufficient attention in river management. Scientists could further this perspective, and promote adoption by decision-makers, by framing research at the watershed scale: "Need to articulate a new vision for the basin that articulates a sustainable water supply for the environment and human needs based on principles that benefit the economy and the environment."
    - Ensure that funding for research and restoration is distributed throughout entire watershed – not just along the mainstem.
    - Decision-making tools for water resources management have been developed (e.g., by ASU) but have not been tested or implemented in the Colorado River Basin
    - Need for a continuing process of scientific inquiry rather than a commitment to using "best available science" to adequately address change.
    - Need to encourage innovation across the basin; provide the possibility to innovate and opportunities to test new tools/technologies/how to do this in the context of institutional inertia?
- Socioeconomic conditions
    - Direct and indirect impacts of increasing temperatures and decreasing water supply and wildfire on new development
    - River management needs to better consider human population distribution throughout the Basin along with both current land use and projected changes.

- Recreation (fishing, boating, rafting, hiking, hunting, etc); impacts from:
    - increased spring floods and reduced late season baseflow*
    - altered water temperature
    - altered water quality and habitat
    - channel erosion and sedimentation
    - changes in sand bars
    - reduced water levels in reservoirs

- Agriculture
    - Environmental impacts of increased agricultural efficiency,* including impacts to the Salton Sea
    - Impacts to agriculture of increased Lower Basin salinity; what lessons have been learned in the Upper Basin and elsewhere in the world?
- Salton Sea
    - Quantification Settlement Agreement (2003) provides mitigation water through 2017
        - Reductions in lake elevation expose playa, resulting in increased dust and human health impacts
        - Reduced habitat quality for migrating species

    - Reduced recreation activities
- Future mitigation strategies must consider implications for communities and environment related to where source water would come from

APPENDIX D: BIBLIOGRAPHY

Colorado River: Building a Science Agenda

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