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RAND Environment, Energy, and Economic Development Program

Adapting to a Changing Colorado River

Making Future Water Deliveries More Reliable Through Robust Management Strategies

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Cover image: Hoover Dam Water Electricity Power Station, © malajscy/Fotolia. The cover image shows the current low level of the Lake Mead reservoir and two of the four water intake towers that control the supply of water to the power plant turbines at the base of Hoover Dam. The line between the light rock and dark rock around the reservoir indicates the usually higher elevation of the water.

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Summary

Introduction

The Colorado River is the single most important source of water in the southwestern United States, providing water and power for nearly 40 million people. In recent decades, federal managers and Colorado River water users have grown increasingly concerned about the future reliability of the River's water supply. Demand for water in the Lower Basin (California, Arizona, and Nevada) already exceeds the 7.5 million acre-feet (maf) volume allocated in 1922 through the Colorado River Compact (the Compact)—the legal document that determines the allocation of water to the Upper Basin (Colorado, Utah, Wyoming, and New Mexico) and the Lower Basin. Demand also continues to grow in the Upper Basin states.

Water from the River was initially allocated based on two decades of unusually high river flow, meaning it is likely the River was significantly overallocated when the Compact was signed. In addition, an extended drought from 2000 to 2007 has reduced total water storage in Colorado Basin reservoirs from nearly full to 55 percent of capacity; the system remains just over half-full as of this writing. The combination of increasing demand and lower-than-expected streamflow has steadily eroded system resilience.

Moreover, a growing body of literature suggests the Colorado River system is now—or soon will be—operating in a new hydrologic regime for which past data and experience are not an adequate guide for future river conditions. Climate simulations applied in the Colorado River Basin Study (Basin Study) are generally consistent in indicating that the entire Basin will track global trends and become warmer, but climate simulations of regional precipitation changes in the Upper Basin—where most River source water falls as snow or rain—generate very different forecasts. Some models project precipitation *declines* of up to 15 percent over the next 50 years in the Upper Basin, while others forecast an *increase* in precipitation of up to 11 percent over that time. Despite this uncertainty, Basin shortages are projected to increase; the question remains how much and when.

Motivated by these challenges and in response to directives in the United States SECURE Water Act of 2009 (Public Law 111–11, 2009), the Bureau of Reclamation (Reclamation) and water-management agencies representing the seven Basin States initiated the Basin Study in January 2010 to evaluate the resiliency of the Colorado River system over the next 50 years (2012–2060) and compare different options for ensuring successful management of the River's resources.

However, in conducting this evaluation, Reclamation and the water agencies must deal not with a future that is uncertain but well understood; instead, they must plan for a future that is *deeply uncertain* and one that cannot be described statistically because of a lack of knowledge about how changes will unfold. Under these conditions, developing an optimal management strategy designed to perform well for a single deterministic or probabilistic forecast of future conditions is not very useful; rather, planners need a *robust* and *adaptive* strategy—robust in that it performs well over a wide range of possible futures and adaptive in that it can adjust over time in response to evolving conditions.

Given these circumstances, RAND was asked to joined the Basin Study Team in January 2012 to help develop an analytic approach to identify key vulnerabilities in managing the Colorado River Basin over the coming decades and to evaluate different options that could reduce these vulnerabilities. Building off the earlier Basin Study efforts, RAND applied an approach called Robust Decision Making (RDM)—a systematic, objective approach for developing management strategies that are more robust to uncertainty about the future. In particular, RAND researchers:

- identified future vulnerable conditions that could lead to imbalances that could cause the Basin to be unable to meet its water delivery objectives
- developed a computer-based tool to define “portfolios” of management options reflecting different strategies for reducing Basin imbalances
- helped evaluate these portfolios across a range of simulated future scenarios to determine how much they could improve Basin outcomes
- analyzed the results from the system simulations to identify key trade-offs among the portfolios.

This report summarizes RAND’s contribution to the Basin Study (the *Colorado River Basin Water Supply and Demand Study* was released in December 2012). In contrast to Reclamation’s report—which covers the entire Basin Study and comprises seven primary documents, dozens of appendixes, and thousands of pages of results—this document is intended to concisely summarize RAND’s evaluation of long-term water delivery reliability for the Colorado River Basin across the range of future uncertainties and with proposed new options in place. This report focuses more on the analysis of vulnerabilities and how this information can inform the development of a robust management strategy for the Colorado River Basin. We worked closely with the Basin Study Team and state partners to complete this analysis. Here, we use only a small subset of the study results to tell the story of emerging water supply vulnerability and possible actions to reduce vulnerability. For example, although the Basin Study developed a wide range of performance metrics, we considered only broad, high-level performance metrics—each representing delivery reliability for the Upper and Lower Basins.

Developing Robust Management Strategies for the Colorado River Basin

RDM uses a framework called XLRM to summarize scenarios developed to reflect future uncertainty (X), the options (L) evaluated that would compose a robust management strategy, the model used to simulate future conditions (R), and the performance metrics (M) used to evaluate system robustness. Table S.1 shows the XLRM framework for this effort; a much larger set of performance metrics were used in the full Basin Study, but here we focus on two of the key ones to simplify the discussion of RDM’s contribution.

Table S.1
Summary of Uncertainties, Policy Levers, Relationships, and Metrics Addressed in Study (XLRM Matrix)

Uncertainties or Scenario Factors (X)	Management Options and Strategies (L)
Demand for Colorado River water Future streamflow or water-supply climate drivers Reservoir operations post-2026	Current Management Four portfolios composed of individual options • Demand reduction • Supply augmentation
Relationships or Systems Model (R)	**Performance Metrics (M)**
Colorado River Simulation System (CRSS)	*Upper Basin Reliability*—Lee Ferry Deficit *Lower Basin Reliability*—Lake Mead Pool Elevation Cost of option implementation

Scenarios and Uncertainty (X)

During the first year of the study (and before RAND was involved), the Basin Study Team developed a set of supply, demand, and reservoir operations scenarios designed to capture the uncertainties planners face. Each scenario describes one plausible way that each of these three factors could evolve over the study's 49-year time horizon (2012–2060).

The Basin Study Team developed *four supply scenarios* based on different sources of future streamflow estimates. Each scenario is composed of many different 2012–2060 time series of streamflows—known as *future traces or traces*. The first scenario, Historical, is based on the *recent historical record*. Each trace within the Historical scenario is a repeat of the historical record (from 1906 to 2007) with a different starting year. The second and third scenarios are based on streamflow estimates derived from *paleoclimatological proxies*, such as tree ring data. Each trace is consistent with a subset of years from the paleoclimatological record. The fourth scenario is derived from the projections of *future climate conditions* from 16 global climate models and three global carbon emissions projections. Each trace is derived from downscaled results from a single general circulation model (GCM) projection and emissions scenario.

The Basin Study Team also developed *six demand scenarios* that span a range of plausible future demands, not considering additional programs and incentives for water conservation: (1) current projected growth; (2) slow growth with an emphasis on economic efficiency; (3) rapid growth due to economic resurgence; (4) rapid growth with current preferences toward human and environmental values; (5) enhanced environment due to expanded environmental awareness; and (6) enhanced environment due to stewardship with growing economy. As input to the vulnerability analysis, RAND calculated the average demand in the last two decades of each trace (2041–2060). The post-2040 demand ranges from 13.8 maf (slow growth) to 15.6 maf (rapid growth).

Lastly, *two reservoir operations scenarios* were created, reflecting different assumptions about how the system would be operated beyond 2026, when the 2007 Interim Guidelines are scheduled to expire. In one, the guidelines for Lower Basin shortage allocation and reservoir management are extended; in the other, they instead revert to the "No Action" Alternative as stipulated in the 2007 Interim Guidelines Environmental Impact Statement (EIS). Continuation of the Interim Guidelines means the continuation of mandatory, agreed-upon Lower Basin shortages to help maintain storage in Lake Mead if the lake elevation drops below 1,075 feet above mean sea level (msl).

When evaluating the performance of the Colorado River Basin system, the four supply scenarios, six demand scenarios, and two reservoir-operations scenarios were combined and totaled 23,508 individual traces.

Options and Strategies to Improve Performance (L)

The Basin Study evaluated the baseline reliability of the Colorado River system by simulating current operating rules and procedures—what is referred to as the Current Management baseline (as shown in Table S.1). It also evaluated a wide array of different supply-augmentation and demand-reduction options that could improve system performance and reduce vulnerabilities. Such options were organized into eight categories: (1) agricultural conservation, (2) desalination, (3) energy water use and efficiency, (4) water imports into basin, (5) local supply, (6) municipal and industrial (M&I) conservation, (7) reuse, and (8) watershed management. Starting with 150 different options, the Basin Study Team ultimately evaluated a smaller set of these options—about 80—according to cost, yield, availability, and 16 other criteria, including technical feasibility, permitting risk, legal risk, policy risk, and energy intensity.

The RAND team developed a "Portfolio Development Tool" that was used by the Basin Study Team and stakeholders to develop four strategies defined by portfolios of prioritized supply-augmentation and demand-reduction options (drawn from the 80 evaluated ones): *Portfolio A (Inclusive)*, *Portfolio B (Reliability Focus)*, *Portfolio C (Environmental Performance Focus)*, and *Portfolio D (Common Options)* (Table S.2).

To evaluate how each portfolio of options would perform across the wide range of futures, the Basin Study Team defined *dynamic portfolios*, which include rules within the simulation model used in this study to implement options only when conditions indicate a need for them. The RAND and Study Team developed a set of "signposts" for six different water delivery metrics, including the two discussed in this report—Lee Ferry Deficit and Lake Mead Pool Elevation. Signposts specify a set of observable system conditions and thresholds that indicate that vulnerabilities are developing. During a simulation, the model monitors the signpost conditions; if any thresholds are crossed, then it implements options from the top of the portfolio option list. In this way, the dynamic portfolios seek to more realistically mimic how options would be implemented over time in response to system needs.

Table S.2
Descriptions of Four Portfolios

Portfolio Name	Portfolio Description
Portfolio A (Inclusive)	Includes all options included in the other portfolios
Portfolio B (Reliability Focus)	Emphasizes options with high technical feasibility and high long-term reliability; excludes options with high permitting, legal, or policy risks
Portfolio C (Environmental Performance Focus)	Excludes options with relatively high energy intensity; includes options that result in increased instream flows; excludes options that have low feasibility or high permitting risk
Portfolio D (Common Options)	Includes only those options common to Portfolio B (Reliability Focus) and Portfolio C (Environmental Performance Focus).

NOTE: The portfolio names in parentheses were developed for this report only. The *Colorado River Basin Water Supply and Demand Study* used only the lettered names (Reclamation, 2012f, 2012h).

Simulating the Colorado River System and Performance Metrics (R and M)

The Basin Study used the Colorado River Simulation System (CRSS), Reclamation's long-term planning model, to simulate the Colorado River system. CRSS estimated the future performance of the system with respect to a large set of different types of performance metrics—*water deliveries* (nine metrics), *electric power resources* (two metrics in three locations), *water quality* (one metric in 20 locations), *flood control* (three metrics in ten locations), *recreational resources* (two metrics in 13 locations), and *ecological resources* (five metrics in 34 locations).

While the full Reclamation report used all the performance metrics, this report focuses on two key water delivery metrics—Lee Ferry Deficit and Lake Mead Pool Elevation. These were the metrics used in the Basin Study to compare the performance of options and strategies, as they broadly summarize the reliability of the Upper and Lower Basins, respectively. If there is a Lee Ferry deficit, then there could be delivery reductions in the Upper Basin to augment flows to the Lower Basin. The health of the Lower Basin system and deliveries to the Lower Basin states are similarly closely tied to the Lake Mead elevation.

Future Vulnerabilities to Colorado Basin Water Deliveries

Using the RDM approach and inputs described above, RAND and the Study Team first evaluated the vulnerabilities of the Colorado River system. We addressed two key questions: (1) under which futures does the Basin not meet water delivery objectives, and (2) what future external conditions lead to vulnerabilities? Again, here we focus on the two key water delivery performance metrics.

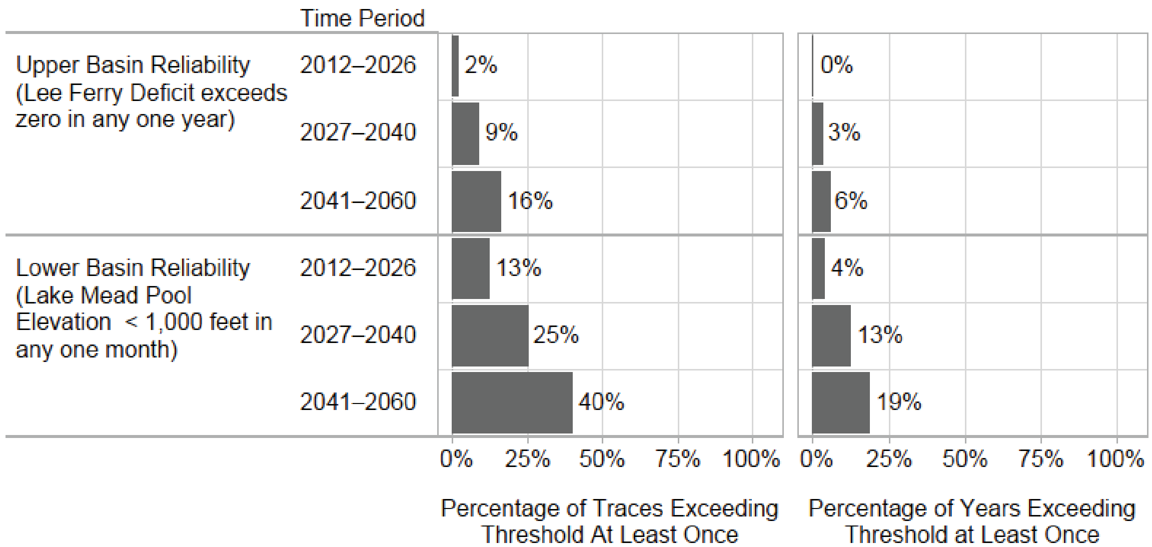
Under Which Futures Does the Basin Not Meet Water Delivery Objectives?

Figure S.1 summarizes Upper Basin Reliability (Lee Ferry Deficit) and Lower Basin Reliability (Lake Mead Pool Elevation) across all 23,508 traces representing future uncertainty in two ways: (1) the percentage of traces in which management objectives are not met at least once during the time period (left side), and (2) the percentage of all years in the simulation in which outcomes did not meet objectives (right side). For Upper Basin Reliability, the percentage of traces in which at least one Lee Ferry deficit occurs increases from 2 percent (from 2012 through 2026) to 16 percent (from 2041 through 2060), with Lee Ferry deficits occurring in 6 percent of the years (three years) in the last period (top half of the figure). Similarly, for Lower Basin Reliability, Lake Mead elevations fall below the 1,000-foot elevation threshold more frequently across traces and years in later periods.

What Future External Conditions Lead to Vulnerabilities?

While the above analysis tells us how vulnerable the Current Management approach is over time, it does not tell us what external conditions lead to those projected vulnerabilities. Using RDM vulnerability analysis techniques and statistical summaries of streamflow at Lee Ferry, we looked for a set of future conditions that best captures the vulnerable traces. We find that the Upper Basin is susceptible to a Lee Ferry Deficit when two future conditions are met: long-term average streamflow declines beyond what has been observed in the recent historical record (below 13.8 maf per year) and there is an eight-year period of consecutive drought years where the average flow dips below 11.2 maf per year. Traces that meet both of these

Figure S.1
Summary of Long-Term Water Delivery Outcomes That Do Not Meet Objectives



RAND *RR242-S.1*

conditions—called Declining Supply vulnerable conditions—lead to a Lee Ferry deficit 87 percent of the time.

Using the same approach, we find that Lake Mead elevation is vulnerable to conditions in which supplies are simply below the long-term historical average—specifically, when long-term average streamflow at Lees Ferry falls below 15 maf, and an eight-year drought with average flows below 13 maf occurs.[1] We call these conditions Low Historical Supply vulnerable conditions, and they describe 86 percent of all traces that lead to unacceptable results. We also defined vulnerable conditions for both the Upper Basin and Lower Basin delivery reliability using climate inputs to describe supply in the Historical and Future Climate supply scenarios.

Reducing Vulnerabilities Through New Management Options

RAND and the Basin Study Team evaluated the four portfolios of supply-augmentation and demand-reduction options—*Portfolio A (Inclusive)*, *Portfolio B (Reliability Focus)*, *Portfolio C (Environmental Performance Focus)*, and *Portfolio D (Common Options)*—across all the scenarios described above. We next reviewed how each performed under the vulnerable conditions—Declining Supply and Low Historical Supply. We find that implementation of the portfolios reduces the number of years in which the system fails to meet Basin goals across many, but not all, scenarios.

[1] Lee Ferry is close to, though slightly downstream from, the U.S. Geological Survey flow gauge at Lees Ferry, Arizona. The Paria River enters the Colorado River between these locations, leading to small differences in flows between the two points. In this report, we use "Lee Ferry" when referring to the Compact delivery requirements from the Upper to Lower Basin, and "Lees Ferry" when referring to natural streamflow measurements of the Colorado River.

How Well Do Portfolios of Options Reduce Vulnerabilities?

For the Upper Basin Reliability metric—Lee Ferry Deficit—implementation of the portfolios reduces the percentage of years and traces in which deficits occur. *Portfolio C (Environmental Performance Focus)* is more effective than *Portfolio B (Reliability Focus)* in reducing vulnerabilities. For the Lower Basin Reliability metric—Lake Mead Pool Elevation—implementing the portfolios significantly reduces the number of years in which the Basin goals are not met. Even in the most stressing Declining Supply vulnerable conditions, the percentage of years is reduced from 50 percent to around 25 percent. These reductions in yearly vulnerability, however, do not lead to significantly fewer traces in which Lake Mead elevation drops below 1,000 feet in at least one year. The results also show that *Portfolio B (Reliability Focus)* is somewhat more effective at reducing Lower Basin vulnerability than *Portfolio C (Environmental Performance Focus)*.

The implementation of portfolios increases the robustness of the system and shrinks the set of conditions in which the system would not meet its goals. The Basin becomes less vulnerable to lower flow sequences and drying periods. In terms of climate conditions, with a portfolio in place, the Basin performs well over warmer and dryer climate conditions. Chapter Five provides more specific detail.

What Are the Key Trade-Offs Among Portfolios?

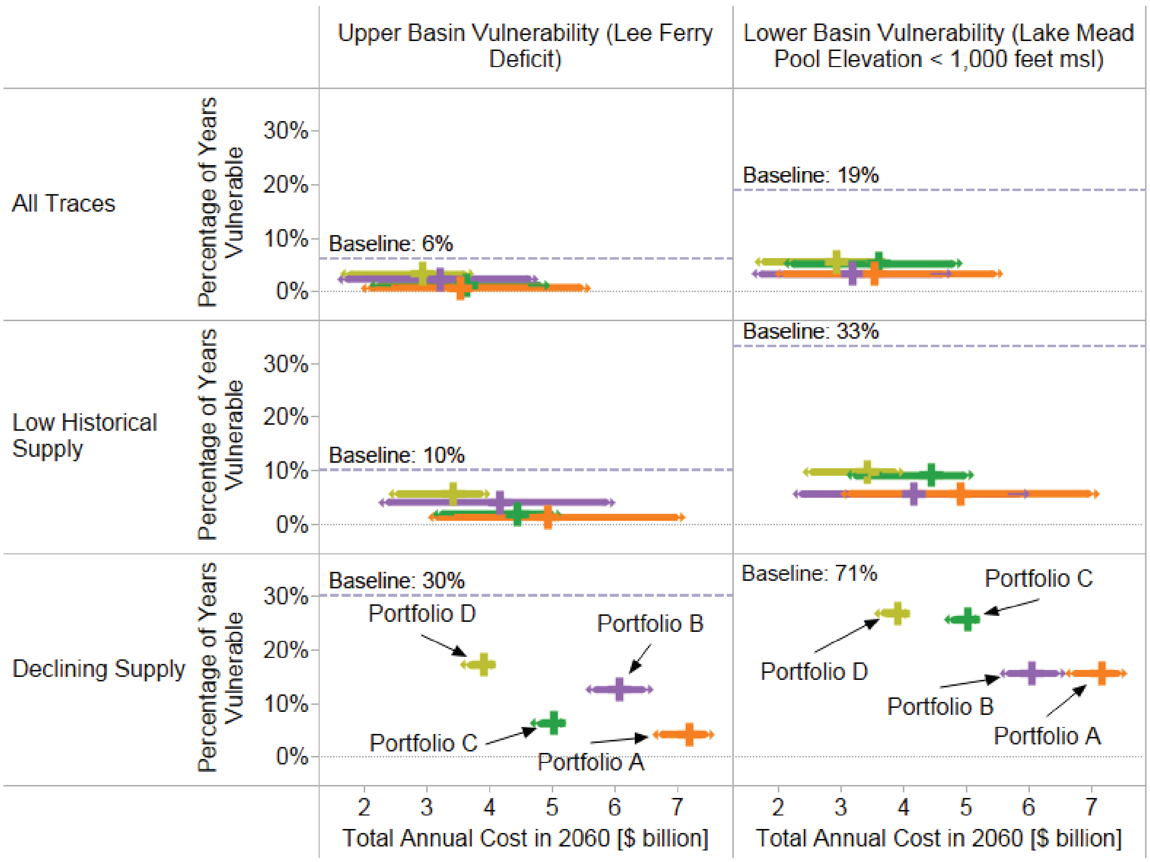
How effective the portfolios are in reducing vulnerabilities is not the only criterion for assessing them. Implementation costs, which increase over time as options are implemented in response to the signposts, are another assessment criterion. There is a wide range in costs across the traces. For *Portfolio A (Inclusive)*, for example, the costs range from just under $2 billion per year to more than $7 billion per year in 2060. This wide range of costs indicates that the dynamic portfolios as designed for the study help restrain unnecessary investment in futures when conditions do not warrant it.

One of the advantages of the RDM approach is that it allows us to combine the cost and vulnerability results together to draw out the distinctions and trade-offs among the four portfolios. Figure S.2 shows total annual implementation costs in 2060 for the four portfolios (the horizontal axis) and the percentage of years vulnerable from 2041 to 2060 (the vertical axis) for all traces and for the two vulnerable conditions. We are looking for portfolios that have the lowest costs (farthest to the left in all the graphs) and that reduce vulnerabilities the most (the lowest on all the graphs). The portfolios are distinguished by color here, with the labeling shown in the bottom band in the figure.

As shown in the figure, we find little difference among portfolios when looking across *all traces* evaluated. That is, the range in vulnerability reduction and costs overlap significantly for all the portfolios (the top band in the figure). This is not surprising because there are many traces evaluated in which there is only a modest need for improvement. All four of the portfolios can address those needs using options with similar costs.

However, when we focus on traces corresponding to the two vulnerable conditions, we see some differences across the portfolios. First, in the Low Historical Supply conditions (the middle band in the figure), we see that the portfolio with the most options (*Portfolio A*) most reduces the number of years in which the Upper Basin and Lower Basin goals go unmet. The ranges in costs (horizontal spread) across the traces increase significantly, but there is again significant overlap among the portfolios.

Figure S.2
Trade-Offs Between Portfolio Costs and Vulnerabilities (2041–2060) Across Portfolios for the Upper and Lower Basins



RAND *RR242-S.2*

When we only include traces in the *Declining Supply* vulnerable conditions (the bottom band in the figure), the trade-offs become clear. For the Upper Basin (left panel of the figure), *Portfolio C (Environmental Performance Focus)* is not only more effective than *Portfolio B (Reliability Focus)* and *Portfolio D (Common Options)*, it costs significantly less than *Portfolio B (Reliability Focus)*. Only *Portfolio A (Inclusive)* reduces vulnerability more, but it does so at significantly higher cost. *Portfolio C (Environmental Performance Focus)* dominates because it includes an Upper Basin water bank, which is used at Lee Ferry to maintain flow to the Lower Basin and excludes other, more expensive, new supply options (discussed more in Chapter Six).

However, performance with respect to the Lower Basin objectives in the Declining Supply vulnerable conditions (the bottom band in the figure, right panel) shows that *Portfolio B (Reliability Focus)* improves reliability as well as or better than the other portfolios in all three sets of conditions. *Portfolio B (Reliability Focus)* includes more options that directly benefit the Lower Basin, including Pacific Ocean desalination projects. Given this more focused investment, *Portfolio B (Reliability Focus)* dominates *Portfolio A (Inclusive)* by being just as effective but less costly.

Implementing a Robust, Adaptive Strategy for the Colorado River Basin

The CRSS simulations of portfolios reveal traces in which options are implemented. Options that are implemented across many traces soon after they become available can provide the foundation of an initial robust strategy. We focus this analysis on the two vulnerable conditions (i.e., Declining Supplies and Low Historical Supplies) identified by this study, because these represent conditions when options are generally needed to alleviate system imbalances.

Identification of Near-Term Options as a Foundation of a Robust Strategy

For each portfolio, we identified those options that are almost always needed regardless of differing assumptions about future conditions. Because *Portfolio D (Common Options)* includes only options selected for both of the two stakeholder-derived portfolios (*Portfolios B* and *C*), options always or frequently implemented in this portfolio as soon as they are available can be considered both near-term and high priority.

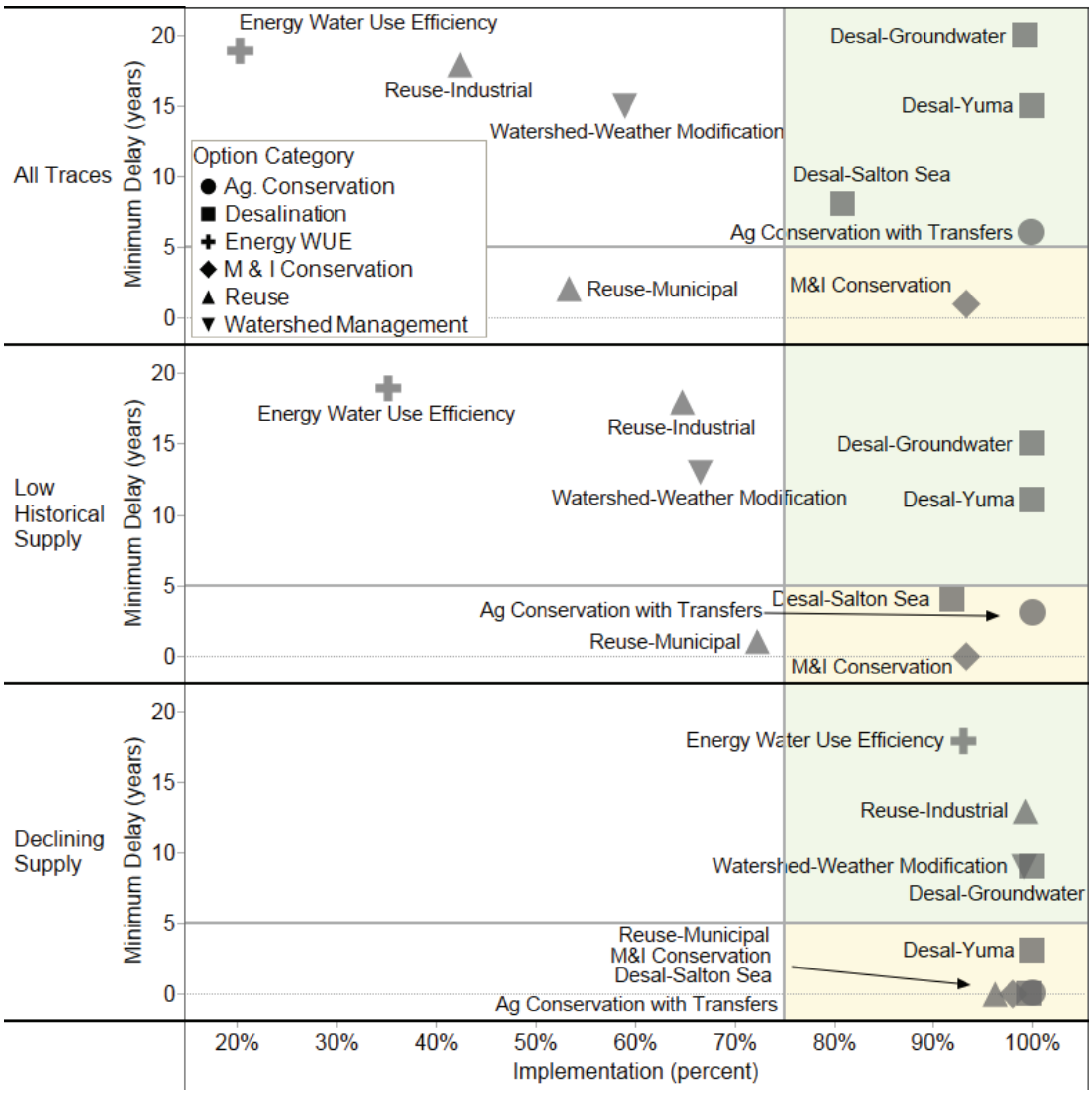
Figure S.3 summarizes how frequently options from *Portfolio D (Common Options)* are implemented by 2060 (horizontal axis) and the delay in their implementation (vertical axis), expressed as the median delay across all traces relative to the time they become available. The results are presented for three sets of traces—all traces (top panel), those traces in the Low Historical Supply vulnerable conditions (middle panel), and those traces in the Declining Supply vulnerable conditions (bottom panel).

Results in the lower-right corner of the all traces panel (bounded by five years or less and 75 percent implemented or more) are near-term, high-priority options. In this case, M&I Conservation is shown to be required in more than 90 percent of all traces examined in the study with a minimum delay of only one year. Agricultural Conservation with Transfers is implemented in almost 100 percent of traces, but with a delay of six years. Three desalination options—Desal–Salton Sea, Desal-Yuma, and Desal-Groundwater—are all high-priority but are needed only after delays of eight years or more.

For future conditions consistent with the two key vulnerable conditions—Low Historical Supply and Declining Supply—more options are needed, with less delay. The middle panel of Figure S.3 shows that for the Low Historical Supply vulnerable conditions, the urgency of implementation of Agricultural Conservation with Transfers and Desal-Salton Sea increases, making them both near-term, high-priority options. The Reuse-Municipal option is also required in more than 70 percent of traces. The bottom panel shows that for Declining Supply vulnerable conditions, all options in *Portfolio D (Common Options)* are needed by 2060 in nearly all traces.

Figure S.3 shows that most of the options in the *Portfolio D (Common Options)* are needed in only some future traces and in many cases are implemented only after a delay. However, the conditions corresponding to the Low Historical Supply vulnerable conditions have been experienced in the recent past and those corresponding to the Declining Supply are predicted by many global climate model simulations. As the Basin Study highlights, the Basin does not need to commit to all possible options now, but it might use the available lead time to prepare to invest in new options if conditions suggest they are warranted. The implementation of some options with longer lead times will need to be initiated soon so they would be available if needed under particular future traces. Exploring plans during this time for design and permitting of selected options would provide decision makers with a hedge against potential delays in implementation if the options are needed in response to changing conditions.

Figure S.3
Percentage of Traces in Which Options Are Implemented and Associated Implementation Delay for *Portfolio D (Common Options)*



NOTE: Ag = agricultural; Desal = desalination; WUE = water use efficiency.
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Monitoring Conditions to Signal Implementation of Additional Options

Reclamation and other agencies are already collecting critical information (e.g., streamflow, climate conditions, status of the reservoirs) that can be used to inform assessments of which options should be implemented in the future. Building this information into systematic and recurring system assessments would enable managers and users of the Basin to better understand how conditions are evolving and plan for additional management options accordingly.

The vulnerability analysis specifically showed that the Upper Basin is vulnerable to climate conditions that are consistent with many of the simulated conditions emerging from a variety of global climate models. Over the next few years, new climate models or higher-resolution regional climate projections might make it easier to discern whether the future climate is going continue to deviate from the historical record. If the results from improved models are consistent with the more pessimistic current projections, the Basin is increasingly likely to face vulnerable conditions for the Lee Ferry Deficit and Lake Mead Pool Elevation levels. Many of the options identified as necessary under these conditions would need to be considered for implementation.

Options to Implement If Future Conditions Warrant

The analysis has shown that as vulnerable conditions develop in the Basin, increasingly expensive adaptations will be required. The analysis highlighted which options would be needed and when. However, for many of these options, preparation would need to begin well before the time of implementation. For this mid- to longer-term implementation period of a robust, adaptive strategy, Reclamation and the Basin States could identify the key long lead-time options that may be needed and begin to take near-term planning and design steps to ensure their availability.

It may also be beneficial to consider additional management and governance-based approaches for addressing future imbalances. Many of these options, such as some types of water transfers, could be consistent with the current Law of the River, but could not be easily modeled by CRSS within the time available to complete the study. As suggested by the Basin Study, evaluating these additional options in the coming months could further improve the ability for the portfolios to address supply and demand imbalances. Revisiting the options included in the portfolio is fully consistent with the RDM analysis framework used in the Basin Study. Comparing and contrasting the performance and other attributes of additional approaches alongside the adaptive options evaluated for the Basin Study would support the successful implementation of a robust, adaptive strategy.