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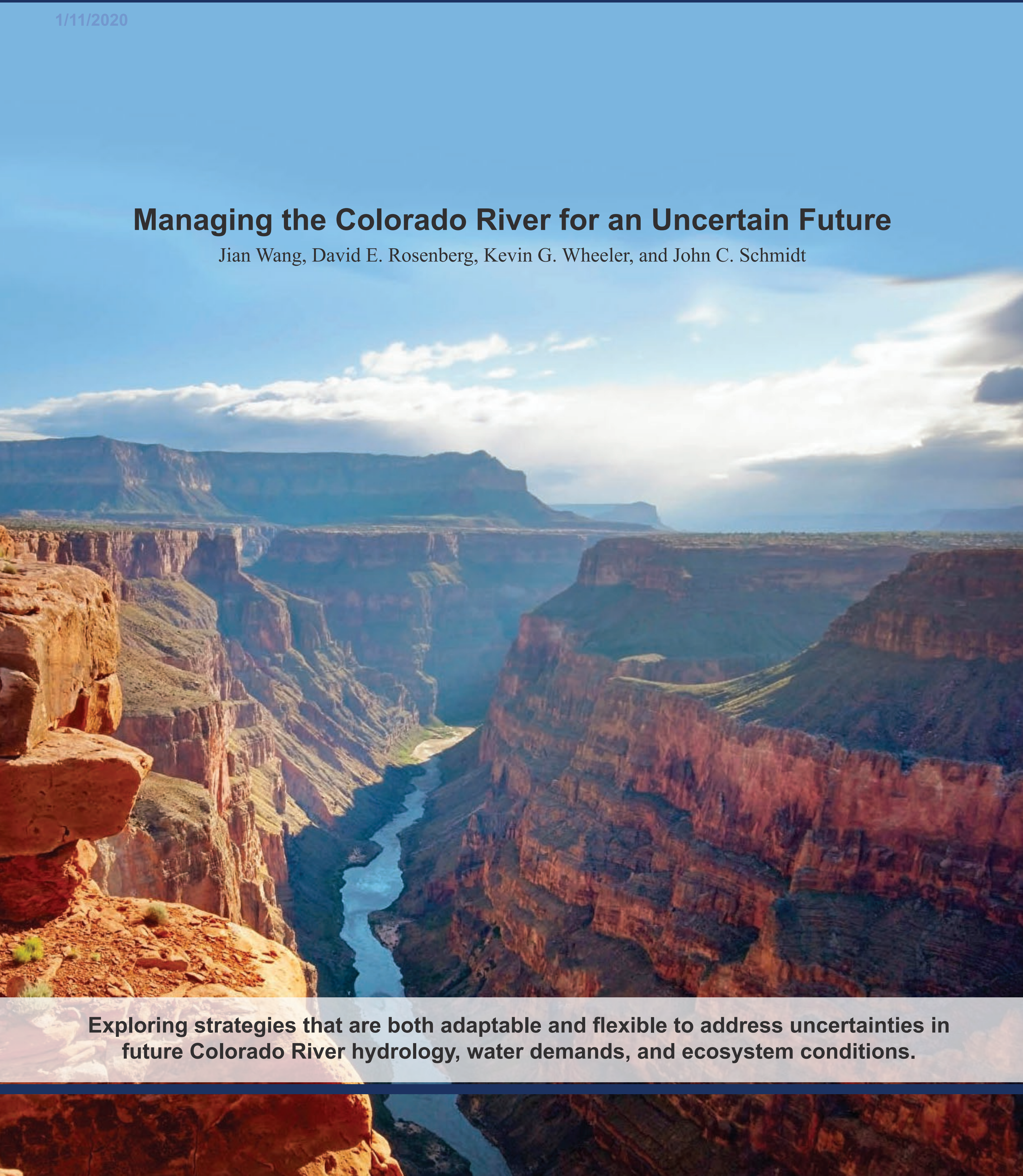

Managing the Colorado River for an Uncertain Future

Jian Wang, David E. Rosenberg, Kevin G. Wheeler, and John C. Schmidt

Exploring strategies that are both adaptable and flexible to address uncertainties in future Colorado River hydrology, water demands, and ecosystem conditions.

Executive Summary:

- Colorado River managers and stakeholders face many uncertainties—issues like climate change, future water demand, and evolving ecological priorities. Managers and stakeholders are looking for new ways to communicate about uncertain future conditions, help cope with an uncertain future, and develop public policy when future conditions are highly uncertain. Historically, Colorado River managers have operated Lake Powell and Lake Mead under the assumption that the future natural flow regime of the Colorado River at Lee Ferry will resemble the previously observed regime, but most climate scientists believe that the flow regime is changing, and that future flows will be lower, more variable, and more uncertain.
- It is also difficult to predict future demand for Colorado River water, future river ecosystem conditions, or the values that future generations will attach to those ecosystem conditions. These uncertainties present immense challenges when developing river management policies to enhance water supplies and ecosystem condition.
- To help Colorado River stakeholders think about, talk about, and better manage the river in the face of these unknowns, this white paper distinguishes four levels of uncertainty. Future conditions can be described by point estimates with small ranges (Level 1), probabilities (Level 2), scenarios of possible future conditions (Level 3), or a level of complete unknown (Level 4).
- We represent each level with day-to-day and Colorado River examples. These examples illustrate how the further a stakeholder attempts to peer into the future, the greater the level of uncertainty.
- Managers and stakeholders can classify the uncertainty level of each key system factor to guide decisions about which modeling tools and public policies to use. Tools include defining alternative scenarios, Many Objective Robust Decision Making (MORDM), Decision Scaling (DS), and Dynamic Adaptive Policy Pathways (DAPP) for uncertain future conditions that can only be described by scenarios (Level 3).
- There is need to expand the discussion about how to renegotiate the Interim Guidelines and the Lower Basin Drought Contingency Plan (DCP). This discussion should consider uncertainties in future hydrology, demands, and river ecosystem conditions that can only be described by scenarios (Level 3). Revisions to the Interim Guidelines should (1) include more information about future conditions as new information becomes available, (2) define interim decision points (called signposts) when existing policies should be reconsidered, and (3) allow more flexibility in day-to-day management decisions that respond to unforeseen conditions.
- This white paper suggests that new guidelines designed to adapt to uncertain future hydrology, water demand, and river ecosystem conditions are likely to look quite different than the current guidelines, which seek to provide certainty about the amount of water managers can divert.
- New guidelines that acknowledge different levels of uncertainty levels will be more adaptable, more flexible, and will be better able to anticipate and respond to a wider range of future Colorado River conditions. This adaptability and flexibility can help avert future crises.

Continue the Conversation:

- Tell us what you think! Send feedback at https://tinyurl.com/ColoradoUncertaintyFeedback

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White Paper 1

Fill Mead First: A Technical Assessment

Brief • Full Paper

The Fill Mead First (FMF) plan would establish Lake Mead reservoir as the primary water storage facility of the main-stem Colorado River and would relegate Lake Powell reservoir to a secondary water storage facility to be used when Lake Mead is full. The objectives of the FMF plan are to re-expose some of Glen Canyon's sandstone walls that are now inundated, begin the process of re-creating a riverine ecosystem in Glen Canyon, restore a more natural stream-flow, temperature, and sediment-supply regime of the Colorado River in the Grand Canyon ecosystem, and reduce system-wide water losses caused by evaporation and movement of reservoir water into ground-water storage.

White Paper 2

Water Resource Modeling of the Colorado River: Present and Future Strategies

Brief • Full Paper

The CRSS is an important water-policy planning tool used by the Bureau of Reclamation and other stakeholders in numerous major efforts. Given the complexity of the CRSS, experts and stakeholders must invest significant resources to explore alternative paradigms to manage water supply in the Colorado River system, such as alternative strategies that might enhance water supply reliability and/or river ecosystem health. This white paper explores alternative management strategies for the Colorado River that might provide benefit to water-supply users and to river ecosystems.

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1. Introduction

The Colorado River basin drains approximately 8% of the continental United States, provides water supply, irrigation water, and hydroelectricity to 40 million people in the United States and Mexico. The river includes the two largest reservoirs in the country, and flows through iconic landscapes such as the Grand Canyon and other national park units. Management of the river is governed by a bi-national treaty, two interstate compacts, Supreme Court decisions, laws and administrative rules, and numerous inter-party agreements collectively called The Law of the River.

The Law of the River began to be codified in the 1920s when the Colorado River Compact was negotiated (Hundley, 1975; Kuhn and Fleck, 2019) and is designed to provide certainty about the volume of water that basin states and users can divert. Today, runoff is decreasing in the watershed (Udall and Overpeck, 2017; Xiao et al., 2018), and there is renewed concern about how to allocate a diminishing and uncertain supply. Although the focus of river management in the early and mid-20th century was on water supply and hydroelectricity production, modern river management also considers ecosystem services provided by the river, native and endemic species that are endangered or threatened, and protection and enhancement of national park system units.

Future management of the Colorado River will be affected by many factors, including changing climate, decreasing watershed runoff, population growth, changing patterns of consumptive use, selecting reservoirs to emphasize for water storage, evolving water allocation policies, changes in the temperature of water released from reservoirs, changes in river ecosystems (especially fish communities), and changing societal values. Many of these factors are difficult to predict, especially several decades from now. The uncertainties associated with predicting future conditions and predicting interactions among these factors present immense challenges in the development of policies to guide operations and management of the river. It is impossible to know what users want from the river or how those demands may change in the future—but decisions still have to be made today that will guide management in the future. This paper explores the nature of uncertainties and suggests some broad strategies for how to develop public policies in the face of the Great Unknown.

This white paper:

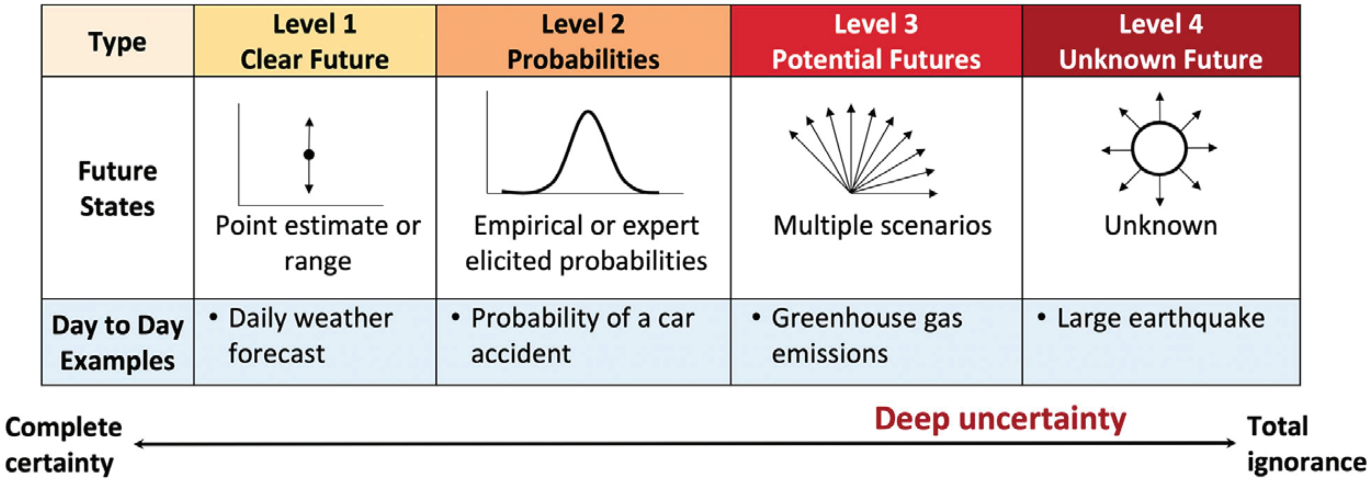
- Describes a classification system for uncertainties that distinguishes four levels ranging from small and short-term to deep and long-term;
- Provides examples of these uncertainties for many future Colorado River hydrologic, demand, operational, and ecosystem components;
- Describes how the existing Colorado River Simulation System (CRSS) model and other recent modeling efforts consider these uncertainties;
- Assesses alternative state-of-the-art tools to model and manage the Colorado River in the face of uncertainties; and,
- Suggests strategies for defining new guidelines that can better adapt to uncertainties.

The intended audience for this white paper is decision-makers and stakeholders who are involved or concerned about planning a sustainable future for the Colorado River and who want to include those uncertainties in current and future planning. This examination of uncertainty supports the goal of the Future of the Colorado River project to identify and evaluate alternative management paradigms (AMPs) that are responsive to society's needs for water supply, yield desirable environmental outcomes for river ecosystems, and inform negotiations about the policies that will guide future river management.

2. Multiple Levels for Classifying Uncertainty

There are several types of uncertainties associated with predicting the future state of climate, water demands, river management and operations, and ecosystems. In some cases, uncertainties result from the highly stochastic and unknowable nature of complex natural systems. These types of uncertainties have been referred to as random, or aleatoric (Dobson et al., 2019). Other types of uncertainties result from an incomplete understanding of physical or biological processes, and have the potential to be decreased as better information becomes available and scientific research progresses. Other types of uncertainties result from unanticipated interactions among physical and biological processes or unanticipated responses of society reacting to changing conditions.

It is helpful to classify the hydrologic, demand, operations, ecosystems, and other components of the Colorado River system in terms of the type of uncertainty faced in predicting future conditions. Following the approach of Walker et al. (2013), van Dorsser et al. (2018), and Marchau et al. (2019), we distinguish four levels of uncertainty ranging from complete certainty to total ignorance (Figure 1). These levels describe our knowledge about current and future aspects of a management problem, particularly: (a) our ability to predict future outcomes, and (b) the importance of those outcomes to different stakeholders. Here, we define each uncertainty level and provide examples.



Type	Level 1 Clear Future	Level 2 Probabilities	Level 3 Potential Futures	Level 4 Unknown Future
Future States	Point estimate or range	Empirical or expert elicited probabilities	Multiple scenarios	Unknown
Day to Day Examples	• Daily weather forecast	• Probability of a car accident	• Greenhouse gas emissions	• Large earthquake

Figure 1. Classification of levels of uncertainty, from complete certainty to total ignorance, with examples (adapted from Walker et al., 2013, van Dorsser et al., 2018).

Level 1 uncertainty ("Clear Future") exists when upcoming conditions can be defined, with a specified degree of precision. People use short-term weather forecasts to make decisions about what clothes to wear to work and where to schedule flights. Using this information, we can predict today's high temperature, tonight's low, or how much precipitation will occur—we know enough about the forecast to decide whether to bring an umbrella to work and whether storms will be sufficiently severe to prompt a change in flight plans.

Level 2 uncertainty (sometimes referred to as "Probabilities") is any unknown that can be described in terms of statistical probabilities defined from historical observations or elicited from experts. People drive cars and board airplanes knowing that most people safely undertake these activities, and that the probability of a crash is low—even if the consequences of a crash would be severe or fatal. Farmers decide when to plant and harvest their crops based on the probability of late season frosts. Other people use probabilistic weather forecasts of snowfall or precipitation to decide when and where to ski or hike.

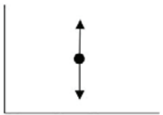
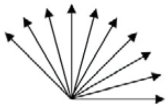
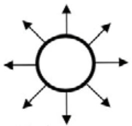
Level 3 uncertainty (referred to as "Potential Futures") is a situation in which one can describe alternative possible future conditions, but cannot assign a probability or likelihood to those possible futures. In some cases, it may be possible to rank the likelihood of alternative possible futures, but statistical probabilities cannot be assigned. Because there is an infinite number of scenarios for the multiple future conditions, managers typically only consider a select few scenarios, although the number of scenarios differs by planning context. The high degree of uncertainty at Level 3 is partly due to a lack of scientific understanding about the linkages among the physical, ecological, and/or social processes that interact as time progresses.

An example of Level 3 uncertainty is the magnitude of future anthropogenic greenhouse gas (GHG) emissions. These future emissions are the product of complex, dynamic systems driven by population size, economic activity, lifestyle, energy use, land-use patterns, technology, and climate policy (Pachauri et al., 2014). Future emissions rates will be affected by factors such as future patterns of personal and mass travel, how electricity is produced, trends in industry and manufacturing, and national or international treaties that seek to limit greenhouse gas emissions. Another example is population growth rates during the next 20 years—we can assume different scenarios based on factors (child birth rates, death rates, in and out migration patterns, and so on), but no probability can be assigned to those possibilities.

Level 4 uncertainty (called "Unknown future") represents the deepest level of uncertainty. In these cases, we know only that we don't know what will happen. People might encounter this level after an earthquake whose magnitude is larger than any yet recorded and whose epicenter is in a major urban area. Would buildings remain standing? If they did, would they be safe to enter? Would transportation, communication, food, energy, water, and other systems persist? Who might survive, and to what degree could survivors organize and respond? What social systems might develop in the long-term aftermath? Although one can conjecture, these factors are all completely unknown.

3. Examples of Uncertainty for the Future of the Colorado River

Despite myriad uncertainties, Colorado River managers and stakeholders decide reservoir releases and water allocations. Managers and stakeholders don't know with certainty the magnitude of future watershed runoff, the duration of droughts, trajectory of consumptive water use, future operations, or the characteristics of river ecosystems. Below are examples of uncertainties specific to future Colorado River conditions at each level of uncertainty (Figure 2).

Type	Level 1 Clear Future	Level 2 Probabilities	Level 3 Potential Futures	Level 4 Unknown Future
Future States	 Point estimate or range	 Empirical or expert elicited probabilities	 Multiple scenarios	 Unknown
Day to Day Examples	• Daily weather forecast	• Probability of a car accident	• Greenhouse gas emissions	• Large earthquake
Colorado River Examples	• Short term rainfall prediction • 1-2 year projections of population growth • Estimation of sand delivered by the Paria River in the current year	• Annual flow and the magnitude of next year's snowmelt flood • Current annual water use among single-family households • Frequency in next 20 years that flash floods deliver sufficient sand to trigger release of an HFE	• Duration and magnitude of mega floods • Long term consumptive water use • Native and nonnative fish population interactions	• Society's response to: - Large earthquake on Hayward fault - Glen Canyon dam failing

Complete certainty ↔ **Deep uncertainty** **Total ignorance**

Figure 2. Colorado River basin examples of uncertainties at different levels.

3.1 A clear future (Level 1)

Today, the Colorado River is managed and operated using many sufficiently accurate and precise predictions of near-term future conditions whose uncertainty can be quantified within a narrow range. For example, we can predict rainfall during the next few days in each part of the Colorado River watershed, because weather forecasts are accurate for short-duration planning horizons. These weather forecasts are used to guide flood damage reduction operations for some headwater reservoirs.

There are also examples of Level 1 uncertainties that concern 1-2 year projections of population growth in the many service areas of the Colorado River. Accurate population projections allow for accurate estimates of municipal water use within that short planning and management horizon. When a water utility faces drought conditions, managers often initiate campaigns to reduce outdoor landscape watering, even when they do not know exactly how many people will respond to campaigns or the resulting magnitude of water savings. Regardless, planning efforts can make well-informed estimates based on projected regulatory compliance.

An example of a Level 1 uncertainty dealing with ecosystem processes is found in the estimation of sand delivered in the current year by the Paria River to the Colorado River by individual flash floods in late summer and fall. Reclamation uses these estimates to determine the amount of sand available for transport by a controlled flood (administratively called a High Flow Experiment) that might be released from Lake Powell in the late fall or in the spring. Estimates of the sand supplied by flash floods are made by the U.S. Geological Survey Grand Canyon Monitoring and Research Center (USGS/GCMRC), and the estimates of sand transport during controlled floods are based on a model developed by the USGS/GCMRC (Wright et al, 2010) and made operational by Reclamation.

3.2 Uncertainties for which the probability of occurrence can be estimated (Level 2)

On the Colorado River, total annual flow and the magnitude of next year's snowmelt flood are predicted as probabilities that the flow will equal or exceed flows observed in the past. For example, Figure 3 shows the forecast made in early January of unregulated inflow into Lake Powell for the upcoming Water Year 2020. Because this estimate was made at the beginning of the snow-accumulation season, the uncertainty of the estimate of the spring snowmelt runoff was large, and the minimum forecast was 6.4 maf (59 percent of average) and the maximum forecast was 12.8 maf (118 percent of average). This early winter forecast is updated by the Colorado Basin River Forecast Center (CBRFC), and the early April forecast is used to develop reservoir operation plans. The exceedance probability of the minimum and maximum probable forecast is 10% and 90%, respectively, which means there is a 10 percent chance that 2020 unregulated inflow to Lake Powell could be higher than the maximum forecast or could be lower than the minimum forecast. The range between the upper bound and the lower bound decreases with time as the winter snowpack conditions become better known.

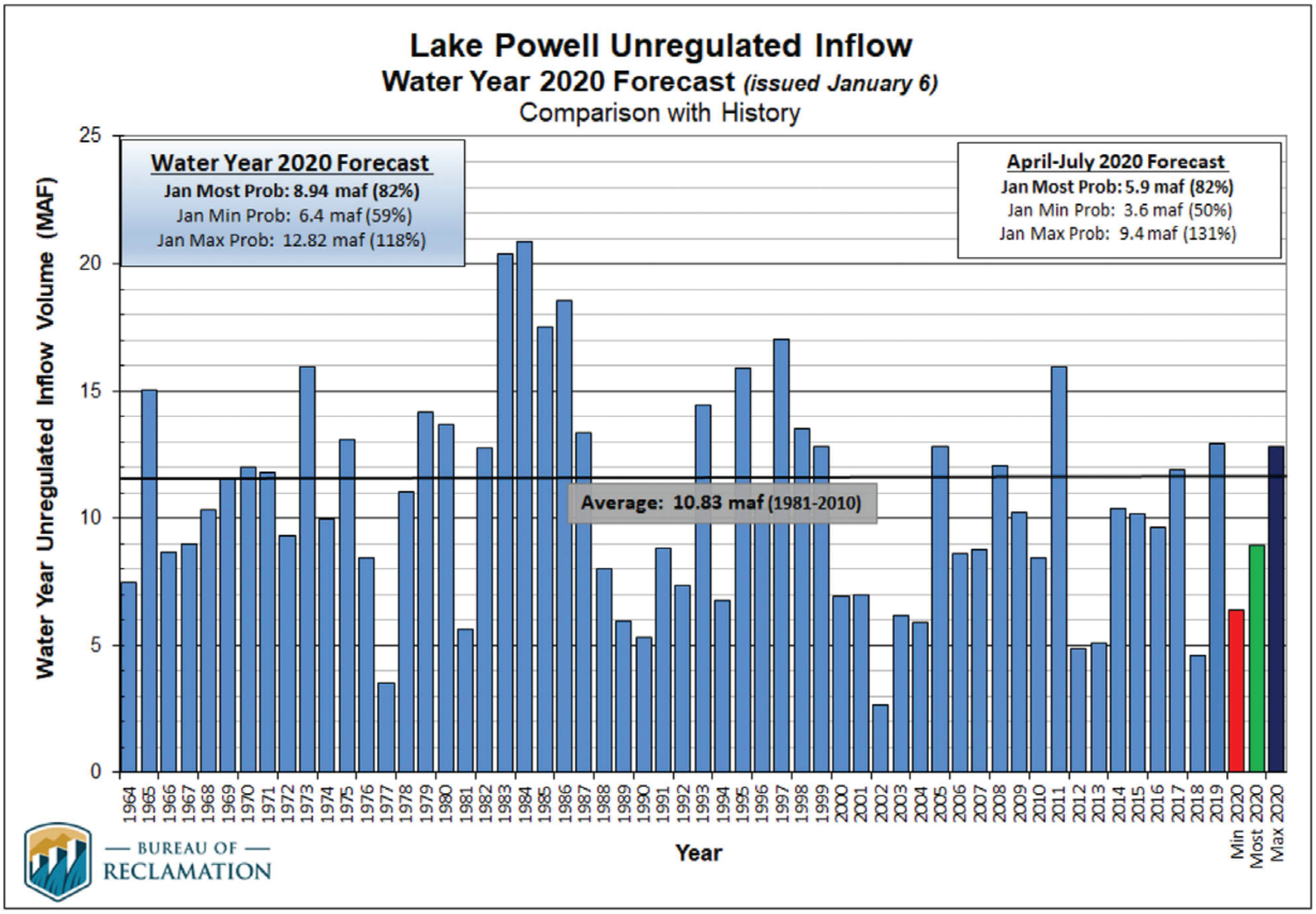


Figure 3. A prediction of unregulated inflow to Lake Powell for water year 2020 made in early January 2020. The red bar at the right side of the graph is the estimated total inflow to Lake Powell for which there is a 90% probability of flows exceeding this value. The dark blue bar is the 10% exceedance estimate. The Green bar is the median estimate. Throughout the winter, these estimates are updated based on the measured accumulation of winter snowpack, and the uncertainty range decreases.

In another analysis, Udall and Overpeck (2017) estimated the probability density (i.e., likelihood) of decreased watershed runoff in mid- and end of the 21st century, based on a range of uncertainties in the magnitude of future warming of the global climate (Figure 4). The range of uncertainty is primarily related to the uncertainty about the magnitude of future emissions of carbon and the sensitivity of the relationship between reduction in watershed runoff to unit increase in regional temperature. The red probability density curves for -10% reduction in watershed runoff per degree C are shifted right compared to the blue and green curves. This shift suggests we should expect larger flow reductions for the red scenarios. The red curves are also spread wider and have lower peak densities than the blue and green curves. This wider spread suggests the actually future flow reduction value will fall within a wider range.

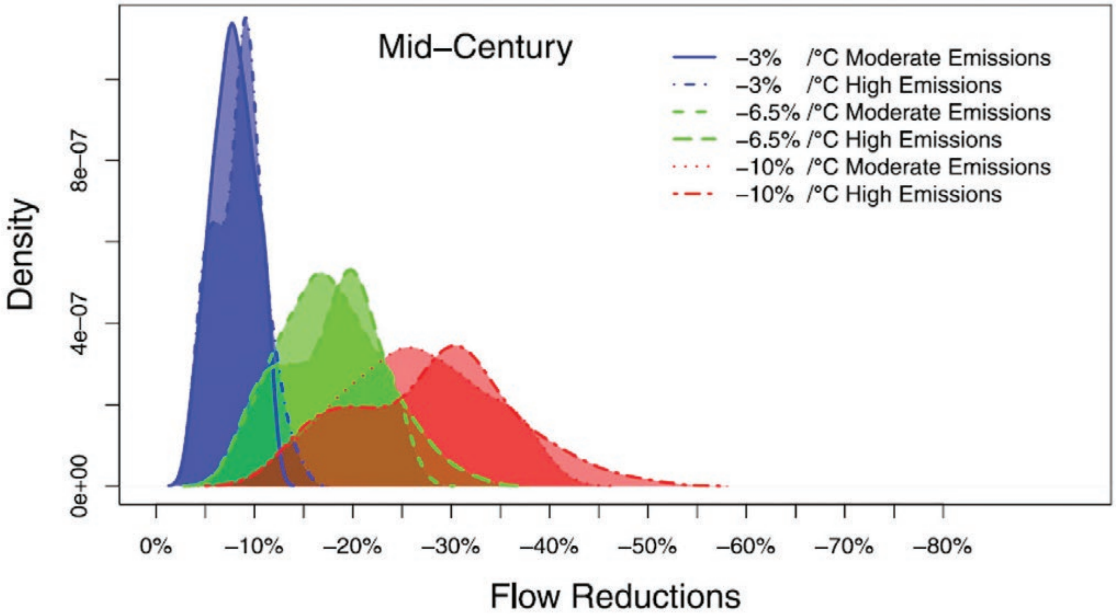


Figure 4. Probability of reduction in stream flow of the Colorado River at Lees Ferry in mid-21st century based on two scenarios of carbon emissions into the atmosphere and three levels of sensitivity of the relation of runoff to temperature (Udall and Overpeck, 2017, fig. 4).

Another example of Level 2 uncertainty are the statistically quantifiable variations in current annual water use among single-family households. In the Residential End Uses of Water 2016 study, DeOreo et al. (2016) collected and analyzed billing data from 23,749 households in 23 U.S. cities that included Aurora, CO; Denver, CO; Fort Collins, CO; Scottsdale, AZ; Sante Fe, NM; Henderson, NV; and Otay, CA. They reported a histogram of household water use (fraction of households using water within specified intervals) that was skewed: 60% of households used less than 100,000 gallons per year but the other 40% of households used 100,000 to 1,200,000 gallons per year. The skewed distribution means that the largest users are raising the average and can be identified and targeted to adopt conservation actions.

Another example of decision-making using probabilities concerns the policy that implemented the High Flow Experiment (HFE) Protocol for releases of controlled floods from Glen Canyon Dam, as initially developed in 2011 (Upper Colorado Region, 2011). Whereas the estimation of the delivery of sand from the Paria River in any specific year is a Level 1 uncertainty, as described above, prediction of the frequency for the next 20 years that flash floods in the Paria River deliver sufficient sand to trigger release of an HFE is a Level 2 uncertainty. Level 2 uncertainty exists here because of the observed, year-to-year variability in sand delivery. In some years, there are multiple flash floods on the Paria River, and in some years there are none. Because it is impossible to predict this year-to-year variation, stakeholders evaluating future policy decisions, such as in the long-term experimental and management plan (LTEMP) environmental impact statement (EIS) process, generated multiple sequences of years with high and low sand inputs from the Paria River. These sequences were used to predict the number of times there would be sufficient sand accumulated in the Colorado River to trigger an HFE release under different policy options.

3.3 Uncertainties for which the probability of occurrence cannot be estimated (Level 3)

There are many situations in which future conditions can only be described using scenarios of possible future conditions with unknown probabilities or rank (Level 3 uncertainties).

Scenarios allow people to envision future possibilities, including extreme events for which it is not possible to describe the probability of occurrence. Planning under different scenarios helps improve system performance under different conditions. Although the probability of future near-term average watershed runoff is described above as a Level 2 uncertainty, the sequence of hydrologic events cannot be probabilistically described. For example, it isn't possible to estimate the duration of a severe drought or the probability that a few very wet years might follow an extreme drought, or vice versa. The Colorado River Conversations project hosted at the University of Arizona is developing descriptive scenarios of possible sequences of hydrologic events coupled to socio-political-economic events using the scenario planning approach. These scenarios (see Sidebar 1) have no explicit probabilities of occurrence, but they are all possible and plausible. The eight scenarios articulated by the Colorado River Conversations group are a small proportion of an infinitely large number of potential scenarios that represent combinations of potential hydrologic, social, political, and economic events.

One strategy for quantifying the magnitude of future droughts is to evaluate reconstructed flows from tree ring data and evaluate the longest duration and most intense droughts that have occurred in the past. We don't know whether these droughts will occur in the future, but their occurrence in the past suggests river managers should consider them in future planning.

We can also develop scenarios to describe the duration and magnitude of extremely large floods (often called *megafloods)*. Geologic records provide evidence that such floods have occurred during the last few millennia

Sidebar 1: Description of Scenarios of Future Hydrology and Socio-Political-Economic Conditions that Are Under Consideration by the Colorado River Conversations Project

1. The **Caught Off Guard scenario** includes (1) a rapid shift from wet to dry conditions, (2) infrastructure failure, and (3) governance failure. Precipitation changes from extreme wet to extreme dry conditions. During the wet cycle, managers are assumed to have released stored water to prevent catastrophic flood damage. There is, therefore, not much water in storage at the beginning of the dry cycle. Quite quickly, the policies and collaboration achieved in the wet cycle disintegrate due to the extreme drought.

2. The **Water on the Move scenario** includes (1) a wet to dry shift, (2) increase in water markets, and (3) increased tribal engagement in the Upper Basin. Precipitation changes from extremely wet to extremely dry. As water supplies dwindle, more water transactions are encouraged by Upper Basin policies and institutions, and tribes are trusted partners in water management.

3. The **Arid and Unfair scenario** is described as (1) a very long duration dry period, (2) increased gap between wealthy and poor parts of American communities, and (3) decreased ability for poor communities to participate in water-supply decisions. Runoff continues to decrease, recharge rates drop, soil moisture levels decline, and evapotranspiration rates increase. Relatively wealthy communities can access more water, which will produce more wealth and thus will further deepen the divide by the rich and poor. Poor communities are excluded from the decision-making process.

4. The **Rural Revival scenario** includes (1) a long-duration dry period, (2) increased rural agriculture investment; and (3) transition from global to regional economies. The hydrologic conditions are the same as in the Arid and Unfair scenario. Investments in irrigation infrastructure in local agricultural communities is both a political and cultural priority throughout the Basin. These investments ensure stable regional agricultural markets.

5. The **Sad Skiers scenario** includes (1) less snow, (2) low environmental values, and (3) decreases in recreational economy. Warming temperatures shift snowfall patterns and the total amount of snowpack decreases. Water storage is prioritized above recreational and cultural values of rivers. Thus, communities whose revenues are derived from skiing, rafting and snow or water sports struggle to find new opportunities.

6. The **Disaster Strikes scenario** includes (1) short system shock of wet to dry period transitions, (2) collapse of California water-delivery systems, and (3) a bad national economy. Hydrological conditions dramatically shift to extreme drought with little warning. An earthquake destroys the water delivery system and storage facilities in northern California and leads to significant water delivery reduction to southern California, putting intense pressure on the Colorado River to meet the demand of southern California. At the same time the United States slides into a recession similar to the Great Depression.

7. The **Dig it Deeper scenario** includes (1) no monsoon, (2) completely depleted aquifers, and (3) increased tribal engagement in lower basin. The North American monsoon season shifts to a new pattern that starts later and ends earlier with more intense storms that cause flooding and changes in the timing and location of ground-water recharge. As the monsoon weakens, aquifers in the Lower Basin crash. Tribes are fully engaged in water management and have developed water management tools such as water banking and aquifer recharge projects.

8. The **Flood Gates scenario** includes (1) a dry to wet shift, (2) technological advances, and (3) increased US-Mexico collaboration. There are consecutive winters of high snowpack and strong summer monsoon storms after the "new normal" of increasing aridity. Technological advances developed in the dry period are now available to respond to the unexpectedly high precipitation. Mexico and U.S. are working together to explore innovative ideas for river management.

(O'Connor et al., 1994; Greenbaum et al., 2014). These megafloods were larger than any that have occurred since European settlement of the Intermountain West, and well before historical gage records began. The largest megaflood identified to date on the Colorado River near Lees Ferry occurred 1600 to 1200 years ago, had a discharge exceeding 490,000 cfs, and was more than twice the largest historically observed flood. Floods of this magnitude would pose a significant challenge for managers if those floods occurred today. We do not know whether the duration and magnitude of future megafloods will be similar to, larger, or smaller than past megafloods inferred from the geologic record, because we do not know much about the meteorological or climate mechanisms that cause these events. We also do not know whether such floods have occurred during periods of otherwise normal, wet, or dry conditions. Thus, the future duration and magnitude of megafloods can only be described as plausible, and we have no way to assign a statistical probability to their occurrence.

Future consumptive water use will be influenced by population growth, the economy, technology (e.g., more efficient water appliances and irrigation practices), air temperature, markets (water trading and agricultural commodity prices), and social values. The combined effects of these factors are appropriately described with scenarios. For example, in the Upper Basin, water supply managers have considered several alternative scenarios with possible increasing magnitudes of demand. During the past few decades, water-supply managers have revised these scenarios as they obtain new information about consumptive water use. This process has a high degree of uncertainty, and we note that every past projection scenario of future consumptive use for the Upper Basin (Figure 5, dashed colored lines) have over-predicted actual water use when averaged over the long term (Figure 5, solid black line). Many other water systems also consistently overestimate their water demands (Heberger, 2016; Kindler and Russell, 1984). The comparison of forecast scenarios to actual use highlights the difficulty of predicting human behavior and reminds us that scenarios do not necessarily span all plausible futures.

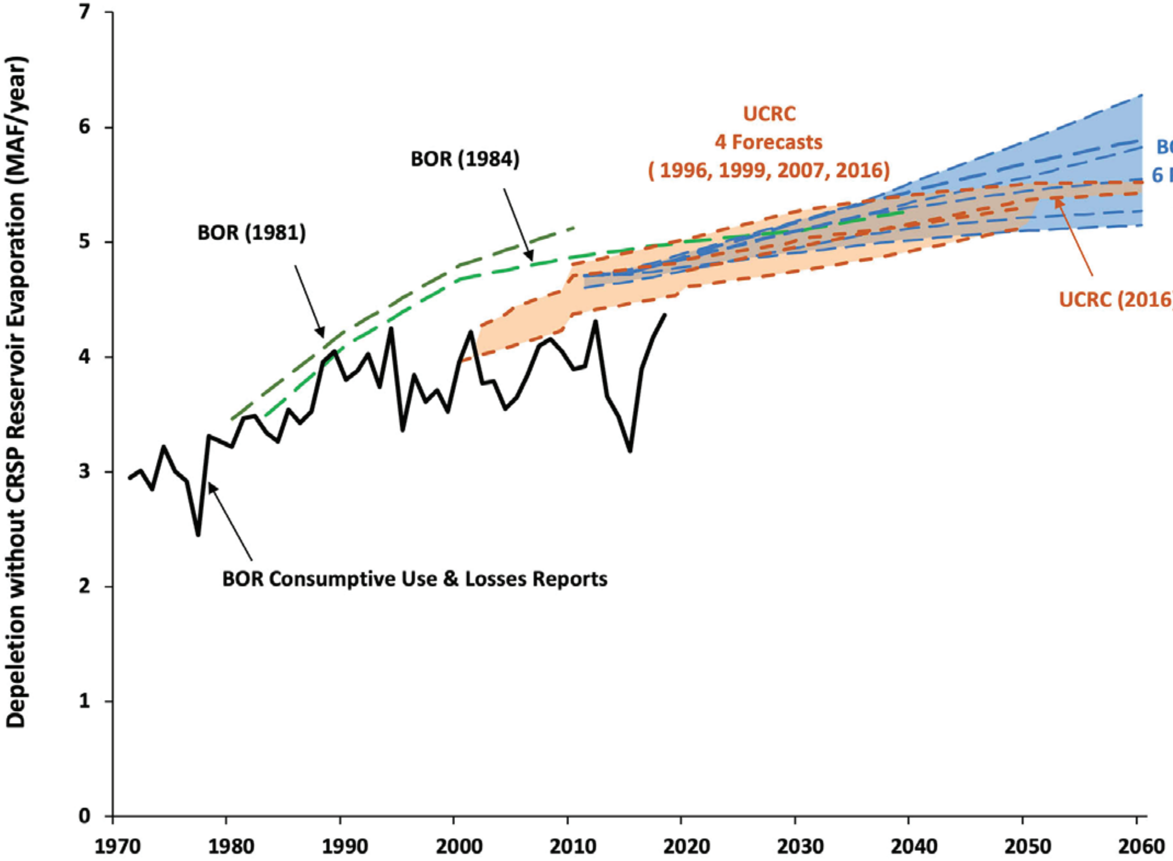


Figure 5. Scenarios (dashed colors) of Upper Basin consumptive water use predicated by Bureau of Reclamation (BOR), Upper Colorado River Commission (UCRC) and used in CRSS (BOR/CRSS) in comparison to actual use (thick solid black). All data used in this figure can be found at Wang (2020). Actual consumptive water use is reported in Reclamation's Consumptive Use reports (Bureau of Reclamation, 1975 to 2018). All projections can be found at Bureau of Reclamation (1981, 1984, 2012a) and Upper Colorado River Commission (1996, 1999, 2007, 2016).

Another example of a Level 3 uncertainty that can only be described with scenarios is the interactions between native and non-native fish species as river temperatures warm in response to releases from reservoirs with less storage. For example, when Lake Powell storage level is low, the warm-water epilimnion is closer to the hydropower penstocks, and warmer water is released (Dibble at al, in review). Warmer releases create warmer summer river temperatures that provide favorable habitat for most native fish species. However, warmer river water also provides favorable habitat to many nonnative species introduced into the river and reservoirs. In many cases, these nonnative species compete for habitat with native fish, and in some cases, nonnative fish species prey upon the native species. At this time, fish biologists speculate on whether warmer river temperatures will give an advantage to native species (one scenario) or will hand the advantage to nonnative species (a second scenario).

3.4 Unknown future (Level 4)

Although most possible future hydrologic events in the Colorado River basin can be described with Level 3 uncertainty, and therefore described as scenarios—uncertainty in how human societies might respond to major challenges is more or less completely unknown. Thus, the aftermath of extremely long droughts or dam-destroying megafloods are likely best considered as Level 4 uncertainties. Bacigalupi (2015) hypothesized a fictional account of conditions in the western U.S. when water supplies dwindle, an example of Level 4 uncertainty. In this unknown and imagined scenario, the federal government is severely weakened by corporate influence; drought-stricken Western states form militias and shut down borders, and massive resorts are constructed to flaunt water-wealth.

There is tremendous uncertainty associated with society's response to extreme drought, extreme floods, or other catastrophic events. One example of such a situation would be the unknown societal response to a very large earthquake along the Hayward fault with an epicenter in the Sacramento-San Joaquin delta. Such an event might destroy the pumps that supply the California State Water Project (SWP) that provide one-third of southern California's water supply. In the short term, southern California might cope by drawing water from the Owens Valley and Colorado River aqueducts and from ground-water banks in the southern Central Valley and along the Colorado River aqueduct. In the longer term, southern California would face major water scarcity and shortage if those water stores dwindled. Could this scarcity be addressed with new and extreme water conservation measures? Would there be political will to construct new conveyance under or around the Sacramento-San Joaquin delta? Would southern California expand the Colorado River aqueduct capacity and enter into new transfer agreements to procure water? Facing long-term water scarcity and shortage, how would the people of southern California react? Would there be social upheaval, would there be outmigration, or would southern Californians develop a survivalist attitude to bear the hardship? Such speculation and questions emphasizes the vast unknowns associated with a hypothetical large earthquake that could decommission southern California's access to the water of the Sacramento River.

A similar unknown situation could arise if Glen Canyon or Hoover Dam were lost to a megaflood. All downstream dams (Davis, Parker, Morelos, etc) would also be lost, there would be extensive flooding, and there would be no capacity to store water to meet demands in southern Nevada, southern California, the Imperial Valley, or in central and southern Arizona.

3.5 Levels of uncertainty depend on planning horizons

The examples presented above demonstrate that uncertainty increases as time horizons lengthen—the further into the future we attempt to peer, the more uncertain things become. Level 1 uncertainty means uncertainty in rainfall a few days into the future, or springtime snowmelt water volume based on the measured winter snowpack. Uncertainty grows to Level 2 when dealing with decadal forecasts such as those made by Udall and Overpack (2017). Uncertainty grows further to Level 3, as we attempt to forecast the temporal sequence of wet and dry years or the occurrence of megafloods. And then at Level 4, uncertainties balloon under futures we cannot anticipate or societal responses to extreme events that we can not foresee.

Time horizons affect on-the-ground decision making. It is easier to estimate Grand Canyon fish populations for coming months when species distributions, river temperature, growth rates, predation, competition, and available food are well characterized by point estimates and probabilities. It is more difficult to estimate future populations years or decades into the future as reservoir storage levels, release temperature regimes, and potential invasions by nonnative species are not yet determined.

Another example of the effect of planning horizons on uncertainty concerns the future role of hydroelectricity. Today, hydroelectricity produced at Colorado River Storage Project (CRSP) facilities is used to meet peak demands typically during daytime hours. Demand patterns for electricity in the western U.S. are evolving, especially as production of renewable energy in southern California has greater impacts on the electrical grid system (see http://www.caiso.com/TodaysOutlook/Pages/supply.aspx). Tomorrow's price for hydroelectricity at peak hours can currently be anticipated as a point estimate (Level 1). Predicting peak energy price next

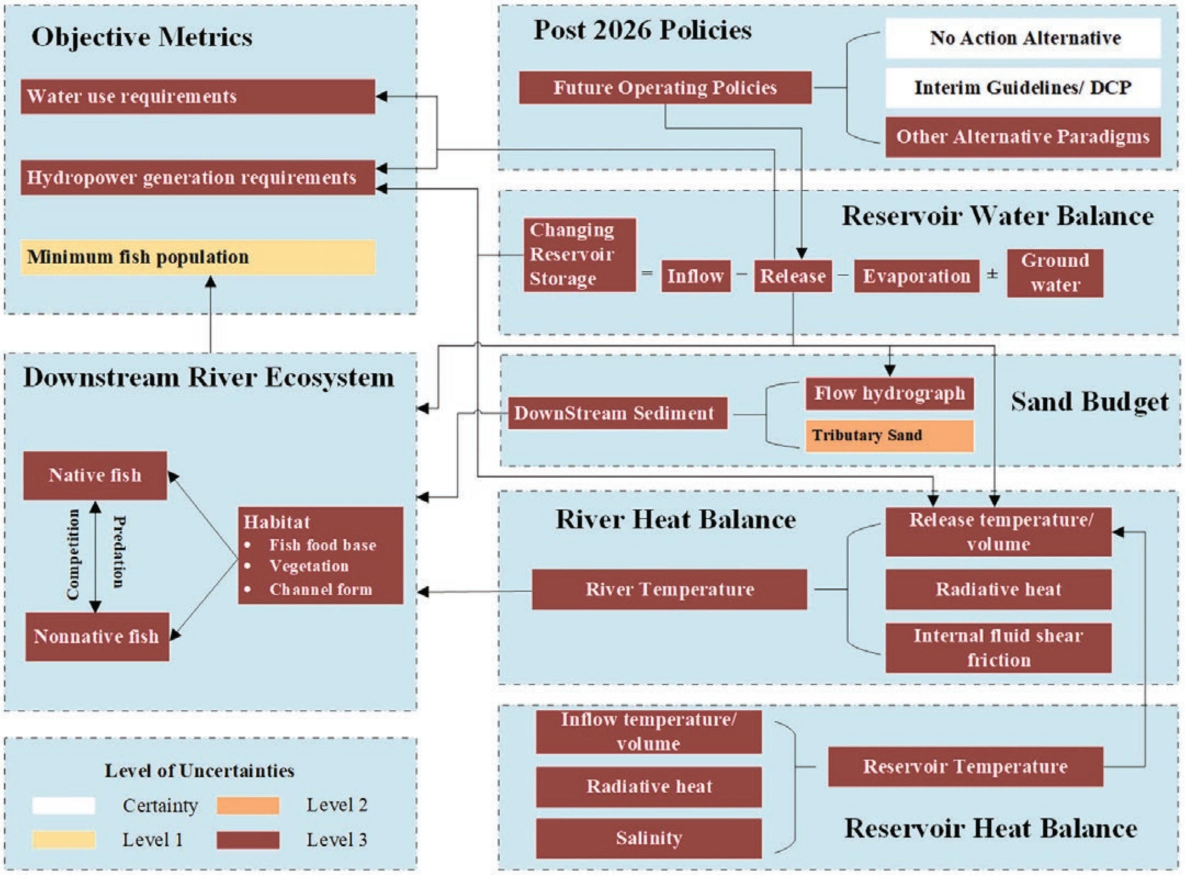


Figure 6. Uncertainty in Colorado River system components connect and propagate through reservoir water balance, sand budgets, reservoir heat balance, river heat balance, ecosystems, policy, and management objectives. The different levels of uncertainty are indicated by colored boxes.

Sidebar 2: Intersection of Levels of Uncertainty in the Reservoir-River Ecosystems of the Colorado River

In long term, decadal-scale planning and future reservoir operating policies (Post-2026 Policies) are highly uncertain. This is explicitly the case after 2026, when the 2007 Interim Guidelines expire. Reservoir release rules that are presently specified by the Interim Guidelines and revised by the Drought Contingency Plan (DCP) of 2019 are the primary determinant of the Reservoir Water Balance. This balance is simply the result of the difference between reservoir inflows and outflows.

Reservoir releases meet the demand for water supply and hydropower (Objective Metrics). Releases also affect downstream river ecosystems. Releases whose transport capacity exceeds the rate at which sand is supplied from unregulated tributaries (e.g., the Paria River downstream from Glen Canyon Dam) cause temporary evacuation of sand from the river corridor (Sand Budget) and especially from eddy sandbars valued by recreationists. Water released when the reservoir is relatively low is typically warmer than when it is relatively full (Reservoir Heat Balance). Further downstream, the rate at which rivers warm in summer depends on meteorological conditions that are impossible to predict in the future (River Heat Balance). In fact, prediction of many aspects of the future climate of each of the Colorado River's reservoirs has great uncertainty.

These three ecosystem drivers (streamflow regime, sediment balance, and river temperature) determine the characteristics and availability of aquatic habitat (Downstream River Ecosystem). The aquatic ecosystem food base, including its rate of production, are therefore greatly affected by the reservoir water balance. The response of fish ecosystems to changing aquatic habitat, especially river temperature, occurs by changes in native and nonnative fish growth rates, predation, competition, and available food supply, prediction of which has large uncertainties. This is especially the case for predicting river temperatures when reservoir releases are lower than what has been historically observed. Ecologists have emphasized that it is highly uncertain how the existing fish communities of the Colorado River basin will respond to river temperatures that have not occurred since completion of the CRSP (Dibble et al, in review).

Additionally, the levels of each of these uncertainties differ from place to place in the watershed. Thus, planning for future water supply and river ecosystem objectives and the management policies, reservoir water and heat balance, river heat balance, and downstream river ecosystem components that affect the objectives has tremendous, variable, and interconnected uncertainties.

month or next year is less certain (Level 2), although the Western Area Power Administration (hereafter, Western) negotiates long-term contracts for energy delivery based on projections of demand and price. When looking at energy prices decades into the future, numerous factors must be considered—renewables, battery storage, and changing electricity use patterns. These uncertainties can only be described by scenarios (Level 3). One possible scenario is that daytime electricity demand declines dramatically due to continued expansion of rooftop solar voltaic. In this case, the price for electricity generated at Glen Canyon Dam and other CRSP facilitates will further decrease. In another scenario, a transformative technology (such as large-scale battery storage) comes online, so that daytime generated solar energy can be stored and drawn on during nighttime hours. This capability reduces the need for nighttime hydroelectric generation and the price for such energy drops. In a third scenario, solar and wind serve as the dominant producers and hydropower becomes a valued support to smooth demand levels during nighttime, cloudy days or calm periods.

3.6 Uncertainty propagation

Earlier sections described and classified uncertainties associated with Colorado River hydrology, consumptive use, and ecosystem characteristics and processes. Here, we expand our analysis to show how these components and their uncertainties are interconnected through physical and social processes that include policies and operations, reservoir water balance, sand budget, river and reservoir heat balances, and downstream ecosystems (Figure 6). Uncertainties in individual components propagate to uncertainties in system management objectives.

For example, consider how releases from reservoirs made for water supply and hydroelectricity production affect the risk of future downstream flooding or drought conditions, as well as the hydrostatic head available to produce hydroelectricity. In the case of downstream river temperature, reservoir release rates, reservoir storage volume, temperature stratification within the reservoir, and solar radiation are all connected. These connections affect ecosystem dynamics like fish population, growth, and competition/predation between native and nonnative species. The above connections may be further affected by the timing of reservoir water release and the location, such as the bottom of an upstream reservoir, from which release water is drawn. Finally, reservoir release patterns combine with tributary sand inputs to affect downstream sediment conditions, which are another primary ecosystem driver.

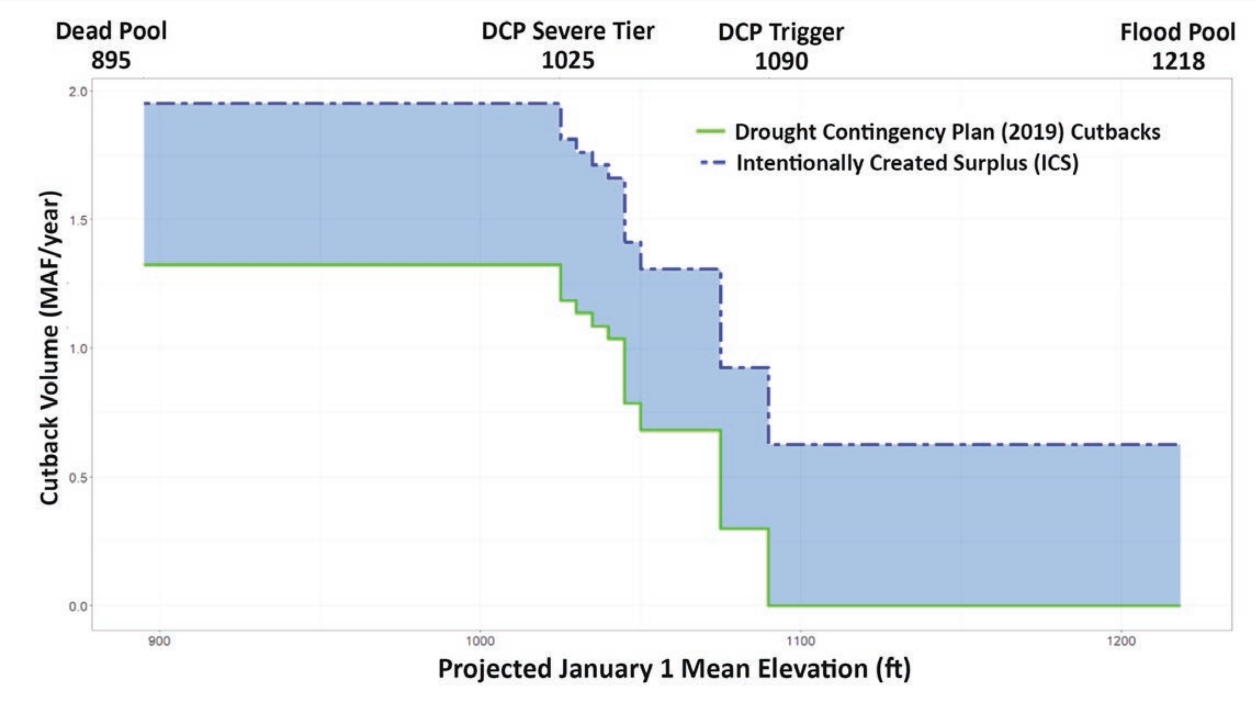
The Colorado River's ecosystem results from the intersection of natural processes and public policies. Each component of these complex interactions can have a different level of uncertainty. Figure 6 shows the numerous Colorado River system components with the levels of uncertainty of each component indicated. The large number of these uncertainties categorized at Level 3 prohibits the quantitative prediction of the outcomes of most specific attributes of aquatic ecosystems and fish communities (see Sidebar 2).

4. How Current Policy and Management Treat Uncertainty on the Colorado River

To some extent, present policies that guide management of the Colorado River acknowledge the different levels of uncertainty described above. In some cases, the same water supply attribute or ecosystem driver is classified with different levels of uncertainty depending on whether the planning horizon is long or short. Here, we describe some of these policies and management strategies that acknowledge different levels of uncertainty. We also show that some current policies increase uncertainty, rather than reduce it (Sidebar 3).

One example of planning in the context of Level 1 uncertainty concerns the development of the hourly and daily operations of reservoirs downstream from Hoover Dam, called the Lower Colorado River Operation Schedule. In this case, the upstream boundary condition of the planning model is the volume of water stored in Lake Mead, which is a well defined value with only Level 1 uncertainty. The time horizon of the Operation Schedule is one month, and daily releases are scheduled to meet downstream municipal and agricultural water demands, and hourly releases coincide with peak hydropower demand. One outcome of the Operation Schedule is the prediction of the elevation of every reservoir on the Lower River. The release schedule is updated hourly with the most recent data and projections, thereby reducing cumulative forecast errors. This strategy of regular updates and re-initialization of the plan model is also implemented elsewhere and is the most common approach to avoiding aggregation of error inherent in problems that involve multiple sources of Level 1 uncertainty.

Sidebar 3: An Uncertain Range of Lower Basin Cutbacks from Lake Mead



Level 1 uncertainty was created as a result of existing agreements that seek to limit consumptive water use during the onset of drought through cutbacks releases from Lake Mead and deliveries to lower basin users. Negotiations that led to the Lower Colorado basin DCP and the strategy of storing Intentionally Created Surplus (ICS) water in Lake Mead to maintain system storage were intended to reduce the rate of depletion of declining water storage during a severe drought. The DCP specifies exactly the reduction in water releases from Lake Mead as a function of the reservoir's elevation (solid green line). However, under the ICS rules, the states of California, Nevada, and Arizona may voluntarily and collectively bank up to 625,000 acre-feet per year in Lake Mead (for later withdrawal if the reservoir rises above 1075 feet). This voluntary banking represents an increased and temporary cutback, but the precise implementation and success of this plan is not currently known. Although, the value of the cutbacks cannot be known with certainty, the outcome can be anticipated within a range (blue area).

An example of planning in the context of Level 2 uncertainty can be found in Reclamation's 24-Month Study. Using the results from the Mid-Term probabilistic Operations Model (MTOM), Reclamation develops reservoir operation decisions based on projections of runoff conditions for the next two years. In early winter, future watershed runoff conditions are estimated within a range between the 10th and 90th percentiles of exceedance probability—as described in section 3.2. These estimates are provided by the Colorado Basin River Forecast Center (CBRFC) with an Ensemble Streamflow Prediction (ESP) model. Generally speaking, ESP generates equally likely sequences of future hydrologic conditions as an ensemble of forecast flows based on historical precipitation data, temperature data, and current hydrologic conditions. Using these hydrologic assumptions, and simulating existing operational policies such as those specified in the 2007 Interim Guidelines, the future elevations of Lake Powell are estimated for the next two years (Figure 7). Similar projections are made for Lake Mead.

Another example of planning in the context of Level 2 uncertainty is the MTOM, which simulates a 5-year planning horizon. The inputs of MTOM include 35 forecast inflow traces that represent different probabilities of runoff for 12 gaging stations where CBRFC makes predictions (Figure 8). Predicted actual streamflow at each of these gages relies on assumed patterns of consumptive water use to estimate natural flow. The model then simulates reservoir operation consistent with existing policy. After simulation, the outcomes of all of the traces are summarized, and include the monthly values for different parameters (elevation, the probability that reservoir elevation exceeds certain levels, the frequency that Lake Powell is in different operational tiers, reservoir releases,

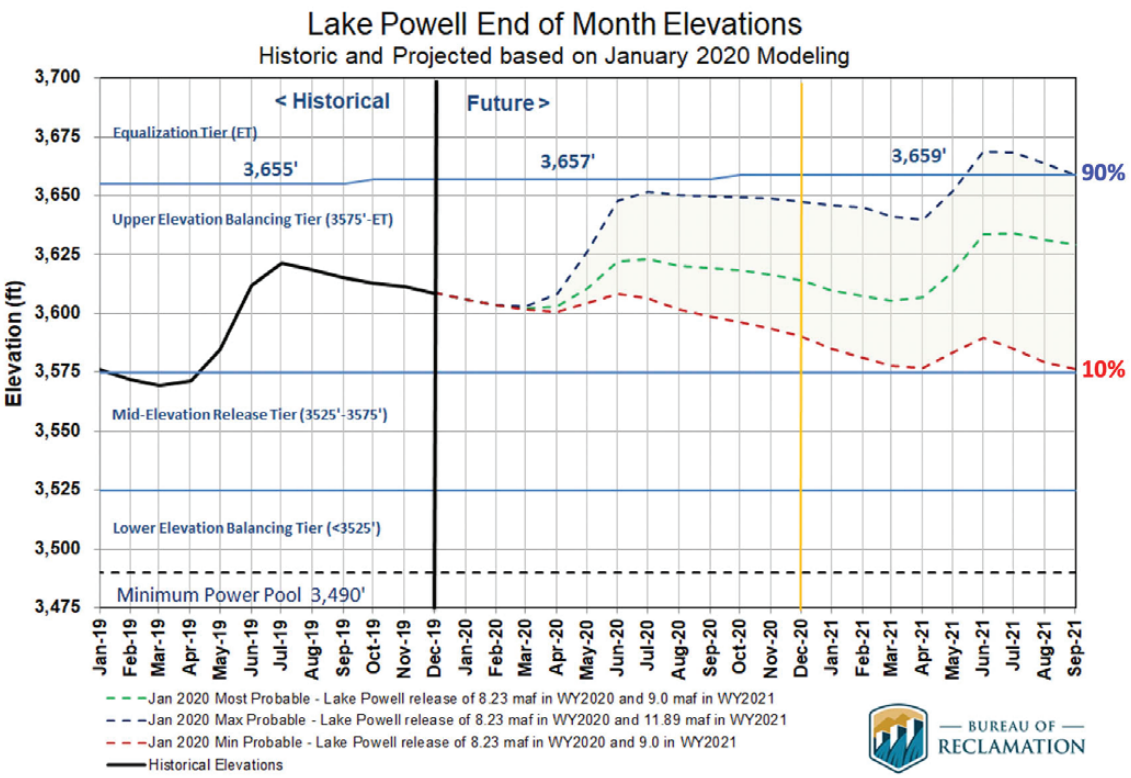
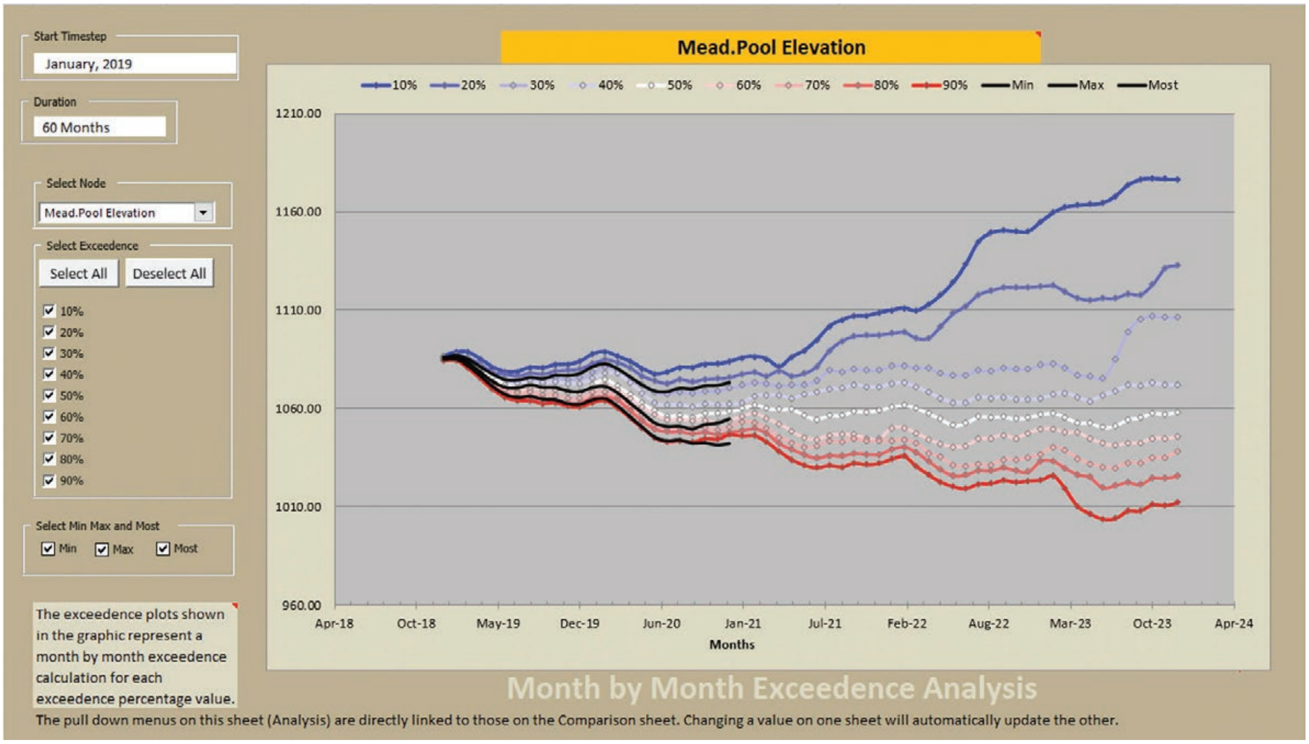


Figure 7. Estimated elevation of Lake Powell based on the uncertain probability of the magnitude of inflow during the next two years (Level 2 uncertainty). Estimates are made by Reclamation every month and are posted here. Ten percent of the time, the actual inflow will be below the dashed red line (labeled as "min probable") while 90% of the time the observed inflow will be below the dashed blue line (labeled as "max probable"). The magnitude of uncertainty increases with time (vertical distance between dashed red and blue lines).



Start Timestep: January, 2019

Duration: 60 Months

Select Node: Mead.Pool Elevation

Select Exceedence:
☑ 10%
☑ 20%
☑ 30%
☑ 40%
☑ 50%
☑ 60%
☑ 70%
☑ 80%
☑ 90%

Select Min Max and Most: ☑ Min ☑ Max ☑ Most

The exceedence plots shown in the graphic represent a month by month exceedence calculation for each exceedence percentage value.

The pull down menus on this sheet (Analysis) are directly linked to those on the Comparison sheet. Changing a value on one sheet will automatically update the other.

Figure 8. Projected Lake Mead elevation for the next 5 years under different probability of exceedance (from Colorado River Basin MTOM Technical User Guide for Stakeholders, version 2.0).

hydropower generation, the probability that the Lower Basin will be in shortage operation, future Lake Mead elevation, and the percentage of time that Lake Powell will be in the Equalization Tier).

The 2012 Basin Study (Bureau of Reclamation, 2012b) assessed a wide variety of potential future supply and demand scenarios and evaluated numerous options to mitigate projected shortfalls and meet future societal needs. In this study, watershed runoff was considered a Level 3 uncertainty, and four methods were used to generate hydrological sequences: Observed Resampled, Paleo Resampled, Paleo Conditioned, and Downscaled Global Climate Model (GCM) Projected. Note that the use of the index sequential method (ISM) in Observed Resampled and Paleo Resampled treated each of more than 100 within-scenario multi-runs as equally probable (Level 2 uncertainty).

Each hydrologic scenario was evaluated using each of six different demand scenarios derived from a variety of assumptions about growth, development patterns, economic conditions, and environmental awareness (e.g., several of the dashed lines in Figure 5). Combinations of supply and demand scenarios were simulated in the Colorado River Simulation System (CRSS; Wheeler et al, 2019) to assess the supply-demand imbalance and proposed mitigation strategies. Throughout the 2012 Basin Study, two policy/operations scenarios were evaluated for operations after the Interim Guidelines expire in 2026: 1) extend the Interim Guidelines past 2026, and 2) revert back to operations as implemented prior to 2007. Such future policy ambiguity demonstrates Reclamation's treatment of this unknown as a Level 3 uncertainty by simulating several policy scenarios, while seeking to identify new potential solutions to fill the supply-demand imbalance.

Currently, no tools or methods exist to assist with decisions under Level 4—the deepest level of uncertainty that encompasses the complete unknown. If we could describe the unknown event, we would be able to characterize the event as a scenario, and the event would shift instead to a Level 3 uncertainty.

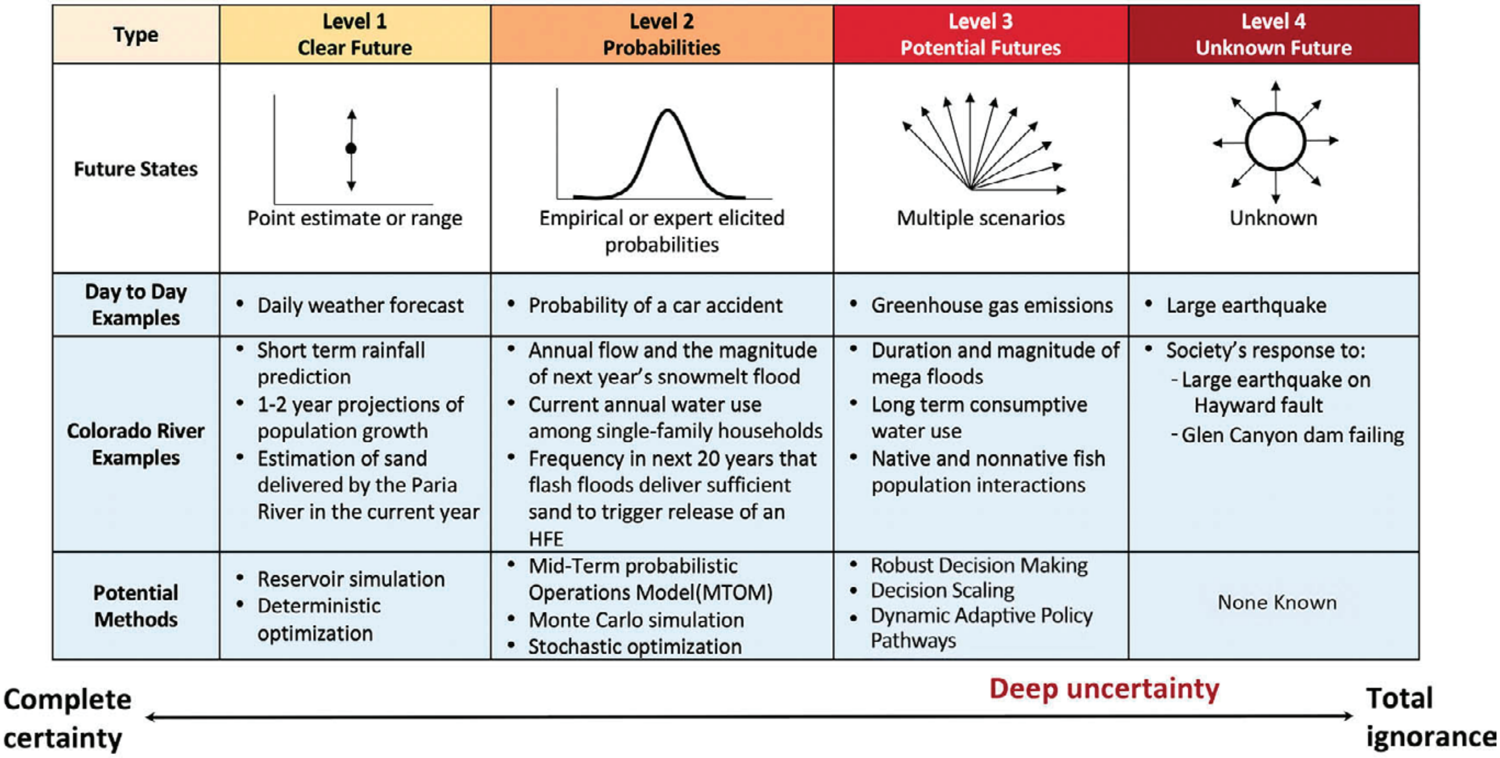
5. Future Decision Support in the Face of Uncertainty

There are multiple analytical and modeling approaches to help decision-makers develop policies to manage water supply and meet natural resource objectives in the face of uncertainty. Many of these approaches assume that the uncertainties associated with predicting future conditions are Level 1 or 2. These methods suggest that future conditions can be reduced to deterministic or probabilistic projections. These methods, however, are not appropriate for making policy decisions under Level 3 and 4 uncertainties—where scenarios, pathways, obstacles and solutions are as yet unknown. The challenge of developing policies that confront Level 3 or 4 uncertainties are substantial, because analysts cannot anticipate all future conditions or scenarios, nor define the likelihood of those future conditions. Even if a wide range of future conditions could be described, there may be computational challenges to exploring all possible future scenarios within a timeframe suitable for decision making.

The ever-evolving science of water-resource planning and management is in the process of developing new methods to address deep uncertainty by shifting modeling and policy-making efforts from the goal of defining a single optimal solution to one of seeking robust/adaptive solutions that provide satisfactory performance for multiple management objectives across many plausible future states of the world. Here, we summarize existing, new, and emerging strategies for planning for each level of uncertainty and each planning horizon (Figure 9). In addressing the challenges faced by decadal-scale climate change, decreasing watershed runoff, uncertain future demands and river ecosystem conditions, we emphasize that it is critical to correctly identify the level of uncertainty and the planning horizon; identifying the correct level of uncertainty permits a match with appropriate modeling and planning strategies.

5.1 Decision support when addressing only Level 1 uncertainties

Obviously, planning for the future would be easier if we could build a time machine and directly observe the future. Future conditions could be treated as single deterministic values, and the performance of future policies could be evaluated as a deterministic operational problem. Deterministic optimization methods could be utilized to derive optimal decisions for operations. For example, Yi et al. (2003) applied dynamic programming (DP) to evaluate how to most efficiently operate the power plants at the dams on the lower Colorado River to produce hydroelectricity during times of greatest demand and throughout the day with available stream flow and available reservoirs. In this lower Colorado River management problem, DP was used to search for the optimal generation schedule of each unit in each hydropower plant at each dam, to achieve the maximum hydropower efficiency given estimated inflows and demands considered to only have Level 1 uncertainty. Even though Yi et al. (2003) only tested DP with precise historical data and assumed no uncertainty, they demonstrated DP's capability to identify optimal unit generation schedules. Besides DP, methods like nonlinear programming, presently used by Western, could also be used to identify optimal operational decisions under circumstances that only have Level 1 uncertainty.



Type	Level 1 Clear Future	Level 2 Probabilities	Level 3 Potential Futures	Level 4 Unknown Future
Future States	Point estimate or range	Empirical or expert elicited probabilities	Multiple scenarios	Unknown
Day to Day Examples	• Daily weather forecast	• Probability of a car accident	• Greenhouse gas emissions	• Large earthquake
Colorado River Examples	• Short term rainfall prediction • 1-2 year projections of population growth • Estimation of sand delivered by the Paria River in the current year	• Annual flow and the magnitude of next year's snowmelt flood • Current annual water use among single-family households • Frequency in next 20 years that flash floods deliver sufficient sand to trigger release of an HFE	• Duration and magnitude of mega floods • Long term consumptive water use • Native and nonnative fish population interactions	• Society's response to: - Large earthquake on Hayward fault - Glen Canyon dam failing
Potential Methods	• Reservoir simulation • Deterministic optimization	• Mid-Term probabilistic Operations Model(MTOM) • Monte Carlo simulation • Stochastic optimization	• Robust Decision Making • Decision Scaling • Dynamic Adaptive Policy Pathways	None Known

Figure 9. Potential methods for different levels of uncertainty.

5.2 Decision support when the likelihood of future conditions can be quantified (Level 2)

The MTOM uses a statistical model to address hydrologic uncertainty across a scheduled planning horizon, and therefore can be used under Level 2 uncertainty. Additional modeling approaches useful for addressing planning problems attached to a Level 2 uncertainty include:

(1) In **Monte Carlo simulation**, one specifies a probability distribution for the uncertainty parameter. This probability distribution may be derived from observed data or expert-elicited information. Random samples of a large number of values are drawn from the derived probability distribution, and each randomly sampled value is modeled to produce a result or output (Law and Ketton, 1991; Loucks and Van Beek, 2017). The probabilities of different outcomes are described based on the range of these outputs. Chen et al. (2016) adopted the Monte Carlo simulation to estimate future ground-water conditions in the alluvial aquifer near Rifle on the upper Colorado River, based on monthly and daily streamflow measured at a nearby gage and ground-water measurements near the site. The use of these measurements of surface water and ground-water have Level 2 uncertainty, because they were assumed to adequately characterize future conditions.

(2) **Stochastic optimization methods** can also be applied to assist in decision making in the face of Level 2 uncertainty. Given the probability distribution of random parameter, stochastic optimization methods search for optimal decisions that can achieve the maximum or minimum expected objective value (expected value means probability weighted average of all its possible values). The most commonly used solving methodology is Stochastic Dynamic Programming (SDP) (Yeh, 1985). For example, Liang et al. (1996) adopted SDP to identify the reservoir operations rule for releases that yielded maximum expected water supply reliability.

5.3 Decision support in the face of Level 3 uncertainty

There are several methods that can be used to develop policy options at Level 3 uncertainty. Traditional optimization methods seek a "best solution" or attempt to define a solution space that explicitly evaluates tradeoffs among different objectives (referred to as a "pareto optimal solution set"). Emerging methods rather seek robust alternatives that perform well across many future scenarios, to quantify system vulnerabilities across combinations of future scenarios, or adapt policies over time as conditions change and information improves. Examples of these emerging methods include Many Objective Robust Decision Making (Kasprzyk et al. 2013), Decision Scaling (Brown et al. 2012), and Dynamic Adaptive Policy Pathways (Haasnoot et al. 2013) as described below.

5.3.1 Achieving Multiple Objectives through Many Objective Robust Decision Making (MORDM)

Robust Decision Making (RDM) is an analytic framework developed by Lempert et al. (2003) which seeks to define a robust strategy that performs well across a range of plausible future states of the world. Many Objective Robust Decision Making (MORDM) extends RDM to identify, quantify, and explore tradeoffs for robust alternatives to multiple competing objectives (Kasprzyk et al, 2013).

Alexander (2018) utilized MORDM to evaluate the performance of different operating rules for Lake Mead which could meet water supply objectives during a 40-year planning horizon at Level 3 uncertainty. In this problem, neither the inflow to Lake Mead or water demands were considered to be known with any certainty. The most important objectives of this analysis were to meet demands, and to maintain reservoir storage levels defined by critical elevations of Lake Mead and Lake Powell. The challenge of this analysis was developing possible operating policies that could perform well across all possible future conditions and to compute and analyze the numerous possible model outcomes.

The problem was formulated with 8 different reservoir elevation and water shortage objectives. All possible future conditions were characterized by defining 107 Direct Natural Flow ensembles and 3 water demand traces. The Borg Multi-Objective Evolutionary Algorithm (Borg MOEA) (Hadka and Reed, 2013) was connected to CRSS to generate and identify 751 possible operating policies. The large computational burden of this analysis restricted the number of possible inflow traces to 12, and the number of water demand traces to three. In this modeling approach, initial operating policies were defined, and each new model computation was based on a slight revision of the operating policies to improve the goal of meeting the objectives. These identified policies were re-simulated across all possible future states of the world (95 additional inflow traces and 2 additional demand traces), and the robustness for each policy was evaluated. Robustness was defined as the number of scenarios that met all minimum requirements for each objective divided by the total number of scenarios. An ongoing challenge is to communicate MORDM results, as described in Sidebar 4.

MORDM results have provided insights into how existing operating policies might later be revised, but policies identified by MORDM have not yet been used to revise Colorado River operations, (Prairie, personal communication, 2019). The Borg MOEA-CRSS tool has also been used to develop possible management alternatives in systems of vastly different scales, including the Tarrant Regional Water District in Texas and the Nile River basin in Africa (Smith et al. 2016, Wheeler et al. 2018).

5.3.2 Decision Scaling

Brown et al. (2012) developed Decision Scaling (DS) as a tool to assess the vulnerability of water systems to combinations of climate, water supply, and demand scenarios. This approach was used in the context of a management problem involving Colorado Springs Utilities (CSU) where Brown et al. (2019) evaluated the effects of future temperature, future precipitation, and two demand scenarios on the reliability of water supply. CSU draws 70% of its water from the upper Colorado River basin which is diverted through transbasin diversions to East Slope Colorado. In this case, CSU defined water supply reliability as the percentage of time that water deliveries meet the water demand target. CSU identified 50-year planning horizons for two development scenarios: (1) the existing footprint of Colorado Springs, and (2) a full build-out condition. CSU developed scenarios of future hydrology using a stochastic climate generator to produce time series of future temperature and precipitation values. The study used the Water Evaluation and Planning (WEaP) System model to simulate system response to the supply and demand scenarios by specifically representing reservoir operations. After reservoir simulation, the water system vulnerability was identified as instances in time when reliability was less than 100% (delivery < demand target). The results were visualized as response surfaces with temperature change on the x-axis and precipitation change on the y-axis. System performance that was acceptable and vulnerable was identified and plotted on this surface (Figure 10).

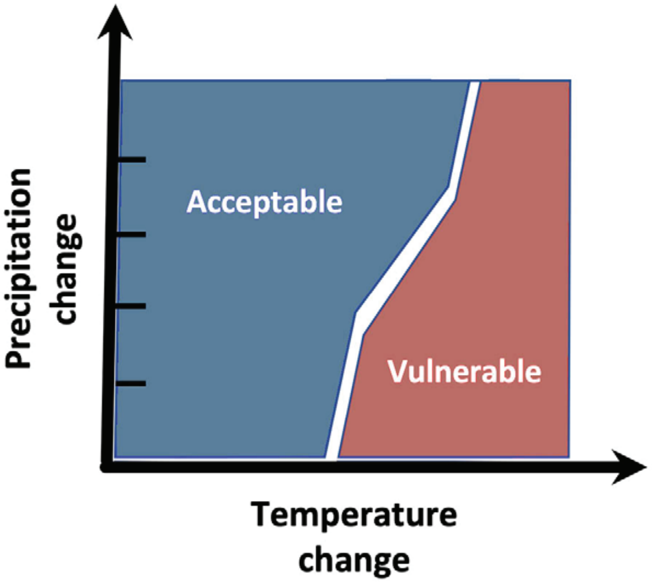
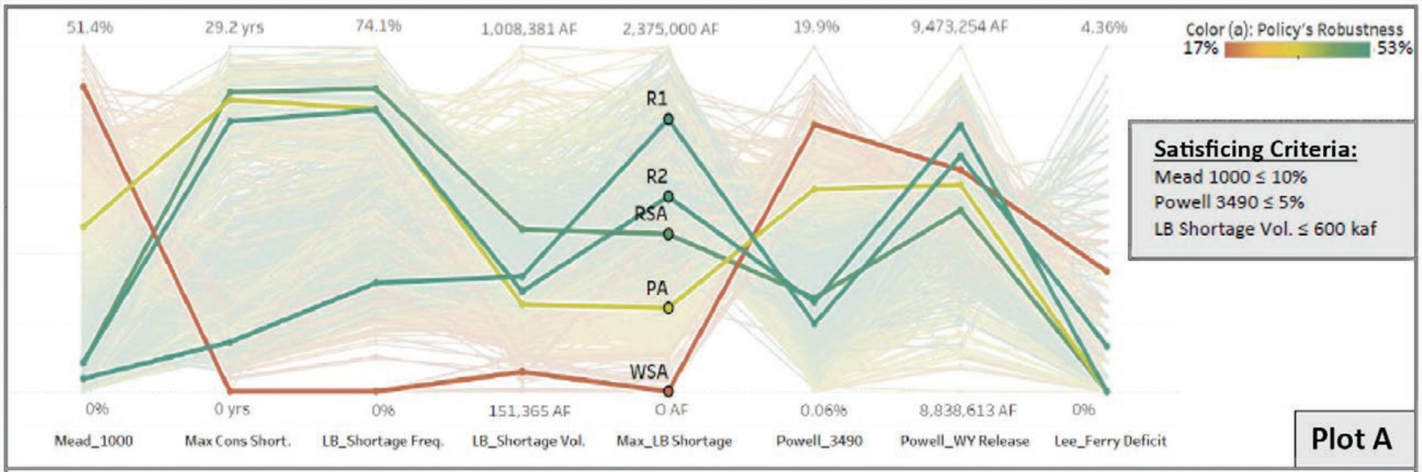
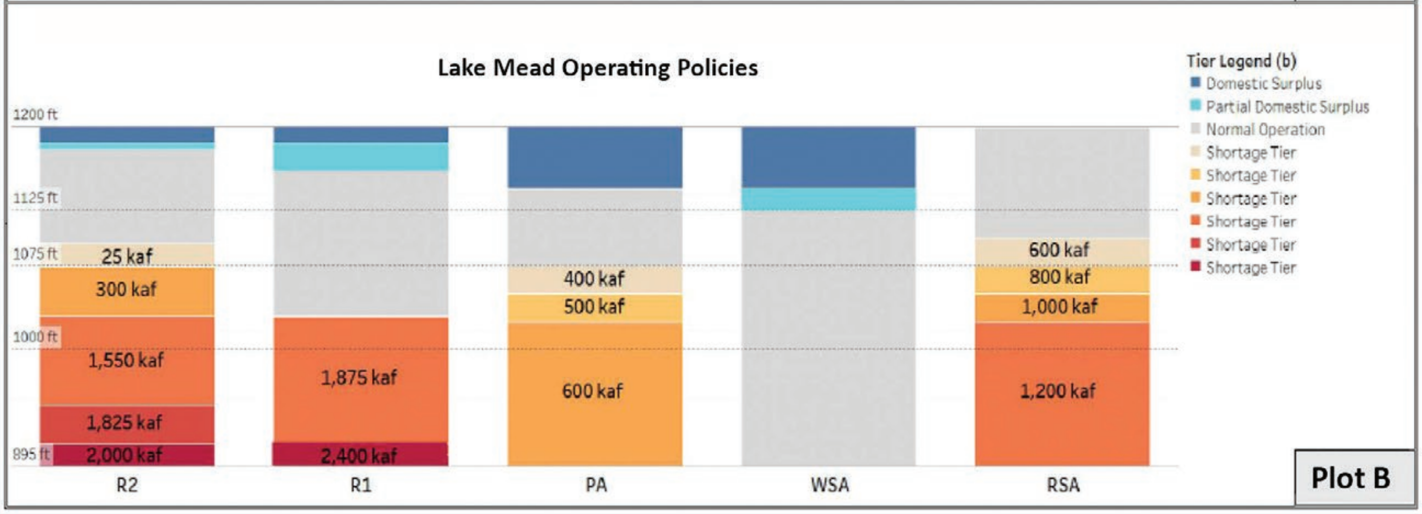


Figure 10. Response surface for different combinations of demands and inflows (adapted from Brown et al, 2019)

Sidebar 4: The Challenge of Reporting MORDM Results



Plot A



Plot B

Plot (a), labeled "parallel coordinate plot" in Alexander (2018), shows the performance of each alternative policy in relation to eight objectives. Lines that plot lower in relation to the y-axis are preferred. The robustness for each policy is shown in color ranges from red (least robust) to green (most robust). The more robust policies in this figure (darker green lines) had more favorable performance (lines cross closer to the bottom of the plot) across more of the objectives. In plot (a), the performance of five representative policies are shown for comparison.

R1 and R2 represent the policy that achieve the highest two robustness among 751 identified policies from MORDM. RSA, PA, WSA are the reservoir storage alternative policy, preferred alternative policy, and the water supply alternative policy from the 2007 Interim Guidelines. Background lines show the performance of another 749 policies identified by MORDM. Comparison of the five policies show that no policy could achieve best values for all objectives. When compared with RSA, R1 showed a little improvement in robustness. Plot (b) shows demand cutbacks at different shortage tiers for each policy. Take R2 for instance, when Lake Mead elevation is higher than 1095 feet, there is no demand cutback; when the elevation falls between 1075 feet and 1095 feet, demand cutback is 25 KAF; when the elevation falls between 1030 feet and 1075 feet, demand cutback is 1550 KAF, and demand cutback increases with the decreasing of Mead elevation. In plot (b), R1 and R2 impose larger demand cutbacks than PA, WSA, RSA, and these large cutbacks greatly increase the chances of Lake Mead elevation higher than 1000 feet—objective 1 in plot (a)—and Lake Powell elevation higher than 3490 feet —objective 6 in plot (a)—thus explaining why R1 and R2 provide higher robustness in plot (a).

Another example of DS is the 2012 Basin Study's simulation of all combinations of 6 demand traces and 1959 hydrology traces and the use of simulation results to identify and plot water supply vulnerabilities under different combinations of conditions. The results might be used to develop new policies that reduce water supply vulnerabilities.

The advantage of DS is to show system vulnerabilities across multiple factors that have Level 3 uncertainty and allow stakeholders to easily see the combinations of conditions that result in acceptable and vulnerable system outcomes. At the same time, it is challenging to represent complicated and interconnected factors and future conditions in ways that are broadly understandable.

5.3.3 Dynamic Adaptive Policy Pathways

The Dynamic Adaptive Policy Pathways (DAPP) method has been proposed as a way to explore policies that can be changed over time as aspects of Level 3 uncertainty become better understood (Haasnoot et al., 2013). Here, we describe an example of how DAPP might be used to develop new rules to guide releases from Lake Powell and Lake Mead to achieve water supply and ecosystem objectives.

In order to provide adaptability in the face of uncertainty, DAPP defines expiration conditions (also known as "signposts" or "off ramps") when there is a need to transition to another policy. These expiration conditions can either be an official expiration date for particular policy elements such as the Interim Guidelines expiring in 2026, or triggered by unacceptable conditions—such as very low reservoir storage or low population of an endangered fish species. If such conditions occur, managers have the opportunity to shift to an alternative policy that was identified in an earlier stage or negotiate a new policy. This type of strategy has a goal of increasing the policy's adaptability in the face of deep uncertainty. DAPP policies are often represented as subway maps (Figure 11) to help stakeholders visualize transitions among potential policies.

Before shifting to an alternative policy, it is important to generate a range of potential operating policies. For example, besides the current rules defined by the 2007 Interim Guidelines and the Drought Contingency Plan (DCP; Figure 11, in black), we might define three distinct policies: (1) an alternative management paradigm with an emphasis on keeping Lake Powell relatively full (i.e., Fill Powell First (FPF), Figure 11, red line; Wheeler et al., 2019), (2) an alternative management paradigm emphasizing keeping Lake Mead relatively full (i.e., Fill Mead First (FMF), Figure 11, green line; Wheeler et al., 2019), and (3) an alternative flow management policy whose goal is to suppress non-native fish reproduction while also benefiting endangered native fish species (Figure 11, orange line). The former two policies (FPF and FMF) are extreme bookends that could be implemented to manage Lakes Powell and Mead.

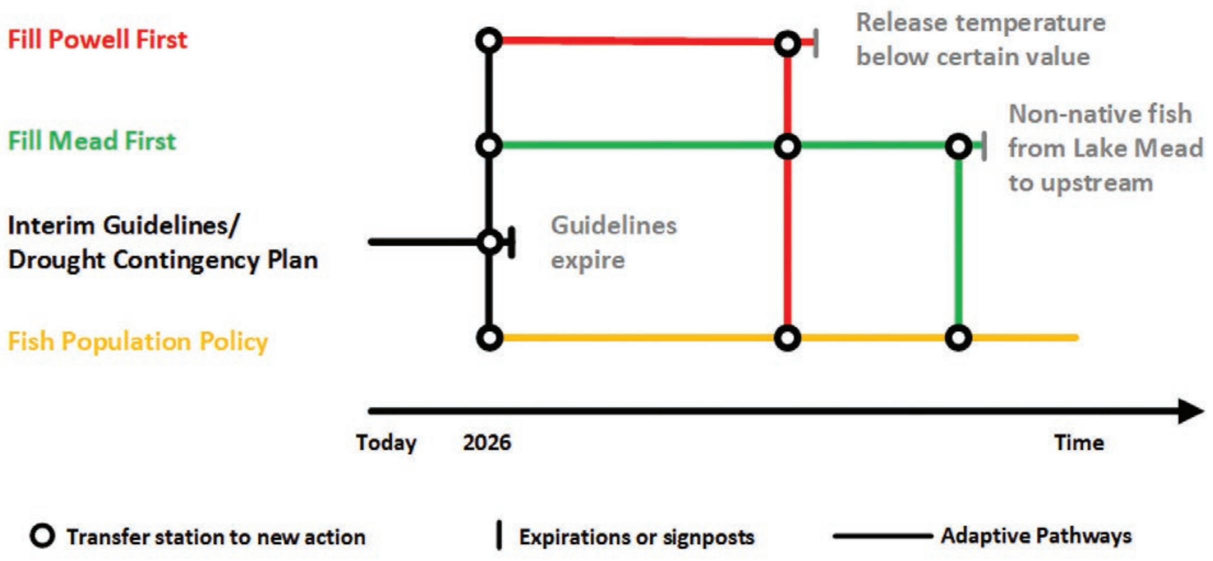


Figure 11. Example of DAPP illustration for future planning on the Colorado River. Color lines represent available paths to go when current policies expire, some of them are mutually exclusive (such as Fill Mead First and Fill Powell First). Once a path was selected, we would keep walking on that path until a new signpost was hit. The triggered signpost would then notify us to select a new path to go to help the system recover from the unacceptable system states.

In the context of DAPP, the expiration of the 2007 Interim Guidelines in 2026 constitutes a signpost and the opportunity to develop a new set of policies. A Fill Powell First policy could be implemented that uses Lake Powell as the primary storage and flow regulation facility, and uses Lake Mead as a backup storage only after Lake Powell is sufficiently full. To implement this policy, a new signpost would surely be defined that would be related to storage contents of Lake Powell. If Lake Powell fell to critical levels, large cutback values to each user would be required to maintain the system's function. These critical levels and cutback values might not necessarily be defined immediately, and some policy paths might only be defined in the future if dire conditions actually occurred. Particularly relevant to the FPF policy, a river ecosystem signpost might be defined as a critical reservoir release temperature threshold. Although Lake Powell has been full as recently as 2000 and released very cool water at that time, it is now known that these cool temperatures severely limit native fish growth and inhibit mainstem reproduction. Based on this evolving understanding of fish biology and river temperature, a policy might be adopted to limit Lake Powell's elevation so as to release warmer water. The highest Lake Powell elevation and the exact release temperature threshold might be defined in future negotiations following additional ecological studies.

A Fill Mead First policy could also be hypothetically implemented that uses Lake Mead as the primary storage and regulation facility, and only stores water in Lake Powell if and when Lake Mead is sufficiently full. Such a policy would certainly require redefinining shortage and surplus conditions, as it would be critical if Lake Mead fell to relatively low levels without available releases from Lake Powell. As defined in the current DCP (Sidebar 3), the critically low reservoir levels and subsequent cutback requirements to Lower Basin users would need to be redefined to values that provided the same degree of long-term stability for the system. A relevant river ecosystem signpost associated with implementing FMF might be defined as the upstream movement of undesirable warm-water non-native fish from Lake Mead. Policies that prevent these invasive fish moving upstream could also be negotiated to respond to this signpost. Besides the two extreme policies of FPF and FMF, other promising policies that perform well in certain scenarios for certain purposes could also be negotiated to increase system's adaptability.

The 2012 Basin Study shares several similarities with DAPP, even though they were developed independently. The 2012 Basin Study used 5 water supply signposts (Lee Ferry deficit, Upper Basin shortage, Lower Basin shortage, etc.) and multiple options in 9 categories such as desalination, reuse, and agriculture conservation to improve water supply performance. The study then developed four portfolios that grouped options. One portfolio included all options and other portfolios consisted of subsets of options that had high technical feasibility, long-term reliability, and/or low environmental impacts. They simulated each portfolio under all combinations of uncertain future demand and supply conditions.

5.4 Decision Support in the face of Level 4 Uncertainty (complete unknown)

We are not aware of any existing tools to manage or model in the face of Level 4 uncertainty (complete unknown). A possible strategy is to try to define a complete unknown by event sequences or scenarios (possible futures) and then model those scenarios with one or more Level 3 techniques presented in Section 5.3. This strategy carries substantial risk to misrepresent the unknown future, because the analyst can only consider a finite number of scenarios that will inadequately characterize the unknown future conditions in most cases. Fundamental questions exist as to whether such uncertainty is manageable.

5.5 Synthesis of methods for different uncertainty levels

Section 5 introduced many analytical and modeling approaches that might help stakeholders develop policies for managing water supply and meeting natural resource objectives. These approaches are specific to the uncertainty level (Table 1). Deterministic optimization methods such as dynamic programming can be used when it is possible to specify all variables with certainty (Level 1 uncertainty). In the face of Level 2 uncertainty when future forecasts are estimated with probability, use Monte Carlo Simulation to compute probabilities of different outcomes. Stochastic optimization methods can also identify optimal solutions that maximize or minimize an expected objective or average outcome. However, these solutions may not be globally optimal, and computational burden will limit the scale of the problem.

When confronting Level 3 uncertainty, scenarios can describe some possible future conditions, but the probability of occurrence is unknown. For these conditions, use MORDM to seek policies that are robust across many scenarios or future states of the world. However, computational burden limits search across a small number of scenarios. Coupling a reservoir simulation model such as CRSS with reservoir temperature, river temperature, and river ecosystem response models will further increase the computational burden, and might limit application for river ecosystem management purposes. Further, MORDM assumes that the same robust policy is implemented across the entire planning horizon and that the policy stays the same through time. Yet new conditions will develop over time and robust policies derived today for the current envisioned scenarios may not remain robust in the future.

Table 1. Brief summary of decision support methods.

Method name	Definition	Strengths	Weaknesses	Example Uses
Dynamic programming (Level 1)	Solve a complex problem by breaking it down into simpler subproblems.	● Easy to code and use ● Can achieve optimal solutions for deterministic problems	● Computational complexity increases exponentially with increasing system states	● Identify the most efficiently way to operate power plants for hydropower operation. Yi et al. (2003)
Monte Carlo Simulation (Level 2)	Draw random samples from distributions of uncertain parameters to characterize variations of system outputs.	● Get probabilities of different outcomes occurring	● Require to know probabilities for uncertain input parameters	● Estimate future groundwater conditions. Chen et al. (2016)
Stochastic Optimization (Level 2)	Optimize over a probability distribution of future outcomes.	● Identify optimal decisions across a set of outcomes.	● Must know the probability for uncertain component ● Computational complexity increases exponentially with the increasing reservoirs and uncertainties ● Global optimum not guaranteed	● Identify the reservoir operations rule for releases that yielded the maximum water supply reliability. Liang et al. (1996)
Many Objective Robust Decision Making (Level 3)	Uses a MOEA to generate planning alternatives that robustly satisfy objectives across multiple future states of the world.	● Provide robust operating rules across all tested objectives and scenarios	● Robustness decreases with the increasing number of objectives ● Identifies static robust policies for current scenarios that may not be robust a decade from now	● Identify robust Lake Mead policies to achieve multiple water supply objectives. Alexander (2018)
Decision Scaling (Level 3)	Identify system vulnerability to combinations of uncertain future conditions	● Identify the combinations of future conditions for which the system is vulnerable	● Don't generate policies or decisions	● Evaluate the effects of future temperature, future precipitation on the reliability of water supply for Colorado Springs Utilities. Brown et al. (2019)
Dynamic Adaptive Policy Pathways (Level 3)	Develop pathways for dynamic adaptive strategies that include current policies, signposts to signal when system performance deteriorates, and alternative policies to switch to improve system performance.	● Improve system adaptability by identifying multiple signposts and policies	● Does not consider multiple objectives explicitly ● Adaptability is not quantitatively calculated	● Improve system performance with portfolios that combine different water supply options. (2012 Basin Study)

DS can help identify the combinations of future conditions and scenarios for which will make existing or alternative policies vulnerable to failure. DS can be coupled with MORDM to check system vulnerability for a robust policy. And like MORDM, the computational burden limits the number of uncertain factors, scenarios, and combinations of factors and scenarios that a DS study can consider.

DAPP defines signposts to signal the future conditions and scenarios when system performance deteriorates. When a signpost triggers, the method also identifies alternative policies to switch to. This adaptability recognizes that Level 3 uncertainty includes a large number of potential scenarios and stakeholders are unlikely to find a single policy that performs well across all scenarios and purposes. DAPP instead identifies different policies for different scenarios and adapts policies over time as conditions change and information improves. This adaptability is already part of recent Colorado River management that began with the 2007 Interim Guidelines and continued with the 2012 Basin Study and 2019 DCP. For example, the expiration of the 2007 Interim Guidelines in 2026 provides stakeholders an opportunity to consider more recent hydrological information, signposts, and alternative policies. Below, we discuss how these steps can be strengthened and formalized to enhance water supply and ecosystem outcomes in the face of future hydrology, water demand, and river ecosystem uncertainties that can only be described by scenarios (Level 3 uncertainty).

6. Suggested Principles for Developing New Guidelines for Colorado River Basin Shortages and Coordinated Reservoir Operations in the face of deeply uncertain future conditions

The 2007 Interim Guidelines were developed to make informed operational decisions in response to the severe drought conditions in the Colorado River from 2000 to 2007. In the 2007 Interim Guidelines, discrete Lake Mead elevations were used to define surplus, normal, and shortage conditions for the Lower Basin, and a policy was implemented wherein various volumes of reduced consumptive water uses would be triggered to conserve water under different shortage conditions. These cutback volumes were revised in the 2019 DCP due to an inadequate anticipation of future conditions. If the 2019 DCP rules are also found to be inadequate to safeguard downstream users from catastrophic conditions, stakeholders will again need to re-negotiate during a critical moment.

In this white paper, we assert that most future hydrology, water demand, and river ecosystem attributes and objectives have at least Level 3 uncertainties that can only be described with forecasts and scenarios that do not have rank or probabilities. We know that the forecasts will be wrong and the scenarios will not span all possible future conditions. Nonetheless, managers must still operate reservoirs and allocate water all the while knowing that better information and technology will become available in the future. Challenges (Sidebar 5) in making good decisions in the face of these uncertainties include: (1) identifying and correcting the biases between generated scenarios and the actual future; (2) choosing an ap-

Sidebar 5: Challenges to Developing New Guidelines in the Face of Deep Uncertainties in Future Hydrology, Demands, and River Ecosystem Conditions

(1) Identifying and correcting the bias between generated scenarios and the actual future. As shown in Figure 5, almost all future predictions overestimate water demand for the upper Colorado River basin. The deviations are small in early years, but grow over time.

(2) Choosing an appropriate time horizon to model. The planning horizon for Colorado River basin studies is often 40 years from 2020 to 2060. The largest and deepest levels of uncertainty are for conditions the furthest out from present. At the same time, system states will evolve over time and more information will become available. Thus, optimal or robust operating policies derived from today's information will likely not be robust or optimal in the future.

(3) The computational burden grows as more uncertain factors and conditions are included. In Colorado River basin, there are multiple uncertainties related to hydrology, demands, operations/policy, and river ecosystems (shown in Figure 6). Scenarios of future conditions must include combinations of conditions for each factor. The computational burden increases exponentially as the number of uncertain parameters and values for those parameters increases.

(4) Assigning appropriate cutbacks among individual users. Assigning larger cutbacks (reducing use) among individual users is often a shrinking pie or lose-lose game. These cutbacks also trade off benefits from full deliveries today against future benefits to store water and later use stored water. For users to accept increased reductions, as the lower basin states did for the Drought Contingency Plan, the users must see and value the system-wide benefits from increased reductions. These benefits may (a) improve reliability of future water supply, or (b) reduce vulnerability when more extreme future droughts strike.

propriate time horizon to model; (3) the computational burden grows as more uncertain factors and conditions are included; and (4) assigning appropriate cutbacks to individual users.

Here, we put forward three overarching principles to help formulate new guidelines for Colorado River reservoir operations and water allocation policies in the face of deeply uncertain hydrology, demands, and river ecosystem conditions whose future states can only be described by scenarios without rank or probabilities. These principles follow a progression of steps to (i) include more information about future conditions as information becomes available, (ii) adapt policies to new information, and (iii) allow users more flexibility to respond to changing conditions. In the remainder of this section, we provide 10 suggestions to help the Bureau of Reclamation, basin states, and users to apply these principles in new guidelines. These suggestions draw on the best aspects of existing modeling tools such as DAPP, DS, and MORDM. The suggestions also synthesize our own experiences working in river basins throughout the world that face uncertain, future hydrology, water demands, and ecosystem conditions (Schmidt, 2016; Rosenberg, 2015; Wheeler et al 2018, Wang et al. 2019).

1. Classify uncertainties. Colorado River basin states and users should identify the major uncertain hydrology, water demand, operations, river ecosystem, and other factors that influence water supply and river ecosystem outcomes and classify the uncertainty level of each factor. Classifying the uncertainty level for each key factor will help managers identify and prioritize additional information to collect. Classifying the uncertainty level for each key factor will also point managers to more appropriate management and modeling methods to use to understand the effects of uncertainties on system outcomes.

2. Include and track more information. Include more information about key uncertain hydrology, water demand, and river ecosystem factors and track information as it becomes available. Besides information about reservoir levels that are the focus of the current guidelines, include a wider array of information such as near- and longer term projections of reservoir inflow, decadal climate patterns, water demands, and populations of key indicator species. Track this information to help determine whether existing reservoir operation and water allocation policies are performing acceptably or unacceptably.

3. Define many specific signposts. Define many specific signposts for when hydrology, water demand, and ecosystem conditions will lead to undesirable water supply and river ecosystem outcomes. Example signposts can include severe low reservoir inflow, future large water demands, low total reservoir storage (Powell + Mead), or storage for individual reservoirs falling to low levels so that the water temperature of released water is warm and favors the growth of nonnative fish species over native species. Other potential signposts include high Lake Mead levels that will allow the upstream movement of undesirable warm-water, non-native fish or small and declining native fish populations. In the current guidelines, one set of signposts are the reservoir tiers and levels that trigger equalization releases or lower basin delivery cutbacks. Another signpost is the expiration of the guidelines themselves in 2026. Defining additional signposts will provide more opportunities to avoid undesirable water supply and river ecosystem outcomes.

4. Identify more alternative policies. Identify more alternative policies that might be adopted when circumstances trigger a signpost**.** Alternative policies may include policies such as FMF, FPF, intermediate storage policies between FMF and FPF (Wheeler et al. 2019), or rules that release water as a function of reservoir storage and inflow. Alternative policies can include demand management, water trading, or reservoir accounting to allow flows for fish, sand bar building, or habitat enhancement. Identifying more alternative policies would offer managers the opportunity to plan in advance about how to respond when a signpost triggers rather than react ad hoc. Identifying more alternative policies to switch to when a signpost triggers allows managers to build more adaptability into new guidelines.

5. Construct potential pathways. Construct potential pathways that connect signposts and alternative policies over time. A pathway connects one signpost to an alternative policy that later may trigger another signpost and so on (Haasnoot et al. 2013). These pathways allow and define adaptations over time as managers learn about major uncertain factors, signposts get triggered, and managers switch to an alternative policy. Additionally, simulate potential pathways across multiple, uncertain future scenarios of water supply, demand, and river ecosystem conditions. These simulations can help identify the combinations of conditions where policies and adaptations fare well. Simulations can also show where pathways can be improved with alternative signposts or policies that more quickly detect problematic conditions or recover from those problem conditions (Brown et al, 2019). By constructing potential pathways now as part of negotiating new guidelines, managers can later follow the pathways without having to renegotiate the guidelines at each signpost or crisis.

6. Match the planning horizon to the uncertainty level. The uncertainty examples in Section 3.5 show that there are lower levels of uncertainty (ranges and probabilities) for shorter time horizons and higher levels of uncertainty (scenarios and unknown) as the time horizon grows.

Similarly, the Bureau of Reclamation, basin states, and basin users are more comfortable with near-term projections of supply and demand even though long-term forecasts, such as in the 2012 Basin Study, are essential for long-range planning. To resolve this conflict, we recommend matching the planning horizon to the uncertainty classification (Suggestion #1). To plan, manage, and model at acceptable levels of uncertainty, it may be more appropriate to choose a shorter planning horizon. If working for longer time horizons, build more signposts, adaptability, and flexibility into agreements.

7. **Retain more reservoir storage at the end of the planning horizon.** Seek to retain more total-watershed reservoir storage at the end of the model planning horizon to save water for future managers and future generations to use. In subsequent planning periods, future managers can use this ending reservoir storage to supply water users and ecosystems across a wider range of future uncertain conditions. Linking reservoir storage at the end of the planning period to future use will allow modeling efforts for shorter time horizons (see suggestion #6) to look further ahead. This suggestion is already implemented in the Interim Guidelines as the Intentionally Created Surplus program for Lake Mead. The program allows major users to voluntarily cut back some deliveries now, save that water in Lake Mead, and withdraw that water for future use to meet water supply objectives. This program could be extended to allow users to store water in other reservoirs for future water deliveries or allow managers to store water to meet future river ecosystem objectives.

8. Seek better policies rather than best policies. Seek policies that improve water supply and river ecosystem outcomes under a wider range of future conditions. The best (optimal) policy depends on the management objectives, available policies, and constraints. All of these system components are uncertain. For example, Colorado River ecosystem management objectives vary by stakeholder group (Runge et al, 2015) and will likely continue to change over time. It is hard to know today what technologies and policies will be available in 5, 10, or 20 years. We are uncertain how future hydrology and water demands will constrain available water. Thus, what may be optimal under one set of hydrologic, water demand, or ecosystem conditions may be suboptimal under other conditions. Instead, future guidelines should focus efforts to find operating policies that improve on (are better than) the current policy.

9. Allow users more flexibility. Allow users more flexibility to respond individually to changing conditions. The current ICS program gives Lower Basin users flexibility to store water in Lake Mead. The stored water is owned by the user, who has the flexibility to withdraw the water for use (under certain conditions). Demand management, water trading, or reservoir accounting policies for water users or river ecosystems (see suggestion #4) could each allow users more flexibility to store, trade, and later use water. A large challenge to allow users more flexibility is the need to monitor, track, and account for activities and ensure that transactions are for real, wet water. Monitoring, tracking, and accounting are easier for Lower Basin states where there are fewer diversion points, nearly all diverted water is consumptively used, and there is little return flow back to the Colorado River. Monitoring, tracking, and accounting are much more difficult in the Upper Basin where there are a much larger number of water rights holders and return flows are larger and difficult to measure. Allowing users more flexibility empowers users to develop individual plans to respond to uncertain, changing future conditions.

10. Visualize adaptive policies. Visualize adaptive policies to help stakeholders see adaptations over time and how system components relate to each other. One visualization technique is a map of signposts (suggestion #3), alternative policies (suggestion #4), and pathways (suggestion #5; Figure 11). Policies can also be visualized as a decision tree (Herman and Giuliani, 2018).

In Figure 12, we show an example decision tree to help visualize complex Lake Mead water releases and show the benefit to include information about Mead inflow. The existing Interim Guidelines and DCP define releases as schedules of lake level (blue boxes). Considering Lake Mead Inflow and adding a new signpost for low inflow (yellow box) can help identify low flow and low storage conditions when a new adaptive action to release less water than specified in the DCP (red box) may better protect Lake Mead level. Stakeholders may add more signposts to consider additional demand and other factors whose uncertainty levels are high. Visualizations help stakeholders to identify gaps in existing policies and modify and adapt policies to include new information such as forecasts of near-term or longer-term inflows. A decision tree also lays out a set of IF-THEN-ELSE hierarchical rules that can then be coded in CRSS and other modeling platforms.

We recognize that many details must be worked through by the Bureau of Reclamation, basin states, and users to apply the above 10 suggestions to develop new guidelines that consider future uncertainties in hydrology, water demands, and river ecosystem conditions that can only be described with scenarios. To better consider these uncertainties, new guidelines should (i) include more information about future conditions as information becomes available, (ii) adapt policies to new information, and (iii) allow users more flexibility to respond to changing conditions. Seeing these suggestions into practice will require experiments with new techniques

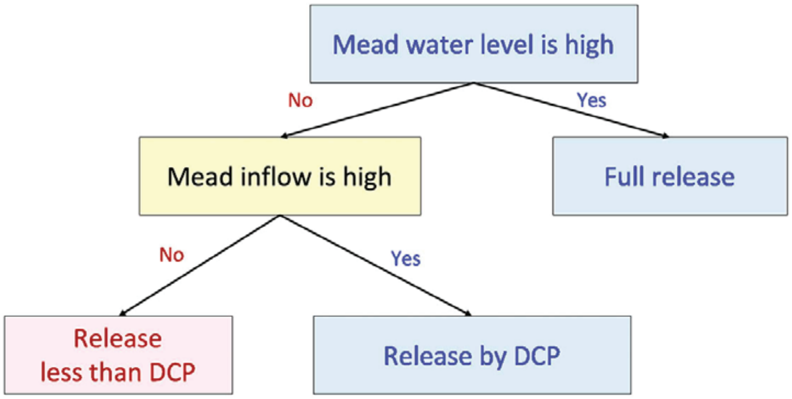


Figure 12. Add more signposts to Lake Mead release policy that includes information about Lake Mead inflow.

and new combinations of techniques to deal with Level 3 uncertainties as well as a collective development process that is itself adaptable and flexible.

7. Conclusions and Summary

Historically, Colorado River managers have operated Lake Powell and Lake Mead under the assumptions that future natural flow at Lee Ferry will resemble the past observed flow regime, water demands will grow, and future river temperature will stay within the range of historically observed water temperatures. These future conditions are difficult to predict in the coming years and decades, and these uncertainties present immense challenges to develop river management policies to enhance water supplies and ecosystems.

To help Colorado River stakeholders think about, talk about, and better manage the river in the face of these uncertainties, this white paper distinguished four levels of uncertainty. Some future conditions can be described by point estimates with ranges (Level 1) or probabilities (Level 2). Other future conditions can only be described by scenarios of possibilities (Level 3). Other future conditions are completely unknown (Level 4).

Stakeholders should differentiate uncertainty levels to guide use of appropriate management and modeling tools. For example, stakeholders should consider use of emerging tools such as MORDM, DS, and DAPP to manage for future uncertain basin hydrology, water demand, and river ecosystems conditions that can only be described with scenarios.

To manage for uncertain future conditions that can only be described with scenarios, we see the need to expand the Interim Guidelines and the Lower Basin DCP. Expansion should: (i) include more information about these future conditions as information becomes available, (ii) define more signposts and alternative policies and adapt policies over time to new information, and (iii) allow users more flexibility to respond to changing conditions. New guidelines that differentiate uncertainty levels, are more adaptable and flexible can better anticipate and respond to a wider range of future Colorado River conditions before a crisis strikes.

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