

**Colorado River: Building a Science Agenda  
Decision-Makers and Interested Parties Workshop  
Final Report**

Support provided by the Janet Quinney Lawson Foundation, Bureau of Reclamation, and  
Denver Water  
University of Arizona, April 3-4, 2018



Hoover Dam, Lake Mead (US Department of the Interior, Bureau of Reclamation, 2018)

## Table of Contents

I.	Executive Summary.....	3
II.	Introduction and Background.....	7
III.	Session Summaries.....	9
	Welcome Session.....	9
	Basin Study Overview.....	9
	Overview of Research Themes from October 2017 Workshop.....	12
	Stakeholder Key Issues Discussion.....	16
	Facilitated Breakouts.....	18
	Dinner Comments.....	19
	Report Back from Breakouts.....	21
	Research Theme Priority Panels.....	27
IV.	Conclusions.....	40
Appendices		
A:	References Cited.....	44
B:	Participant List.....	46
C:	Reasons for participating.....	48
D:	Themes and Priorities from Researchers' Workshop.....	49
E:	Final Suggestions/Priorities from Participants.....	53
F:	List of Research Priorities from the Sticky Notes Exercise.....	55

Colorado River Science Agenda  
Stakeholders and Decision-Makers Workshop  
Hosted by the University of Arizona  
Tucson, Arizona  
April 3-4, 2018

## I. EXECUTIVE SUMMARY

The Center for Climate Adaptation Science and Solutions at the University of Arizona, in partnership with the University of Colorado at Boulder, has held two workshops to develop a broad, interdisciplinary science agenda and to identify existing scientific information that could be used to support management decisions on the Colorado River. The first workshop, held in October, 2017, brought together an array of physical and social scientists to develop a “science-focused” version of such an agenda. The second workshop, which included a broad array of stakeholders, was held in April of 2018. We are grateful for the support of the National Science Foundation, the Lawson Family Foundation, US Department of the Interior, Bureau of Reclamation, and Denver Water and for all of those who volunteered their time and expertise to these conversations.

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.

The management challenges on the Colorado River have been highly visible for almost a century now, but the stress on the river system itself has never been higher. With additional warming and anticipated future changes in precipitation patterns, it is expected that average streamflow will continue to diminish, while extreme events will become even more prominent influences on already highly variable streamflow volumes.

The depletion of reservoir storage on the Colorado River is the most visible evidence that the current management system is over-allocated. Other issues that have been discussed and addressed to varying degrees are: current and potential changes in water temperature, chemistry and sediment load; the need to consider the possibility of extreme flooding events in addition to decades-long droughts; climate change vulnerabilities across coupled human-environment systems (including the possible role/implications of economics, groundwater, governance, culture, etc.); environmental services implications of alternative management approaches (including recreation, ecosystems and species, etc.); and the needs of environmental managers and water users in Mexico and the Colorado Delta. Both physical and social science can play a larger role than they have historically in addressing all of these issues, and there is a need to establish priorities for science investments.

In addition to these needs for *information*, a parallel issue is the actual potential that this information can and will be *used and useful* in real-world decision contexts. This factor is dependent on timeliness and access to data, as well as the credibility, salience, and legitimacy of the information. The barriers to connecting science and decision-making are well-documented, but actually overcoming this problem even on a small scale is a grand challenge. These two workshops, in combination, were intended to help build a science agenda and also solicit suggestions on how to support enhanced use of existing knowledge from western science

as well as traditional ecological knowledge. At the second workshop, members of the academic community learned from stakeholders firsthand about both information needs *and* obstacles associated with integrating information into decision-making processes.

The following is a high-level summary of the outcomes of the second event, the “Decision-makers and Interested Parties” Workshop. In addition to the high-level themes and priorities of the science workshop (see Appendix D), which were broadly supported by the stakeholders, many of the priorities from this workshop include recommendations for improvements in processes for connecting science to decision-making.

## **High Level Summary of Outcomes and Theme Areas Stakeholders and Decision-Makers Workshop**

**Basin-wide science meetings** to better integrate science and management overall in the Basin as well as to support the renegotiation of the interim guidelines.

**Scenario planning** at the basin scale that encompasses and examines a wide range of risk and that can be used as a framework by states, utilities, tribes, and resource managers at smaller scales. This effort should take into account black swans (low probability, high consequence, unanticipated extremes), cascading effects, and explore topics that are difficult to discuss in other contexts.

**Increased and sustained dialog and relationship development**, including informational exchange, within and across the broad community of stakeholders and researchers. We need to explore forums and processes that encourage interdisciplinary conversations and identify opportunities moving forward.

**Better communication of science, risks, and uncertainties** across the Basin. This effort calls for engaging academics in work on bridging communication gaps related to climate change and extreme events and risk management in a more coherent and strategic way.

**A more coordinated research agenda** across the basin that includes ways to coordinate, prioritize, collect and monitor data and develop water budgets for watersheds as well as ways to coordinate funding and resources. Consider establishing a center for research on the Colorado River that includes scientists and science translators who can respond in real-time to management needs across the Basin.

**Applied physical science research** that anticipates low-probability/high-consequence events and helps us recognize triggers, thresholds, and “**signposts of change**.” This includes anticipation of thresholds and tipping points, along with more integrated systems science that is focused on sustainability. There was strong support for the physical science priorities identified in the first meeting (see summary in Appendix D).

**Improved monitoring of water demand and consumptive use**, and of groundwater and surface water in the basin.

**Understanding unintended consequences of future management decisions or actions**, including understanding the full range of effects of alternative management strategies, such as with agricultural efficiency improvements leading to negative impacts on species and ecosystems.

**The exploration of institutional arrangements** that could help improve governance and decision-making in the Basin. There is broad recognition that our institutions were created in an era of different challenges, and now we are facing a more complex set of issues that may require new solutions. Individual and organizational behaviors, markets, and exploration of other institutional models were discussed.

**Integrating environmental goals and management** into broader management strategies in a changing climate. The Endangered Species Act protects species (rather than ecosystems), and may be focusing on species that are not suited to current and evolving conditions, at least in their historic habitats. Specific research needs in this area included ways to facilitate a more

system-wide approach to managing water, water quality, species, land, sediment, and forests to ensure that conservation outcomes are supported.

**Transformational vs. incremental change toward improved outcomes.** There was recognition of a tension between the need to improve short-term water delivery reliability in incremental stages (the river as a delivery system) along with long-term sustainability and equity (the river as a functioning river, incorporating environmental (non-human) and social values). How might it be possible to optimize both, and how can efforts be scaled up and sped up to get to better outcomes?

**Greater recognition of diversity and social justice.** Under-representation of tribes and other constituencies was mentioned numerous times, but the discussion did not go far beyond questions of how to get meaningful engagement from underrepresented groups who often cannot be at the table. More work is needed on incentives for broadening representation and/or making sure that diverse views are truly heard and accurately represented within decision-making bodies.

**A comprehensive study of groundwater and climate implications** in the Basin is needed that goes beyond studies of the main stem and includes springs and tributaries but also addresses groundwater contributions to tributary flows, environment, habitat, and cultural and economic values.

## II. INTRODUCTION AND BACKGROUND

These two “Science Agenda for the Colorado River” workshops, in combination, were focused on developing interdisciplinary and holistic science priorities to support the management of the Colorado River. We approached this goal from multiple perspectives. The **Decision-makers and Interested Parties Workshop** was the second workshop on this topic hosted by the Center for Climate Adaptation Science and Solutions (CCASS) at the University of Arizona, in partnership with the University of Colorado at Boulder.<sup>1</sup>

The first workshop on **Building a Science Agenda for the Colorado River**, held October 10-12, 2017, was designed to be an interdisciplinary conversation among scientists. It was attended by approximately 35 academics and researchers from a wide array of disciplines, including aquatic ecologists, sediment experts, tree-ring researchers, climate scientists, experts in tribal and institutional governance issues, and others. The second workshop, with 60 participants, was focused on giving water users, water managers, environmentalists, tribes, states, NGOs, and other organizations an opportunity to weigh in on science needs to support Colorado River management.

Both workshops built on the foundation laid by the U.S. Bureau of Reclamation’s Colorado River Basin Water Supply and Demand Study of 2012 (“Basin Study”). The intent of these workshops was to identify priority areas for interdisciplinary science research going forward 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 went beyond what was addressed in the Basin Study, including the full range of plausible future flow reductions, groundwater impacts, flood management, ecological conditions, water quality, potential changes to governance processes, and climate change vulnerability across coupled human-environmental systems.

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.

The highly visible and closely monitored depletion of reservoir storage on the Colorado River is one of many issues that managers of the River face. Other issues that have been discussed and addressed to varying degrees are the implications for river flows of climate variability in combination with long-term changes in temperature and precipitation; current and potential changes in water temperature, chemistry and sediment load; the need to consider the possibility

---

<sup>1</sup> Support for the first workshop was provided by the National Science Foundation and the Janet Quinney Lawson Foundation; the second was also supported by the Lawson Foundation with additional travel support from the U.S. Bureau of Reclamation and Denver Water.

of extreme flooding events in addition to long-term depletions; climate change vulnerabilities across coupled human-environment systems (including the possible role/implications of economics, groundwater, governance, culture, etc.); environmental services implications of alternative management approaches (including recreation, ecosystems and species, etc.); and the science needs of managers in Mexico and the Colorado Delta.

In addition to these needs for *information*, a parallel issue is the actual potential that this information can and will be *used and useful* in real-world decision contexts. This factor is dependent on timeliness and access to data, as well as the credibility, salience, and legitimacy of the information. We are all aware of the barriers to connecting science and decision-making, but actually overcoming those problems even on a small scale is a grand challenge. These two workshops, in combination, were intended to help build a science agenda and also solicit suggestions on how to support enhanced use of existing knowledge from western science as well as traditional ecological knowledge. Members of the academic community learned from stakeholders firsthand about both perceived information needs *and* obstacles associated with integrating information into decision-making processes.

Two management topics made these workshops especially timely: the upcoming renegotiation of the Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operation of Lake Powell and Lake Mead (“Interim Guidelines”) and the pending Drought Contingency Plan (DCP) processes. The Interim Guidelines were adopted in 2007, the first of several efforts to address the operations of Lakes Powell and Mead during drought and low reservoir conditions. Renegotiation of the Interim Guidelines is required by 2026, but must be before the end of 2020. Two very low years of inflow in Mead and Powell in 2012 and 2013 initiated discussions of the DCP to try to avoid hitting the target levels in Lake Mead that trigger shortages.<sup>2</sup> 2018 is expected to be another very low flow year.

---

<sup>2</sup> 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 DCP. The risk of Lake Mead reaching critically low elevations (1,025 feet) is now assumed to be 50% by 2026.



### III. SESSION SUMMARIES

#### TUESDAY, APRIL 3

##### 1:00-1:50

##### **WELCOME SESSION: Purpose, Expectations, and Introductions**

Doug Kenney, University of Colorado; Kathy Jacobs, University of Arizona; Larna Kaatz, Denver Water

The Drought Contingency Plan for the Colorado River is currently being negotiated and the renegotiation of the Interim Guidelines looms before 2026. With aridification and warming affecting the Lower Basin and ongoing uncertainties about climate and climate impacts across the whole of the Colorado Basin, water practitioners, decision-makers, and other stakeholders need to engage in the conversation about science needs. The organizers and participants of the Colorado River: Building a Science Agenda workshops are committed to the coproduction of knowledge (scientists working together with stakeholders and managers) and to building a sustained effort to help inform what science pertaining to the River should be the focus for years to come. There is a need to embrace change and uncertainty given the magnitude of the challenges, rather than sticking to old paradigms. This workshop was conducted under Chatham House rules: there was no attribution of comments and opinions, so that all might speak freely.

The purpose of this second workshop was to start a community conversation to develop a research agenda that can promote sustainable Colorado River management, finding points of overlap between the research and stakeholder communities, and building relationships between people and organizations that might not otherwise engage with each other. Reports from both workshops are intended to be useful to a variety of groups and agencies.

Participants were asked to introduce themselves and very briefly state their main interest in attending the meeting; their responses are summarized in Appendix C.

##### 1:50-2:10

##### **BASIN STUDY OVERVIEW, REGIONAL ISSUES, RISKS, AND CURRENT EVENTS**

Jim Prairie and Carly Jerla, Bureau of Reclamation

The Basin's current and recent hydrological history and context for this conversation was provided by two staff members of the Department of the Interior, Bureau of Reclamation. Reclamation operates the mainstem infrastructure of the Colorado River.

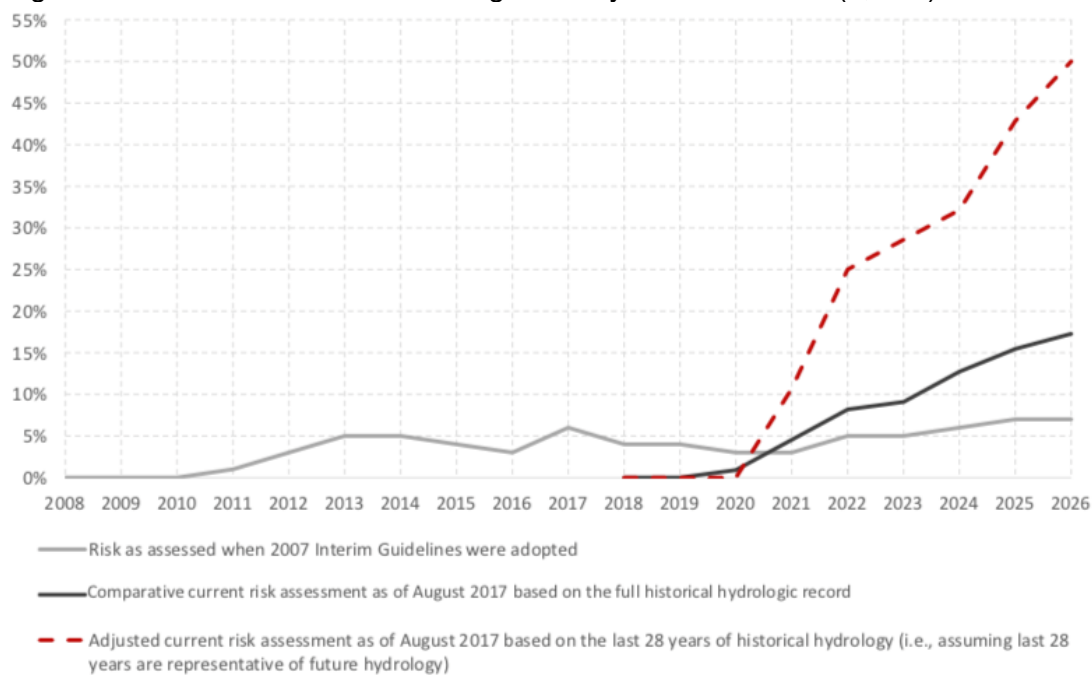
In 1922, The Colorado River Compact allocated 16.5 million acre feet (maf); 7.5 maf are presently allocated to the Upper and Lower Basins, with the division point being the gage at Lee's Ferry, plus 1.5 maf to Mexico. It was not widely recognized at the time that this was an era of high streamflow, which was incorrectly presumed to represent the norm. Recent flows have been in the range of 13 to 14.5 maf annually, putting the River on a very constrained hydrologic budget. To date, over-allocation of the River has been tolerable only because the Upper Basin does not yet use its full allocation. Flow in the Lower Basin is expected to decrease in the future even if average precipitation does not decline because of increased heat and evapotranspiration losses (Udall and Overpeck 2017). The next set of Interim Guidelines, due at the end of 2026, must address these supply/demand imbalances and rapidly changing conditions.

Reclamation’s shorter-term operational decisions focus on the 1 to 2 year timeframe. Inflows are the place of most uncertainty for both short-term and mid-term (to 5 years in the future). Reclamation is looking within these time frames at the likelihood of getting to various trigger points for a shortage. How do we better understand uncertainty and change the decision-making process to incorporate it?

Long-term natural flows at Lees Ferry from 1906 to the present show remarkable variability, with long-term average flows slowly on the decline. Reclamation has taken heed of scientists who said that looking only to past conditions for guidance about the future is no longer helpful (Milly et al. 2008), but the long-term (paleo and historical) record can still inform us about how the system has reacted to previous droughts. The current Lower Basin drought is considered to have started in 2000, the first year of significantly lower flow. Beginning with reservoirs at full capacity, levels have now declined to 52% capacity.

Water levels are now twenty feet higher in Lake Mead than they would otherwise have been due to the adoption of the Interim Guidelines, the approval of International Boundary Water Commission (IBWC) Minutes 318 and 319 (which adjusted delivery schedules for water allotted to Mexico), and adoption of the Pilot System Conservation Program and Lower Basin Drought Memorandum of Understanding. A good water year in 2010 also helped keep Lake Mead from going below 1075’ (a level-one shortage). The risk of Lake Mead reaching critically low elevations (1,025’, the lowest level specified in the Interim Guidelines) has been calculated at 5% or below since the Guidelines were adopted, but with adjusted risks based on the last 28 years of hydrology as a new normal, the probability rises to 50% by 2026 (see Figure 1). Under the same scenario, Lake Powell has a 32% probability of reaching critically low levels for generation of power (3,490 feet) by 2026.

Figure 1. Risk of Lake Mead Reaching Critically Low Elevations (1,025’)



(US Department of the Interior, Bureau of Reclamation, 2017)

The 2012 Colorado River Basin Water Supply and Demand Study (subsequently referred to as the Basin Study) is the most recent formal effort to provide a long-term view on these topics (to 2060). This was a planning study, meant to establish a technical foundation; no decisions came from it or were expected.

### **Reclamation's Active and Ongoing Research**

The Center for Advanced Decision Support for Water and Environmental Science (CADSWES) at University of Colorado Boulder developed Appendix U of the 2007 Interim Guidelines to initiate discussion of incorporating climate science into the management of water in the Colorado River Basin. The Colorado River Hydrology Workgroup contributed to this work; it focused on actionable information that could be applied in a one-to three-year time frame, but also considered long-term planning and forecasting needs.

Reclamation has worked with sister agencies to develop additional reports that incorporate climate change and identify information gaps in water resources (U.S. Army Corps of Engineers 2011, Raff et al. 2013). This information was incorporated into a matrix to use for climate and hydrology science, short- through long-term. A 2017 Colorado River Hydrology Research Symposium led by the Southern Nevada Water Authority reviewed the science needs analysis for climate and hydrology, bringing stakeholders and researchers together, including states, feds, academics, NGOs, and tribes, and investigated ways to leverage funding for pertinent projects. A Basin States and Utilities Climate and Hydrology Research Group has been established as an offshoot of that symposium, looking to bring people together to improve understanding of uncertainty of supply.

Reclamation's areas of current research focus are:

- Improving the transition from research to experimentation to application
- CMIP5<sup>3</sup> integration into long-term planning
- Decision-making under deep uncertainty and robust planning frameworks
- Exploring irrigated agriculture consumptive use estimation
- Updating reservoir evaporation coefficients

Reclamation's current relevant projects:

- Streamflow testbed for the Colorado River Basin: hindcasts to see if forecasting is improving
- Improve Climate Prediction Center (CPC) forecasts for the River Forecast Center (RFC) for the Colorado, including North American Multi-Model Ensemble (NMME) information, to improve synergies
- Future Basin climate and hydrology under CMIP5
- Multi-objective optimization and robust planning approaches
- Assessing agricultural consumptive use in Upper Basin
- Reviewing evaporation coefficients at Lakes Mead and Powell

---

<sup>3</sup> Coupled Model Intercomparison Project, a model ensemble used by the Intergovernmental Panel on Climate Change to understand differences in projections across a multitude of global climate models. CMIP3 (2010) was used in the Fourth IPCC Assessment Report and CMIP5 (2013) in its Fifth Assessment Report.

Possible future areas of focus:

- Presenting climate variability and resilience to stakeholders and general public in ways that are useful to decision-making
- Drought prediction and characterization
- Effectively using storylining in decision support, examining different time frames to help decision-makers

**2:35-3:30**

### **THE OCTOBER 2017 WORKSHOP ON BUILDING A RESEARCH AGENDA**

This segment provided an overview of the four research themes and related priorities that emerged from the October 2017 workshop for researchers, presented by participants of that workshop.

***Theme 1: Interdisciplinary and Integrated Basic Research*** (Mark Stone, University of New Mexico; and Jack Schmidt, Utah State University)

This theme focused on understanding the multiple dimensions, processes, and drivers of change at work in the Basin, using a system-wide perspective. Priority topics included:

- Temperature – How do rising temperatures impact other processes and systems, such as evapotranspiration, sublimation (loss of snowpack to water vapor rather than melting), wildfire, and species diversity?
- Process-based understanding of change – how and why do Basin conditions change? Why does recent global modeling provide different precipitation forecasts than past efforts? What factors that influence snowpack, snowmelt, sediment and sediment transport are not yet fully incorporated into modeling efforts? Can we achieve 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 seasonal flows and ecosystems?
- Scientific foundations and baseline data – Improved monitoring of groundwater, surface water, sediment flows, agricultural return flows, consumptive use, and system losses can lead to better understanding of the impacts of alternative management practices and improve modeling. Research on aquifer storage is in its infancy, compared to streamflow. The paleorecord will continue to provide insights into past conditions, while big data and remote sensing provide new tools for analysis.

Discussion on this topic centered on the comparative perspectives of basic science researchers and practitioners/managers. Is the Colorado River a water supply system or a river? While the water supply - climate science agenda is largely set by academia and Reclamation, it is the adaptive management programs that dictate river management. Dialogue between scientists and stakeholders is needed. In integrating river natural science with water resource modeling, modelers, stakeholders, and practitioners want to know how environmental functions can be optimized for particular solutions, and how to build efficient programs that accomplish greater good.

***Theme 2: Science of Crises and Tipping Points*** (Brad Udall, Colorado State University; and Julie Vano, National Center for Atmospheric Research)

This theme stressed the importance of identifying and exploring 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.

Priorities included:

- Drought/flood interface – Droughts and floods have traditionally been examined in isolation, but there is substantial potential to move quickly from serious drought conditions to extreme flooding (“weather whiplash”). Understanding the probabilities, causation, impacts, and management implications associated with past rapid swings between wet and dry extremes would be very useful to water managers.
- Extreme events and “black swans” (rare, unpredictable events that have extreme impacts) – How often have these occurred in the past, what is their future probability, and how might climate change 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 – Resilience is largely related to institutional capacity to prepare and respond to extreme events. Comparative studies of river basin governance regimes can help identify opportunities, constraints, and useful lessons for governing the river in the context of very difficult challenges. There is a need to leverage what is known and put realistic bounds on what is not.
- Dealing with transformative change – The tails of the distribution for low probability/high consequence events are hard to define or plan for. What events could overwhelm human and natural systems in the Basin? What step changes might be required of our management systems to anticipate tipping points in human and natural systems?

Related concerns are the role of temperature in drought; how and why evapotranspiration is changing; how snowpack changes resonate throughout water processes; the dynamics of change across processes (for example, vegetation impacts hydrology and the altered hydrology has impacts on vegetation).

Discussion on this topic centered on the grand challenge of institutional and infrastructural capability to deal with extreme or unknown events. The near failure of the Oroville Dam and its spillways in 2017 is a cautionary tale.

How can we identify long-term triggers of transformational change so that we know what to look for and take action before they occur? With increased variability, can these triggers be identified in advance? Is it best to look for long-term triggers or just be better prepared for a broader range of possibilities? Interdisciplinary research can help with this. Can the adaptation process be staged so as to help managers who find it difficult to respond to potential major risks with near-term major responses? How do we lessen the gap between understanding and implementation of effective adaptation strategies? Institutions may understand the risks of known high-consequence, low-probability extreme events without recognizing the *unknown* threats or the degree of response that is necessary to mitigate risk.

**Theme 3: Holistic Watershed Scale Management** (Karl Flessa, University of Arizona; and Dave Kreamer, University of Nevada, Las Vegas)

This theme advocated the development of 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. Priorities included:

- Incorporate sediment and other water quality considerations as explicit objectives in water management and environmental frameworks
- Identify transferable lessons in species management

- Encourage groundwater assessment, including surface water/groundwater connections, aquifer storage and recovery, and the institutional changes needed for sustainable groundwater management
- Enhance ability to project/understand human adaptive behavior for improved scenario planning
- Understand implications of alternative management schemes
- Identify triggers, thresholds, and indicators of change for adaptive management

Discussion focused on how a holistic management system can provide different or additional perspectives on what might otherwise be overlooked. The Colorado River Basin is more than a single river; it is thousands of ecosystems and drainages flowing into the main stem. Funding for hydroecology is evaporating. A healthy environment is good for both our long-term hydrology and the economy. Small changes in a water table can completely dry up springs and habitats for millennia. Springs have considerable ecological, spiritual, and recreational value and provide habitat for unique species. Agriculture and industry need to be looked at from both long-term and short-term perspectives when developing policy positions. Economic drivers can lead to unwanted outcomes, for example by drying up aquifers or creating water quality issues such as increased salinity or accumulation of contaminants. Some good holistic work is being done, for example, in conservation and habitat preservation through the Multiple Species Conservation Plan, in the Las Vegas Wash wetlands, and sediment studies in the Grand Canyon.

The supply side of water is well-studied, but other uses of water are not so well integrated at the basin scale. Groundwater is also a cross-border issue; an honest transboundary aquifer assessment is needed, despite the political issues it might raise. Because Basin groundwater was specifically excluded from the Interim Guidelines, due to pending lining of the All-American Canal, a recommendation calling for a transboundary aquifer assessment would be timely.

The recreation/outdoor economy is perceived too narrowly by the public and managers. There needs to be a shift to seeing the river and its tributaries and reservoirs in the context of a quality-of-life economy. Outdoor recreation in the west is worth billions of dollars.

**Theme 4: Science for Adaptive, Just Institutions** (John Weisheit, Living Rivers; and Andrea Gerlak, University of Arizona)<sup>4</sup>

In a more perfect world, a systems-based approach to management would respect both ecological systems and social systems (cultures, institutions, etc.) and treat them in a more integrated way. Research needs identified at the October meeting included:

- Enhancing justice and equity in management (the distribution of costs, benefits, risks, and opportunities across sectors and populations)
- Learning from others through comparative governance in other basin, sectors, and in other parts of the world. How is restoration done?
- Interdisciplinary and outcome-oriented environmental management – what are our goals and are we meeting them?
- Agricultural stewardships as a solution to broader water management issues and collaborative futures

---

<sup>4</sup> Andrea Gerlak and John Weisheit did not attend the October workshop but were briefed prior to this presentation on outcomes from the workshop.

- Identifying barriers to broader engagement in science and governance and empowering stakeholders to participate more fully in resource management decisions

Basin residents want to be engaged in helping to achieve a sustainable river. This is particularly true of the indigenous communities; respecting traditional knowledge and wisdom is an important foundation to facilitating their engagement. To create or maintain a future for the Colorado River that meets a broad set of needs will require a broadening of the management processes/approaches.

Participants in the fall workshop felt that communication and communication sciences can provide essential tools to further effective decision-making and public engagement. What are the scientific aspects of human behavior that need to be incorporated into a systems analysis of water demand, for example? Behavioral and social sciences, economics, and governance are all critical elements in this analysis.

We need to be more aware of the human systems and values that are evolving and impacting the river system. Human-system responses may have radical new impacts on future Colorado River water use that are currently not being considered. For example, how we think of peak electrical or water demand may completely change. On sunny days in California, the price differential between peak and base costs of electricity is inverting because people are generating so much solar power during the day. This outcome was not anticipated when solar power was being introduced.

3:30-4:15

## STAKEHOLDER KEY ISSUES DISCUSSION

Laurna Kaatz, Denver Water; and Kathy Jacobs, University of Arizona

Workshop participants were asked individually for their top three ideas for research priorities or solutions that could be implemented soon in response to the research objectives outlined above. Results are summarized in Appendix F. A small-group exercise followed, in which each group identified a single research objective or solution to present to the entire group.

Reports back from small groups:

- **Marrying the human, physical, and scientific processes.** For example, the U.S. Drought Monitor last year showed no drought in the Basin, though the ongoing moisture deficit continued. Information communicated to the public should have both human and technical components.
- Incorporate **economic tradeoffs with system uncertainties.** Bring diverse stakeholders together to examine a realistic scenario for 50 years in the future; what are the tradeoffs for reaching that with an incremental approach?
- What are the **unintended consequences** of an implemented or planned action on another sector and will it make your original problem bigger?
- **When does a river cease to be a river/natural system?** What modifications change the fundamental character and functioning of the river?
- **Why don't all states simply agree to reduce demand by 15%?** 10% of savings could be applied to address the structural deficit on the River, and 5% to the environment. In the recent California drought, conservation goals were reached through mandates to reduce water use. The concept is simple and easy to communicate and would buy time to allow a focus on the other institutional problems.
- What is a **better way to communicate risk** to the environment, water supply, agriculture, quality of life?
- The wide range of possible futures, e.g., in climate model and flow projections, stymies decision-makers. Explore a **different way to do decision-making under large uncertainty** that people can understand.
- The current governance model for making decisions on the river is static, and not getting us to desired results. **What other governance models could build consensus and buy-in, while still protecting the water supply and bringing more people into the conversation?**
- **Hydrologic impacts on the Basin of fallowing irrigated lands.** This information is needed in advance of water supply crises and could feed into a systems dynamics model.
- Communication science: how to **communicate long-term uncertainty** to customers to get them to realize the importance of the river?
- We need a **fully coupled hydrologic/environmental process model** that transcends political and scientific boundaries and explains economic benefits and tradeoffs.
- **River management questions:** 1) Explore the possible **responses to a great flood** in the system. 2) What is the **time frame for decisions?** 3) Define **clear objectives for managing each part of the river network.** Which parts should be pursued as novel ecosystems and which do we attempt to preserve as native ecosystems? 4) **Reconsider the funding structure for river science** to match science needs.
- **Work basin-wide** to develop better models and processes for understanding evapotranspiration (ET), etc.



- **Science has a role in being predictive but also needs to be prophetic;** help develop a vision for a future that is desirable.
- **Balance the long-term/short-term dialogue with stakeholders so that future water needs are addressed as well as economic benefits.** Short-term economic gains can often harm the long-term sustainability of economies and natural systems.
- **Promote the acceleration of ideas on recycling water** in a changing world.
- **Scientific communication: academic institutions are primed** to lead this effort. If the public remains outside of the conversation about sustained and integrated approaches, the challenges will not be recognized as important or difficult. Universities are uniquely poised to communicate with the private and public sectors.

**4:15-5:30**

**FACILITATED BREAKOUTS**

Based on the day's discussions, workshop participants agreed on five topics for facilitated breakout sessions, exploring the topic within the context of a research agenda and thinking about solutions. Communication science and research were to be integrated into each topic as an overarching theme. The agreed-upon topics were:

1. Decision-making, risk, and uncertainty (and unintended consequences)
2. Role of markets, economics, conservation, and agriculture in solutions
3. Governance, management, and institutions (and evaluation of progress)
4. Establishing goals and priorities for integrated science observations and management
5. Integrating social/human and natural systems in modeling

**7:00 PM**

**Dinner Comments from Lester Snow, natural resources consultant, and Mike Connor, WilmerHale, LLC**

**Lester Snow:**

In recent decades, water management has been siloed. Integrated management has been difficult; jurisdictional issues have been manageable only when there is a lot of money available. The Clean Water Act, for example, was implemented thanks to massive grants from the federal government, and probably wouldn't have been feasible without that support. It is widely viewed as a major environmental success for the country. The United States is now falling behind in terms of climate adaptation; our natural resource conditions are changing faster than our institutions can adapt. Climate adaptation has not had the high profile support required for success because of fears that supporting adaptation lessens the pressure to mitigate climate change by managing carbon emissions. Climate deniers, on the other hand, don't acknowledge the causes of impacts that have to be addressed. This creates an odd agreement between climate mitigators and deniers – both are opposed to adaptation efforts. Yet, with or without mitigation action, we need to adapt to changes that are inevitable over the next many years. Even if zero-level emissions could be achieved immediately, the impacts of climate change will be felt far into the future.

Drought and water supply, flood, land use, watersheds, and forest health are all being impacted now and need to be addressed with adaptation measures. How do we reform institutions to encourage this? Connecting knowledge with decision-making needs to take place at the basin or sub-basin level, where the impacts are visible. Politicians only react to crisis. The perfect storm of drought, wildfire, and flood occurring in sequence recently in California has prompted adaptation action and a more integrated approach. Water and resource managers and scientists must know what they want to accomplish and be ready to move when a crisis becomes an "opportunity" to make changes.

We need to be able to do real-world experiments to support adaptation, but they require access to money and water.

**Mike Connor:**

Our institutions and governing principles don't keep up with challenges, particularly as they are related to climate change. There have been some positives, however: Two million acre feet were added to Lake Mead due to recent efforts, and the Multiple-Species Conservation Plan (MSCP) has had some success. Nevertheless, there is a 50% chance of shortage on the Colorado River by 2020. Unfortunately, as we've seen recently, policy changes are NOT tough to implement in a political climate in which facts and science are no longer foundational to our decision-making. Hopefully, that is only a temporary condition.

Connor's goals with regard to water are certainty and sustainability. What is undermining these goals? Drought, endangered and non-native species issues, water rights disputes, aging infrastructure (e.g. Oroville), and water quality issues. How are these issues being addressed? The 2007 Interim Guidelines defined how the river would be operated under shortages. Mexico's rights when shortages are taken were clarified only under Minutes 319, 320, and 323, driven by the 2010 earthquake in Baja California. The risk now of Lake Mead falling to critically low levels must be addressed through research and continued dialogue about risk management by the stakeholders. The Drought Contingency Planning process was about reducing risk and it continues to require information. Can the Interim Guidelines be improved in the next round? In the Upper Basin, how do you track conservation successes? New endangered species issues

can crop up quickly, as they did in 2016, with the delta smelt population crashing, requiring a hasty rewrite of the Biological Opinion in the Sacramento-San Joaquin Delta. Continued monitoring of these issues is necessary.

There are concerns about the federal role in science, including continued access to data. The Ten Tribes Partnership report was almost finished in 2017 but has not yet been issued. The failure to release it is a concern. Past bipartisan reports from the Western Governors' Association are a good model for the future. He is also concerned about the future of public policy advisory boards and shortened timelines for public processes.

So what is the role of federal government in science and science policy, given the current political climate? It is not clear. Hopefully, demand for sound science and adherence to facts will return as fundamental to balanced decision-making.

## WEDNESDAY, APRIL 4

8:30-1:30

### REPORT BACK FROM BREAKOUTS

Group leaders and note-takers summarized the discussion and recommendations that emerged from the previous day's breakout sessions.

#### ***Group 1: Decision-making, risk, and uncertainty***

Facilitator: Mohammed Mahmoud, Central Arizona Project; notetaker: Ashlee Simpson, University of Arizona

Main topics in breakout discussion:

- **Importance of educating and communicating to the public about water issues**  
An educated public can help to increase the political will of decision-makers and elected officials to address issues related to a sustainable river. Water utilities are generally seen as a trusted and politically neutral source of information.
- **Explore and acknowledge the full extent of risk**  
Are we focusing on a subset of strategies to address risk because it is too scary to address the full range? Are we more/too comfortable with incremental solutions? Communicating about risk can itself be risky; for example, risk assessment can negatively impact bond ratings because convincing the public that a problem is serious may affect investments. There are few incentives for practitioners to communicate the potential for extreme events and it can even harm their careers. However, if the risks of water scarcity are not communicated effectively, there is no incentive for conservation.
- **Employ strategic messaging of decision-making information**  
Information must be made available in a way that is useful for decision-making. In transmitting the information, consider the audience, optimal timing for engagement, the content to be delivered, and how to tailor it to particular decisions. Examine whether existing models are useful for future planning.
- **Use scenarios in addition to probabilistic projections**  
What thresholds, triggers, and signposts should be examined and how do we know they are meaningful indicators of change? Indicators must be linked to their implications and the strategies to address them.
- **Consider coupled systems and cascading effects**  
In extreme events, what coupled systems (such as groundwater/surface water) could fail simultaneously and what are the thresholds? Coupled systems increase the potential for additional cascading effects if they fail. Optimizing many things simultaneously and use of structured decision-making can help.
- **Recognize opportunities as well as challenges**  
Look for synergetic solutions, i.e., win-wins. An example: To rehabilitate a riparian food web, managers worked with citizen scientists and found that management of flows was the causal issue. A project to stabilize flows on weekends proved to generate more hydropower during the week while also protecting biodiversity.
- **Discovery tools and decision-support tools to address uncertainty**  
Not every uncertainty matters unless there is a huge disparity in actions on either end of the distribution tail. Discovery tools can help us see what we aren't looking at that might be important to measure. There are existing tools for decision-making in uncertainty, but it is difficult to design a tool that translates across geographies and circumstances. Targeted tools, based on geography and particular circumstance, can be designed jointly by academics and decisions makers.

- **Shift from crisis and response mode to a long-term planning/decision-making and preparedness approach**

It is vastly preferable to be more proactive than reactive to problems. However, the short-term nature of politics and economics work against this, as does a human disinclination to face unpleasant possibilities.

**Plenary discussion:**

There's a tendency to miss opportunities because managers are so focused on the challenges. An example of a missed opportunity is examining how a drier, hotter future impacts energy costs and can benefit a solar energy industry.

Are academics and practitioners exploring the full range of risk? How do we encourage people to think about the extremes of risk when there is a bias toward assuming the worst won't happen or unanticipated events will cascade into multiple impacts? Water managers maintain that they do consider the full range of risk as they understand it from the data that are available and are not inherently fearful of bad outcomes.

The available data is not science; science is about discovery. It is not the role of scientists and researchers to dictate action.

**Group 2: Role of markets, economics, conservation, and agriculture in solutions**

Facilitator: Doug Kenney, University of Colorado; note-taker: Tao Liu, University of Arizona

Main topics during breakout discussion:

- **Agricultural water is the primary focus in discussions about economic markets to address shortages**, although these markets are also distorted by various subsidies. How do we use market forces to influence agricultural practices?
- **On-farm and off-farm hydrologic and economic impacts of alternative transfer mechanisms** (ATMs), such as deficit irrigation and temporary fallowing. How much water can be saved and what could be the unintended consequences? A lot of experimentation is going on at a small scale. Projects are isolated and there's much more work to be done.
- **The human factor** -- How do human values/needs change over time and influence water uses? Changing values and societal priorities can become more influential than finding the right answer. But is there really one right answer?
- **Need for identifying baseline economic drivers and trends in water demands**, such as urbanization. Demand in Upper Basin, for example, has been flat for 20 years and we don't know why. This is a critical question for research.
- **Catalog and develop viable market mechanisms for water reallocation** (including tribal water rights). A huge diversity of markets already exists within states, tribes, and Mexico already, along with rules for them. These should be documented and explored.
- **What are the roles of markets in managing water risks?** Infrastructure (e.g., dams and reservoirs) has historically been used to manage risk. Market mechanisms (such as a dry-year option negotiated with urban areas and agriculture) will be increasingly important as an insurance option going forward to conjunctively manage risk.

**Group 3: Governance, management, and institutions (and evaluation of progress)**

Facilitator: Julie Vano, NCAR; notetaker: Mira Theilmann, University of Arizona

Main topics in breakout session:

## What governance, management, and institutional processes will get decision makers to do things differently?

- We can learn by **exploring what worked in the past and in other basins.**
- **We need to rethink the timing of monitoring and management decisions on the river, though the history of system rules and timing of monitoring must be known in order to optimize decisions.** This can help find opportunities to increase flexibility. Exploring timing options systematically and optimizing for multiple objectives could reveal new solutions.
- **Timing is critical in short-term decision-making.** For example, decisions for water management that are based on multiple yearly observations can add flexibility to management, although there may be sectoral or political conflicts in defining when they occur.
- **Develop adaptive governance.** Evaluate laws that align with adaptive management. Find ways to move away from single decisions, yes/no rules, a negotiating period or timeline that is set in stone. Better communication of risk can help government institutions become more resilient and ready to adapt. Reclamation and the Dept. of Interior create important, large forecasts but are removed from river decisions. How can they incentivize resilient activity?
- On the management side, **financial and insurance institutions could provide some models for identifying ways to predict and address challenges.** However, land use and climate change risk are disconnected in real estate markets.

## Paths forward: How to broaden engagement and democratize the process

- **Identify other fields that need to be included in river management conversations,** such as communications, business, insurance, planning, political science, and law.
- **Avoid overwhelming stakeholders by asking for engagement on everything.** Make the discussion tangible by identifying vulnerabilities in the groups involved in the conversation.
- **Coproduction with stakeholders, including nontraditional groups, is critical for both decision-makers and scientists,** but time and resources to incorporate coproduction into decision processes are needed.
- **Is the playing field level?** For example, Lower Basin managers may have more funds to influence decision-making.
- **Uncover ways to foster a common identity; what makes bioregionalism work and what can make the average person care about the Basin as a whole?** Conversely, if we understand what divides us in the Basin (e.g., states, rural vs. urban interests, Upper vs. Lower Basin etc.) and why, we can move forward and find ways to embrace competing narratives and build diverse coalitions.
- **Storytelling and a focus on common interest help bring people together for discussion.** Leverage science and policy communication to improve the dialog about risk, use storytelling, focus on common values.
- **Focus beyond humans to give more voice to the natural world.**

## Plenary discussion:

There was disagreement about whether scientists should play a role both in communicating information to the public and suggesting how it can be used.

There are lessons to be learned from big businesses in managing risks.

Some participants felt that democratizing the process does not help. The Colorado River Basin is exemplary for doing water management in a collaborative and inclusive way. It's a state-run river, not a federally run river. When the group gets too big, it becomes very difficult to function and get more done. You can broaden engagement, but not at the decision-making and basin-wide table. It's at the state level where engagement should be encouraged. Smaller is better for creative thinking and making policy.

However, others felt that there are other mechanisms through which conversations can be held with a broader group of stakeholders. Some stakeholder processes and structures have worked well elsewhere; for example, an international science team for the Colorado River Delta, funded by both the U.S. and Mexican governments, runs on an annual calendar. It is not a decision-making group but is a functional and well respected part of the process.

#### ***Group 4: Establishing goals and priorities for integrated science observations and management***

Facilitator: Carrie Enquist, DOI Southwest Climate Science Center; notetaker: Amanda Leinberger, University of Arizona

#### **Breakout discussion summary:**

What are the Basin-level questions we should be asking, as well as at the more specific, local scale?

Following a lively discussion, breakout participants agreed on the following proposal:

**Reclamation should lead (or co-lead with an academic partner) the organization of a Colorado River Conference (or at least a symposium) within the next 2 years.** It has been a decade since the last such conference focused on river science, and is critical for researchers to understand who is doing what in the basin. The meeting would have the following goals:

**Goal 1: Launch the *development of a Colorado River Science agenda*** inspired by the California Bay Delta's science agenda work, incorporating their scientist-stakeholder process and building on their key outcomes. An articulate advance agenda is required for there to be funding for this effort. It must be an integrated agency and academic community effort. Because Reclamation is the transcendent river agency, it should take the lead.

**Goal 2: Using a process and structure similar to Minute 323 and/or the California Delta work, identify subject matter experts and develop a stakeholder engagement strategy** that could culminate in a large conference to move this process forward.

Main themes that emerged:

- Based on the conceptual model of concentric circles, **the conference would establish a process for basin-wide conversations on what a science grant program could and should look like** (including more targeted conversations at sub-basin or topical scales). These would involve all key players, academics, stakeholders, policy makers, etc.
- **Propose/establish a science grant program** – supported by a tax on water use (measured by acre feet) or on power. An opt-in payment for ecosystem services was also proposed as an alternative to a tax.
- A Basin-wide adaptive management program should take a more holistic approach – **need for better integration across the whole basin on some issues** (e.g., restoration in the delta linked to what is going on upstream).



- **Funding could be based on public-private partnerships.**

**Plenary discussion:**

This conversation should be international (e.g. include Mexico). Some said the investment of dollars with regard to near-term risk might be better served at more local levels for adaptation options.

**Group 5: Integrating social/human and natural systems in modeling**

Facilitator: Colby Pellegrino, Southern Nevada Water Authority; notetaker: Neha Gupta, University of Arizona

**Breakout discussion:**

- **Common reporting requirements don't exist for water consumption/managed water balance in the Upper Basin** at a granular level (UCRC is working on this) – the four states use four different methods. Upper Basin states are starting to explore this to know what to do in event of compact call. They currently do a combined report at the basin-scale only every 5 years, not well-tracked, except in Colorado. The Lower Basin issues a “decree of accounting report”; the Arizona vs. California decree made it easy to define water use from main stem. There is reluctance to change use modeling and reporting of ET.
- **How do individual communities or water users get represented within basin-scale models?** How do they respond to stress? Basin-wide modeling might miss the individual risks and successes.
- **How will agriculture change with climate change?** Will we still be growing the same crops in the same way?
- There is a strong reluctance to compile information that pits one use sector or state against another, e.g., the economic value of water across use sectors differs dramatically and **we cannot just consider economics alone as the standard for decision-making, particularly across state lines.**
- **Find a hypothesis you want to test before building the model**, models built to answer one question are not interchangeable for use in other applications.

Other topics determined to be of lower priority:

- Are shifts between wet and dry patterns chaotic or predictable? What causes a wet year vs dry year? Is there any progress on predicting these shifts? **An early warning system would create the ability to generate incremental change and policies.** In California, the distinction between wet and dry is dictated by just a few big events each year.
- Do we understand the benefits of conservation in the Upper Basin? We don't understand groundwater/surface water interactions, or the sediment/flow interactions. **Will changing water use behaviors have impacts on the entire basin, e.g., potential increases in consumptive use with more center-pivot irrigation?**
- **How do we integrate our understanding of water use and measurement across state lines** in a uniform way to understand the overall impact of relatively small changes?

**Plenary discussion:**

Variability, volatility, and black swan events in economic markets (not just in the environment) also deserve study. The environment is not the only thing that is unstable. Trade wars, for example, can trigger agricultural tariffs (!). Changes at the irrigation district level can also

translate into changes at basin-wide level (Imperial Irrigation District, for example, currently takes its maximum from river despite dry or wet years). How much do individual water users and communities matter when doing basin-scale modeling?

Water quality issues in river management are equally important; the topic should not simply be water quantity, because quality impacts linger.

9:20-12:25

## RESEARCH THEME PRIORITY PANELS

The four priority theme areas below are those that emerged from suggestions made at the first Building a Science Agenda workshop in October 2017 (see Appendix D). Panelists were asked to present their perspectives on these themes from a stakeholder perspective.

### **Theme 1 Priority: Building an Integrated Approach to Research in the Colorado River Basin**

Moderator: Eric Kuhn, Colorado River Water Conservation District; Panelists: Chuck Cullom, Central Arizona Project; Jennifer Pitt, National Audubon Society; Ted Kennedy, U.S. Geological Survey/Northern Arizona University; and Estevan Lopez, Occam Engineers, Inc.

The panelists chose to discuss this theme through the lens of the Drought Contingency Plans (DCPs), which hopefully will be implemented before the drafting of new Interim Guidelines which expire in Dec. 2025 and cover the 2026 water year. The Interim Guidelines are a consensus approach to administering shortages, with the Secretary of Interior having the ultimate decision if there is no consensus. They also outline the criteria for equalization releases from Lake Powell to Lake Mead. This panel addressed: **How can science be used to put in place a better set of guidelines?**

Political institutions that have historically focused on water development are undergoing a paradigm shift, now wanting to reduce consumption. What is the role of science when there is a culture of development? How do we selectively “undevelop?” An alternate framing is building a new economy around current and projected hydrology. The Grand Canyon and Lees Ferry gauge are two principal constraints in operations.

#### **Panel comments:**

- It is doubtful that a new science agenda can inform this process within what managers view as a compressed timeline (consultation should restart within 18 to 20 months), but clearly the science agenda can and must continue forward. **How can science help with a better set of guidelines post-2026 that will be used in the decision process?** The DCPs and new Interim Guidelines will likely be merged.
- The Lower Basin has Intentionally Created Surplus (ICS) regulations as part of the Interim Guidelines.<sup>5</sup> While the Upper Basin has the System Conservation Pilot Program (SCPP)<sup>6</sup> (as does the Lower Basin) that could be expanded, **robust market mechanisms for the Upper Basin (such as a viable water market or water bank) would be very helpful** for these discussions. **Scenario planning for extreme drought and extreme floods is important and can feed into these discussions.** Reclamation did some work on paleofloods a decade ago.
- We should rethink how we deal with the Endangered Species Act. **We need to protect ecological functions but are we spending too much time, energy, and money to try to get back to a perceived past ideal?** Where can we allow novel ecosystems and where can we keep or regain something pristine?

---

<sup>5</sup> The ICS provides rules in the categories of tributary conservation, groundwater imports, system efficiency, and extraordinary conservation.

<sup>6</sup> SCPP is designed to explore potential solutions in regard to declining water levels in Lakes Mead and Powell, as well as the potential for long-term drought in the Upper Colorado River Basin.

- **A science agenda can still inform the negotiations (even if all the answers haven't yet been generated)** and might help us think about the post-negotiation world. What are the opportunities? Tribal Intentionally Created Surplus, tribal water in markets, water banking in the Upper Basin, and generation of new funding for habitat restoration?
- **Questions of special interest:** 1) What are the unintended consequences of demand management in Upper Basin? What do birds do if crops aren't there, for example. 2) Invasive species are moving in with shifts in landscapes, how do we manage that? 3) What can academics do to point to successful rural community transitions? 4) What are the risks and vulnerabilities to habitat sustainability as restored habitats are set in place? 5) What strategic communications can create a more diversified and transparent engagement? Although the regulatory board size must be constrained, the governance structure is by state. A basin-wide perspective is needed as well or instead.
- USGS is evaluating the Interim Guidelines in the context of the Grand Canyon's ten or eleven resource goals. They are **particularly interested in water quality, the role of nutrients, and maintenance of sediment for physical habitat and recreation**. The big equalization pulse flow significantly eroded the beaches; could it have been spread out over several years? Habitat has been affected. Water quality is a big driver of food webs and fish populations. Water temperatures and nutrient levels are all changing appreciably. There were substantial increases in nonnative fish during pulse flows and it is not clear if this was because of the increased temperatures or water volume.
- What do we think about scenario planning versus probabilistic planning in hydrology? **What are the adaptive strategies we can use to address reservoir operations and water management?** Is the Basin water community ready for Interim Guidelines that might include scenario planning and adaptive strategies?
- We can't demand immediate answers from scenario planning because decision-makers often politically cannot acknowledge risks. However, we need to talk about the future we see unfolding before us rather than the past and not pretend things will remain static over time. Gallons per capita per day (GPCD)<sup>7</sup> clearly has not remained static over time. Participants in the DCP processes seem more willing now to talk about the drier side of the scenarios. **Decision-makers are reluctant to accept risk because solutions are not readily available, but when people collectively decide to pursue a question, there is greater willingness to move forward.**
- The Basin is technically ready, but not yet politically ready. **To start this process, we could set up a scenario to help explain the need for this type of planning and options, and let the stakeholder community select outcomes.** We must broaden participation so that tribes are more involved; they control a lot of the river water and need to figure out how they want to use it and how they can participate. The proposal for Upper Basin water banks will require improved reporting protocols for water use.
- We should **wholeheartedly endorse engaging more widely and deeply with tribal interests, especially for the DCPs**. This has been a persistent shortcoming that must be remedied in reconsultation conversations. Tribal Intentionally Created Surplus (ICS) is already an active process and so will continue to be available in the Interim Guidelines renegotiation.
- CAP is well equipped to engage in scenario planning processes to inform the next set of guidelines or implementation of DCPs. It is not ruling out probabilistic analysis either, but **scenario planning will allow better communication of uncertainty and**

---

<sup>7</sup> GPCD is a method utilized internationally to measure water use by drinking water suppliers and is most commonly used to describe historical and current water uses. It provides a baseline of water use that is not as susceptible to changes in population as other methods.

**vulnerability** – a vital step. We need to transition from robust to resilient solutions across a broader spectrum, and build or support institutions that can respond easily to risk.

- Adaptive management often puts science at cross purposes with users and stakeholders; it is not always what it is cracked up to be. There seems always to be something new that you haven't expected and modeled for (citing a case where a new non-native species appeared in great numbers shortly after the issuance of an environmental impact statement that covered twenty others). As pointed out by Roger Pielke (2008) **we model what we know, and what we overlook always bites us.**

### **General discussion:**

Even if new science can't be accomplished in time to inform the new Interim Guidelines, a lot of science is already available for use. It may be sketchy but it is often pertinent. There is tension between scientists and policy people, but the scientific community would really like to know what others want and need to know.

The National Environmental Policy Act (NEPA) and Endangered Species Act (ESA) are not designed for adaptive management but we need their coverage. The NEPA and the ESA compliance network mandate staying within probabilistic models. Under the current framework, the moment we fall out of whatever was modeled, we risk being sued. The inflexibility is confounding.

Scenario planning can be effective for utilities to manage and address the range of risks. If you set aside the probabilities of the risks you can engage more. Stakeholders stay at the table if you don't discount their concerns as improbable.

What is so cumbersome about the NEPA/ESA process? If there is transparency, there is generally no problem and the consultation process can still provide sufficient flexibility. However, others believe there is incompatibility between these regulatory mechanisms and adaptive management. The Council on Environmental Quality (CEQ) issued a report about a collaborative and more iterative NEPA process in 2007. Have agencies considered the proposals it contained? The NEPA process currently relies on agencies to issue notices and solicit comments; a collaborative process would include stakeholders in advance of comments.

In 319 Minute negotiations, scenario planning was useful in guiding discussion and speculation. On the other hand, in the Mekong River (Thailand), negotiations completely broke down over scenarios to model. This may be more analogous to the situation with Interim Guideline negotiations. You have to be very careful about setting up the scenarios.

Scenario planning has been done for the Basin before on multiple levels. There's skepticism about the possibility of gaming the system by constraining what is looked at (e.g., concerns about storylines that include importation from other basins and aggressive conservation requirements), but it is acceptable to incorporate different scenarios to allow flexible thinking. The new Interim Guidelines will have compliance attached to operational guidance; this is not just a planning exercise.

To date, in the context of the Colorado, we have not usually considered scenarios that embrace the tail-ends of the distribution of possible futures. There is an opportunity to do this now.

## **Theme 2 Priority: Anticipating Future Colorado River Challenges: Science of Crises and Tipping Points**

Moderator, Peter Culp, Culp & Kelly, LLP; Panelists: Dan Cayan, University of California, San Diego; Vic Baker, University of Arizona; Eric Kuhn, Colorado River Water Conservation District; Laina Kaatz, Denver Water

What is the new normal? The separation between precipitation and anticipated vs actual runoff is notable in recent years. Water managers need a roadmap toward providing a reliable water supply somehow despite the fact that the future will not look like the past. We need to identify and explore relevant research questions on tipping points, feedback loops, and extreme events so as to mitigate or at least identify these risks. Water quality, groundwater impacts and ecosystem vulnerabilities can all be tipping points. The drought/flood interface must be better understood so there is more flexibility in reacting to them if there are quick reversals. **What threshold events could overwhelm our systems? And who are we not informing?**

### **Panel comments:**

- Scenario planning is good for Black Swan and extreme events planning. The Severe and Sustained Drought Panel in 1995 was useful (Powell Consortium 1995).<sup>8</sup> **Scenario planning exercises can be done in advance of guideline development, incorporating stakeholders in the planning process.** Then the process could move forward with decision-making.
- California and the West Coast have different atmospheric patterns from the Colorado Basin, which is harder to understand from a predictive viewpoint. California weather is dictated by a winter storm track with bold signatures; the teleconnections are pretty clear. In the Colorado Basin, the situation is more variable. There you can get wet conditions from a broader season and from different atmospheric patterns. The Basin as a whole is getting warmer and will continue to do so. The Upper Basin is on the dividing line between a dry and wet future, while the Lower Basin will pretty clearly become more arid; model outcomes consequently vary quite a bit throughout the Basin, with a scattershot of possible futures. **The scenarios for the Interim Guidelines will have to have a wide spread of options.**
- We can learn from big extremes in the past, and there is a 4.5 billion-year record to study; the paleoview has resonance. We are overly infatuated with the hope that we can have certainty in the future. “Do we want that which we can ideally contemplate without error, or that which we can act upon without fear?”
- **The topic of extremes and tipping points was big in the October 2017 workshop hosted in Las Vegas and is of critical importance.** We need to undertake process exploration to understand what is or could be going on or what might occur in the future. Economic, human, atmospheric processes are all important.
- **We need a shared vision of what we’d like the future to be while being prepared for things outside our control.** These two approaches have competing objectives, but both are necessary to make informed decisions. Practitioners do not want to be dealing with surprises. If we look at both plausible and implausible scenarios, we will not be caught off guard in a crisis. Explorations should include changes in warming and vegetation, markets and economies, and species migration.

---

<sup>8</sup> This work defined a representative Severe Sustained Drought (SSD) to assess its hydrologic impacts, forecast the economic, social and environmental impacts on the southwestern U.S.; and assess alternative institutional arrangements for coping with an SSD.

**Is scenario planning the best alternative? And if so, how do we begin to talk about, develop, and communicate those scenarios?**

We tend to develop science around extremes because it's a way to communicate system challenges, but if scenario planning is the right approach, how can we develop it to help inform decision-making and not just scare the public or make it more difficult to make decisions?

- Communication to the greater public is helpful in the longer term, but communication presently uses 100-year floods and probabilistic language that confuses people, a huge travesty. That model was designed for the insurance industry and hasn't worked as a communication device. **What is effective in getting people's attention is when floods actually happen or paleo evidence of floods.** A just-released article in *Nature* used tree-ring data and other paleodata to conclude that climate change is a factor in increasing floods on the Mississippi River by about 25%, but 75% of the increase in flooding is from construction of levies and other flood control works (Munoz et al. 2018). *Nature* is the true expert.
- **Why isn't it a practice to plan for megadroughts as we do earthquakes?** Scenario planning can help us explore this in a safe way as a community. In scenario planning, we don't have to come to agreement on a single future, but the current paradigm of regulatory regimes isn't prepared for a sufficient number of possibilities. We can't predict our way out of this but must have a systematic approach to challenges so that we can build in flexibility.
- Denver Water's scenario planning has been very instructive. **It would be good to examine what would happen if an extreme flood and extreme drought occurred in rapid succession.** What are the common problems and solutions on the river in terms of human and ecosystem responses? A 40 million acre-foot inflow is possible, which would wipe out Glen Canyon Dam. Scenario planning can't replace probabilistic planning but it can supplement it in the development of new Interim Guidelines.

Systems can break in places where they have never been stressed before. Can we model what it takes to break the system? Should we do research and science on how infrastructure might fail or governance break down?

- **Reclamation wants to look at robust decision-making approaches and examine dozens of scenarios that could break the system.** Which of the many vulnerabilities could interact and exacerbate vulnerability? Signposts (triggers) could inform us when to move into a different mode. If we can start doing holistic exploration it will change our ability to be pre-informed.
- There's an infinite range of possible ways to fail. If you start thinking that way, it opens up a different way of thinking. For the Colorado River, we quantify floods, but they have many different causes and we're comparing apples and oranges. The big question is epistemic. **What has happened *can* happen and looking to past extreme events can constrain your scenarios to make this a useful exercise.** Losing the dams on the Colorado would be much more catastrophic than any multiyear drought.
- The nature of storms we can expect will not be totally foreign to what we've seen in the past. **Look beyond the Colorado River Basin for signatures, triggers, and signposts of change: what is upstream of us that is unusual and can be a marker of what might be coming?** Extreme precipitation can be more destructive now because snow lines are higher. People pay more attention to risk when they have personal experience and this can help start the conversation.

### **Open discussion:**

Do we pay enough attention into turning Black Swans into four-leaf clovers? There are upsides to climate change: longer growing seasons, filling of reservoirs, the opening of the Northwest Passage, invasive species reducing other invasive pests, for example. Do we over-focus on the negative?

Of course we are taking a negative look. We are in a time of extreme change, which is stressful, so we are more motivated to look at risks than opportunities. How do we make the vision broader to set ourselves up for a more successful discussion and outcome?

What is the scale that is of interest here – community, regional, or basin-wide scenario planning? How might the scales be integrated? Are there tools and lessons learned that can be shared?

Climate models are hard to use at the local level, but a collective basin-wide scenario can be used within a community, based on a common starting point. Representative Concentration Pathways (RCPs)<sup>9</sup> are a good place to begin, then there can be a deeper dive to see impacts more locally. Do a proof-of-concept pilot of a basin-wide scenario, perhaps?

What are we doing in the Basin to capture precipitation events outside the Basin proper, e.g., along the Front Range? The South Platte, for example, is of interest to basin states. The places of highest variability of runoff are where there are the fewest gauges. The measurement problem is a tragedy of the commons; no one wants to pay for monitoring. USGS, however, has looked at Midwest gauges for the historical record and patterns, and there seem to be increases in flows in that region. Nature has given us evidence of past floods in the areas of most variability.

Testing scenarios requires systems models that you are confident in, so work on improving models is beneficial. An alternative view is that the usefulness of models in science is questionable. Models are only good if they have the correct assumptions and properly defined processes. Otherwise you get certainty about something that is incorrect.

### **Theme 3 Priority Discussion: Holistic Management of Integrated Systems at Landscape Scales**

Moderator: Doug Kenney, University of Colorado; Panelists: Eloise Kendy, The Nature Conservancy; Jessica Gwinn, U.S. Fish and Wildlife Service; Jim Holway, Babbitt Center of Land and Water Policy; Greg Auble, Ft. Collins Science Center, USGS

Decision-makers work at smaller scales than the scale of the Colorado Basin and under constrained time frames. **Given that this workshop aims to align the interests of the research community with those of decision-makers and managers, where do the spheres of scholarly inquiry and decision-makers overlap?**

#### **Panel comments:**

- **Agriculture should be an integral part of the Basin water research.** A lot of recent forest dieback work shows much of the gap in water needs and availability is due to

---

<sup>9</sup> RCPs are greenhouse gas concentration trajectories, ranging from a low-emissions future to a “business as usual” future, adopted by the IPCC for its fifth Assessment Report in 2014.



evapotranspiration (ET) and drought. The same thing is happening with agriculture. **Projections are for very much higher ET, which will increase water demand dramatically.** This needs to be considered in all its cascading social and economic effects. The information is there to play out in scenarios. It is important to pay attention to moving sediment as well as water and try to understand sediment as it is tied to the geodynamism of geomorphic surfaces. Dams are more effective at trapping sediment than water.

- The Nature Conservancy (TNC) looked at the Colorado River as one of its inaugural whole-systems projects. It took years to develop a whole-system conservation program. They landed on **environmental flows as an integrating topic. Flow is considered the master variable and key integrator, with physical, chemical, and biotic systems coming into play, as well as energy cycles.** However, a healthy flowing river is not a priority for most people. Most are concerned with water use and water supplies for people in cities and rural areas. TNC looks for urgent common problems it can solve and still give environment a seat at the table. Environmental flows into the Delta were a priority for a coalition of environmental groups. They felt that NGOs could serve as informal diplomats to incorporate this in Minute 319 and get Mexico and the United States talking. Water for the environment got to tag along on the journey. NGOs helped improve an initially contentious relationship and served as shuttle diplomats whose work culminated in formal negotiations; they now are leading in creativity and systemic thinking.
- Governments are increasingly looking to NGOs for solutions to intractable problems because of their systems perspective. **Science needs are: good water budgets, a transboundary water model, remote sensing for monitoring of restored areas, and optimization of water deliveries.** A lot of this gap is just basic science, e.g., flow measurements. Water marketing may have been of passing interest; TNC is committed to maintaining economically viable rural communities rather than buying out water. Alternative Transfer Mechanisms are promising, because they create interdependencies rather than conflict.
- **Water budgets are an overarching need in every basin. Agricultural water use and consumption data at the field level is also needed.** Wastewater treatment and wastewater swapping are in progress; Mexicali is exceeding its capacity and can't afford to expand its system. It is now negotiating with the Sonoran Institute and TNC to expand their wetlands to dedicate water to the environment. What is the scope for wastewater bartering across the Basin; what effluents are available for ecological restoration? To TNC, a holistic approach includes both human and institutional systems, and this is where they find their solutions.
- Where do we need knowledge? Is it at the interface of land and water? How do land use decisions impact water, water demand, water quantity, and water quality? Who is doing what? New tools can be developed to do this analysis, and existing ones can also be employed or evaluated for their usefulness in this, including technical evaluations, landscape ordinances, and capital improvement plans. **A valuable exercise might be to think through the best way to build a new community from scratch, removing constraints to increase innovation and perspective.**
- The Section 7 consultation process in the Endangered Species Act is intended to determine whether an action jeopardizes an endangered species. However, **the driving force for ESA work is to respond to environmental pressures, so integrated management makes for more recovery opportunities.** It is not possible to focus on a species' "entire universe." The Lower Colorado River Multiple Species Conservation Program is an example of good holistic and landscape-scale approach, not without

criticism, in which multiple interests address recovery and conservation. Habitat has been created as a result, but patience is required in addition to science. It took 10 years to design.

**Open discussion:**

What is the definition of systemic modeling or holistic management for a river system? A holistic model could include human, economic, hydrologic, and geochemical systems. Reclamation cannot do this work alone. The river systems include tributaries, not just reservoirs. That isn't Reclamation's mission; if you need a systematic multi-agency effort, there has to be involvement of all the federal agencies involved, and agreement at DOI Deputy Secretary level. The U.S. Geological Survey (USGS), Fish and Wildlife Service (FWS), and National Oceanic and Atmospheric Administration (NOAA) take more of a systems approach. Reclamation hasn't been charged to lead Colorado River work at that level. The Basin Study had a limited focus but was a first step in a planning process. Where do we go from here as a community?

We know very little about groundwater, particularly in the Upper Basin. We know little about its contribution to baseflow, as a buffer to megadrought, or how it affects forest transformation and vice versa. Should the water management community be concerned about this lack of information and how little it is talked about? Arizona is ahead of the others in this respect, with its Groundwater Management Act and (limited) Active Management Areas. More importantly, how do we manage groundwater and surface water and treated water systems holistically and conjunctively? The Salt River Project (SRP) is well placed to do that kind of thinking, not just from a vulnerability perspective, but also in terms of optimization of the whole system. Climate will affect groundwater directly and indirectly. If we understand the baseline, we can begin to understand changes and plan for them.

Recent papers have been released on groundwater contributions to base flow that could be very useful to managers. USGS was developing a flow model that couples groundwater and surface water. It is trying to use mass balance as part of its approach. When Reclamation measures water withdrawals, surface and groundwater are not adequately distinguished. Surface water and groundwater interactions are complex and diverse, and it's not clear if we are asking the right questions yet. Some groundwater is directly connected to flows, other groundwater has much longer time periods of intersection with flows. Groundwater flows must become better understood at the smaller scale as well, including the impacts from water markets. Water transactions with adverse impacts downgradient will stymie future water transactions.

To some, a black swan on the horizon results from the bifurcation of water law (having separate water management systems for surface and groundwater). Managing it conjunctively would be a game changer in some states. There is a strong movement in the West to privatize public lands which are the source of much of our water. What are the implications of that, when those lands are the source of the groundwater that supports the surface water? The potential privatization of the water supply in general is a greater concern because almost 100% of groundwater used in the West is nonrenewable.

**12:25-1:30**

**Lunch Talk by Robert Glennon, Regents' Professor and Morris K. Udall Professor of Law and Public Policy, University of Arizona**

Colorado River water allocations are much higher than the average current flows in the River due to over-allocation in the original 1922 Colorado River Compact, compounded by climate change, increased agricultural needs, and ET from reservoirs. The Upper Basin states have not

used their full allocations in the past, but this could change quickly: Utah, Colorado, and Wyoming are all in the process of building dams. Seven major new diversions are planned in Colorado alone.

Our water infrastructure is in a state of disrepair, as evidenced by the near failure of the Oroville Dam and its spillways in fall 2018. The dam's design relied on a particular hydrograph and set of assumptions that no longer apply and that cannot accommodate the much larger swings between droughts and floods that are occurring today. The need for time and money to bolster and repair infrastructure is real, but there have instead been very significant drops in federal funding to water utilities in the overall infrastructure budgets. Infrastructure funding by the federal government is now 90% less than it was at its high point in 1977. Water infrastructure in the United States is currently funded at a level equal to \$11 per person. The current Administration's \$200 billion infrastructure budget is considered to be smoke and mirrors, achieved by cutting existing programs. This leaves states and local government in a quandary; municipalities for the most part must finance their own reforms and are looking to 100-year bonds instead of the traditional 20- to 30-year bonds to finance water projects. Public/private partnerships must be part of the solution. The Poseidon Water desalination projects off the coast of southern California, for example, will cost over \$1 billion, but will provide a very secure water supply to San Diego at no financial risk to the city.

A recent report co-authored by Glennon (Culp et al. 2014), describes how the use of market forces can mitigate the risk of water shortages. Water for irrigation and livestock is estimated to comprise 85% of consumptive water use. Just a 4% reduction in water consumption for agricultural use would increase by almost 50% the water supply available for residential, commercial, and industrial consumption. How would this be achievable and still keep the agriculture sector vital, secure, and productive? The 4% reduction goal could be realized if municipalities pay farmers to reduce their water use through a fund to help them modernize their infrastructure. Installation of subsurface drip irrigation costs \$2,500 to \$3,000 per acre—a very significant amount of money to a farmer but as insignificant as a rounding error for cities. Cities could pay for the technology upgrades and get the water that is saved, while farm production would remain constant.

Water exchanges are another market strategy that can reduce the risk of water shortages. These could include forbearance agreements, Intentionally Created Surplus (ICS), system conservation, DCP-Plus (an Arizona-only plan to incentivize reductions in water use and water storage programs so that unused water can be safely stored in Lake Mead), and Minute 323; all these options provide financial leverage to leave water in the system. Arizona has also used “in lieu” recharge, whereby farmers use CAP water rather than groundwater for irrigation.

Water rights exchanges have also provided flexibility in maintaining water security. The Gila River Indian Community gave up its rights to Gila River water in exchange for CAP water, made other deals with the SRP, and has negotiated other water leases. The cities of Tucson and Phoenix have agreed to work together on CAP water exchange and storage.

Glennon was somewhat skeptical of water augmentation proposals, three of which have been discussed more than others. Desalination of brackish water in the West Salt River Valley (in the western Phoenix metropolitan area) has merit because of its relatively low cost and high quality of input water, but would pose both legal and environmental problems in disposal of its brine. Desalination of ocean water off the California coast is considered politically unfeasible. An off-coast desalination plant in Mexico would require a new power plant and a 50-mile pipeline to Mexicali, with attendant transport problems.

The CAP canal has substantial capacity if the Lower Basin is in a shortage sharing situation (because deliveries will be reduced), but otherwise does not. Perhaps there won't be 1.4 maf in the CAP anymore. The discussion about capacity and expectations from the CAP must be reframed; there will never be as much water in the CAP as we expect. Arizona has never paid for a water project and can't expect that situation to last.

The tools to address the risk of water shortage already exist: conservation is still an option, supplemented by reuse, some desalination, and economic and marketing strategies. What is needed is the moral courage and the political will to act.

**Discussion:**

How could his proposal on agricultural conservation be incentivized to permanently reduce demand? How can an agreement that is economically viable be secured?

Mexico is concerned about system deficits and their impacts, and would like this issue to be included in the discussions.

How do we manage unintended consequences of system adaptation/water conservation that sometimes occur (e.g., higher efficiency drip irrigation systems reduce return flows)?

1:30-2:25

## RESEARCH THEME PRIORITY PANELS

### Theme 4 Priority Discussion: Science for Adaptive, Resilient, and Just Institutions

Moderator: Kathy Jacobs; Panelists: Karen Schlatter, Sonoran Institute; Robert Adler, University of Utah; Lester Snow, natural resource consultant; Forest Cuch, Ute Indian Tribe

#### How do we energize and build capacity for tribes and other groups to participate more fully?

##### Panel comments:

- This question connects to six topics starting with “C”: 1) **Connectivity**: If the goal is basin-wide improvement, a better understanding of connections is needed. Types of connections include longitudinal (Upper and Lower Basin), vertical (groundwater and surface water), lateral (land versus water), temporal, quantity and quality, and political/human. 2) **Change**: We need to understand change to become more adaptive. We need both adaptive management (risk-based decisions) and scenario planning work. Modeling needs to match timescales of geological and hydrological systems with human decisions. Care must be taken that short-term decisions don’t lead to poor long-term decisions and outcomes. 3) **Collaboration**: tribes, environmental and recreational interests, Mexico, and future generations have all been underrepresented. What science will enhance the role and participation of diverse interest groups? More social science would help. What are the true values of ecosystem services to humans? Who bears the costs and who reaps the benefits? 4) **Conservation**: we need to be more efficient to be more adaptive. What incentives lead to better efficiencies? 5) **Complexity**: how can complexity be communicated effectively to induce progress and incentivize action? There is always a tension between the simplicity needed for management decisions and academic rigor. 6) **Conditions**: There is considerable focus on science to predict future conditions. Less attention is being paid to our desired vision for the future. The future will be where we end up versus where we want to be.
- Recent research has shown that 3,000 years ago, the Pharaohs of Egypt recognized early stages of a prolonged drought and took adaptive action by increasing grain production and crossbreeding cattle. The efforts delayed the fall of the Egyptian empire by 50 years, but were ultimately insufficient to overcome the megadrought that occurred (Finkelstein et al. 2017). **We too are adapting too slowly and need to get out in front of impacts.**
- In decision-making, would-be participants think “The room is the right size if I am in it. It’s too small if I’m not.” **If not all can participate at the table, someone in the room should be able to articulate and represent the point of view of anyone on the outside.** Colorado River decisions are highly distributed and not centralized and so there are very high transaction costs to be continually engaged in this discussion. Ecosystems and tribes have been systematically left out. Decision-making on the Colorado River relies ultimately on the Secretary of the Interior’s involvement in the Interim Guidelines. Is that the optimal structure? Would a Colorado River Basin Commission make more sense? Should we have a water master instead? The current structure can’t prepare us for a black swan event.
- **A water fee that supports investment in science and participation is needed;** and the price of water has to start approaching its cost.

- **Water rights and the Colorado Compact are unlikely to survive unchanged for the next 100 years. Markets can help in this transition.**
- The Sonoran Institute (SI) works on the water and ecosystem program in the Colorado Delta, including the Minute 323 monitoring program and designing the restoration program. SI also does environmental outreach and education in the United States and Mexico and represents views on both sides of the border. Scientists were amazed at the huge human positive response to the pulse flow delivery of 2014. Water is a critical part of communities and who we are as Westerners. **Communities all along the river must be taken into account.** What will following programs do to rural communities? **Unnecessary harm can be done to communities without sufficient foresight about potential impacts (and unintended consequences) of well-intentioned projects.** The linkages of restoration work to communities that are remote from the restoration sites must also be communicated (e.g., impacts of ecosystem services in the Delta on bird habitat, communicated to U.S. birdwatchers or residents of Los Angeles). Studies are showing that some ecosystems are dependent on groundwater that is recharged from agricultural return flows. Scenario planning can be used to investigate the longer-term impacts of conservation, climate change, and land-use changes that affect water use and habitat. Water conservation should be achieved without creating justice and equity issues.
- Water wars have already begun in Utah. Diversions of water through the Central Utah Project are affecting tribal water and the Ute Indian Tribe has filed suit. Because the tribe did not have a voice in this issue, it felt compelled to litigate. Staying at the table would have been preferable. The tribe will have to adapt if they lose, and return to hunter/gatherer way of life, although the land is no longer the utopia it was when Dominguez and Escalante came into Utah. **Scientists are like scouts, warning of the dangers ahead, but the leaders are currently ignoring the vital information they provide.** The Ute world view and that of other Southwestern tribes is egalitarian, cooperative, matriarchal, and uses situational leadership. Native people feel closely connected to habitat and wildlife. The New Zealand bill of rights for nature and ecology is a good model<sup>10</sup>.
- What the shaman calls spirit, the scientists call energy, but not all energy can be observed and that is the entry into the spiritual realm. **Native people can play a role in representing environmental interests. There is concern about the “development at all costs” mentality in the world.** To help with adaptation and improved utilization of resources, the Ute Tribe started raising four species of buffalo years ago and the herd continues to grow. Buffalo now rival elk as a rich source of protein and a commercial market is being developed. Cattle, in contrast, consume considerably more resources and contribute to air pollution. It is important to learn lessons by looking at nature to see what has happened in the past.

### Open discussion:

Is there an interactive map that identifies professionals and groups in conservation so that people can get help with science questions?

There are unintended consequences when the cost of water goes up. In California, outside speculators are buying farmland not for farming but for the water rights. There is a perverse

---

<sup>10</sup> According to the Earth Law Center, in the first half of 2017, four rivers in New Zealand were granted legal personhood status, that is, they were granted the same legal rights as a juristic person.

incentive to maximize (increase) water use so the new owners can then “conserve” and get paid by the cities. Highly subsidized water rights in California have resulted in massive unintended consequences, such as the wide expansion of farmland in the San Joaquin Valley. A regulated and transparent market might be necessary. Institutions and state water rights systems aren’t capable of changing fast enough to match the pace of market changes.

What is the alternative to doing away with water rights? Redoing the Compact is not something that would be embraced; it’s like a “nuclear” option, but having the Secretary of Interior in charge of the river is an anachronism that won’t be successful in the future. Doing away with water rights would get peoples’ attention.

You can’t have a market without rights. Water rights aren’t like land rights, because water is a public good and people have the right to use it, not own it, as long as the use is beneficial and not wasteful. The beneficial use legal system, however, has been broken and unenforced for years.

## IV. CONCLUSIONS

2:40-3:40

### NEW AND EXISTING THEMES AND PRIORITIES DISCUSSION

Eric Kuhn, Colorado River Water Conservation District

Recap of common themes/ideas from a water manager's perspective in a diverse district:

- Are we building an agenda that is primarily academic (basic research or focused on an educational aspect) or one more focused on specific decisions that need to be made in the Basin that may be less than basin-wide? The answer is probably both. **Research is needed to inform the revised Interim Guidelines and it is likely to be interesting to scientists.**
- **The basin has undergone a paradigm shift from an era in which institutions and water law focused on development and big-project construction to one focused on “undevelopment.”** (Reduction of consumptive uses by 1.4 maf, a DCP goal in the Lower Basin, is a huge “undevelopment” project on a scale of some of the biggest infrastructure projects, such as the California River Aqueduct). The River is acknowledged to be over-allocated at least during dry periods, but probably on a permanent basis going forward. Is this paradigm shift reflected in decision-making organizations? Does the scientific community recognize this? How can this undevelopment become a selective process?
- **More social science and economic studies are needed.** Some exist but they do not have sufficient focus on hydrology. Most scientific programs for the Colorado River are associated with resources rather than economics, governance, and social science.
- **A lot of science goes toward predicting the hydrological future. Less so on climate change, changes in the Basin's basic systems, and their impact on management institutions.**
- **More information is needed on black swans;** this is an opening for research to point out through history what has occurred and will occur in the future.
- **Water providers use scenario planning in their own efforts, but can we scale that up to the Basin? Who will take the lead that will include both ends of the hydrograph and how will institutions across the Basin respond?** This could inform decision-makers and people at the renegotiating table. Educating them in advance through scenario planning can supplement probabilistic efforts.
- **The Secretary of Interior wears too many hats to also serve as water master in the Lower Basin.** This is the situation because California, Arizona, and Nevada could not agree among themselves about allocations and consequently federalized the River. It's both a cautionary tale and a self-inflicted wound.

#### Open discussion:

Some participants objected to the phrasing of development vs. undevelopment; instead they see this process as a shift in economy in the Basin. However, the River is clearly over-allocated and consumption needs to be reduced at the basin scale.

Has the research community recognized the shift? Yes. Can institutions respond and be nimble in the face of these water supply challenges? Well, yes. The Metropolitan Water District of Southern California, for example, reduced their water use dramatically to get California to 4.4 million acre-feet in 18 months when faced with shortages on the river. Institutions have successfully worked collaboratively and raised conservation programs in both parts of the Basin



to help supplement reservoir levels. So it seems that water managers can be nimble in the face of changing circumstances.

Is academic research equipped to address these problems and be helpful in renegotiating guidelines? Not if you follow the traditional academic model that has incompatible time frames. If there were something like a Center for Colorado Basin Research that hired research professors to do multiyear, cross-disciplinary work, it might work.

Academics will keep pursuing this topic despite the Interim Guidelines deadline. The Venn diagram of what practitioners want to know and what researchers want to investigate is of interest; the hope is there is great congruence. Rather than framing river management changes as “un”-development, it is more important to academics to contribute to the discussion about how water can be used more efficiently. A counter-argument: the math is clear; we are using more water in the Lower Basin than is sustainable. Conservation is a tool, but how do water agencies deliver water to customers when the system has been overdeveloped over 100 years and someone has to reduce their consumptive use?

Funding has been tied to showing science is directly applicable in responding to users’ needs. This will continue as a trend. Nevertheless, science for science’s sake also has value. How do we blend objectives from the last workshop with this workshop? Perhaps two strong sets of research priorities? The voices of the ecosystem and tribes need to be brought into all aspects of work so that governance reflects them. This can be done in scenario planning and in a safe space.

## RECAP OF MAIN POINTS OF INTEREST FROM THE WORKSHOP

Kathy Jacobs, University of Arizona

Here are some of the main themes that came up multiple times during the the past two days:

- **Need for a coordinated research agenda.** This should include ways to coordinate and prioritize research and data for the gaps that are identified.
- **Need for coordinated funding sources.** Agencies and NGOs already fund Colorado River work. How can we raise the impact of this existing funding to incentivize more cooperation and collaboration in addition to setting priorities? Right now water utilities are communicating, for example, but the wide diversity of affected organizations are not talking with each other.
- **Increased flexibility and regulatory improvements.** Ensure conservation outcomes are understood and accepted so that we’ll know if we’re making progress. Are the metrics we are using now connected to the articulated goals? (The 2007 CEQ report on improving NEPA outcomes has a good process to model.)
- **Scenario planning improvements at the basin scale.** These are a means to an end, not an end in themselves, but can help us plan for multiple futures and take a broad view of risk.
- **Adaptation.** We keep talking about the “adaptation deficit” – the difference between our current capacity and what is actually needed. We are not investing at a rate commensurate with the amount of risk. How do we scale up adaptation from where we are now and go from individual efforts to work on collective risk?
- **Weather patterns that led to past extreme events could help with signposting/understanding thresholds and anticipating changing conditions.**
- **Democratizing processes and enhancing social justice** are not going well. What does true engagement mean? Being at the table is not the same as being able to

influence outcomes. If not everyone can be at the table, is there a better way to represent them or help them be more influential in the outcome? Representation in these conversations must improve.

- **Evaluation of alternative institutions is needed.** Are there big changes that could be made that would be supported by water users, e.g., with a water master or markets?

#### **Open discussion:**

- A basic science research agenda IS important to practitioners, to possibly include wet to dry transition signals (and vice versa); triggers, thresholds, and signposts; the difference between extreme events and black swans, etc. There is a need to collect, coordinate, and prioritize research and data. Water budgets are needed in basins – where and when the water is – are of particular interest.
- If you are looking for a multi-sector agenda, a fundamental climate science agenda is where there is consensus. It requires agreement between sectors. Practitioners can only implement changes at an incremental level; suggestions that require wholesale change, such as in socioeconomics or governance, are not useful to water agencies. Practical science, not social science, is of interest to them.
- Water managers have been working hard for the past two decades to make incremental changes more nimble and broader in scope. But being prepared for dramatic changes is still a good idea.
- Focus on the intersection of science and practice interests, along with the funding component. It is difficult to get foundations and NGOs to cooperate except when you put them in a room together. There's a huge appetite for basin science and for water budget development, but not a coherent set of funding priorities. Major institutions in the Basin such as the University of Arizona, Central Arizona Project, and Metropolitan Water District are pursuing important goals but not conversing about how to align their efforts and leverage resources. Steering philanthropic money to fill research gaps requires more than issuing workshop reports. Scientists must align their research interests with what can get funded. A science "moonshot" around some critical issue (e.g., developing indicators of change) might get attention. Need to have a more centralized effort to determine priorities in a coordinated way.
- Still, there is interest in research on governance and communication. We don't have to reject the whole regulatory system. How do we make institutions more adaptable? How do we get broader engagement? The utopian belief in democracy holds that an educated electorate will make the best decisions.
- A basin-wide analysis/synthesis of groundwater resources is essential. Users always take advantage of groundwater while not recognizing its true value.
- There are models for collaborative research, such as NOAA/RISAs and USGS Climate Science Centers, that are already in place. It's not just basic or applied research, but use-inspired research that is a great model for how we could move forward.
- The public must be engaged in a separate stand-alone financing model, such as payments for ecosystem services programs.
- Some water managers may be uncomfortable with transformational research, but we are in uncharted waters. Just since 2012, it's .5 C° warmer in the Basin. There is no new normal. Your worst nightmare is not what we've already seen in the last 18 years. More investigations similar in focus and approach as the Severe and Sustained Drought project of the early 1990s are needed.

## **PARTING WORDS**

Which of the topics discussed during the workshop should be prioritized? Participants were asked to express their opinions individually in the form of a brief final suggestion at the end of the workshop. See Appendix E for their suggestions<sup>11</sup>. In the meantime, the organizers will be soliciting feedback on the findings of this workshop and developing collaborative proposals to move the priority ideas forward.

---

<sup>11</sup> A summary of major themes, produced by the organizers, was distributed two weeks after the workshop in addition to the overall notes of the meeting. There were no comments received on those themes. They appear in the Executive Summary of this document.

## APPENDIX A: References Cited

- Bureau of Reclamation. 2012. Colorado River Basin Water Supply and Demand Study.
- CADSWES. 2007. Review of science and methods for incorporating climate change information into Reclamation's Colorado River Basin planning studies. Appendix U of the Interim Guidelines.
- Council on Environmental Quality (CEQ). 2007. Collaboration in NEPA: A Handbook for NEPA Practitioners.
- Culp, P.W., R.J. Glennon, and G. Libecap. 2014. Shopping for Water: How the Market Can Mitigate Water Shortages in the American West. Stanford Woods Institute for the Environment, Discussion paper 2015-05, 40 pp.
- Finkelstein, I., D. Langgut, M. Meiri, and L. Sapir-Hen. 2017. Egyptian imperial economy in Canaan: Reaction to the climate crisis at the end of the Late Bronze Age. *Ägypten und Levante* 27: 249-260.
- James, I., and S. Roth. California's dying sea. Four-part series published online in the *Desert Sun*. <http://www.desertsun.com/series/salttonsea/>
- Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, and D.P. Lettenmeier. 2008. Stationarity is dead. Wither water management? *Science* 319(5863): 573-574.
- Munoz, S.E., L. Glosan, M.D. Therrell, J.W.F. Remo, Z. Shen, R.M. Sullivan, C. Wiman, M. O'Donnell, and J.P. Donnelly, 2018. Climatic control of Mississippi River flood hazard amplified by river engineering. *Nature* 556: 95-98.
- Pielke, R.A. A Broader View of the Role of Humans in the Climate System. *Physics Today*. November, 2008
- Powell Consortium. 1995. Severe Sustained Drought: Managing the Colorado River System in Times of Shortage. Papers reprinted from *Water Resources Bulletin* 31 (5). <https://wrrc.arizona.edu/publications/other/severe-sustained-drought>
- Udall, B., and J. Overpeck. 2017. The twenty-first century Colorado River hot drought and implications for the future. *Water Resour. Res.* 53(3): 2404-2418.
- U.S. Army Corps of Engineers. 2011. Addressing Climate Change in Long-term Water Resources Planning and Management: User Needs for Improving Tools and Information. U.S. Army Corps of Engineers Civil Works Technical Series CWTS-10-02.
- Raff, D., L. Brekke, K. Werner, A. Wood, and K. White. 2013. Short-term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information. U.S. Bureau of Reclamation, Bureau of Reclamation, National Oceanic and Atmospheric Administration.

U.S. Secretary of the Interior. Record of Decision - Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. December 13, 2007.

**APPENDIX B:  
List of Participants**

	<b>Last name</b>	<b>First name</b>	<b>Affiliation</b>	<b>Position title</b>
1	Adler	Robert	University of Utah, S.J. Quinney College of Law	Dean and Distinguished Professor of Law
2	Auble	Gregor	Fort Collins Science Center, USGS	Research Ecologist
3	Baker	Vic	University of Arizona	Regents' Professor of Hydrology and Atmospheric Sciences
4	Black	Mary	University of Arizona	Retired
5	Bunk	Dan	Bureau of Reclamation	Supervisory Hydrologist
6	Connor	Michael	WilmerHale	Partner
7	Cuch	Forrest	Ute Indian Tribal	Elder
8	Cullom	Charles	Central Arizona Project	Manager, Colorado River Programs
9	Culp	Peter	Culp & Kelly, LLP	Managing Partner
10	Dahm	Cliff	University of New Mexico	Emeritus Professor
11	Elder	Nathan	Denver Water	Interim Manager of Raw Water Supply
12	Enquist	Carolyn	SW Climate Science Center, USGS	Deputy Dir.
13	Ester	Charlie	Salt River Project	Manager/Surface Water Resources
14	Flessa	Karl	University of Arizona	Professor
15	Gerlak	Andrea	University of Arizona	Associate Professor
16	Glennon	Robert	University of Arizona, Rogers College of Law	Regents' Professor and Morris K. Udall Professor of Law and Public Policy
17	Gupta	Neha	University of Arizona	Graduate Student
18	Gwinn	Jessica	US. Fish and Wildlife Service	Colorado River Coordinator; Fish and Wildlife Biologist
19	Gyawali	Rabi	Arizona Department of Water Resources	Water Resources Engineer
20	Harris	Christopher	Colorado River Board of California	Executive Director
21	Hasencamp	Bill	Metropolitan Water District of Southern California	Manager, Colorado River Resources
22	Hermosilla	Victoria	University of Arizona	Graduate Student
23	Holway	Jim	Babbitt Center for Land and Water Policy	Director
24	Jacobs	Kathy	University of Arizona	Director, CCASS
25	Jerla	Carly	Bureau of Reclamation	Operations Research Analyst
26	Kaatz	Laurna	Denver Water	Climate Program Director
27	Kanzer	Dave	Colorado River District	Deputy Chief Engineer
28	Kendy	Eloise	The Nature Conservancy	Senior Freshwater Scientist
29	Kennedy	Theodore	US Geological Survey	Research Ecologist
30	Kenney	Doug	Univ. of Colorado	Director, Western Water Policy Program
31	King	J. Phillip	Elephant Butte Irrigation District/NMSU	Consultant and Professor
32	Kreamer	David	University of Nevada, Las Vegas	Professor
33	Kuhn	Eric	Colorado River Water Conservation District	Consultant on Col River Matters (retired General Manager)
34	Leinberger	Amanda	University of Arizona, CCASS	Adaptation Program Manager
35	Liu	Tao	University of Arizona	Graduate Student

36	Lobato Sanchez	Rene	Instituto Mexicano de Tecnologia del Agua	Hydrologist
37	Lopez	Estevan	Occam Engineers Inc.	Sr. Engineer
38	Mackey	Craig	Business for Water Stewardship	Policy Director
39	Mahmoud	Mohammed	Central Arizona Project	Senior Policy Analyst
40	McCoy	Amy	Aylward, McCoy & Piltz Consulting	Director
41	Megdall	Sharon	University of Arizona Water Resources Research Center	Director and Professor
42	Miller	Paul	NOAA - Colorado Basin River Forecast Center	Service Coordination Hydrologist
43	Pellegrino	Colby	SNWA	Director
44	Peters	Bob	Denver Water	Water Resources Engineer
45	Pitt	Jennifer	National Audubon Society	Director, Colorado River Program
46	Prairie	James	Reclamation	Hydrologic Engineer
47	Rice	Matt	American Rivers	Director, Colorado River Basin Program
48	Schlatter	Karen	Sonoran Institute	Associate Director, Water and Ecosystem Restoration
49	Schmidt	Jack	Utah State Univesity	Professor
50	Simpson	Ashlee	University of Arizona	Graduate Student
51	Smith	Rebecca	Reclamation, Lower Colorado Region	Civil/Hydrologic Engineer
52	Snow	Lester	Natural Resource Consultant	President
53	Springer	Abe	Northern Arizona University	Professor
54	Stone	Mark	University of New Mexico	Associate Professor
55	Theilmann	Mira	University of Arizona	Graduate Student
56	Udall	Brad	Colorado State University/Southwest Climate Science Center	Senior Scientist
57	Vano	Julie	NCAR	Project Scientist
58	Weisheit	John	Living Rivers & Colorado Riverkeeper	Colorado Riverkeeper
59	Wolff	Steve	Wyoming State Engineer's Office	Interstate Streams Administrator
60	Woodhouse	Connie	University of Arizona	Professor
61	Zurita	Brianna	University of Arizona, CCASS	Project Coordinator

**APPENDIX C:**  
**Participant Interests (from the Introductions on Day 1)**

What is your particular interest in this workshop?

- Concern about the long-term sustainability of the river, river system, and water supply; effective management to benefit both people and the environment (4 responses)
- Developing a science action agenda; where are the research gaps and how can best available science be incorporated into management; better tailoring of research products for decisions (4 responses)
- Communication issues: how can academia help us think about communication science; how do we talk about water and risk; how do we talk to each other (3 responses)
- Disconnect between science, law and policy; enhancement of the nexus between science and policy (2 responses)
- Disconnect between science and decision-making -- why is this happening; develop a policy agenda based on science (3 responses)
- Bridge between academic world and world of water policy
- Spent life working on the headwaters and Delta, line between science and public policy
- Interested in learning
- Care about the river; conduit between the October 2017 workshop and this one
- Management decisions as stresses increase
- Colorado River Delta – put science to work: restoration, ecological monitoring, science solutions for the U.S. and Mexico
- Springs, holistic management
- Living rivers, river stewardship
- Aquifers as an important component of the river supply and barometer of ecosystem health
- Build a more resilient future based on facts
- How institutions work and change
- Moving science and knowledge into effective climate adaptation
- Policy, impacts, climate change
- Paleoflood hydrology – what nature tells us about past conditions
- Drought, hydrology, climate change
- Colorado River Team in the Delta
- Whole-basin approach
- Science for water management, especially trees along river
- Flow management and food webs
- Partnering with river guides and citizen scientists
- Endangered species
- Climate forecasts, climate change – building partnerships
- River operations, near- and long-term water supply sustainability



**APPENDIX D:**  
**Overarching Themes and Research Priorities Identified in the first workshop,**  
**October 2017**

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 recent global climate modeling (Coupled Model Intercomparison Project, 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 thresholds 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 (thresholds, triggers, or 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.

## **APPENDIX E: Final Suggestions/Priorities from Participants**

- A Colorado River Science Symposium with a couple of different tracks. Spend a day to synthesize what is known, and another focused on cutting-edge science and a vision for the science in the Basin. Include socioeconomic and hydrologic modeling. The approach should be holistic and include social science and communication. This would be a good way to kick off scenario planning.
- Transformative research: we need to be brave and have hard conversations that are scary and uncomfortable.
- The water management community doesn't want to be part of transformational governance and is more comfortable with incremental changes. Look for overlapping interests.
- Build bridges/relationships between academics and managers.
- Is there a better way for scientists to communicate "realistic risks" that we can take to our boards and to inform the Interim Guidelines?
- Scenarios supported by physical process elements. ARkStorm, a hypothetical but scientifically realistic "megastorm" scenario developed by the U.S. Geological Survey that looked at emergency preparedness, is a good example. It was strongly inspired by a black swan series of atmospheric rivers in 1861-1862.
- Tributary ecohydrology; don't spend so much time on the main stem when you should also be looking at groundwater and springs and native interests.
- The good history of coordination between funders and NGOs should be transferred to research – bring in funders and agencies as customers and users to initiate scenario planning.
- A basin-wide multi-day scientific conference, as already suggested, but more directed and goal-oriented. It should not be just an exercise in intellectual gratification.
- Research is not valuable if it is blocked or manipulated by big business (protect scientific integrity).
- Basin-wide workshop or something similar as a starting point for scenario development. Define simple goals and variables for a basin-wide model.
- Include the study of human institutions in addition to physical sciences.
- A clearinghouse of all physical and social science relevant to the Colorado, with information widely accessible and user-friendly.
- Irrigated agriculture needs to be part of the discussion of a basin-wide model.
- Do scenario planning on black swan events on both ends of the distribution. This could scare enough people into doing transformational science.
- A concise report on groundwater conditions throughout the Basin, emphasizing the large contributions of groundwater to flows in the river
- Communication is important; reach out and come together with allies in the business community, NGOs, and foundations. Help interpret what climate change means.
- We need to get stakeholders, practitioners, and researchers together more often. We generally have good collegial relationships across sectors, but there is some tone-deafness regarding expanding the relationships. Some topics are not helpful. When we have tried to communicate boundaries we sometimes get comments that are patronizing. We need to find common ground where we can move forward together to understand how change occurs in the Basin.
- Droughts, black swans, and climate change are the three major challenges. They do not have political boundaries, so perhaps we should work at the regional scale rather than basin scale.

- Focus on cascading or unintended consequences and consider the full scope of possible futures.
- In decision-making under uncertainty, focus more on opportunities and unintended consequences. Looking at the worst case is OK, but also look at other outcomes to consider the full range, and don't be dismissive of options you don't like, such as augmentation.
- Reach out to funders and NGOs – how can we communicate better with each other?
- Science to inform decision-making: identify the decision problems and narrow them in terms of spatial and temporal scales. From there identify how science can be used.
- A residency program for academics in agencies such as Reclamation.
- Explore black swan events, particularly floods and droughts, as probable maximum ends of the distribution. Identify mitigation and adaptation strategies to bookend the problem.
- Explore the role of citizen science in closing uncertainties.
- Ecology and species-specific questions should be on the list.
- Explore black swans through scenarios.
- Communication: engage public information officers to move information to higher levels.
- Use the California Delta experience in creating a science agenda for the Colorado River, possibly with an independent science board. How can this science agenda be more than shelf art?
- If you are bored, you are not paying attention. Climate change is a serious threat happening faster than anyone acknowledges.
- Communication and collaboration meetings must be spearheaded and organized by managers and stakeholders (this from a scientist).
- Reflect on and build on past successes to guide future actions.
- Black swans we don't see coming, such as the transition of peak energy demand in CA when residential solar took hold.
- An interactive GIS tool for NGOs and resources for watershed restoration.
- Data in near-real-time on supply and demand in the Upper Basin.
- Talk more about the stakeholder engagement processes. Continue dialog in a meaningful way and with better definition of terms such as governance. Pay attention to the really good work that has already been done.
- Use the network of university water centers. There is already a subgroup for the Basin. The Powell Consortium involves Arizona, California, Colorado, Nevada, New Mexico, Texas, Utah, and Wyoming, and was formed to work on water resources problems of the Colorado River/Great Basin region.
- Producing a “Severe and sustained drought version 2” might be good to explore. There are ways to make incremental progress through research grant proposals with letters of support from agencies.
- Agenda should be driven by water users. Advisory committees of real-world people can be very useful in forming and expanding networks.
- Don't get too broad in a symposium agenda; it won't do justice to the many complex topics. You need a narrow focus to be meaningful.
- Leverage the untapped resources of the science community. Target something to them. Peer-reviewed literature on science needs, focused on science to action. There is a growing community within the sciences interested in this.
- Things are bad and getting rapidly worse. Look at least at very extreme events and explore mitigation and adaptation options through scenario planning. Would like concrete outcomes, not just a workshop report.

**APPENDIX F:  
List of Research Priorities from the Sticky Notes Exercise**

***I. Category: communication/outreach/risk/uncertainty***

How can we radically shift communications on water risk, climate change, and our dependence on water so the message both resonates with and motivates people to work together?

How can science communication inform public outreach campaigns to communicate importance, challenges, and urgency of water issues in the basin?

Articulate risk more effectively to state, local, regional, etc. decision makers through improved technology, different platforms, and mediums.

How to communicate effectively to the public why science/facts/research results matter in setting water and environmental policies.

(Additional) research on effective ways to engage the public in thinking about or addressing long-term water challenges. The human dimension is key!

How do we engage the public so they demand a resilient and reliable CO River water supply and river? → Communications research to help water managers/conservation advocates create public demand for policy and management change (the building blocks of political will).

How can we better present the range of uncertainty available on projected hydrology ensembles so decision makers can effectively use these wide ranging ensembles to craft policy?

Which future/storyline are we “in”?

How to move decision making entities toward accepting decision making under deep uncertainty.

Quantify hydrologic uncertainty in 2-5-year timeframe.

Identify key uncertainties (e.g., hydrology, human behavior, ecological response) and which should be considered under which planning horizon.

How to help decision makers and the public better understand and deal with complexity and uncertainty.

Develop data on water/water risk by business sector—data each silo can interpret, understand, disseminate.

Communication science: How to talk about controversial water management issues without getting the public and politicians into a tizzy that paralyzes further discussion and stifles ideas.

The urgent need to educate the general public about water scarcity and conservation and management in the years to come. I.e., what we can learn from water shortages and crises such as with Cape Town, South Africa.

The importance of communication and responding to the disconnect between various sectors of society—scientists, lawyers, politicians, educators, different groups, races, cultures.

Many mention “disconnect” between science and policy/management. How do we define the disconnect? Seems to me if we understand the disconnects, we’ll know better what to study.

## ***II. Category: science/role of science***

High-resolution remote sensing study of basin-wide evapotranspiration.

Better understanding of snowpack→water supply conditions; use of remote-sensed data; by April 1 and must be affordable.

Water balances at multiple spatial and temporal scales including ET, return flows, and groundwater-surface water interactions. We can’t balance supply and demand if we don’t know what the numbers are!

Improved understanding of vegetation, snowpack, and soil moisture interactions.

Improved understanding of uses—basin-wide real-time CU monitoring?

Range expansion of non-native species of concern in regard to rising temps and drought. (Conversely: range decrease of sensitive species.)

What are relative impacts of various changes (e.g., temp, precip, climate generally, vegetation, land use, other human behaviors, etc.)

Are there precursors in the climate system to large floods on the Colorado River?

Improved CMIP/5/6 model outputs with more interactions processes.

Process-based understanding of change.

When new water efficiencies may lead to loss of habitat as a consequence.  
Routing big floods.

Impact to water quality when reservoirs empty.

Sediment storage impacts to water storage and flood control.

Research on how to define, articulate, and measure progress toward desired future conditions (what we want the system to be in x years, as opposed to predicting where it might be).

Stress testing the system using lower flows and societal responses to handle shortage.

Need to recognize that the river and all its contexts (for water, life, culture, etc.) are continually changing. Science is emphatically NOT the facts of any particular instant in time, but rather a continuing process of discovery in regard to a changing reality.



Need to balance the idea of science as expertise, authority, and objective truth with the idea of science as an interaction and investigation of science's truths, which is something in which the public can participate.

Understanding fundamental science drivers for how temperature will holistically impact supply and demand.

Low flow conditions are turning perennial streams and rivers into intermittent systems. How is the aquatic community affected by these changes?

Spring and ecosystem sustainability.

Accelerated landscape change is occurring throughout the western US. How is water quantity and water quality changing with these landscape changes?

Science better evaluating how the river system is connected: upstream to downstream; groundwater to surface water; and watershed to hydrosched.

Is a drought a single, coherent atmospheric/ocean event or is it the union of different types of events? This bears on modeling and predicting as well as understanding.

Temperature impacts to hydrological processes are "low hanging fruit."

Understanding how vegetation will change over time across the entire basin and the impacts to ecosystems and hydrology.

Basin-wide assessment of groundwater resources.

Forest fires are larger, more intense, and occurring over longer duration. What are the hydrologic, geomorphic, and water quality impacts of this new normal?

Wet to dry or dry to wet signals—sign post?

Understanding changes in duration and extent of low elevation snowpack (below SNOWTELS) and its contribution to streamflow.

Examining what warming means to \_\_\_\_\_ (all possible topics).

Need to better understand our current timeframes to make system decisions. What do we have to decide in: 1-2 yrs, 3-5 yrs, 5-10 yrs?

How to create actionable science that is mutually beneficial to science and policy?

Coordinated vulnerability studies to identify widespread/common signposts that many entities could collaborate to study.

How to optimize ecological restoration efforts to maximize benefits as opposed to simply throwing \$\$ at trying to restore a situation that cannot be achieved given changed circumstances.

Need a comprehensive river science research agenda that is complementary to a climate/water supply research agenda. Must incorporate this river science research agenda into the research/monitoring of the adaptive management programs.

### **III. Category: climate change/adaptation**

In terms of adaptation/strategies to address issues, we are used to exploring the worst case or the extreme combination of events to solve challenges: e.g., extreme heat, dry conditions, high energy cost, etc. But to be more responsive to surprises, some combination of events is not all negative/extreme, creating opportunities instead of challenges to adapt to. From a management perspective, we need to be open to these potential outcomes. I.e., “explore opportunities from extreme events/crises, not just the challenges.”

How can we adapt institutional arrangements in a way that better balances risks associated with climate trends, extreme events, and demographic changes that go beyond the recent experience?

Reach ecosystem-based adaptation.

How can we incorporate climate change information into relatively short-term forecasts that depend on historical hydroclimatic information?

Climate whiplash is going to get even worse. How can we shave the peaks and troughs to better manage the extremes?

Collaboration basin-wide (US and Mexico) between restoration and resource managers on adapting to and planning for climate change.

### **IV. Category: management/how to manage**

Looking into staged adaptive decision modeling approach for water management. (Includes an illustration)

Moving to non-stationary approach in decision making and communicating this effort to decision makers. E.g., incorporating climate model outputs, regional climate mode.

Better understanding of land use and water planning and management linkages. Including: efficiency improvements and ensuring local land use decision makers understand and consider both local and regional water issues.

Transboundary aquifer assessment in the Delta (Calif, BC, AZ, Sonora) = the first step toward improving GW management to reverse aquifer depletions, which threaten the newly restored habitat in the Delta.

Basin-wide demand management along-side existing basin-wide supply management.

What are the management changes that both: improve river ecosystem health AND align with water user management priorities? This is the low hanging fruit that should be implemented, but we need to ID the opportunities.

How can we accelerate forest restoration treatments to make our forested headwaters more resilient to drought and pests and unexpected futures?

What climate metrics allow us to know whether long-term or short-term management actions are appropriate? [Many actions are very complex and take time to implement...need to be careful not to waste limited time and \$\$.] Another way to ask: How do we know a sign post is meaningful?

Consequence of Black Swan events on infrastructure and water management. Huge floods.

#### **V. Category: stakeholders/governance/policy/water rights**

Investigating 'black swan' scenarios as a researcher-stakeholder collaboration to inform planning and decision-making.

Develop a "new" basin-wide governance process that can ensure that all stakeholders are involved in ensuring that the best science is brought to bear in public policy decision-making. [Current Minute process could be a starting template...]

The Colorado Basin is over-allocated. We all know that. Why doesn't everyone agree to reduce their "right" by 10% (or more for climate change). It would help relieve the immediate issue and could free up some H2O for the environment.

What level of governance needs to be involved to bring about a change to working in the Colorado River Basin as a holistic approach?

#### **VI. Category: ag/economy/funding**

Scenarios for future of agriculture and implications for water management topics including:

- Role of agriculture in local and regional economies
- Role of ag in local food production
- Potential for efficiency improvements and crop changes
- Potential for water saved to go to:
  - o Preservation of natural system and supply reliability
  - o Local non-ag uses
  - o Transfer for urban growth areas
- Tribal and non-tribal ag

More analysis of economic implications of alternatives—but not only that associated with engineers costing out options from the perspective of utilities and agencies.

Cropping patterns and agricultural revenues (monthly, annual) at the field scale; and what drives cropping decisions...to understand demands and how to manage them...as basic underpinning of water markets for re-allocating water use.

Estimate optimal distribution of agriculture in basin (net profit under open market water pricing) under (a) current conditions, and (b) 30% greater crop water demand.

Agricultural water use efficiency studies and strategy development to address agricultural productivity needs under climate change.

How can ag best adapt to lower flows? What options (with economic analysis!) are available?

Hydrologic impacts of partial or full fallowing of irrigated land in multiple locations/climates in the basin. Follow-up: institutional and economic impacts.

What is the value of snowpack (economic but more)?

Non-market ecosystem services values of all hydrological processes in the Colorado River Basin and what users are willing to pay to sustain them.

Long term economic growth and environmental health in the Colorado River Basin vs short term profit/jobs/etc. "We do not inherit the earth from our parents, we borrow it from our children."

Follow the money! What are the policy incentives and disincentives to water use and "stewardship?"

- UB hydropower revenues and lowering outflows @ Powell
- "Free" ag water vs. expensive urban water
- Disincentives to ag "stewardship" investments

Analyze feasibility of effective integration of market-driven solutions that can bridge a viable agricultural economy with state-of-the-art water conservation practices.

Interactions between coupled economic systems and water demand and water supply and water systems. E.g.:

- Trade policy and high/low water use agricultural commodities.
- Consolidation/vertical integration of food systems and crop choices, investment in agricultural lands.
- Jack's peaking power issue; changes in hydropower need/demand.

Use foundation \$ and academia and NGOs to identify the "quality of life" economy and roles of water therein.

Need to reform funding approach to river science studies and monitoring. (Streamflow gaging funding system of USGS is broken; no sediment gaging funding; no funding for ecosystem science on comprehensive scale—too focused on ESA)

Reallocation funding structure to match science needs.

## **VII. Category: human component/social systems/communities/equity**

How/what behaviors of use/demands change under stress?

- How will communities respond (panic?, rational?, trust experts?)?

Fully coupled hydrological-ecological-socioeconomic model for entire Colorado River basin. [Hydro (climate, surface water, groundwater); Eco (plant water, aquatic env flows); Socio (people and prosperity)]

Near-real time understanding of water use. Both by the traditional water user as well as evap./transpiration/sublimation/albedo/etc.

What does “equity” mean in terms of water management? E.g. price? How water is used and where? Benefits derived from water use (shade, food, parks, rivers, etc.) and distribution of those benefits? How can “equity” be improved?

Difference between embedded expectations and reality. There are (politically difficult) expectations within both the water community and the science community that have become embedded through culture—how can we change these?

More investigation on how water conservation projects (canal lining, fallowing, etc.) affect habitat and human communities—find long-term solutions to mitigate impact.

How can the tribes be engaged in a meaningful way in solving basin problems?

How to build equitable institutions that are more focused on distribution of costs and benefits?

## **Solutions**

### ***I. Category: communication/outreach/risk/uncertainty***

Incorporate “business” community (ag, industry, retail, tech, etc.) in translating, interpreting, packaging, messaging, and disseminating CO River/water data/challenges/solutions.

We need to develop better tools that incorporate both policy and hydroclimatic conditions to communicate information, such as drought conditions.

### ***II. Category: science/role of science***

Improve uptake of science by water managers by locating/hosting scientists inside water management agencies, sharing early-stage results, getting input on study design as research proceeds from leadership/staff.

### ***III. Category: management/how to manage***

An integrated management system that focuses on how to insert scientific information into decisions.

We need to incorporate more opportunities to be flexible and change resource management actions in response to changing hydroclimatic conditions.

### ***IV. Category: stakeholders/governance/policy/water rights***

Incentivizing multi-sectoral participation and partnership building for building more resilient and informed communities.

Conduct a gaming exercise with major agencies and science/environmental advocates under three or four different (hydrology) scenarios—historical, deep climate change, and paleo. How to build and nurture a network of practitioners, academics, and NGOs for the Colorado River?

**V. Category: *enhancing justice and equity***

Increase emphasis on the socio-economic-ecological connections across borders. So, consider how restoration or water deliveries in Mexico can benefit U.S. and vice versa.