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# Colorado River Basin Water Supply and Demand Study

## Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies

U.S. Department of the Interior
Bureau of Reclamation

December 2012

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# Acronyms and Abbreviations

| | |
|---|---|
| 2007 Interim Guidelines | *Record of Decision for Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* |
| 2007 Interim Guidelines Final EIS | *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement* |
| af | acre-feet |
| Ag | agricultural |
| Basin | Colorado River Basin |
| Basin States | Colorado River Basin States |
| CDF | Cumulative Density Function |
| cfs | cubic feet per second |
| Compact | Colorado River Compact |
| CRSS | Colorado River Simulation System |
| desal | desalination |
| DOI | U.S. Department of the Interior |
| EC | extraordinary conservation |
| EIS | Environmental Impact Statement |
| ft | feet |
| GCM | General Circulation Model |
| GWh | gigawatt-hour |
| Gulf | Gulf of California |
| ICS | Intentionally Created Surplus |
| kaf | thousand acre-feet |
| kafy | thousand acre-feet per year |
| M&I | municipal and industrial |
| maf | million acre-feet |
| mafy | million acre-feet per year |
| Mexico | United Mexican States |
| msl | above mean sea level |
| MWD | Metropolitan Water District of Southern California |

| | |
|---|---|
| PBO | Programmatic Biological Opinion |
| Reclamation | Bureau of Reclamation |
| ROD | Record of Decision |
| SJCP | San Juan Chama Project |
| SNWA | Southern Nevada Water Authority |
| SoCal | Southern California |
| SSI | self-served industrial |
| Study | Colorado River Basin Water Supply and Demand Study |
| USFWS | U.S. Fish and Wildlife Service |
| WAPA | Western Area Power Administration |
| YDP | Yuma Desalting Plant |

# Technical Report G — System Reliability Analysis and Evaluation of Options & Strategies

## 1.0 Introduction

The Colorado River Basin Water Supply and Demand Study (Study), initiated in January 2010, was conducted by the Bureau of Reclamation's (Reclamation) Upper Colorado and Lower Colorado regions, and agencies representing the seven Colorado River Basin States (Basin States) in collaboration with stakeholders throughout the Colorado River Basin (Basin). The purpose of the Study is to define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin States that receive Colorado River water over the next 50 years (through 2060), and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The Study contains four major phases to accomplish this goal: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Options and Strategies for balancing supply and demand.

Spanning parts of the seven states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming, the Colorado River is one of the most critical sources of water in the western United States. The Colorado River is also a vital resource to the United Mexican States (Mexico). It is widely known that the Colorado River, based on the inflows observed over the last century, is over-allocated, and supply and demand imbalances are likely to occur in the future. Up to this point, this imbalance has been managed, and demands have largely been met as a result of the considerable amount of reservoir storage capacity in the system, the fact that the Upper Basin States are still developing into their apportionments, and efforts the Basin States have made to reduce their demand for Colorado River water.

Concerns regarding the reliability of the Colorado River system to meet future needs are even more apparent today. The Basin States include some of the fastest-growing urban and industrial areas in the United States. At the same time, the effects of climate change and variability on the Basin water supply has been the focus of many scientific studies that project a decline in the future yield of the Colorado River. Increasing demand, coupled with decreasing supplies, will certainly exacerbate imbalances throughout the Basin.

It is against this backdrop that the Study was conducted to establish a common technical foundation from which important discussions can begin regarding possible strategies to reduce future supply and demand imbalances. The content of this report is a key component of that technical foundation and describes the Study's analysis of system reliability.

This technical report includes an evaluation of the system reliability without options and strategies, identification and an assessment of vulnerable conditions, an evaluation of system reliability with implementation of different combinations (portfolios) of future potential options, and an assessment of those portfolios in terms of cost and timing of option implementation.

# 2.0 Approach

The overall analytical Study approach and the technical reports that correspond with elements of that approach are shown in figure G-1. As outlined in *Technical Report E – Approach to Develop and Evaluate Options and Strategies*, the Study objectives are centered on addressing the two focal questions of the Study:

1. What is the future reliability of the Colorado River system to meet the needs of Basin resources[1] through 2060?
2. What are the options and strategies required to mitigate future risks to these resources?

The first question requires an understanding of the underlying components of future reliability: water supply and water demand. Specifically, what are the factors that will determine the future availability of water, and what are the factors that will determine the future demand for water? The scenario development process, described in *Technical Report A – Scenario Development*, addresses these questions and results in scenarios that define a range of plausible future water supply and water demand. The scenarios for both water supply and water demand are described in *Technical Report B – Water Supply Assessment* and *Technical Report C – Water Demand Assessment.* The first question also requires an understanding of the needs of Basin resources. These needs are identified via the system reliability metrics described in *Technical Report D – System Reliability Metrics.* Combined, Technical Reports A – D describe the components needed, i.e., future scenarios of water supply and demand and resource metrics, to address the first question.

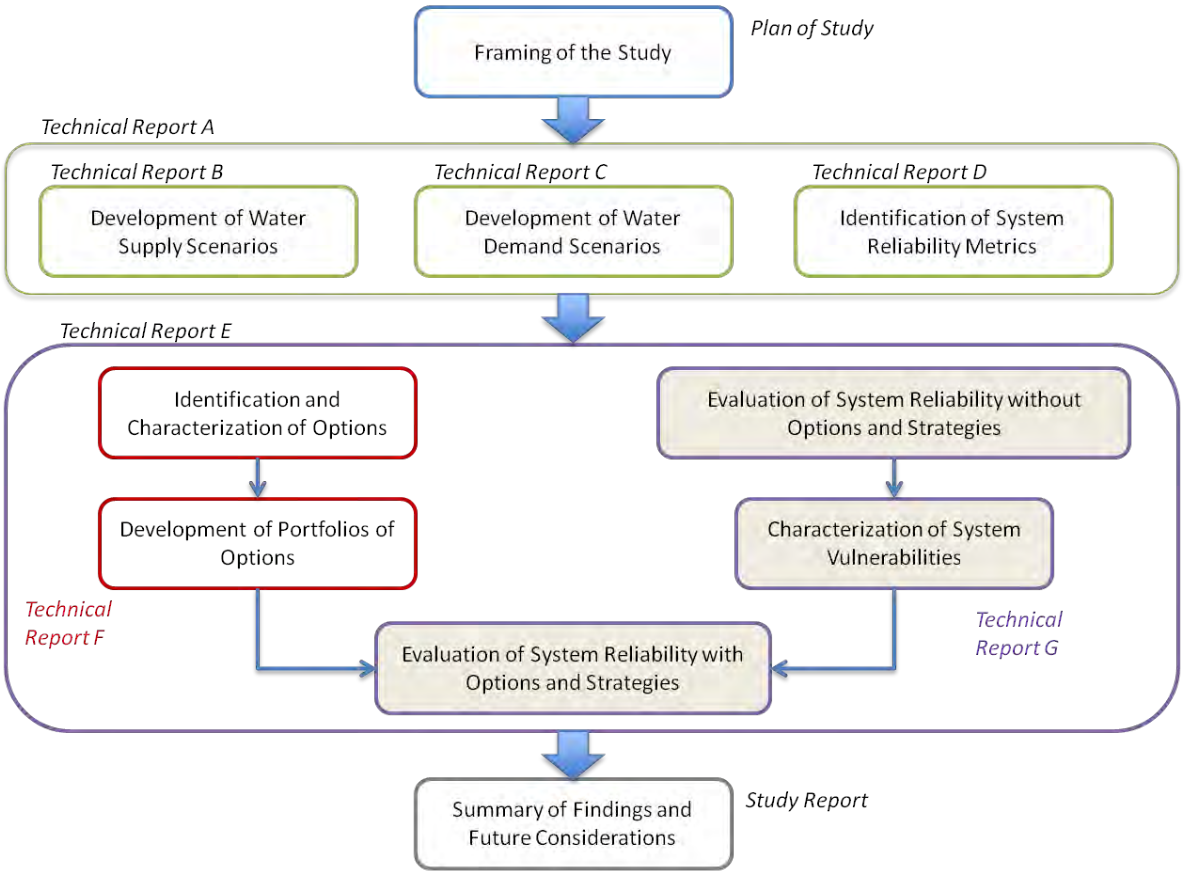
The process to address the first question required evaluation of the system reliability without options and strategies and the assessment of the outcome through the characterization of system vulnerabilities. Both are presented in this report along with the findings related to the first question, as indicated by the first two shaded boxes in figure G-1.

The second question relates to water management responses to mitigate and adapt to the potential impacts to Basin resources under plausible scenarios of the future. The main components in addressing this question are first, the identification and characterization of options and second, the development of portfolios of options. The outcomes of these two steps are the focus of *Technical Report F – Development of Options and Strategies*.

This report further presents the findings related to the second question describing the effectiveness of the portfolios at reducing system vulnerabilities through evaluation of system reliability with options and strategies, as indicated in the third shaded box in figure G-1.

[1] Resources include water allocations and deliveries consistent with the apportionments under the Law of the River; hydroelectric power generation; recreation; fish, wildlife, and their habitats (including candidate, threatened, and endangered species); water quality including salinity; flow- and water-dependent ecological systems; and flood control.

FIGURE G-1
Overall Study Approach




The activities documented in this report were carried out through a collaborative process involving representatives of numerous organizations, including Reclamation, the Basin States, federally recognized tribes (tribes), and conservation organizations. A Modeling Sub-Team and Options and Strategies Sub-Team, composed of representatives from these organizations, were established to review key modeling assumptions and results from this phase. The Modeling Sub-Team members are listed in appendix G1 of this report. Options and Strategies Sub-Team members are listed in appendix F1 of *Technical Report F – Options and Strategies*.

This report presents the methods and analysis for the 1) evaluation of system reliability without options and strategies, 2) characterization of system vulnerabilities, and 3) evaluation of system reliability with options and strategies, all shaded in figure G-1.

The general approach for the system reliability analysis and evaluation of options and strategies are summarized as follows.

- ***Evaluation of System Reliability without Options and Strategies –*** The Baseline system reliability without options and strategies was evaluated to understand current risk for comparison to system reliability with options and strategies. Under the Baseline system reliability, plausible supply, demand and operational assumption combinations were considered.

- ***Define Vulnerable Outcomes and Vulnerable Conditions* –** Based on the six resource categories, definitions of vulnerability were developed for a group of system reliability metrics. System conditions often preceding or associated with these system vulnerabilities were explored, and findings from this analysis were used to guide the implementation of options by the Colorado River Simulation System (CRSS) as part of the system reliability analysis with options and strategies.
- ***Evaluation of System Reliability with Options and Strategies* –** The system reliability was evaluated with the inclusion of options and strategies to quantify reliability improvements. A progression of four steps was taken within this analysis:
  - Evaluate how the system reliability could be improved using a portfolio in which a large set of feasible options are implemented as soon as they are available – the static framework. Within this step, demands above Lower Division States' basic apportionments were met only during Surplus Conditions[2].
  - Evaluate how the system reliability could be improved using a portfolio in which a large set of feasible options are implemented as soon as they are available. Demands *above* Lower Division States' basic apportionments can also be met by options.
  - Evaluate how the system reliability could be improved using a portfolio that triggers options in response to evolving conditions suggestive of increasing vulnerability– the dynamic framework. Demands above Lower Division States' basic apportionments can also be met by options.
  - Analyze the frequency and timing of option implementation in the dynamic portfolios gaining insight toward effectiveness of options at improving system reliability. Define common, short delay options; common, long delay options; and contingency options and explore changes in option definition based on different vulnerable conditions.

# 3.0 System Reliability Methodology

The Study developed an analytical framework that balances the capability for evaluating numerous future scenarios with providing sufficient model resolution to represent Basin resources. This section presents the main components of such a framework: 1) the inputs that define a wide range of plausible future conditions, or scenarios; 2) an appropriate Basin-wide model; and 3) a means to evaluate system performance. This section concludes with a discussion of how the study analyzes and interprets the simulation results and a description of key figures.

## 3.1 Scenarios Reflecting Uncertain Future Conditions

The Study evaluates uncertainty about future management conditions through water supply and demand scenarios, and two assumptions regarding Lakes Powell and Mead operations post-2026 (see *Technical Report A – Scenario Development*).

[2] In accordance with the Consolidated Decree and Article III of the Long-Range Operating Criteria, the Secretary of the Interior determines yearly the water supply condition for the Lower Division states.

The supply uncertainty is represented through four water supply scenarios and associated themes, each comprising many individual sequences of streamflow:

- **Observed Resampled:** Future hydrologic trends and variability are similar to the past approximately100 years—comprises 103 sequences.
- **Paleo Resampled:** Future hydrologic trends and variability are represented by reconstructions of streamflow for a much longer period in the past (nearly 1,250 years) that show expanded variability—comprises 1,244 sequences.
- **Paleo Conditioned:** Future hydrologic trends and variability are represented by a blend of the wet-dry states of the longer paleo-reconstructed period (nearly 1,250 years), but magnitudes are more similar to the observed period (about 100 years)—comprises 500 sequences.
- **Downscaled General Circulation Model (GCM) Projected:** Future climate will warm, with regional precipitation and temperature trends represented by an ensemble of future downscaled GCM projections—comprises 112 sequences.

Collectively, these four supply scenarios are modeled by approximately 1,960 future supply sequences.

Demand uncertainty is represented by six water demand scenarios, each reflecting different assumptions about future demographics and land use, technology and economics, and social values and governance. Each demand scenario is modeled by a single time sequence of water demand across the Basin, except when evaluated along with a Downscaled GCM Projected trace. In these cases, demand is calculated to vary in accordance with the climate conditions reflected by the supply trace. These storylines and their associated themes are:

- **Current Projected (A):** Growth, development patterns, and institutions continuing along recent trends
- **Slow Growth (B):** Low growth with emphasis on economic efficiency
- **Rapid Growth (C1 and C2):** Economic resurgence (population and energy) and current preferences toward human and environmental values
- **Enhanced Environment (D1 and D2):** Expanded environmental awareness and stewardship with growing economy

Under the storylines, two logical branches or directions were considered for the Rapid Growth (slower technology adoption—C1 and rapid technology adoption and slight increase in social values—C2) and Enhanced Environment (current growth trend—D1 and higher growth and technology—D2) scenarios.

Two operating assumptions reflect different Lakes Powell and Mead operations beyond 2026, when the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (2007 Interim Guidelines) (U.S. Department of the Interior [DOI], 2007), provided in the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement* (2007 Interim Guidelines Final Environmental Impact Statement [EIS]) (Reclamation, 2007), expire. In one assumption, the 2007 Interim

Guidelines are assumed to be extended through 2060; in the other assumption, operations revert to the No Action Alternative from the 2007 Interim Guidelines Final EIS.

Collectively, these scenarios and the post-2026 operations assumption describe a wide range of plausible future conditions and can be used to develop quantitative estimates of the range of system performance and Basin resource conditions. The specific way in which the Study interprets these results is provided below.

## 3.2 Simulating the Colorado River System

CRSS, Reclamation's long-term planning model, was the simulation tool utilized in the Study. CRSS simulates operations at a monthly time step and is developed in the RiverWare® modeling software (Zagona et al., 2001). Within this framework, rule-based simulation represents management policy using "If -Then" logic. This capability allows for evaluation of alternative operations and has been used in numerous Colorado River policy and environmental impact studies by both Reclamation and stakeholders.

CRSS includes a total of 12 reservoirs (Fontenelle, Flaming Gorge, Starvation, Taylor Park, Blue Mesa, Morrow Point, Crystal, Navajo, Powell, Mead, Mohave and Havasu), each with unique operational rules. In addition to policy rules for the modeled facilities, streamflow and demand input data are also required. These data constitute the various supply and demand scenarios developed as part of the Study. For streamflow, the model has 29 input nodes in the Basin, corresponding with the reaches used by Reclamation for natural flow and salt computations. Each quantified demand scenario contains data for the more than 400 water users in the model. Appendix G2 describes the key assumptions common to all simulations.

CRSS simulates future conditions based on the future supply and demand sequences, resulting in thousands of individual traces; one trace for each combination of supply, demand, and assumption regarding Lakes Powell and Mead operations beyond 2026. Table G-1 summarizes the total traces resulting from combinations of the water supply and demand scenarios and the post-2026 Lakes Powell and Mead operations assumptions. The analysis of these traces constitutes the basis for the system reliability analysis.

TABLE G-1
Summary of Scenarios and Number of Traces Used to Evaluate System Reliability

| **Supply Scenarios** | | | **Demand Scenarios** | | **Post-2026 Operation of Lakes Powell and Mead** | | **Traces** |
|---|---|---|---|---|---|---|---|
| Observed Resampled | 103 | x | 6 | x | 2 | = | 1,236 |
| Paleo Resampled | 1,244 | x | 6 | x | 2 | = | 14,928 |
| Paleo Conditioned | 500 | x | 6 | x | 2 | = | 6,000 |
| Downscaled GCM Projected | 112 | x | 6 | x | 2 | = | 1,344 |
| **Total** | **1,959** | **x** | **6** | **x** | **2** | **=** | **23,508** |

## 3.3 Performance Measures

Performance measures are critical for evaluating system reliability and facilitating the comparison of different strategies to address imbalances. Collectively referenced as system reliability metrics (metrics), these measures are distributed geographically throughout the Basin and span the six Basin resource categories considered in the Study (water deliveries, electrical power, water quality, flood control, recreational, and ecological). The metrics were developed through a collaborative process involving representatives of numerous organizations, including Reclamation, the Basin States, U.S. Fish and Wildlife Service (USFWS), National Park Service, Western Area Power Administration (WAPA), tribes, U.S. Forest Service, conservation organizations, water delivery contractors, contractors for the purchase of federal power, and others interested in the Basin.

The Study utilizes three types of metrics:

- *System response variables* representing a high-level depiction of the system operation and response to varying hydrologic, demand, and operating criteria.
- *System reliability metrics* representing more-detailed, targeted measures that aim to evaluate specific attributes of interest within each resource category. These were developed primarily through the work detailed in *Technical Report D – System Reliability Metrics.*
- *Indicator metrics* presenting a high-level view of system resources by either elevating an existing metric that is particularly telling or by combining multiple metrics into one, thus reflecting a larger area or broader scope.

Each metric type in the system reliability analysis is described in more detail below.

### *3.3.1 System Response Variables*

System response variables describe Basin conditions for the various scenarios. System response variables are a first step in investigating system performance under plausible future conditions. The variables are primarily direct model trace results such as pool elevations, hydropower generation or flow.

When describing results across the multiple traces consisting of water supply, water demand, and operational assumptions quantitative summaries of the distribution of results are often presented. For example, for a given simulated year, a figure could present the 10th, 50th, and 90th percentile results. The 10th percentile result is the level at which 10 percent of the traces have not exceeded the value shown. This output provides a gross estimate of possible future trends and operational ranges for major Basin components. The results should not be interpreted as probabilistic estimates of what could happen and therefore are more useful as measures for comparisons of different strategies rather than providing a definitive assessment of a particular resource of the Basin. Table G-2 lists the system response variables examined in the Study.

TABLE G-2
System Response Variables

| System Response Variable |
|---|
| Annual Flow of Green River at Green River, Utah |
| Annual Flow of Colorado River near Cisco, Utah |
| Annual Flow of San Juan River near Bluff, Utah |
| Total Storage Above Lake Powell |
| Upper Basin Annual Shortage |
| Lake Powell Pool Elevation above mean sea level (msl) |
| Total Upper Basin Energy Production (Cumulative Density Function [CDF] and by year) |
| Lake Powell Water Year Release |
| Lee Ferry Deficit |
| Lake Mead Pool Elevation msl |
| Lower Basin Annual Total Shortage (includes remaining demands above Lower Division States' basic apportionments) |
| Lower Basin Annual Regulatory Shortage |
| Lower Basin Surplus Probability |
| Hoover Energy Production (CDF and by year) |
| Parker and Davis Energy Production (CDF and by year) |

### 3.3.2 System Reliability Metrics

As described in *Technical Report D – System Reliability Metrics*, metrics were defined for 6 resource categories and 25 attributes of interest that can be quantified directly or indirectly based on CRSS results at one or more of 47 locations throughout the Basin. In total, approximately 100 individual metrics were developed. Table G-3 lists the resource categories and individual metrics as well as the number of locations for which each metric is quantified. The full suite of metric results is available in appendix G4.

TABLE G-3
System Reliability Metrics and Number of Locations

| Resource Metric | No. of Locations |
|---|---|
| **Water Delivery Resource Category** | |
| Upper Basin Shortage | 1 |
| Lee Ferry Deficit | 1 |
| Lower Basin Shortage | 1 |
| Lake Mead Pool Elevation < 1,000 feet msl | 1 |
| Remaining Demands above Lower Division States' Basic Apportionments | 1 |
| Upper Basin Delivery | 1 |
| Navajo Reservoir Pool Elevation < 5,990 feet msl | 1 |
| Lower Basin Delivery | 1 |
| Annual Flows at Morelos Diversion Dam Above Treaty Delivery | 1 |
| **Electrical Power Resources Category** | |
| Electrical Power Generated | 3 |
| Available Generation Capacity | 3 |
| **Water Quality Resource Category** | |
| Salinity Concentration | 20 |
| **Flood Control Resource Category** | |
| Flood Control | 1 |
| Reservoir Spill | 6 |
| Critical River Stage Related to Flooding Risk | 3 |
| **Recreational Resource Category** | |
| Shoreline Public Use Facility | 5 |
| Boating Flow Days | 8 |
| **Ecological Resource Category** | |
| Flows to Support Threatened and Endangered Species | 13 |
| Instream Flow Rights | 2 |
| Cottonwood Recruitment | 6 |
| Flow-Dependent Ecological Systems | 4 |
| Wildlife Refuges and Fish Hatcheries | 7 |

Metrics vary considerably in development complexity; some metrics only expand the type of reporting described for the system response variables, while others required specific model development and significant post-processing.

### *3.3.3 Indicator Metrics*

To provide a summary view of resource performance in different parts of the Basin, indicator metrics were developed. These indicator metrics either elevate a single metric that is particularly significant for a given Basin resource in a particular area or combine multiple metrics to provide a more regional average perspective on the Basin resource. In total, 30 indicator metrics across the 6 resource categories were developed, as detailed in table G-4. The disparate number of indicator metrics amongst resource categories is not reflective of importance, but rather the relative ease or difficulty associated with a high-level representation of a given category. For example, in the water quality resource category, the Parker to Davis reach was identified as a reasonable indicator of water quality conditions in the Lower Basin and represents a concise depiction of Basin water quality conditions. Recreation, on the other hand, includes different metrics such as river boating and lake-based recreation, which are largely dependent upon the hydrology of Upper Basin tributaries and reservoir operations. As such, a single site cannot be used to indicate the reliability of the recreational resources. Therefore, more indicator metrics are needed to represent the vulnerability of some resources.

TABLE G-4
Indicator Metrics by Resource Category

| Water Delivery | Electric Power | Recreation |
|---|---|---|
| Upper Basin Shortage<br>Lee Ferry Deficit<br>Lake Mead Pool Elevation < 1,000 feet msl<br>Lower Basin Shortage<br>Remaining Demand Above Lower Division States' Basic Apportionment | Lake Powell Pool Elevation < 3,490 feet msl<br>Upper Basin Electrical Power Generated<br>Lake Mead Pool Elevation < 1,050 feet msl | Colorado River Optimal Boating Flow Days<br>Green River Optimal Boating Flow Days<br>San Juan Optimal Boating Flow Days<br>Colorado River Total Boating Flow Days<br>Green River Total Boating Flow Days<br>San Juan Total Boating Flow Days<br>Blue Mesa Shoreline Public Use Facility<br>Navajo Shoreline Public Use Facility<br>Flaming Gorge Shoreline Public Use Facility<br>Powell Shoreline Public Use Facility<br>Mead Shoreline Public Use Facility |
| **Ecological** | **Water Quality** | **Flood Control** |
| Colorado River[1]<br>Green River<br>San Juan River<br>Yampa River<br>Hoover Dam to Davis Dam Flow reductions | Numeric Salinity Criterion below Parker Dam | Lake Mead Downstream Safe Channel Capacity |

[1] Target flows or flow recommendations from Programmatic Biological Opinions (PBOs) to support threatened and endangered species.

## 3.4 Interpreting Scenario Outcomes

The scenario planning approach considered in the Study resulted in scenarios for water supply and water demand. Combining these scenarios, along with operational assumptions related to the operation of Lakes Powell and Mead, results in a large set of plausible future conditions. Each individual combination is simulated in CRSS and the results for each combination thus define a range of plausible outcomes.

It is common practice, when using supply data based on resampled historical conditions, to weight the results of each trace equally and interpret the distribution of results probabilistically (Groves et al., 2008). For example, system reliability in a given year could be calculated as the percentage of traces in which supply was sufficient to meet demand. This approach may also be valid when using supply data based on directly sampled paleo data, such as the Paleo Resampled scenario or data conditioned on paleo sequencing, such as the Paleo Conditioned scenario. Reliability in this context is relevant to the conditions that occurred during the portion of the paleo record that was sampled and the resampling techniques are ground in accepted time series analysis (Ouarda et al., 1997; Prairie et al., 2008).

When using downscaled GCM data (i.e. Downscaled GCM Projected scenario), however, there is no theoretical basis for assuming that each sequence is equally likely. The distribution of sequences reflects the data available from GCM simulations, which is determined by different research teams and the assumptions they used. When using this type of data, the distribution of simulation results should only be interpreted as representative of the distribution of results that could be experienced under the conditions described by the scenarios.

This information, while not useful for simulating absolute outcomes, can be very useful for comparative purposes. For example, two different sets of options could be compared to understand the distribution of results across a set of GCM scenario traces. More favorable shifts in the distribution due to one set of options would suggest more favorable impacts on the system for that set of options.

The scenarios can also be pooled together to compare how distributions change. The traces should not be considered as equally likely, but simply as plausible. Note that how the scenarios are pooled will determine the final distribution. For example, if one scenario includes more traces than another, then the pooled distribution will emphasize the scenario with a greater number of traces.

The study uses the scenario results for comparative purposes only. To summarize these distributions, statistics are used that specify the level above which a particular percentage of results have not been exceeded. For example, the 10th percentile results for flows at a particular location for a specific year would be the level of flow not exceeded by 10 percent of the traces. Similarly, the 50th percentile, or median, is the level of flow not exceeded by 50 percent of the traces. The median value should not be interpreted as an average or most likely outcome—rather it is simply the central tendency of the distribution.

When pooling scenarios, the Study resampled the results so that each supply scenario contributes the same number of observations to the pool. The Paleo Resampled scenario at 1,244 traces has the largest pool and all other scenarios are resampled to match when describing system response outcomes or vulnerabilities. Practically, this means replicating results for the other scenarios such that the number of traces is equal for each scenario. For example, for the system response results presented below, the 112 Downscaled GCM Projected results are each replicated 11 times to increase the sample size to 1,232. Then 12 more sequences are randomly selected to bring the total to 1,244. To create a manageable sample set for the analysis of option implementation, results are replicated and/or sampled so that each scenario contributes 500 observations, rather than 1,244 traces. This means 500 observations were randomly sampled from the Paleo Resampled results for the options analysis, and the result from Observed Resampled at 104 traces and Downscaled GCM Projected results were replicated and/ or sampled so that each scenario contributes 500 observations, thereby matching the sample size for the Paleo Conditioned scenario. Options analysis was them performed on the equally weighted and pool scenarios.

Pooled scenario data are first evaluated in a later section using robust decision methods (Lempert et al., 2003; Groves and Lempert, 2007; Dessai and Hulme, 2007; Lempert and Groves, 2010). This approach views the scenario results not as predictions of the future, but rather a means to expansively trace out the plausible futures that may be faced by the Basin. Analysis of these results then defines those future conditions that represent vulnerabilities to the system. These vulnerabilities represent the future conditions in which the system performance is not achieving predefined goals. The options and strategies analysis, described later, then evaluates different ways to alleviate these vulnerabilities. This information can support decisions without an explicit assignment of probabilities to the scenarios.

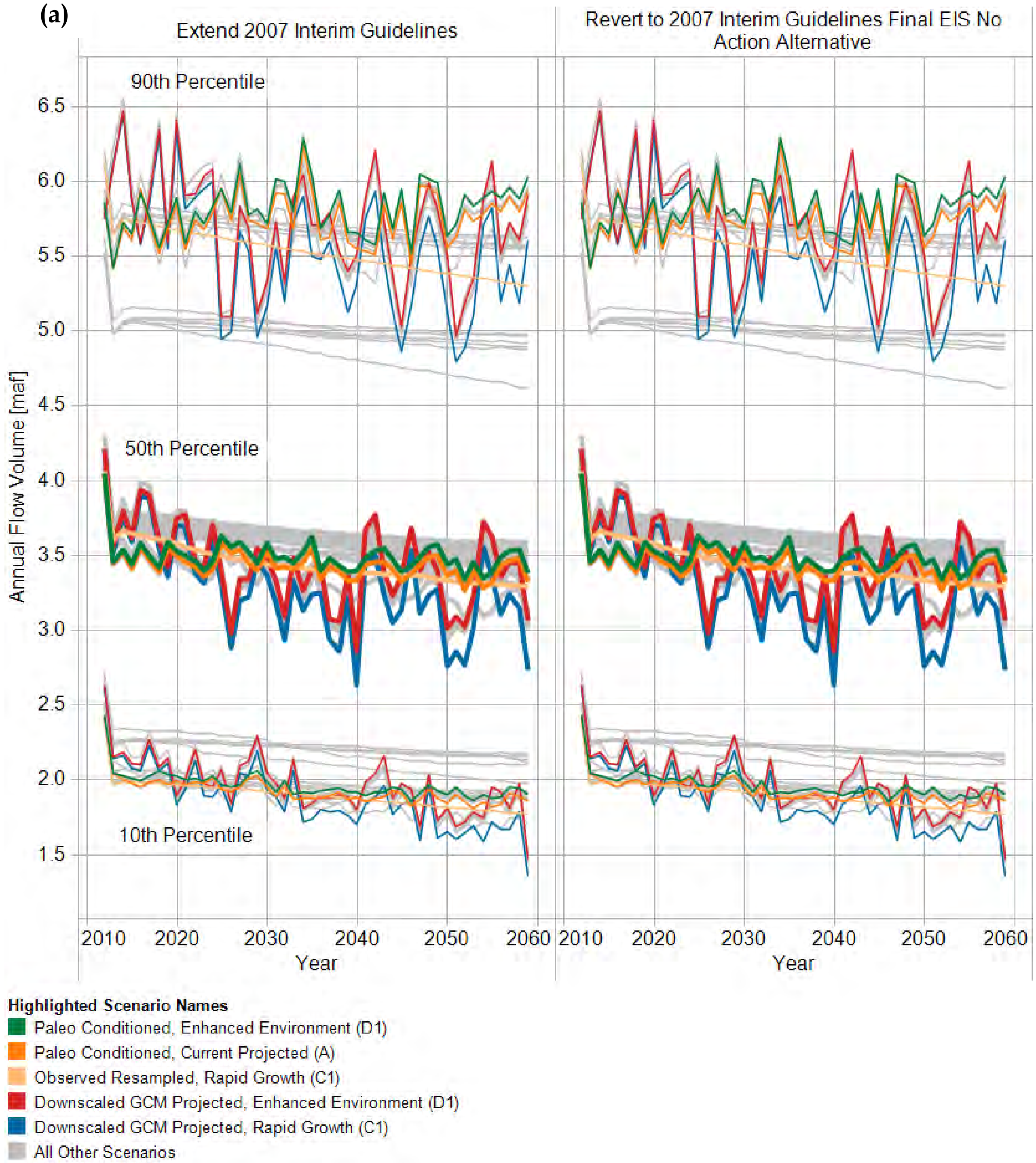
# 4.0 Evaluation of System Reliability Without Options and Strategies (Baseline Conditions)

Results for select system response variables are shown across the Basin for each combination of supply and demand scenario and assumption regarding Lakes Powell and Mead operations beyond 2026 building—a total of 48 combinations. These combinations are explored across five system response variables: Upper Basin tributary flow, Upper Basin shortage, Lake Powell pool elevation, Lee Ferry deficit, Lake Mead pool elevation, and Lower Basin shortage.

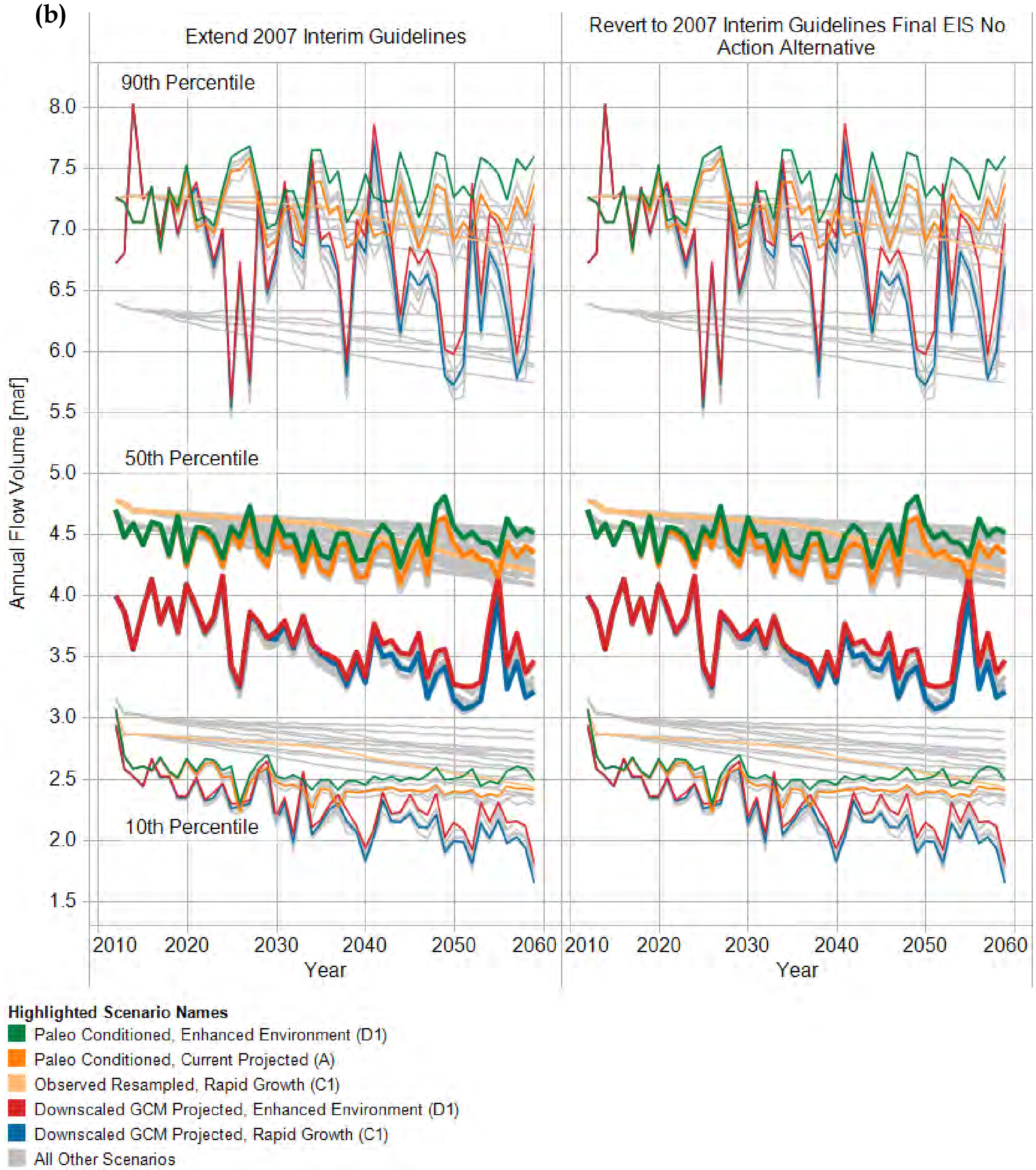
## 4.1 Upper Basin Tributary Flow

Results are presented for three key system response variables, specifically, percentiles for annual flow for three major Upper Basin tributaries. Figure G-2 presents simulated 2012 through 2060 gaged annual flow at (a) the Colorado River at Cisco, Utah ; (b) Green River near Green River, Utah; and (c) San Juan River near Bluff, Utah. Results are presented for the 48 scenario combinations. Both sides display 24 lines resulting from the combination of 4 water supply and 6 water demand scenarios. With each panel further splitting the scenarios by post-2026 operation of Lakes Powell and Mead, where the left panel is based on extension of the 2007 Interim Guidelines operation and the right panel is based on reverting to the No Action Alternative (DOI, 2007). Five scenario combinations that generally bound and fill out the results spread are highlighted and the remaining combinations are presented in gray.

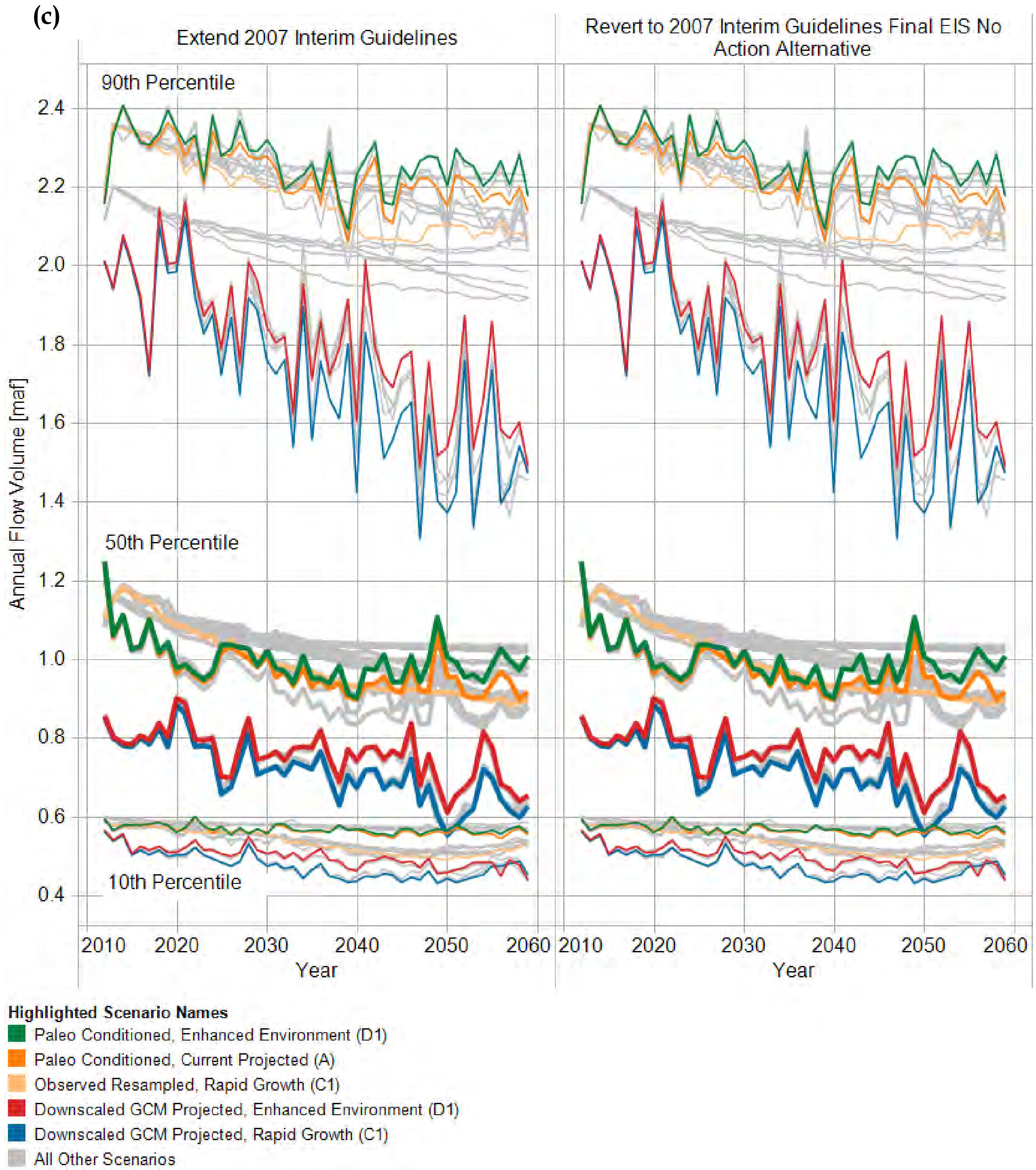
FIGURE G-2
10th, 50th, 90th Percentiles for Annual Flow at Green River, Utah (a), at Colorado River near Cisco, Utah (b) and San Juan River near Bluff, Utah (c)



**(b)**


Extend 2007 Interim Guidelines
Revert to 2007 Interim Guidelines Final EIS No Action Alternative
90th Percentile
50th Percentile
10th Percentile
Annual Flow Volume [maf]
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
2010 2020 2030 2040 2050 2060
Year
Highlighted Scenario Names
Paleo Conditioned, Enhanced Environment (D1)
Paleo Conditioned, Current Projected (A)
Observed Resampled, Rapid Growth (C1)
Downscaled GCM Projected, Enhanced Environment (D1)
Downscaled GCM Projected, Rapid Growth (C1)
All Other Scenarios

**(c)**




All sites exhibit a reduction in annual flow over the simulation period across all percentiles, primarily as a result of the increasing demands, as exhibited by the highlighted Observed Resampled, Rapid Growth (C1) scenario. The supply scenarios show the widest range of variability with the demands providing additional variability exhibited through further spread around each supply cluster. Demand variability is slightly more pronounced at the 10th and 90th percentiles, compared with the 50th percentile indicating demand variability is more pronounced at the extreme high and low flows rather than at the median.

The Green River exhibits a similar central tendency (represented by the 50th percentile) of flow magnitudes across all scenarios, indicating little change in annual flow across the four supply scenarios. Whereas for the Colorado and San Juan rivers, the Downscaled GCM Projected supply scenario has a lower central tendency than the Observed Resampled, Paleo Resampled and Paleo Conditioned scenarios indicate reduced flows in these tributaries under a Downscaled GCM projected scenario.

The highlighted Paleo Conditioned, Enhanced Environment (D1) scenarios generally provide the upper bound for the 90th percentile resulting from the more-frequent and longer-duration surplus spells exhibited by the scenario.  Whereas on the Green and Colorado Rivers, the Paleo Resampled (shown as the bottom cluster of smooth gray lines) generally provides the lower bound indicative of the reduced variance seen with the Paleo Resampled scenario, with years when Downscaled GCM scenario dips below this bound. Of note, on the San Juan River, the Downscaled GCM Projected scenario indicates a stronger reduction in high flows (displayed by the reduced 90th percentile) than any other scenario; showing the starkest change in flow under the Downscaled GCM Projected scenario across all sites.

At the 10th percentile, the Downscaled GCM Projected flows again tends to provide the lower bound across most sites, indicating a shifted distribution of lower flows produced by the Downscaled GCM Projected scenario, especially on San Juan River, where the lower 10th percentile, coupled with reduced 90th percentile flows, indicate a shift to lower flows along with a reduced variance compared with the other supply scenarios. The Paleo Resampled (shown as the cluster of smooth gray lines) generally bounds the higher 10th percentile flows, except on the San Juan River, where the Paleo Conditioned scenario serves this role, indicating higher low flows in the Paleo Conditioned scenario than the Paleo Resampled scenario. The post-2026 management assumption does not impact this response variable because no impacts are realized above Lake Powell.

## 4.2 Upper Basin Shortage

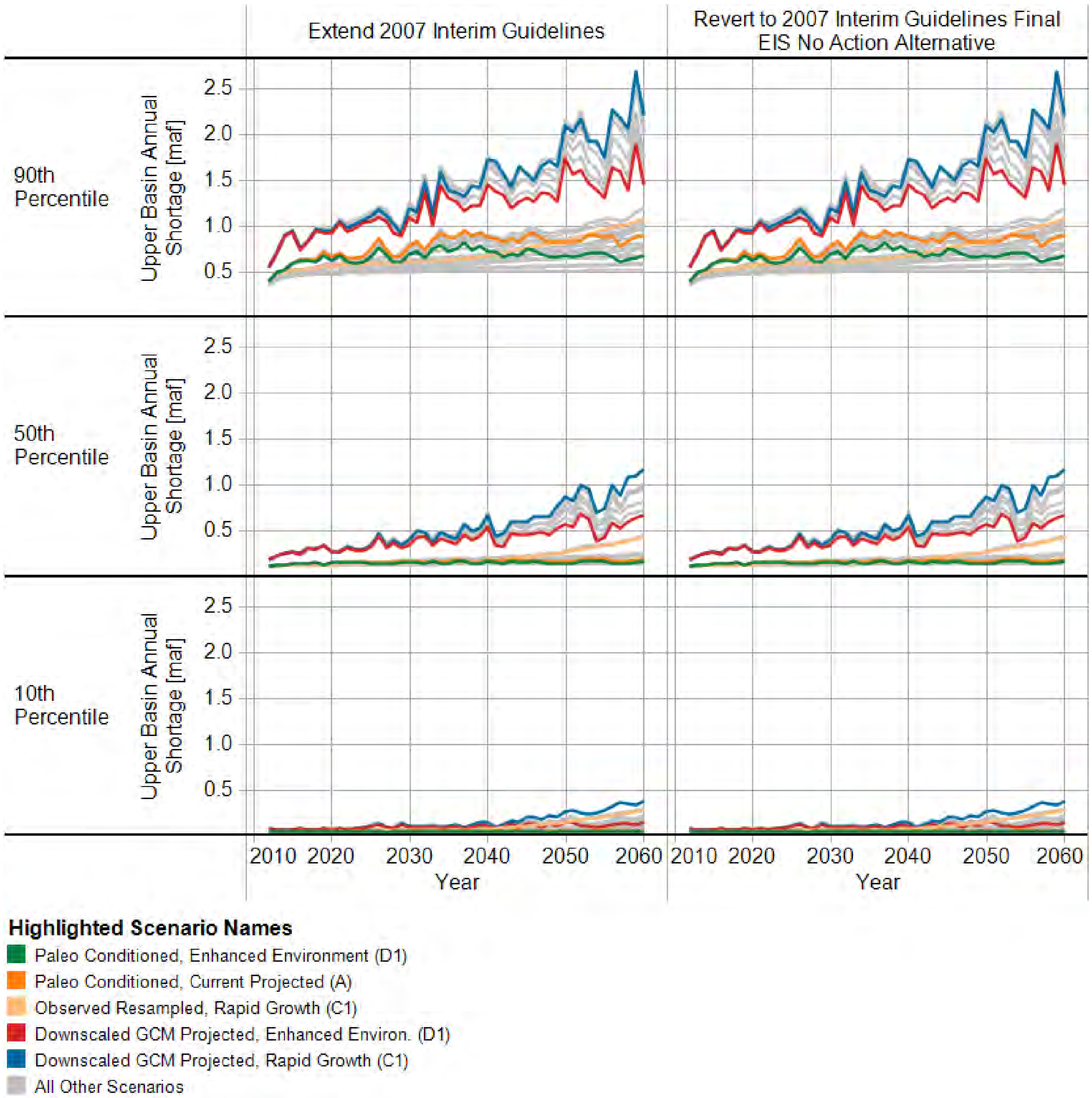
Figure G-3 presents the total Upper Basin 2012 through 2060 annual shortage, defined as requested demand minus actual delivery. However, there are significant limitations associated with CRSS when calculating annual shortages in the Upper Basin because most of the shortages are hydrologic shortages that occur on the tributaries within the Upper Basin. Therefore, this figure significantly underestimates the shortages in the Upper Basin.

Upper Basin median shortage increases significantly across all scenarios as a result of median supplies decreasing in the future, coupled with median demands increasing. Similar to historical conditions, there is always some amount of Upper Basin shortage for all traces and all years, largely due to hydrologic supply limitations on the smaller Upper Basin tributaries in the late irrigation season. In many tributaries, downstream senior rights and physical flows do not make storage a feasible option. These shortages are not affected by operation of the CRSP reservoirs. Nor do the post-2026 management assumptions impact this response variable because no impacts are realized above Lake Powell.

The Downscaled GCM Projected scenario results in the highest shortage increase due to its strong reduction in median flow.  The Downscaled GCM Projected scenario’s flow reduction, coupled with the demand increases exhibited by the Rapid Growth (C1) demand scenario, result in the largest shortages across all scenarios. The lower bound of the Downscaled GCM Projected supply scenarios cluster is defined by the Enhanced

Environment (D1) demand scenario. Even though Slow Growth (B) scenario demands were lower than the Enhanced Environment (D1) scenario demands, the latter exhibits less shortage because Enhanced Environment (D1) has lower demands in the Upper Basin than Slow Growth (B).

FIGURE G-3
10th, 50th, 90th Percentiles for Magnitude of Upper Basin Annual Shortage

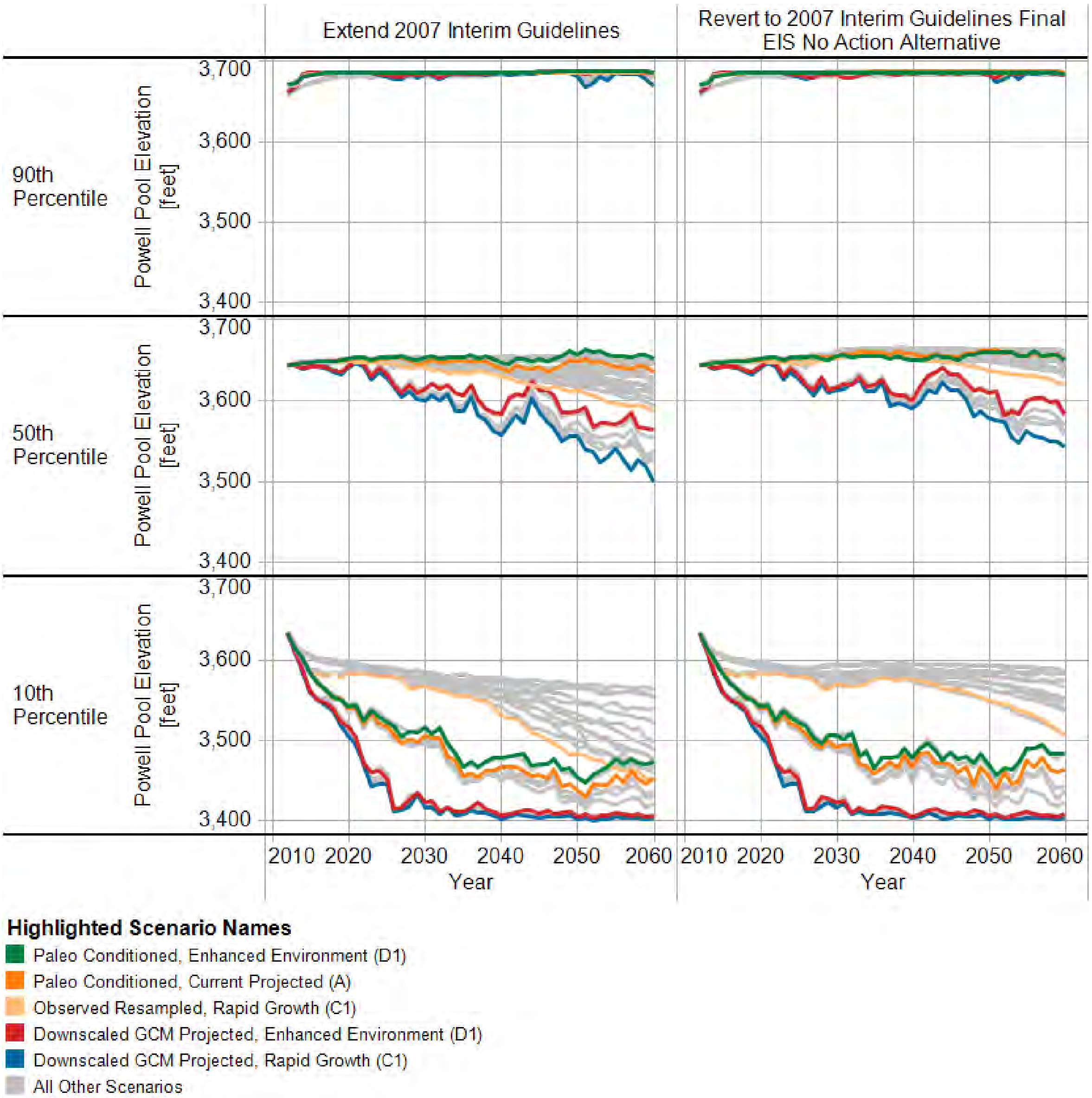



Note that there is always some amount of upper basin shortage for all years and all traces.

## 4.3 Lake Powell Pool Elevation

Figure G-4 presents Lake Powell end-of-December pool elevation. At the 90th percentile level after reservoir elevations have stabilized from initial 2010 conditions, variability across supply and demand scenarios is insignificant. This stable elevation represents the approximate peak elevation seen in December as Lake Powell begins to spill. All scenarios produce sufficient flows to maintain Lake Powell at peak end-of-December conditions.

FIGURE G-4
10th, 50th, 90th Percentiles for Lake Powell End-of-December Pool Elevation



At the 50th percentile, the Downscaled GCM Projected scenario across all demand scenarios results in lower Lake Powell levels than any other supply demand combination. The decline in elevation from 2012 levels range from 80 to 140 (-7.6 million acre-feet [maf] to -11.4 maf) feet msl by 2060, whereas across all other scenarios reservoir elevations either increase about 10 feet msl or decrease by up to 50 feet msl.

Meanwhile, the 10th percentile shows a continual decline across most scenarios. At the 10th percentile, the Downscaled GCM Projected scenario exhibits little variability across all demand scenarios after 2025. Lake Powell pool elevation (before 2030) is simulated at extremely low levels (3,400 feet msl, 0.7 acre-feet [af]), well below minimum power pool (3,490 feet msl). The Paleo Conditioned scenario shows more spread across demand scenarios by 2060 bound by the Enhanced Environment (D1) scenario (3,480 feet msl) at higher elevations and the Rapid Growth (C1) scenario at lower elevations (3,420 feet msl),which is below power pool. These extreme levels are simulated under two supply scenarios (Downscaled GCM and Paleo Conditioned) and result from the increased probability of lower flow displayed through the Downscaled GCM Projected scenario and drought sequences that are plausible based on the paleo record but have not yet occurred since the filling of Lake Powell.

Lakes Powell and Mead operation assumptions post-2026 show some influence on pool elevation. Under the assumed extension of the 2007 Interim Guidelines, generally lower elevations are seen at Lake Powell after 2026, at the 50th and 10th percentiles. This occurs due to Lake Powell balancing operations at various levels with Lake Mead, in addition to equalization operations. This is in contrast to only equalizing lake storage contents when reverting to the No Action Alternative.

## 4.4 Lee Ferry Deficit

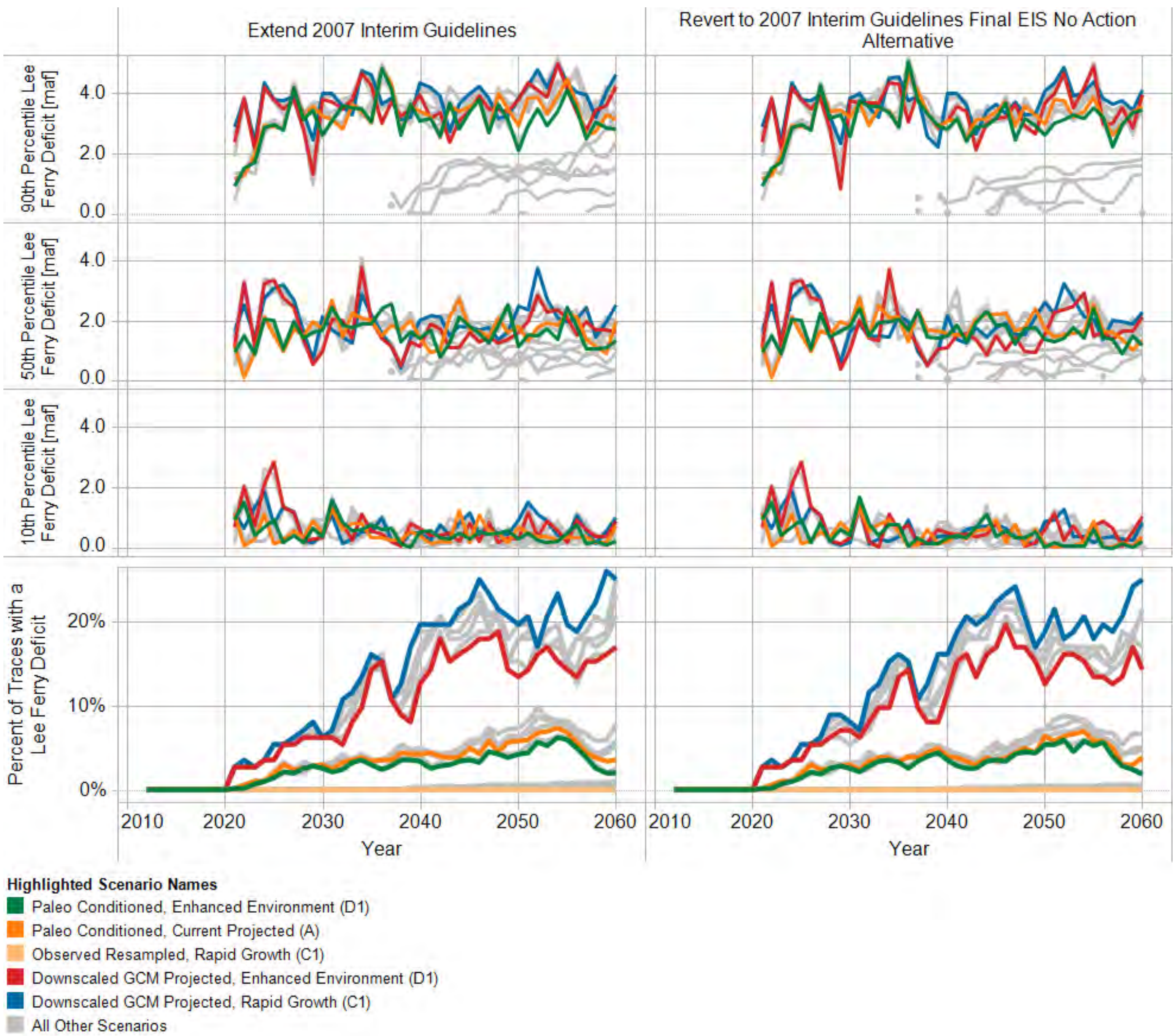
Figure G-5 presents the magnitude (bottom panel) and percent of traces (top panel) with a Lee Ferry Deficit, defined for purposes of the Study as the amount of flow less than an aggregate of 75 maf over 10 years. Lee Ferry is the division point between the Upper and Lower Basins specified in the Colorado River Compact (Compact) and is located below the Paria River.

The percent of traces exhibiting a deficit is primarily dependent on the supply scenario, with the demand scenario producing some variation around each supply. The Observed and Paleo Resampled scenarios show little increase (1 percent) by 2060 in percent of traces with a Lee Ferry Deficit. This result is consistent with this constrained sampling technique, which cannot produce drought spells or magnitudes not found in the observed or paleo reconstructed record. The increased percent of traces with a Lee Ferry Deficit exhibited under the Paleo Conditioned scenario is a result of drought sequences consistent with the paleo sequences but not found directly in the reconstructed record. The Paleo Conditioned scenario Lee Ferry Deficit results in 2 percent of traces in Deficit under Enhanced Environment (D1) demands to 8 percent under Rapid Growth (C1) demands.

The Downscaled GCM Projected scenario stresses the Upper Basin more than any other scenario; the Downscaled GCM Project scenario deficit begins at zero, and increases to 25 percent under Rapid Growth (C1) demands and 17 percent under Enhanced Environment (D1) demands.

The magnitude of deficit is generally not influenced by supply or demand scenarios. Across each percentile, the scenarios crisscross each other through time but are about 3.5 maf at the 90th percentile, 2 maf at the 50th percentile, and 500 kaf at the 10th percentile. Once a trace enters these extreme hydrologic conditions that cause a deficit, magnitudes are limited to a particular response. The post-2026 management assumption does not significantly impact this response variable.

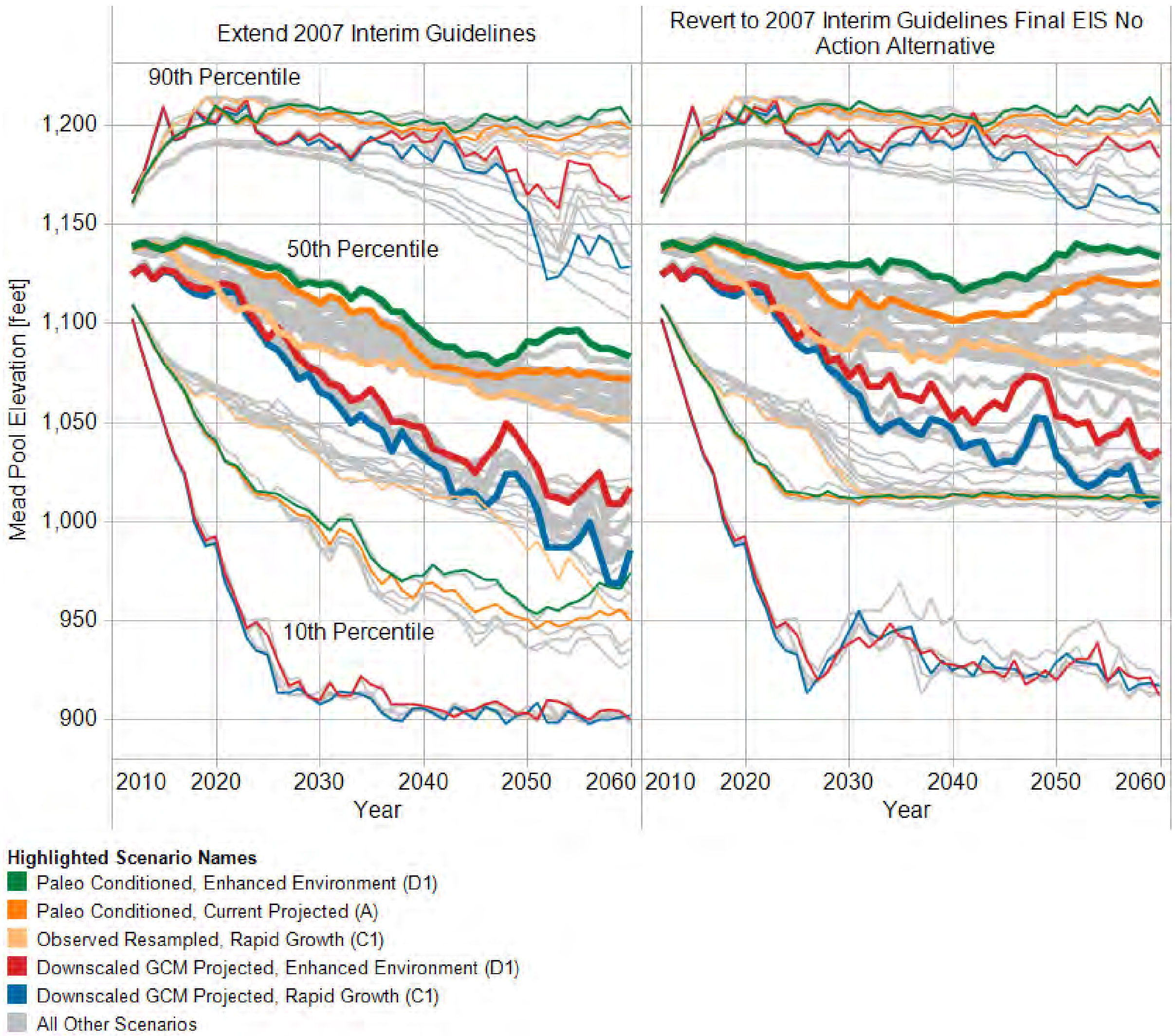
FIGURE G-5
10th, 50th, 90th Percentiles for Lee Ferry Deficit in Years in Which a Deficit Occurs (top) and Percent of Traces with a Lee Ferry Deficit (bottom)



## 4.5 Lake Mead Pool Elevation

Figure G-6 presents Lake Mead end-of-December pool elevation.

FIGURE G-6
10th, 50th, 90th Percentiles for Lake Mead End-of-December Pool Elevation




At the 90th percentile, pool elevation generally increases from initial 2010 conditions before dropping at different magnitudes for each supply scenario. The Paleo Resampled scenario (lowest cluster of smooth gray lines) shows the largest pool elevation drop by 2060, ranging from 0 to 60 feet msl. The variance in this water supply scenario is reduced compared to the observed record and does not generate the frequency of surplus spells of the observed record. Nor does it produce the magnitudes of high annual flows also seen in the observed record. The next-lowest supply scenario is the Downscaled GCM Projected scenario, with a pool elevation drop by 2060 ranging from 0 to 30 feet msl. The remaining two supply scenarios realize an increase in pool elevation ranging from 30 to 40 feet msl by 2060 across all demand scenarios. These declines are a result of less-frequent equalization and balancing releases from Lake Powell, primarily resulting from reduced supplies coupled with increasing Upper and Lower Basin demands.

At the 50th percentile, the Downscaled GCM Projected scenario across all demand scenarios projects Lake Mead elevations at lower levels than any other supply demand combination. This indicates that the reduced supply simulated under a plausible climate assumption sharply diminishes the Basin storage. The drop from 2012 levels ranges from 90 to 140 feet msl by 2060, whereas across all other scenarios the levels range from an increase of about 5 feet to a decrease of 75 feet msl.

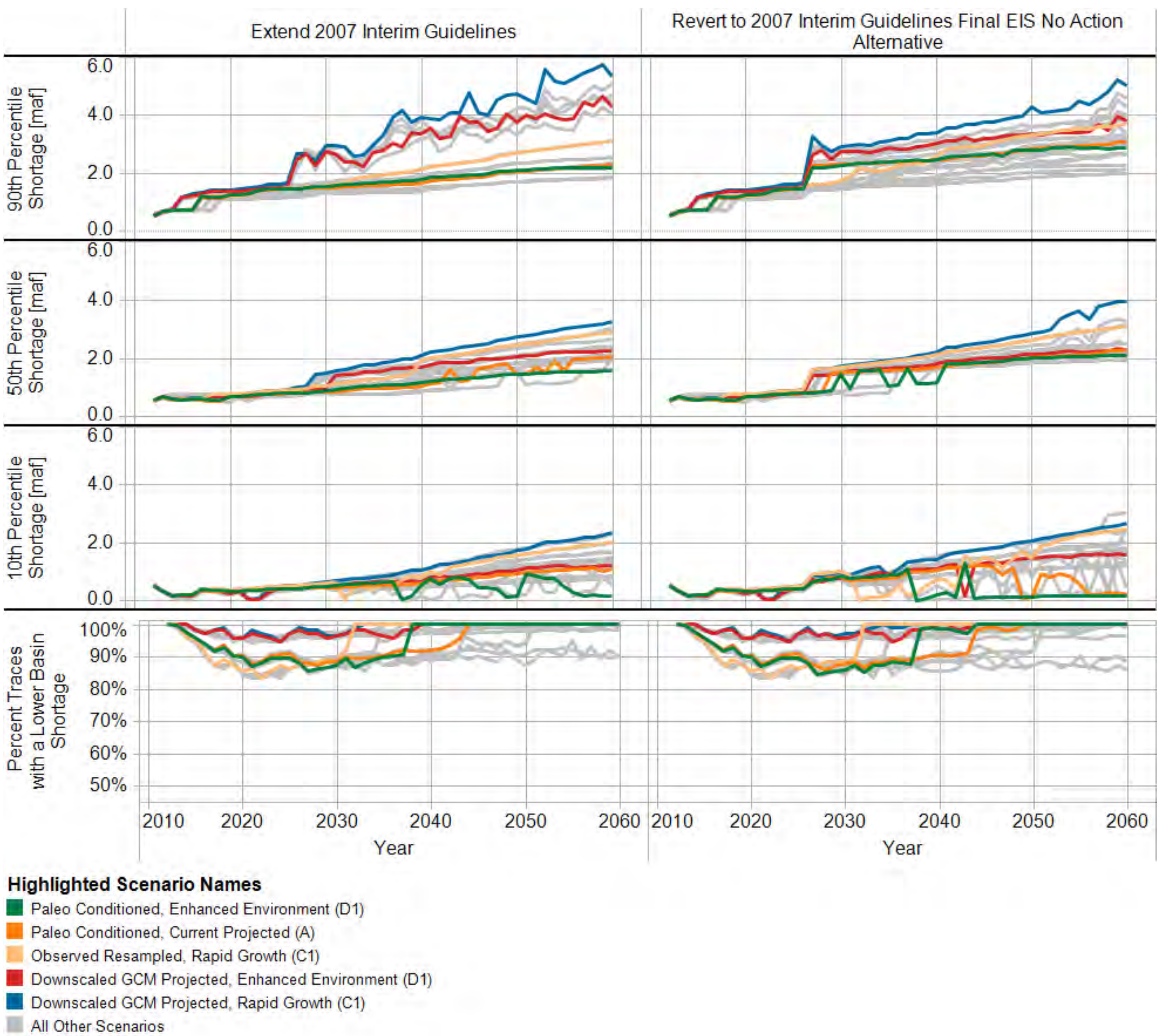
At the 10th percentile, the Downscaled GCM Projected supply scenario exhibits little variability across all demand scenarios. It also shows pool elevation reaching extremely low levels (900 feet msl), which is below the current Southern Nevada Water Authority (SNWA) minimum pumping level (1,000 feet msl). The Paleo Conditioned scenario shows a much greater spread across demand scenarios by 2060 when the 2007 Interim Guidelines (DOI, 2007) are extended. They are bound by the Enhanced Environment (D1) scenario (970 feet msl) at higher elevations and the Rapid Growth (C1) scenario a lower elevations (930 feet msl), also both below SNWA’s current intake minimum pumping level. These extreme levels are produced under these two supply scenarios as a result of an increased number of traces, with lower elevations displayed through the Downscaled GCM Projected scenario and drought sequences that are plausible based on the paleo record but have not yet occurred since the filling of Lake Mead The remaining supply scenarios 2060 pool elevations range from 950 to 1,020 feet msl.

The Lakes Powell and Mead operation assumptions post-2026 again influence results. Under the 2007 Interim Guidelines, generally lower elevations occur at both reservoirs by 2026, resulting from no change in shortage guideline assumptions once Lake Mead reaches elevation 1,025 feet msl. At this level, the Basin States have agreed to consultation to determine actions. When reverting to the No Action Alternative, an operational assumption to attempt to avoid Lake Mead declining below elevation 1,000 feet msl is implemented and effective under all but the worst supply scenario, the Downscaled GCM Projected.

## 4.6 Lower Basin Shortage

Figure G-7 presents the magnitude (top panel) and percent of traces (bottom panel) with the Lower Basin 2012 through 2060 annual total shortage, determined as regulatory and hydrologic shortages plus remaining demands above the Lower Division States' basic apportionments. The percent of traces with shortage begins at 100 percent in 2012. This results primarily from remaining demands above the Lower Division States' basic apportionment initially not being met under any traces until a few years into the future, when demands above Lower Division States' apportionments can be met in a limited number of traces through surplus events (approximately 10 percent) until 2044. After 2044, surplus events cannot cover increasing demands above the Lower Division States' basic apportionments under all traces.

FIGURE G-7
10th, 50th, 90th Percentiles for Lower Basin Shortages when Present (Regulatory, Hydrologic, and Remaining Demand above Lower Division States' Basic Apportionments) (upper panel), and Percent of Traces with Lower Basin Shortages (lower panel)



Across all percentiles, the Downscaled GCM Projected scenario results in the highest shortage increase from 530 thousand acre-feet (kaf) in 2012 to a range in 2060 of about 4 maf to 5.4 maf at the 90th percentile and 2 maf to 3.2 maf at the 50th percentile. This range was defined by the demand variability where the Rapid Growth (C1) scenario exhibited the highest shortage and the Slow Growth (B) scenario exhibited the lowest.

At the 50th percentile the supply scenarios show less difference. The Downscaled GCM Projected scenario is generally higher, with certain of the other scenarios bound by the demand variability of the Downscaled GCM Projected scenario. The remaining supply scenarios show little difference in the magnitude of shortage based on supply scenarios but show that the differences are still influenced by demand scenario variability. As a result, shortages generally increase from 550 kaf in 2012 to a range of 1.8 maf to 4 maf by 2060 at the 50th percentile. This initial 2012 shortage and continual increase in shortage is primarily driven by remaining demands above the Lower Division States' apportionments, which can only be met under surplus conditions.

The 10th percentile is similar to the 50th in that the Downscaled GCM Projected scenario is generally higher, with certain of the other scenarios bound by the demand variability of the Downscaled GCM Projected scenario. Shortage magnitudes range from 550 kaf in 2012 to a range of 100 kaf to 2.8 kaf by 2060.

The Lakes Powell and Mead operation assumptions post-2026 influence Lower Basin shortage. The 90th percentile shortage increases to 3.70 maf, and the 10th percentile shortage climbs at a slower rate to 1.2 maf. The jump in shortage magnitude observed around 2027 results from both the assumed reversion to the No Action Alternative from the Interim Guidelines Final EIS (Reclamation, 2007) for half the traces, and the reduced supplies represented under the Downscaled GCM Projected scenario.

It is important to note that the reasons for Lower Basin shortages are different than the reason for Upper Basin shortages. Lower Basin shortages are influenced by large demands, coupled with Compact allocations available to meet those demands as well as contrived operational rules that define shortages. Upper Basin shortages are caused by the lack of physical water supply, especially on the smaller tributaries.

## 4.7 Summary

System response variable results explored 48 different scenarios – 4 supply, 6 demand, and 2 post-2026 Lakes Powell and Mead operation assumptions.

In summary, without options and strategies, key system response variables indicate diminished system performance across most system measures. The findings based on this analysis are summarized below:

- Upper Basin Tributary flows exhibit a reduction in annual flow primarily as a result of the increasing demands. This reduction is further strengthened on the Colorado and San Juan rivers by the Downscaled GCM Projected scenario's reduced supplies. Further reduction resulting from the Downscaled GCM Projected scenario is minimal on the Green River.

- Upper Basin median shortage increases significantly across all scenarios as a result of median supplies decreasing in the future, coupled with median demands increasing.

Similar to historical conditions, there is always some amount of Upper Basin shortage for all traces and all years, largely due to hydrologic supply limitations on the smaller Upper Basin tributaries in the late irrigation season. In many tributaries, downstream senior rights and physical flows do not make storage a feasible option.

- Percent of traces with a Lee Ferry Deficit shows little increase (1 percent) by 2060 under the Observed and Paleo Resampled scenarios. The Paleo Conditioned scenario Lee Ferry Deficit results in 2 percent of traces in Deficit under Enhanced Environment (D1) demands to 8 percent under Rapid Growth (C1) demands. Under the Downscaled GCM Project scenario, the deficit increases to 25 percent under Rapid Growth (C1) demands and 17 percent under Enhanced Environment (D1) demands as a result of the diminishing supply. The magnitude of deficit is generally not influenced by supply or demand scenarios and ranges from about 500 kaf to 4 maf at the 50th percentile.
- Lakes Powell and Mead pool elevations both indicate a wide range of future levels. At Lake Mead under all scenarios, except the Downscaled GCM Projected, from 2012 conditions, elevations range from an increase of about 5 feet to a decrease of 75 feet msl by 2060. Under the Downscaled GCM Projected, this range shifts down to elevations dropping from 90 to 140 feet msl.
- Lower Basin shortage magnitudes reflect the increasing gap between supply and demand. As a result, shortages generally increase from 550 kaf in 2012 to a range of 1.8 maf to 4 maf by 2060 at the 50th percentile. This initial 2012 shortage and continual increase in shortage is primarily driven by remaining demands above the Lower Division States' apportionments, which can only be met under surplus conditions.

# 5.0 Defining Vulnerable Outcomes and Vulnerable Conditions

The Study uses the concept of vulnerability to aid in summarizing the future conditions in which the system's performance falls below acceptable thresholds across the wide range of indicator metrics. The performance of the Basin resources, as measured by a set of indicator metrics, varies considerably across changing and uncertain conditions. Some performance outcomes can be characterized as a largely linear or proportional response, whereas others are more aptly described in a binary manner. As a result, a unique threshold for undesirable or unacceptable performance or vulnerability was established for each of the indicator metrics. This process involved members of the Metrics and Modeling Sub-Teams as well as outreach to resource experts. The resulting vulnerability thresholds range from long-term minimum average performance to comparison against a historical range to a single-value criterion. By adding these thresholds to the process, two benefits were realized. First, by adding a vulnerability threshold to results, perspective is given as to the health/viability of the resource (e.g., is the resource close to being vulnerable?). Further, by tracking the number and persistence of vulnerable events with and without options over time, portfolio efficacy comparisons can be made using a variety of methods.

## 5.1 Vulnerability Definitions

### *5.1.1 Metrics and Vulnerability Thresholds*

In collaboration with the Metrics and Modeling Sub-Teams and resource experts, one or more vulnerability thresholds for each indicator metric were identified. Thresholds for the Water Delivery category were identified through an iterative process. Information from the WAPA was used to determine Electric Power Generation thresholds based in part on historical energy production from the Hoover, Glen Canyon, and other key hydropower facilities in the Basin. The Water Quality (salinity) and Flood Control thresholds are based on existing planning criteria for their respective indicator metrics.

Vulnerability thresholds for the Recreational and Ecological resource categories were more difficult to identify. To develop thresholds for these metrics, a comparative control-run was simulated with CRSS using constant 2015 water demand and historical hydrology to define quasi-Baseline levels for each metric. Using those results, in conjunction with input from resource experts/managers, vulnerability thresholds were established based on deviation from these control-run outcomes.

Vulnerability thresholds are listed with their corresponding indicator metrics in table G-5. Additional descriptions of these thresholds, including source and rationale, can be found in appendix G3 of this document.

TABLE G-5
Indicator Metrics and Vulnerability Thresholds

| Resource Category/ Indicator Metric | Vulnerability Threshold |
|---|---|
| **Water Delivery** | |
| Upper Basin Shortage | Shortage exceeds 25 percent of requested depletions in any 1 year |
| Lee Ferry Deficit | Running 10-year sum of deliveries falls below 75 maf in any 1 month |
| Lake Mead Pool Elevation < 1,000 feet msl | Reservoir storage is less than 1,000 feet msl elevation (SNWA current lower intake minimal pumping level) in any 1 month |
| Lower Basin Shortage | Two different thresholds are used, either of which indicates vulnerability to shortage (difference between Lower Basin basic apportionment of 7.5 maf and actual depletions)<br>(1) Exceeds 1 maf over any 2-year window<br>(2) Exceeds 1.5 maf over any 5-year window |
| Demand Above the Lower Division States' basic Apportionments | Demand above the Lower Division States' basic apportionments exceeds 1 maf in any year through 2035. Threshold decreases linearly from 1 maf in 2035 to 0.250 maf (250 kaf) in 2060. |
| **Electric Power Resources** | |
| Upper Basin Generation | Power generation falls below 4,450 gigawatt-hours per year (GWh/yr) for more than 3 consecutive years |
| Lake Powell Pool Elevation, 3,490 feet msl | Reservoir elevation falls below power pool of 3,490 feet msl in any 1 month |

TABLE G-5
Indicator Metrics and Vulnerability Thresholds

| Resource Category/ Indicator Metric | Vulnerability Threshold |
|---|---|
| Lake Mead Pool Elevation, 1,050 feet msl | Lake Mead pool elevation falls below power pool of 1,050 feet msl in any 1 month in any year |
| **Water Quality Resources** | |
| Numeric Salinity Criteria below Parker Dam | Salinity exceeds 747 milligrams per liter in at least 1 year in more than 50 percent of traces, for a given supply scenario and time period |
| **Flood Control Resources** | |
| Lake Mead Downstream Safe Channel Capacity | Streamflow below Hoover Dam greater than 28,000 cubic feet per second (cfs) in any 1 month |
| **Recreational Resources** | |
| Optimal Boating Flow Days | At least 1 year in which the number of boating flow days on the Green River, San Juan River, and Upper Colorado River is less than the 10th percentile of the control run[1] |
| Total Boating Flow Days | At least 1 year in which the number of boating flow days on the Green River, San Juan River, and Upper Colorado River is less than the minimum of the control run[1] |
| Public Use Facility Recreation Shoreline Elevation | Elevation of reservoirs drops below certain elevations in any 1 month:<br>• Blue Mesa Elevation below 7,440 feet msl<br>• Navajo Pool Elevation below 6,025 feet msl Flaming Gorge Elevation below 6,019 feet msl Powell Pool Elevation below 3,560 feet msl Mead Pool Elevation below 1,080 feet msl |
| **Ecological** | |
| Streamflow on Yampa River near Maybell, Colorado | Deviation beyond control run[1] results range for (1) base flow target success rate (based on USFWS, 2008) |
| Streamflow on Green River at Green River, Utah | Deviation beyond control run[1] results range for (1) year type distribution (2) peak flow target success rate (3) base flow target success rate (based on Reclamation, 2005) |
| Streamflow on Colorado River at State Line, Colorado | Deviation beyond control run[1] results range for (1) year type distribution (2) peak flow target success rate (3) base flow target success rate (based on McAda, 2003) |
| Streamflow on San Juan near Bluff, Utah | Deviation beyond control run[1] results range for (1) year type distribution (2) year type frequency (3) base flow target success rate (based on Reclamation, 2006) |
| Lakes Mead to Davis flow reductions | Streamflow greater than 845 kaf in any 1-year (based on Reclamation, 2004) |

[1] The control run helps understand current system variability and model biases. Demands were held constant for the entire modeling horizon at the 2015, current projected levels in the control run, and the equalization line is held constant at the 2015 level. Hydrology conditions were simulated for the 49-year period using the Observed Resampled supply scenario. For some indicator metrics, vulnerability was defined relative to control run results. For example, vulnerability could be defined as meeting a flow target less frequently than the control run results (see appendix G-3 for vulnerability detail on each indicator metric).

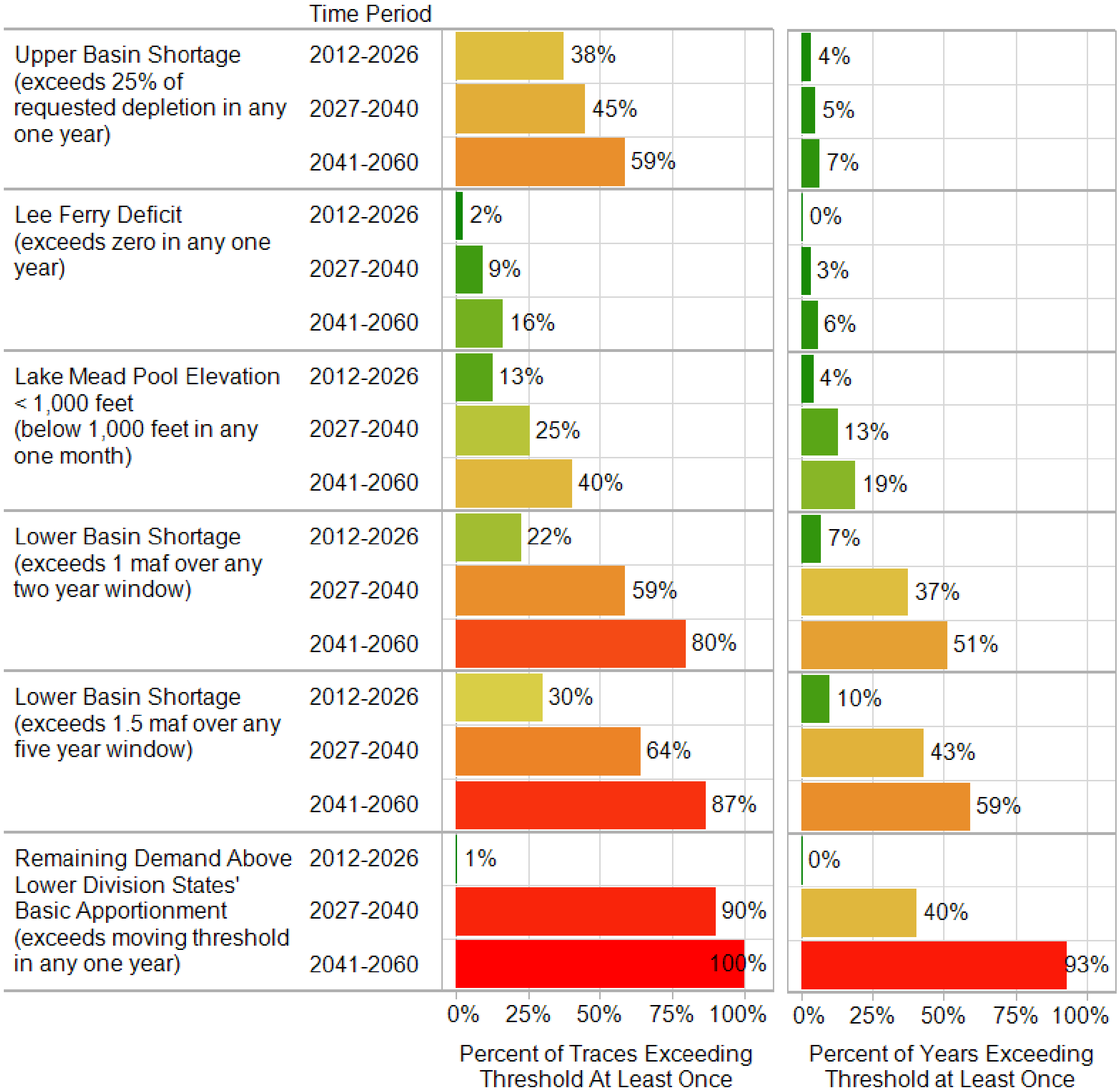
### 5.1.2 Vulnerability Results Without Options and Strategies

Using the vulnerability thresholds described above, vulnerability was summarized for each indicator metric in two ways: 1) the proportion of simulation traces in which the threshold was exceeded at least once during the time period considered, and 2) the proportion of all years in the simulation in which the threshold was exceeded. Because each supply scenario includes a different number of individual traces, these statistics were calculated by resampling traces from each supply scenario to ensure that each scenario received equal weight. Rather than provide an average value for each trace, the proportion of years summarizes the overall frequency of the vulnerability across all traces. This helps to distinguish between, for instance, traces in which the vulnerability threshold is exceeded only once versus traces in which there are many vulnerable years.

Summaries of vulnerability from CRSS simulations shown in this section are aggregated into three future time periods: 2012 through 2026, 2027 through 2040, and 2041 through 2060. The end of the first time period was selected to coincide with the expiration date of the 2007 Interim Guidelines (DOI, 2007), after which two scenarios were considered to represent different assumptions regarding the future operation of Lakes Powell and Mead. Figure G-8 shows a summary of vulnerability results without options and strategies across all scenarios for the six indicator metrics in the Water Delivery Resource Category. The figure provides bar plots of the proportion of traces (left) and years (right) in which a metric crosses the vulnerability threshold. Similar results for the remaining resource categories are provided in subsequent paragraphs after the Water Delivery vulnerability discussion below.

Figure G-8 shows that, in general, water delivery reliability is decreasing over time, resulting in increasing vulnerability. All water delivery indicator metrics show increasing vulnerability across the time periods, although the magnitude varies with each metric and the magnitude of vulnerability is much greater in the Lower Basin. For instance, the proportion of traces in which at least one Lee Ferry Deficit occurs increases from 2 percent in the period 2012 through 2026 to 16 percent in the period 2041 through 2060, with 6 percent of years in the last period yielding a nonzero deficit.  By comparison, Lake Mead storage is also declining a greater proportion of the time, with the percent of traces in which lake levels fall below the 1,000-foot elevation threshold more than doubling from the first to the last period (13 to 40 percent) and the percent of years in which levels fall below 1,000 feet msl more than quadrupling (4 to 19 percent).

FIGURE G-8
Summary of Vulnerability Without Options and Strategies for Water Delivery Metrics




Water delivery shortages to Lower Basin states also occur with greater frequency over time, with shortage vulnerabilities (i.e., exceeding 1 maf over any 2 years or 1.5 maf over any 5 years) occurring in 80 percent or more of the traces, with more than half of all years yielding a vulnerable outcome, by the 2041 through 2060 time period. Remaining demand above the Lower Division States' basic apportionment also increases past acceptable thresholds in CRSS simulations: by the period 2041 through 2060, all traces exceed the threshold at some point, and nearly all years after 2041 would be considered vulnerable. CRSS simulations show that water delivery reliability is threatened by the effects of climate change, but the increasing vulnerability noted above also emerges in simulations derived from the historical or paleo climate record. For example, figure G-9 shows the percent of traces in which Lake Mead pool elevation is projected to be below 1,000 feet msl. These results are disaggregated by time period, supply scenario (columns), demand scenario (symbols), and whether the 2007 Interim Guidelines are extended for Lakes Mead and Powell reservoir operation after 2026 (colors). For each supply scenario subset, the grey region shows range and the middle black bar the scenario median. Similar results for all water delivery indicator metrics can be found in appendix G3.

FIGURE G-9
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Lake Mead Elevation Indicator Metric (Below 1,000 feet in any One Month)

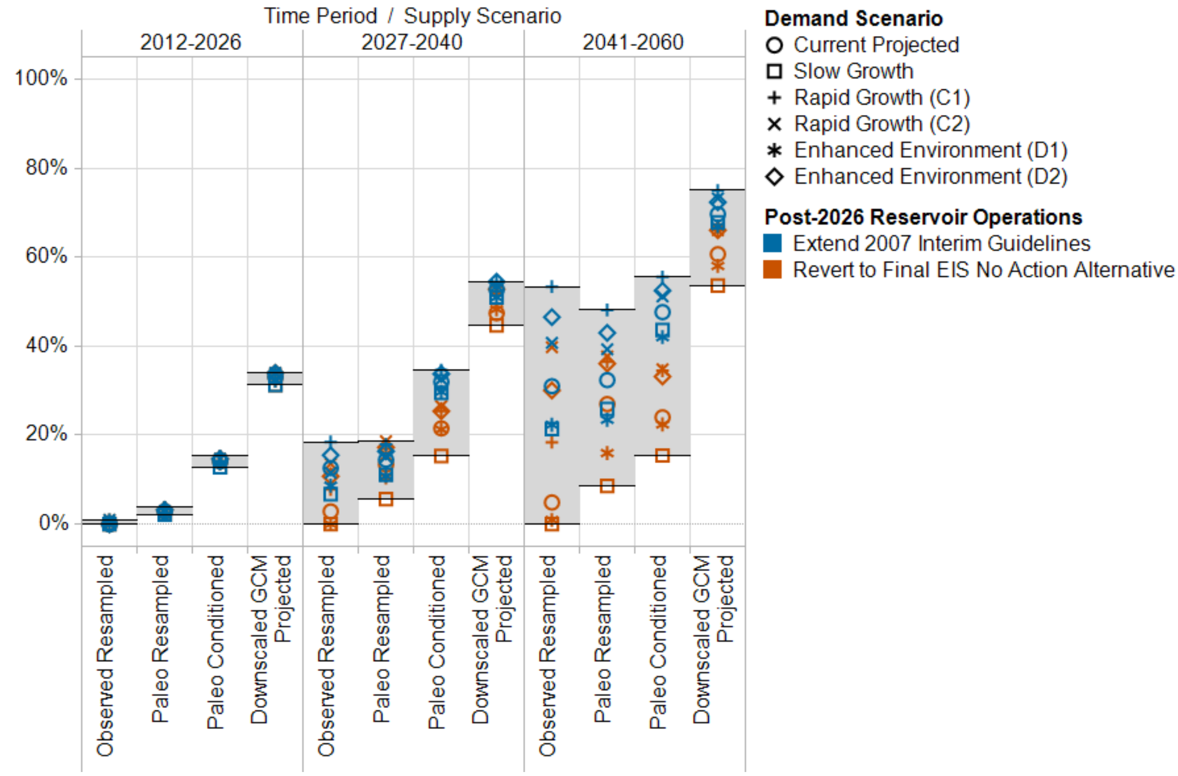



Figure G-9 shows that in the first time period (2012 through 2026), vulnerability in the Lower Basin varies primarily with the supply scenario. The Observed Resampled and Paleo Resampled scenarios cause a lower proportion of vulnerable traces, whereas the Paleo Conditioned and Downscaled GCM Projected results present a step change in percent of vulnerable traces. Little to no variation with demand scenario is noted in the first period (indicated by minimal variation in the demand scenario medians). In the second and third periods, results continue to vary across supply scenarios, but the variation between demand scenarios (same-colored symbols) increases in the Lower Basin, and a greater change is noted between traces in which the 2007 Interim Guidelines (DOI, 2007) are extended (blue) and those in which management reverts to the 2007 Interim Guidelines Final EIS (Reclamation, 2007) No Action Alternative (orange). In the final period, the relative difference between supply scenarios is of the same approximate magnitude as shown for the demand scenarios. Other water delivery metrics generally show similar patterns over variation across scenarios and over time (see appendix G3).

The exception to this pattern is remaining demand above Lower Division States' basic apportionments (figure G-10). Here, a wide range of results across the demand scenarios are seen, from 43 percent to 100 percent of traces vulnerable in the 2027 through 2040 time period. The rate of demand increase in the Lower Division States, coupled with a threshold that drops over time, drives most of the vulnerability in this instance. Further, demands above basic apportionments are only met during surplus conditions. In the Slow Growth (B) scenario, for instance, many traces do not exceed the vulnerability threshold until the final time period, whereas in scenarios with higher rates of demand growth, 75 to100 percent of traces are vulnerable by 2040. The threshold is exceeded in all scenarios by the last time period, suggesting a clear vulnerability related to growing Lower Basin demand.

FIGURE G-10
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Remaining Demand Above Lower Division States' Basic Apportionments for a Subset of All Scenarios

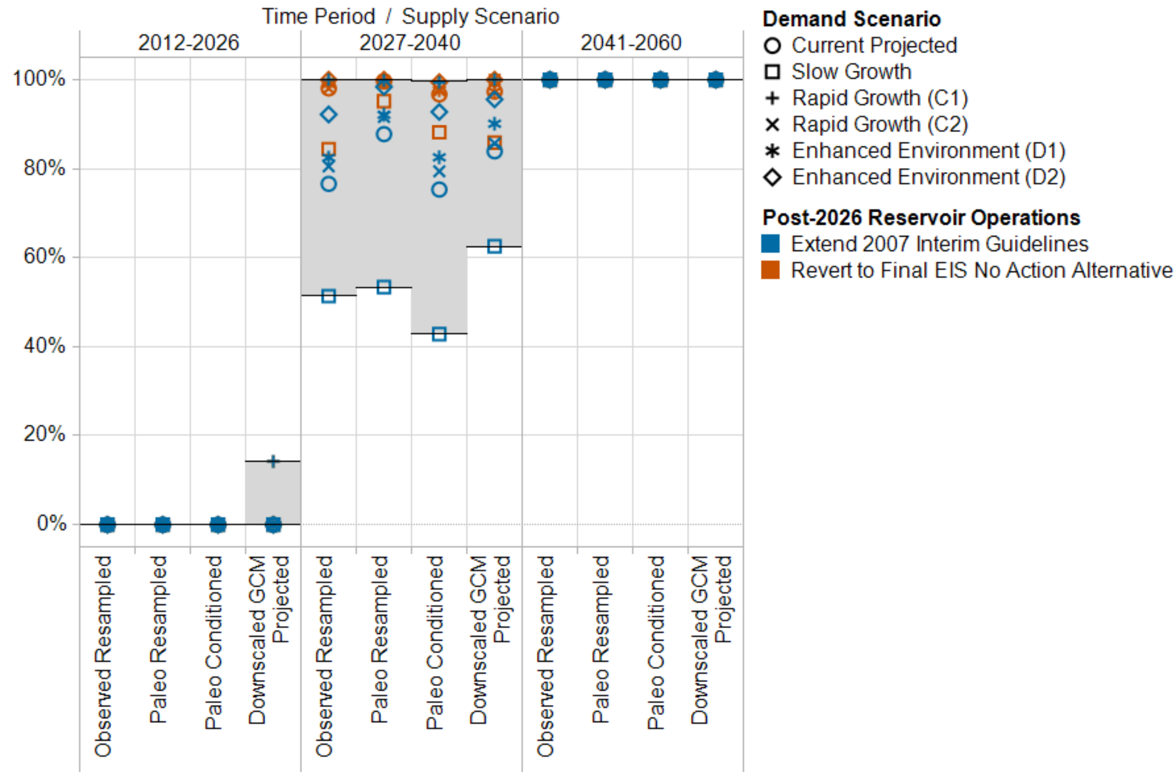


Figure G-11 shows a summary of vulnerability results without options and strategies across all scenarios for the four indicator metrics in the Electric Power Resource category. The figure shows bar plots of the proportion of traces (left) and years (right) in which a metric crosses the vulnerability threshold.

FIGURE G-11
Summary of Vulnerability Without Options and Strategies for Electric Power Indicator Metrics

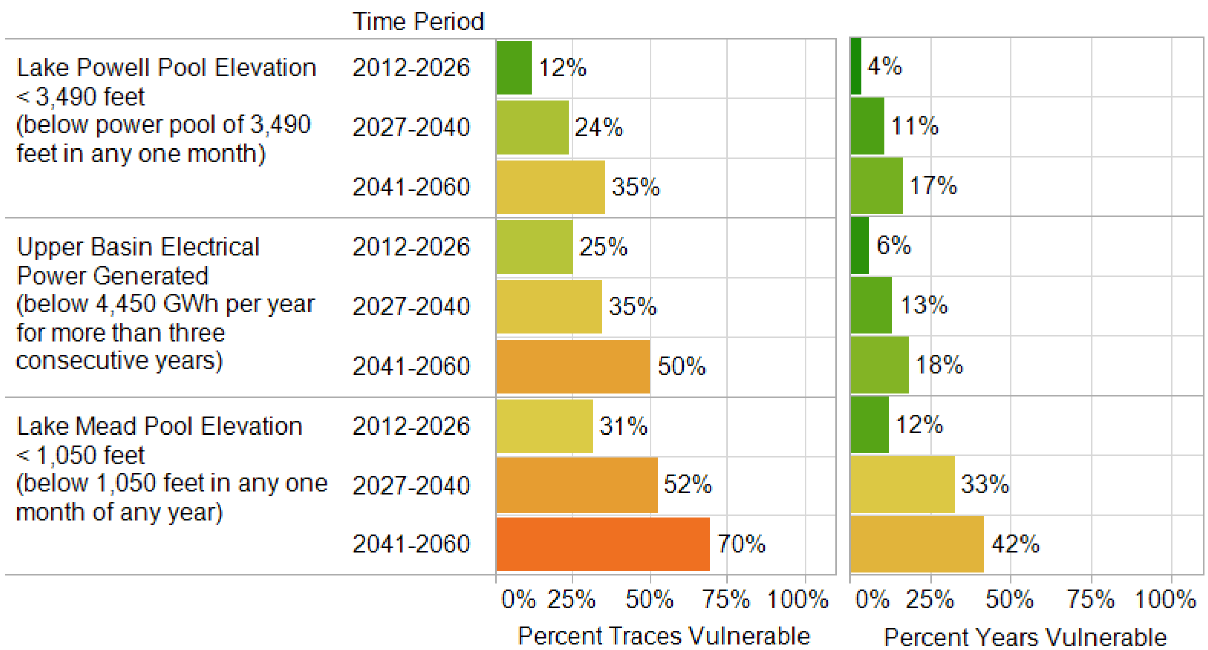



Figure G-11 shows that, in general, electric power reliability is decreasing over time. All electric power indicator metrics show increasing vulnerability across the time periods, although the magnitude varies with each metric. For instance, the proportion of traces in which Lake Mead pool elevation falls below 1,050 feet msl in any one month in any year increases from 31 percent in the 2012 through 2026 time period to 70 percent in the 2041 through 2060 time period, with 42 percent of years in the last period falling below the 1,050 foot elevation threshold

Figure G-12 shows a summary of the vulnerability results without options and strategies across a subset of all scenarios for the one indicator metric in the Flood Control Resource Category. The flood control vulnerabilities were few and actually decreased over time due to the increase in available storage associated with growing demand and reduced supply.

FIGURE G-12
Summary of Vulnerability Without Options and Strategies for Flood Control Indicator Metrics

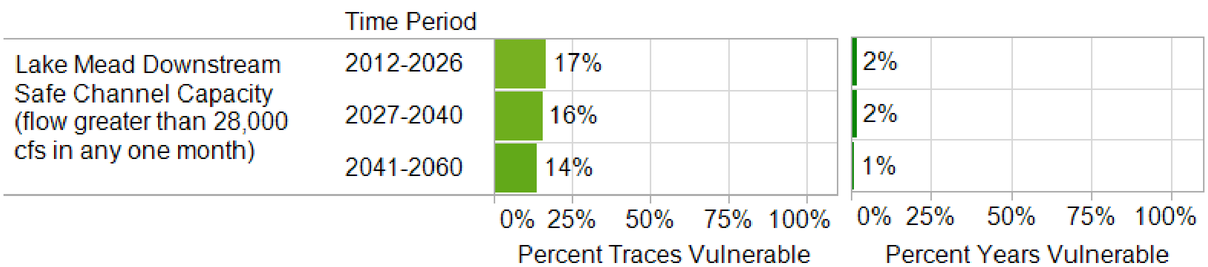
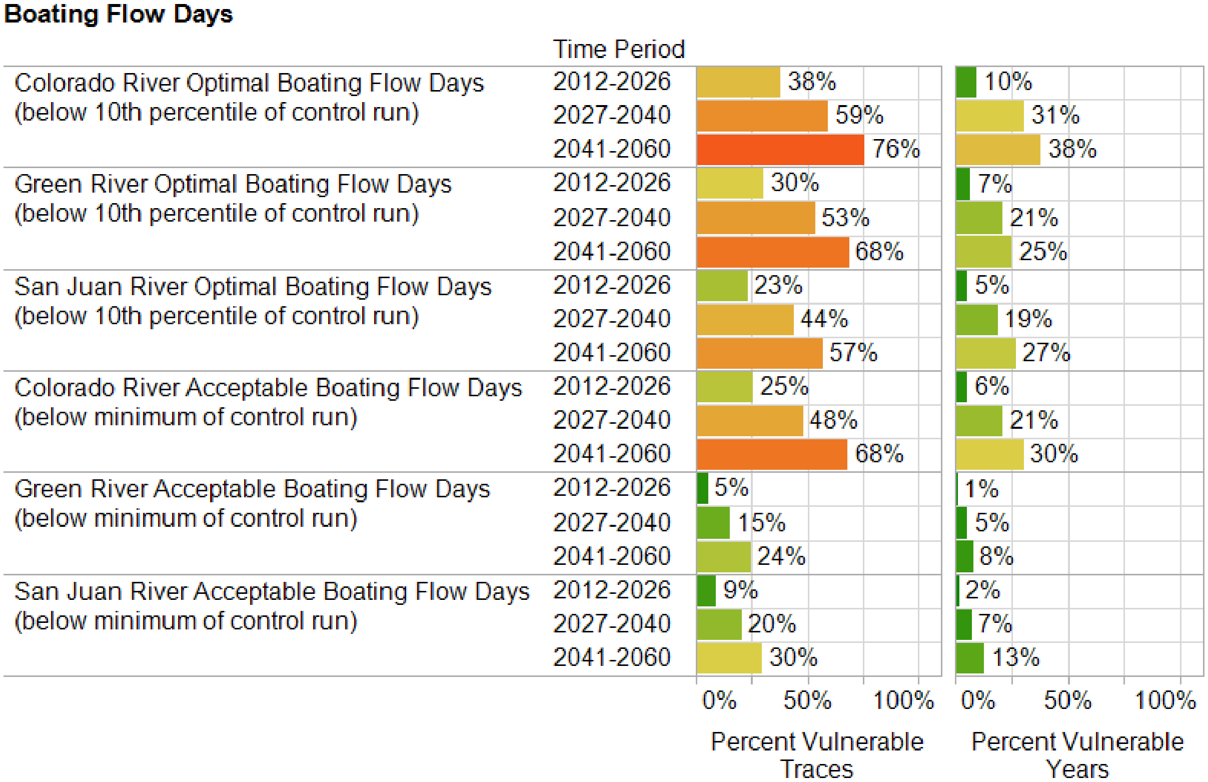



Figure G-13 shows a summary of the vulnerability results without options and strategies across a subset of all scenarios for the 11 indicator metrics in the Recreational Resource Category. River boating indicator metrics (top panel) are based on the shift in long-term average availability of flows deemed *acceptable* (total days) and *optimal* (optimal days) as determined from an American Whitewater survey analysis documented in *Technical Report D – System Reliability Metrics*. Between the total and optimal flow metrics, the optimal metrics were consistently more vulnerable. This is because the window for optimal flows is more stringent and thus more sensitive to changes in flow. For reservoir recreation (bottom panel), Flaming Gorge reservoir performs notably well. This is due to a combination of less reduction in flow projections in the Upper Green River compared to other tributaries and slower growth relative to other regions. Blue Mesa and Navajo reservoirs exhibit the most stress under future demands without options and strategies.

Due to model constraints, the metric for the Water Quality Resource Category, salinity below Parker Dam, is only available in the Observed Resampled and Paleo Resampled supply scenarios. Without options enacted, across the available supply scenarios, salinity below Parker Dam does not violate the numeric criteria.

FIGURE G-13
Summary of Vulnerability Without Options and Strategies for Recreational Indicator Metrics



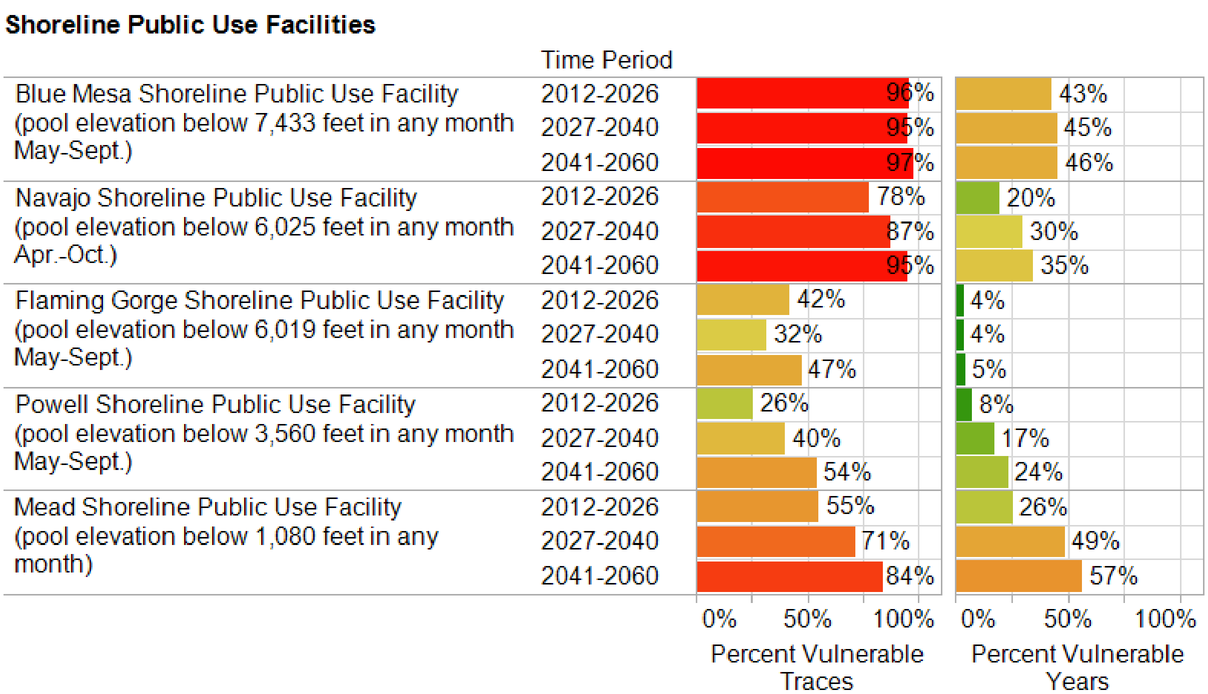
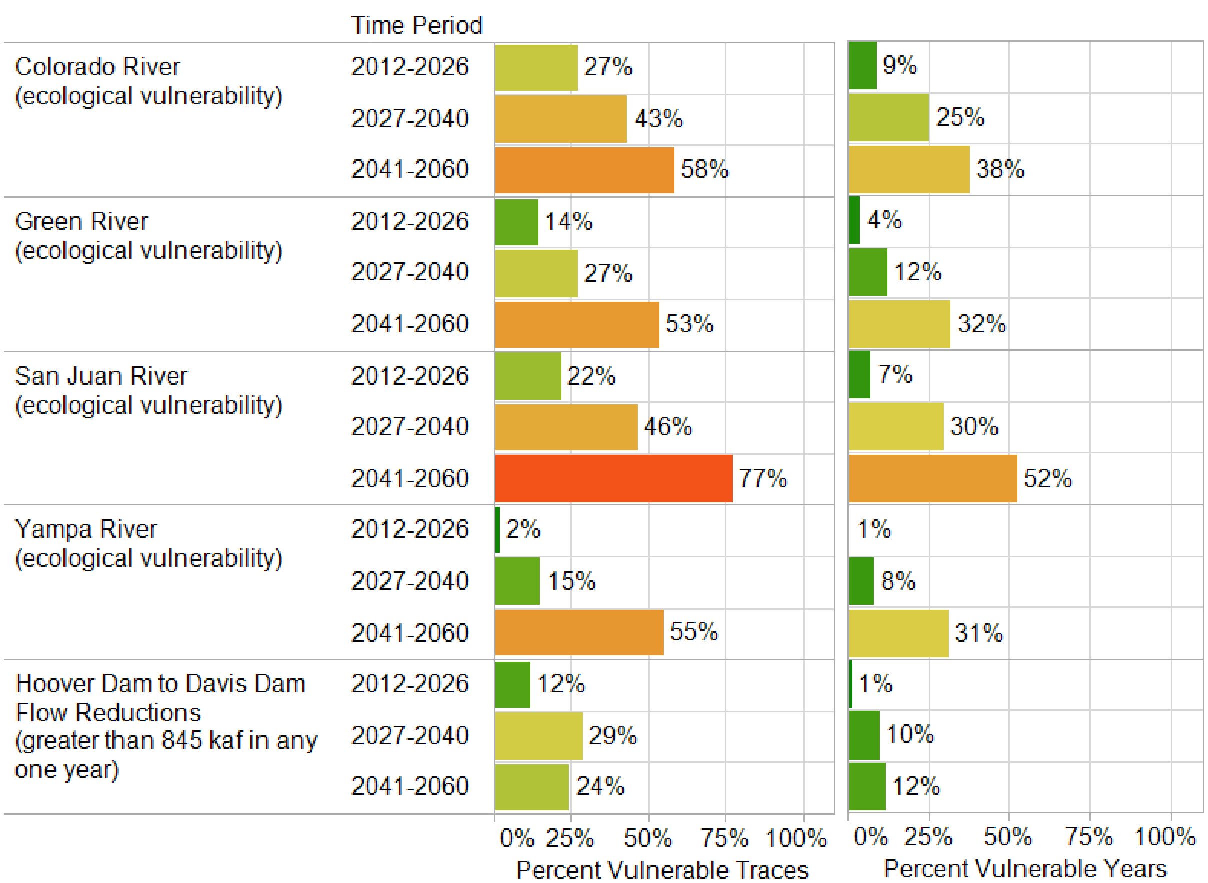



Figure G-14 shows a summary of the vulnerability results without options and strategies across all scenarios for the five indicator metrics in the Ecological Resource Category. As detailed in *Technical Report D – System Reliability Metrics*, ecological metrics are multi-faceted. In order to establish vulnerability criteria, the performance of each metric's components (e.g., meeting base flow or peak flow recommendations) was quantified in a control run based on the historical hydrology scenario and demands fixed at 2015 projected levels. Thus, during the course of a simulation, should the performance of a metric facet become degraded beyond the performance range of the control run, that outcome was deemed vulnerable. The specific details and nuances of the process for each of the metrics presented below can be found in appendix G3. All ecological indicator metrics show increasing vulnerability across the time periods, although the magnitude varies with each metric. For instance, the proportion of traces in which the San Juan River ecological indicator metric is vulnerable increases from 22 percent in the 2012 through 2026 period to 77 percent in the 2041 through 2060 period, with 52 percent of years in the last period indicating vulnerability. Increased vulnerability is primarily a result of decreasing overall flows, increasing demands and shifting monthly flow distributions that may violate existing flow recommendations.

FIGURE G-14
Summary of Vulnerability Without Options and Strategies for Ecological Indicator Metrics



## 5.2 Vulnerable Conditions

### *5.2.1 Defining Vulnerable Conditions*

Resources of the Basin are deemed vulnerable for futures in which an indicator metric violates its respective vulnerability threshold. These futures are a product of specific supply, demand, and management combinations, and vulnerable conditions may be present in any of these future combinations. Rather than defining a specific scenario combination as vulnerable, it is beneficial to identify the shared characteristics that stress the system under vulnerable futures.

A key step in the analysis is to identify *vulnerable conditions*—concise descriptions of the combination of future external conditions that lead the system to underperform relative to the vulnerability thresholds for each metric. This analysis is particularly important because some conditions or combinations thereof may be significantly more telling in whether a threshold is likely to be violated. Vulnerable conditions help focus decision makers' attention on the uncertain future conditions most pertinent to the challenges of concern and help facilitate discussions regarding the best ways to respond to those challenges. Appendix G3 provides more details and an example of this analysis.

An analysis was performed on all five of the water delivery indicator metrics. The process began with the simulation model results under each plausible future generated using CRSS.[3] For each indicator metric evaluated, vulnerability thresholds define futures as either vulnerable or not vulnerable. The Study then identified vulnerable conditions for each metric. The analysis considered the following uncertainties:

- Multiple characterizations of future hydrologic conditions (Supply Scenarios)
- Demand (Demand Scenarios)
- Post-2026 operations for Lakes Powell and Mead uncertainty (i.e., future management after the expiration of the 2007 Interim Guidelines)

Except where noted, these uncertainties were characterized and summarized over the 50-year period of analysis in order to capture the long-term averages or trends that appear to lead to vulnerabilities. Hydrologic uncertainty is represented with a variety of different statistical characterizations of water supply over time.

3 For each supply scenario, some randomly selected traces were included more than once so that each scenario contained the same number of traces (1,244). This, in effect, weights each supply scenario equally in the vulnerability analysis. Sensitivity tests using different weighting approaches (i.e., no weighting and partial weighting) showed only modest difference in these analytically derived vulnerabilities.

Vulnerabilities were first evaluated for all futures by characterizing hydrologic conditions based on Basin-wide flow statistics (Table G-6).

TABLE G-6
Characterizations of Uncertainty For Vulnerable Conditions (All Futures)

| Uncertainty | Characterization |
|---|---|
| Lees Ferry Natural Flow | Annual Mean (2012–2060) |
| | Trend (2012–2060) |
| | Variance (2012–2060) |
| | Annual Mean of Driest N-year Period (examined 5-, 8-, 10-year periods) |
| | Year of Driest N-year Period (examined 5-, 8-, 10-year periods) |
| | Annual Mean Flow of Wettest N-year period (examined 5-, 8-, 10-year periods) |
| | Year of Wettest N-year period (examined 5-, 8-, 10-year periods) |
| Demand | Mean Annual Post-2040 Demand[1] |
| Post 2026-Management Conditions | Extend Interim Guidelines or Revert to 2007 Interim Guidelines Final EIS No Action Alternative (Reclamation, 2007) |

[1] Multiple characterizations of demand over a range were considered, but because of the small number of demand scenarios, alternative characterizations would result in equivalent descriptions of vulnerability.

Analytically defining vulnerable future conditions serves several important purposes for the Study. Vulnerable conditions help to communicate clearly which plausible futures lead to vulnerability, describing a large set of plausible futures as a small, understandable set of conditions. Also, upon implementation of portfolios, the change in vulnerable conditions (i.e., how the pool of still vulnerable traces are best described), offers a quantitative method for evaluation of efficacy.[4]

### *5.2.2 Vulnerable Conditions Without Options and Strategies*

Results from the analysis of vulnerable conditions in a future without options and strategies are shown below. First, the Lee Ferry Deficit indicator metric is described in detail, and then a tabular summary of the vulnerable conditions defined for the remaining water delivery indicator metrics is provided. Additional detail can be found in appendix G3.

Table G-7 provides a summary of the vulnerable conditions identified for the Lee Ferry Deficit indicator metric using the methodology described in appendix G3. Across all traces considered, approximately 19 percent yielded at least one non-zero Lee Ferry Deficit over the 50-year simulation period. This represents the overall proportion of vulnerable traces in CRSS analysis. Using only two characterizations of uncertainty—the long-term mean natural flow and driest 8-year mean natural flow, both measured at Lees Ferry—a vulnerable condition is defined that included 85 percent of these vulnerable traces (coverage). Lees Ferry is the site of the Colorado River gaging station located above the Paria River. In

[4] For example, a portfolio that is vulnerable in a smaller percentage of futures is more resilient to those vulnerable conditions.

addition, the vulnerable condition has a density of 87 percent; meaning that 87 percent of traces with these flow characteristics yielded a vulnerable outcome at some point during the simulation.

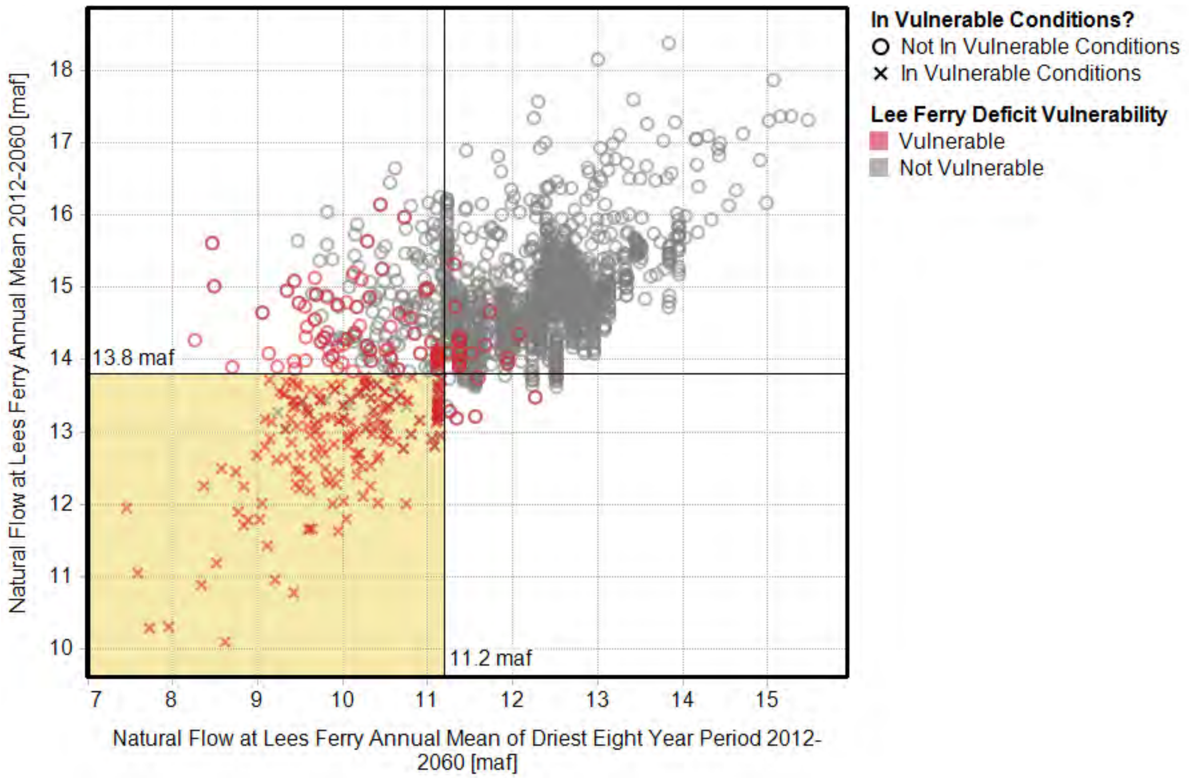
This vulnerable condition is described as *Low long-term average flow (<13.8 maf) and 8-year drought below 11.2 million acre-feet per year (mafy)*. The characteristics include low long-term natural flow of 13.8 mafy, well below the observed historical average, and an 8-year drought with flows averaging below 11.2 mafy. These two conditions capture the vulnerable traces with high coverage and density, and are not sensitive to the range of demand scenarios considered or the possibility of changing operation assumptions after the 2007 Interim Guidelines (DOI, 2007) expire in 2026.

TABLE G-7
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric

<table>
<tr><td colspan="2">Indicator Metric: Lee Ferry Deficit</td></tr>
<tr><td colspan="2">Vulnerable Condition Description: Low long-term average flow (< 13.8 maf) and 8-year drought below 11.2 mafy</td></tr>
<tr><td>Vulnerable Traces: 19%</td><td rowspan="2">Vulnerability Definition:<br>• Annual Mean Natural Flow at Lee Ferry 2012–2060 < 13.8 mafy<br>• Driest 8-Year Period of Annual Mean Natural Flow at Lee Ferry 2012–2060 < 11.2 mafy</td></tr>
<tr><td>Vulnerability Statistics:<br>• Coverage: 85%<br>• Density: 87%</td></tr>
</table>

A visual summary of *Low long-term average flow (<13.8 maf) and 8-year drought below 11.2 mafy* is shown in figure G-15. Each point in the figure represents one trace in the analysis, characterized according to long-term mean annual flow (y-axis) and mean annual flow during the driest 8-year period (x-axis). Red points indicate traces with at least one Lee Ferry deficit vulnerability during the simulation, and gray points mark traces in which no vulnerability occurs. The yellow region (lower left) in the figure summarizes the vulnerable condition boundaries identified in the analysis; each trace that falls within this region is denoted with an X, and each trace outside is marked with an O. This figure shows that, despite the strong correlation between long-term and drought flows, a combination of restrictions in both dimensions is important to identifying a set of vulnerable conditions with high coverage and density. For instance, removing the long-term mean restriction would include all traces in the upper-left quadrant. Although there are some vulnerable traces in this quadrant not captured in *Low long-term average flow (<13.8 maf) and 8-year drought below 11.2 mafy*, a majority of these traces are not vulnerable, and therefore density would drop dramatically were this region included.

FIGURE G-15
Scatter Plot of Vulnerable Conditions for the Lee Ferry Deficit Indicator Metric Without Options and Strategies

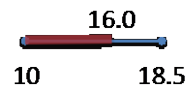
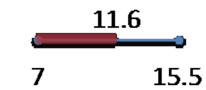
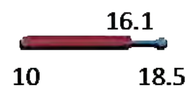
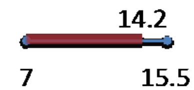



Summaries of the identified vulnerable conditions for all water delivery indicator metrics are shown in table G-8. For each indicator metric, the table provides a brief description of the vulnerable conditions and specifies the percentage of total traces that are vulnerable. Next, the table indicates the set of one or more restrictions on uncertain future system conditions that together describe the vulnerability. For quantitative inputs (e.g., annual mean natural flow at Lees Ferry from 2012 through 2060), the cells include a graphical illustration of the restrictions. In these plots, the blue line shows the range of input values across all traces. Annual mean natural flow from 2012 through 2060, for example, ranges from 10 to 18.5 mafy. The superimposed red line shows the subset of this range included in the definition of the vulnerable condition (e.g., all traces with mean 2012 through 2060 flow less than 13.8 maf). Finally, the words in between the columns indicate whether just one of the conditions needs to be met to fall within the vulnerable conditions (“OR”) or whether all conditions must be met to fall within the vulnerable conditions (“AND”).

TABLE G-8
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric

| Indicator Metric | Description | Vulnerable Traces (2012–2060) | System Condition | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf]** | | **1-Year Minimum Annual Natural Flow at Lee Ferry (2012–2060) [maf]** | | **Post-2026 Operation of Lakes Powell and Mead** |
| Upper Basin Shortage | *Minimum flow below 8.3 maf in 1 year* | 86% | NA | – | 8.3<br>3 12 | – | NA |
| **Indicator Metric** | **Description** | **Vulnerable Traces** | **System Condition** | | | | |
| | | | **Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf]** | | **Driest 8-Year Period of Annual Mean Flow at Lee Ferry (2012–2060) [maf]** | | **Post-2026 Operation of Lakes Powell and Mead** |
| Lee Ferry Deficit | *Long-term average flow below 13.8 maf and 8-year drought below 11.2 mafy* | 19% | 13.8<br>10 18.5 | AND | 11.2<br>7 15.5 | – | NA |
| Lake Mead Pool Elevation | *Long-term average flow below 15 maf and 8-year drought below 13 mafy* | 47% | 15<br>10 18.5 | AND | 13<br>7 15.5 | AND | 2007 Interim Guidelines |
| | | | 14.6<br>10 18.5 | AND | 13<br>7 15.5 | AND | Revert to 2007 Interim Guidelines Final EIS No Action Alternative |
| Lower Basin Shortage (1 maf over 2 years) | *Long-term average flow below 15.6 mafy and 8-year drought below 11.8 mafy and 2007 Interim Guidelines* | 86% | 15.6<br>10 18.5 | OR | 11.8<br>7 15.5 | AND | 2007 Interim Guidelines |
| | *Long-term average flow below 16.1 mafy and 8-year drought below 14.2 mafy and 2007 Interim Guidelines Final EIS No Action* | | 16.1<br>10 18.5 | OR | 14.2<br>7 15.5 | AND | Revert to 2007 Interim Guidelines Final EIS No Action |

TABLE G-8
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric

| Indicator Metric | Description | Vulnerable Traces (2012–2060) | System Condition | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf]** | | **1-Year Minimum Annual Natural Flow at Lee Ferry (2012–2060) [maf]** | | **Post-2026 Operation of Lakes Powell and Mead** |
| | *Alternative* | | | | | | Alternative |
| Lower Basin Shortage (1.5 maf over 5 years) | *Long-term average flow below 16 mafy with 8-year drought below 11.6 mafy and 2007 Interim Guidelines* | 92% |  | OR |  | AND | 2007 Interim Guidelines |
| | *Long-term average flow below 16.1 mafy with 8-year drought below 14.2 mafy and 2007 Interim Guidelines Final EIS No Action Alternative* | |  | OR |  | AND | Revert to 2007 Interim Guidelines Final EIS No Action Alternative |
| **Indicator Metric** | **Condition Name** | **Vulnerable Traces** | **System Condition** | | | | |
| Remaining Demand Above Lower Division States' Basic Apportionment | NA | 100% | NA | | | | |

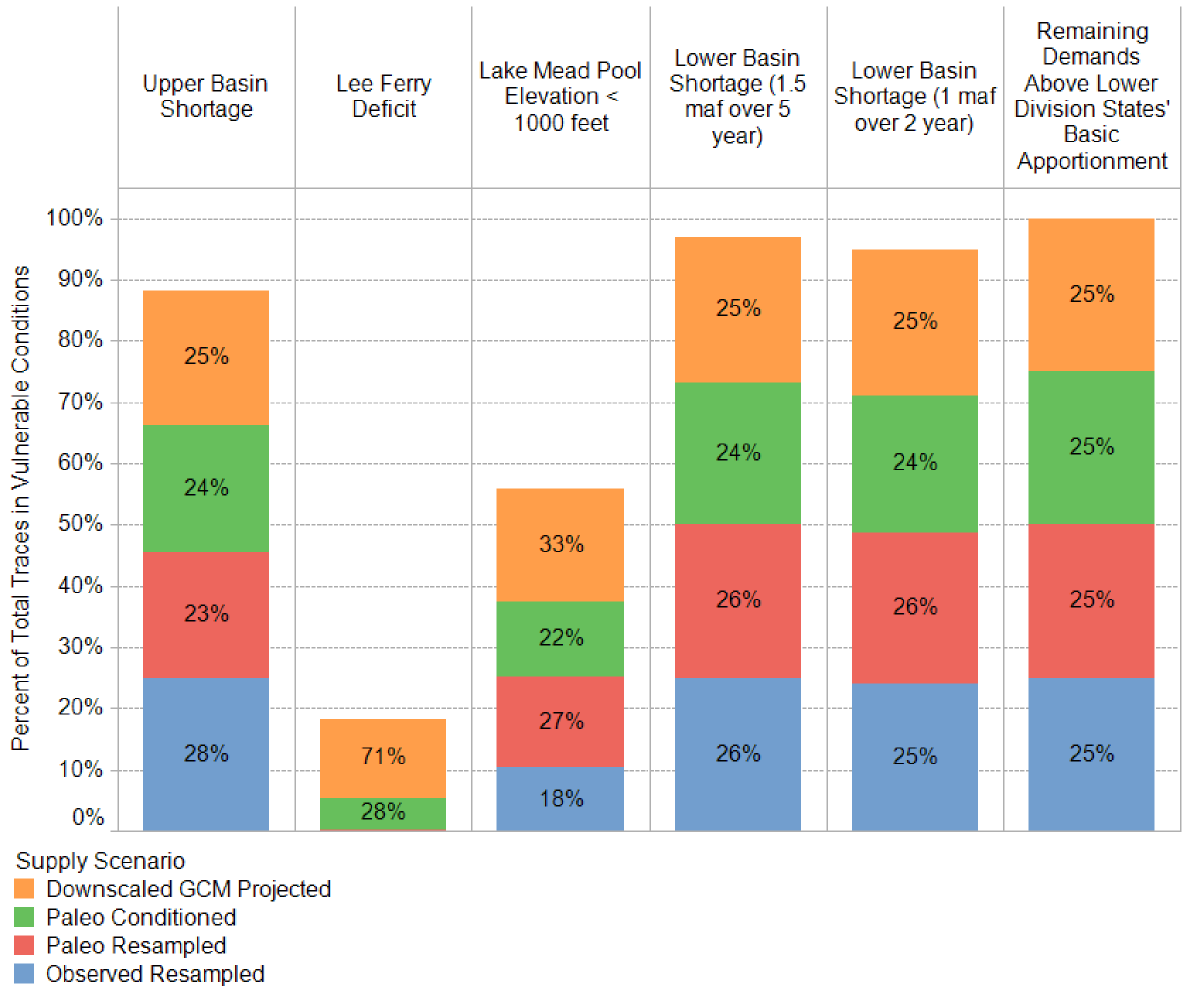
Additional information about the vulnerable conditions, including summaries of the statistical results from the clustering algorithm applied, is provided in appendix G3.

In general, vulnerable conditions for the majority of the water delivery indicator metrics described in table G-8 can be concisely described using two main drivers: 1) Lees Ferry natural flow and 2) post-2026 operations for Lakes Powell and Mead. Furthermore, the analysis shows that natural flow is best described with two of the many characterizations considered: a) annual mean (2012 through 2060) and b) annual mean of driest 8-year period. The specific thresholds for these inputs vary by metric, but a combination of these two flow characterizations and the post-2026 operations for Lakes Powell and Mead fully describe the vulnerable conditions for four of the six indicator metrics in the Baseline simulations.

The exceptions to this are Upper Basin shortage and remaining demand above Lower Division States' basic apportionments. Conditions that typically produce an Upper Basin shortage above the vulnerability threshold are generally related to natural hydrologic flow conditions, not non-depletive flow requirements at Lees Ferry. For remaining demand above Lower Division States' basic apportionments, all traces yield at least 1 vulnerable year in the Baseline simulations, and therefore no non-vulnerable conditions can be identified.

Figure G-16 relates the vulnerable conditions defined for each metric back to the supply scenarios developed as inputs to the analysis. For each water delivery indicator metric, the percentage of traces within vulnerable conditions is shown. Further, of those traces, the percent from each water supply scenario is specified. Because the total percent of traces in vulnerable conditions is rather high for most, their contributions from different supply scenarios are largely comparable (100 percent of traces vulnerable would produce exactly equal contributions from each scenario). The Lee Ferry Deficit and Lake Mead pool elevation indicator metrics are the exception and show a higher percent of traces being from the Downscaled GCM Projected scenario. This indicates that those metrics are more likely to be vulnerable under that particular supply and less so under the others.

FIGURE G-16
Proportion of Supply Scenario Within Each Set of Vulnerable Conditions Without Options and Strategies, by Water Delivery Indicator Metric




# 6.0 Evaluation of System Reliability With Options and Strategies

The Baseline system reliability evaluation section revealed a wide range of plausible future outcomes for the Study Area. The recurrent tendency of these outcomes, however, suggests increasingly challenging future conditions. For example, the median pool elevation at Lake Mead declines significantly across all scenarios evaluated. This discussion was followed by a characterization the external conditions in which the system was vulnerable. For example, Lake Mead levels are likely vulnerable if long-term average natural flow is slightly lower than the mean, and 8-year drought natural flows at Lees Ferry are below 13 mafy. These conditions occurred in almost half of all traces evaluated in the Study.

Given these findings, the key remaining important question the Study strives to address what it will take to solve the supply and demand imbalance problem. In light of increasing demand and possibly diminishing supply, exploration of system imbalances and resource impacts is an important component of the Study. Another challenge not included in the Baseline modeling is the significant demands above Lower Division States' basic apportionment, as quantified in *Technical Report C – Water Demand Assessment*. Over the Study horizon, these additional water needs grow to nearly 2.8 mafy in some scenarios. Understanding the capacity of the system to address this extra demand is also a key part of the Study.

This section begins by summarizing options that are available to address both system needs and remaining demands above Lower Division States' basic apportionment. Next, it evaluates how the system could be improved using a portfolio in which a large set of feasible options are implemented as soon as they are available. The simulations first consider improvements and incurred costs when options only address Lower Division States' demands within basic apportionments. Thereafter, improvements and cost are re-evaluated when also addressing demands above Lower Division States' basic apportionments. The simulations of these static portfolios provide an upper bound for potential system vulnerability reduction by implementing the options modeled quantitatively in the Study. This section describes an analysis of dynamic portfolios, which trigger options in response to evolving conditions..

## 6.1 Portfolios of Options to Address System Imbalances

From November 2011 through February 2012, the Study solicited public input on options and strategies for helping to resolve future water supply and demand imbalances in the Basin. The Study cost-share partners sought input from a broad range of stakeholders and interested parties located within as well as external to the Basin. Through this processes approximately 160 individual option submissions were received. *Technical Report F – Options and Strategies* is a comprehensive documentation of the solicitation and collection process, option organization and classification, and a 17-criteria rating. The following is an overview of the detailed content contained therein and how those options were incorporated into the system modeling.

### *6.1.1 Individual Options*

Of the many submissions received, all were classified as one of four high-level groupings: those that increase supply, those that reduce demand, those that are related to system operations, and those that are primarily related to governance and implementation. Although many of the options are conducive to the quantitative framework employed in the Baseline modeling, others were less amenable and thus were evaluated in a qualitative manner or via a more appropriate, alternate quantitative method.

Because many of the submissions were similar in spirit, these options were combined when possible, as a representative option. The motivation for doing this is largely three-fold. By summarizing like ideas as a representative option, one is not given preference over another. Further, the associated details of timing, yield and implementation can be quantified consistently across all representative options. Last, representative options ensure that the potential benefit of a particular type of option is not overstated or understated by determining yield based on objective review, not relative popularity.

Each of the submitted options was evaluated based on 17 characterization criteria shown in table G-9. The criteria were selected to capture important attributes for the Study and to provide a relative comparison among options. Each option was assigned either a quantitative value (e.g., dollars per af for the cost of water) or a five-point rating ("A" through "E") for each of the criteria, where "A" represents the most favorable rating and "E" the least favorable. A detailed description of the options and characterization process is described in *Technical Report F – Development of Options and Strategies*. The characterization criteria results were used to determine if an option was realistically feasible given the Study time window, and therefore whether it should be included in the system modeling with options and strategies.

TABLE G-9
Criteria Used to Characterize Representative Options

| Criteria | Summary Description of Criteria |
|---|---|
| Quantity of Yield | The estimated long-term quantity of water generated by the option— either an increase in supply or a reduction in demand |
| Timing | Estimated first year that the option could begin operation |
| Technical Feasibility | Technical feasibility of the option based on the extent of the underlying technology or practices |
| Cost | The annualized capital, operating, and replacement cost per af of option yield |
| Permitting | Level of anticipated permitting requirements and precedent of success for similar projects |
| Legal | Consistency with current legal frameworks and laws, or precedent with success in legal challenges |
| Policy Considerations | Extent of potential changes to existing federal, state, or local policies that concern water, water use, or land management |
| Implementation Risk | Risk of achieving implementation and operation of option based on factors such as funding mechanisms, competing demands for critical resources, challenging operations, or challenging mitigation requirements |
| Long-term Viability | Anticipated reliability of the option to meet the proposed objectives over the long term |
| Operational Flexibility | Flexibility of option to be idled from year to year with limited financial or other impacts |
| Energy Needs | Energy required to permit full operation of the option, including treatment, conveyance, and distribution |
| Energy Source | Anticipated energy source to be used to allow option to be operational |
| Hydropower | Anticipated increases or decreases in hydroelectric energy generation associated with implementation of the option |
| Water Quality | Anticipated improvements or degradation in water quality associated with implementation of the option. |
| Recreation | Potential impacts to recreational activities including in-river and shoreline activities |
| Other Environmental Factors | Other environmental considerations, such as impacts to air quality, or aquatic, wetland, riparian, or terrestrial habitats |
| Socioeconomics | Potential impacts to socioeconomic conditions in regions within or outside of the Basin as a result of implementing the option |

### 6.1.2 Static Portfolio of Options

In many plausible future conditions, the implementation of more than one option will be required to address Basin challenges. To evaluate the potential for available options to reduce or eliminate vulnerabilities, a single, static portfolio of options was developed—*Static Portfolio A*. This portfolio includes a large set of options submitted by the public and characterized as described above. The portfolio implementation is static in that it specifies that each option is to be implemented when available, regardless of the simulated system conditions. Therefore, the static portfolio represents an upper bound as to how much improvement the system could experience using the options in the portfolio, even though in many future conditions, the system may not require all the options to be implemented.

Table G-10 summarizes the type, number, and yield of the options included in *Static Portfolio A*, by time period—near-term (years 1 through 25), long-term (years 26 through 50), and total (years 1 through 50). This portfolio considers 36 options, and, when completely implemented, could yield approximately 6.3 maf in increased supply or reduced demand at an annualized cost estimated at $7.9 billion. Although all of these options either increase supply or reduce demand, the spatial differences of the options and methods of integrating within the system may limit the ability to address vulnerabilities. This limitation is particularly true for addressing Upper Basin shortages on tributaries.

TABLE G-10
Summary of the Type, Number, and Yields of Options Included in *Static Portfolio A*

| Option Category | Option Type | Near-Term | | Long-Term | | Total | |
|---|---|---|---|---|---|---|---|
| | | Number of Options | Sum of Yield (kafy) | Number of Options | Sum of Yield (kafy) | Number of Options | Sum of Yield (kafy) |
| Augment Supply | Desalination | 8 | 1,176 | 2 | 300 | **10** | **1,476** |
| | Import | 0 | 0 | 1 | 600 | **1** | **600** |
| | Local Supply | 2 | 175 | 0 | | **2** | **175** |
| | Reuse | 4 | 618 | 3 | 532 | **7** | **1,150** |
| | Watershed Management | 4 | 610 | 1 | 120 | **5** | **730** |
| | **Total** | **18** | **2,579** | **7** | **1,552** | **25** | **4,131** |
| Reduce Demand | Agricultural Conservation | 5 | 1,000 | 0 | 0 | **5** | **1,000** |
| | Energy Sector Water Use Efficiency | 1 | 160 | 0 | 0 | **1** | **160** |
| | M&I Conservation | 3 | 600 | 2 | 400 | **5** | **1,000** |
| | **Total** | **9** | **1,760** | **2** | **400** | **11** | **2,160** |
| **Grand Total** | | **27** | **4,339** | **9** | **1,952** | **36** | **6,291** |

Based on results presented in the previous section on system reliability without options and strategies, significant vulnerabilities exist. In that modeling, demands above Lower Division States' basic apportionments were only met under quantified, domestic, flood control or 70R surplus conditions. Therefore, upon consideration of options, the first undertaking is to explore their capacity to ameliorate those previously identified vulnerabilities. To accomplish this, modeling assumptions remain unchanged and the *Static Portfolio A* is used. However, of the many options included therein, several have capacity to benefit demands above Lower Division States' basic apportionments, and are not included in this exercise. The resulting portfolio has an annual yield of approximately 4 mafy by 2060 with an annualized cost estimated at $5 billion. As option yield enters the system, it is allocated in accordance with the operational framework utilized in the modeling without options. Recall that pursuant to this assumption, deliveries to demand above Lower Division States' basic apportionments only occur during periods of surplus.

Because sizeable demands above Lower Division States' basic apportionments exist, the capacity of options to resolve system vulnerabilities while also delivering to demands above Lower Division States' basic apportionments is also analyzed. The entire *Static Portfolio A*, including options that only address demands above Lower Division States' basic apportionment as described in table G-10, is now considered. This constitutes an additional yield/benefit of about 2.3 mafy by 2060 at an estimated annualized cost of $2.7 billion. When considering the additional options, which directly address demands above Lower Division States' basic apportionments, additional modeling assumptions pertaining to the allocation of the Lower Basin option benefits are required between those demands and the system. Appendix G3 describes an approach and sensitivity analysis of how this might be accomplished. For the results presented in the remainder of this report, when demands above Lower Division States' basic apportionments are met by options, benefits are assumed to offset demands above Lower Division States' basic apportionments until the Lake Mead pool elevation falls below 1,050 feet msl. At this point, options with capacity to do so benefit the system until Lake Mead's pool elevation has recovered above the 1,050–foot threshold.

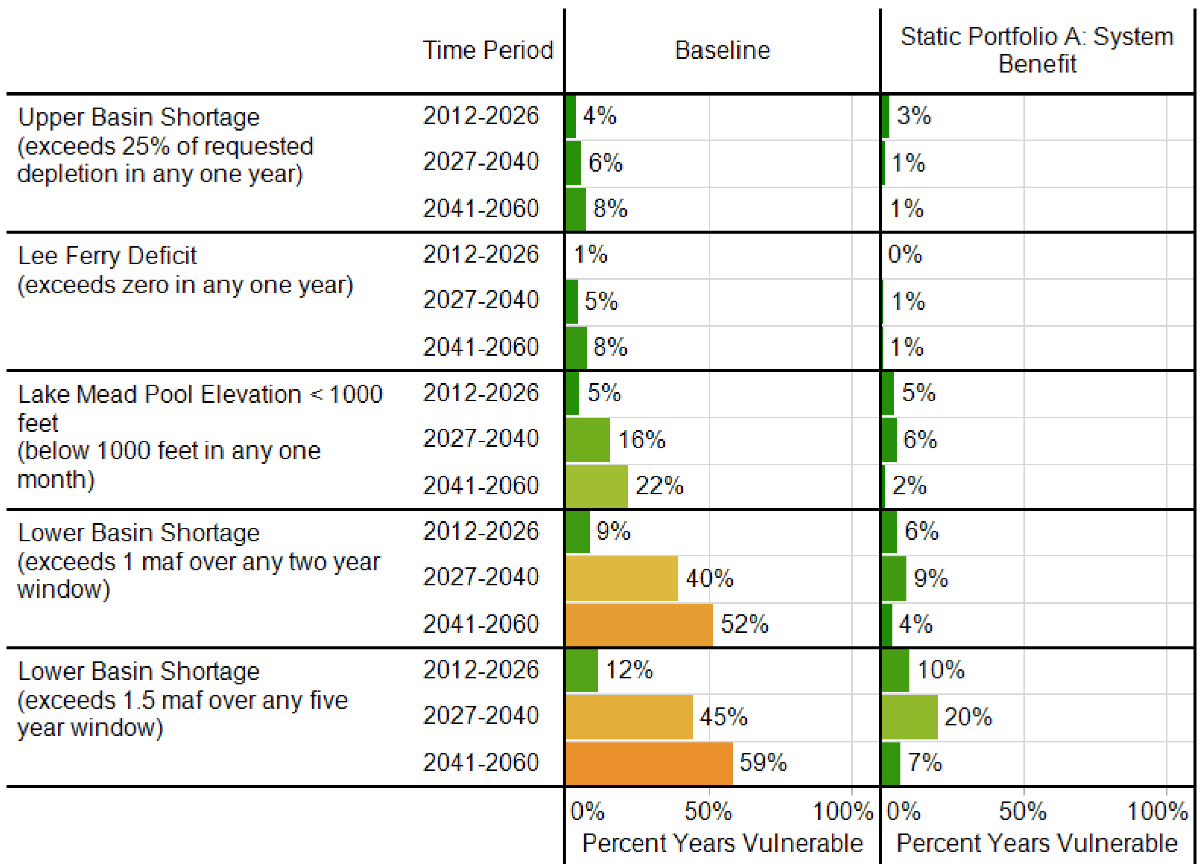
To simulate the above described portfolio, the functionality to augment supply and reduce demands at the appropriate spatial locations was built into CRSS framework (see appendix G2 for additional model details). At the onset of a simulation, a list of the various options, containing their quantified yield and year available, is passed to the model. Under the static portfolio, each option is implemented at the earliest possible year and for the full yield. At the end of each simulation with the full *Static Portfolio A*, all options are implemented with a total annual yield of approximately 6.3 mafy at an annualized cost estimated at $7.7 billion.

Results from these modeling simulations are presented in the sections below and compared with outcomes of the system reliability modeling without options and strategies (referred to as Baseline from here on). In doing so, the capacity to resolve system imbalances is made apparent, both for assumptions that limit deliveries to basic apportionments and those extending it to demands beyond.

Figure G-17 shows the effects of the *Static Portfolio A* on water delivery vulnerabilities for three time periods when not addressing demands above Lower Division States' basic apportionments, across all scenarios. The implementation of all the options in the portfolio significantly reduces the number of years in which the system is vulnerable for all the water delivery indicator metrics. It nearly eliminates years in which there is a Lee Ferry Deficit across all time periods. The number of years in which Lake Mead drops below 1,000 feet msl is reduced from 22 percent to 2 percent, as are the number of years in which a Lower Basin Shortage occurs; from around 50 percent of the years to around 5 percent of the years.

Although the analysis shows the percent of vulnerable years resulting in an Upper Basin shortage decreasing with the portfolio options, this may be a result of CRSS-simplified representation of smaller tributaries in the Upper Basin. Because the smaller tributary demand is placed on the mainstem of the larger tributaries (Yampa, Colorado, Gunnison, and San Juan), the model tends to overestimates the ability of many options to reduce the associated shortages. For example, municipal conservation on the Front Range or in large cities along the mainstem Colorado will not increase flow on smaller tributaries where many of the shortages exist. This observation is true for each of the portfolios considered.

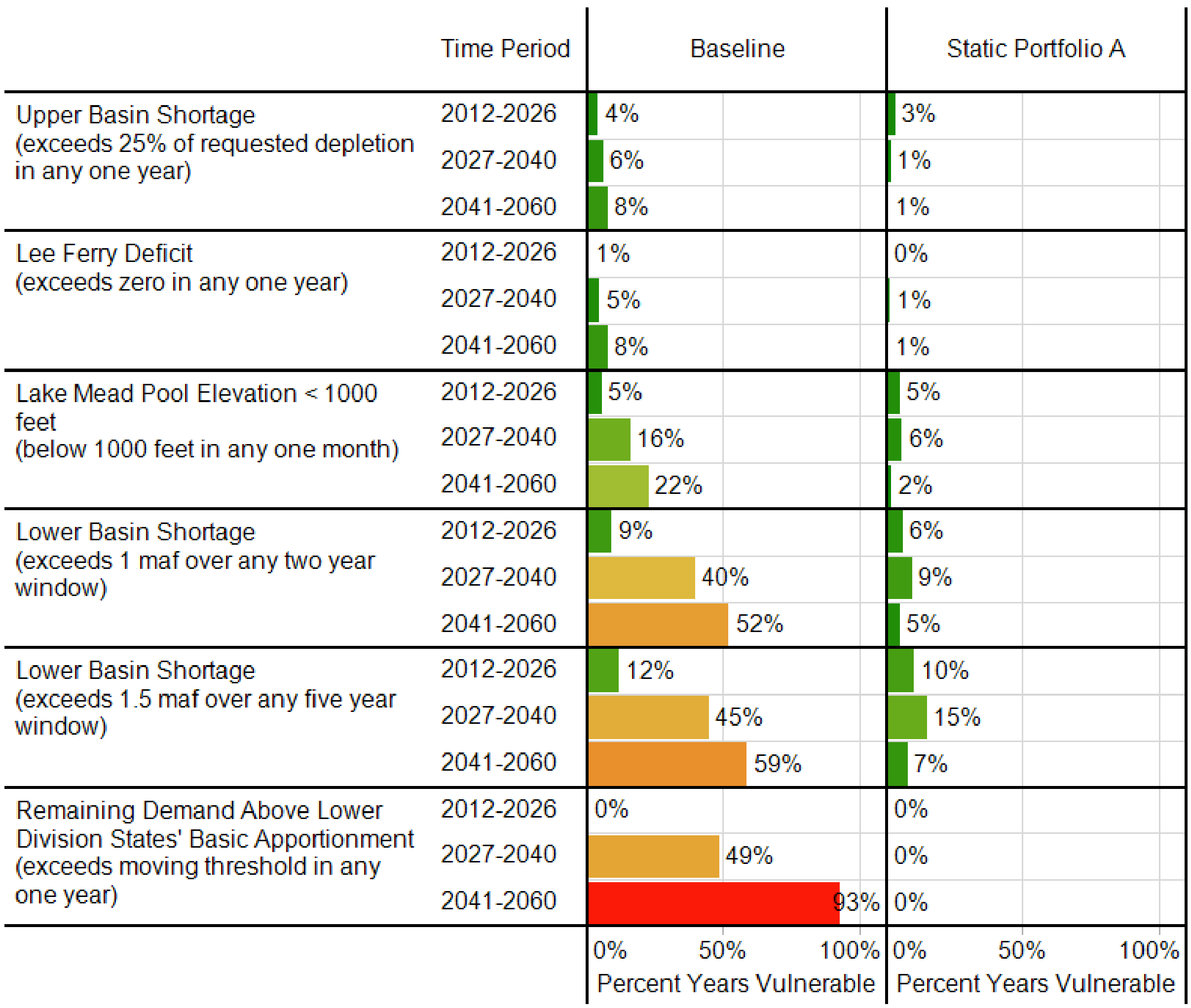
FIGURE G-17
Percent of Vulnerable Years for Each Indicator Metric Across Three Time Periods for the Baseline and *Static Portfolio A*. Includes only system benefits.




Graph reflects a subset of all scenarios evaluated for the portfolio analysis—Supply Scenarios: Observed Resampled, Paleo Conditioned, and Downscaled GCM Projected; Demand Scenarios: Current Projected (A), Rapid Growth (C1), Enhanced Environment (D1); Management Scenarios: Interim Guidelines Continued, Revert to 2007 Interim Guidelines Final EIS No Action Alternative.

Figure G-18 shows the effects that *Static Portfolio A* would have when providing both a system benefit and addressing demands above Lower Division States' basic apportionments, across all scenarios for three time periods. The implementation of all the options in the portfolio significantly reduces the number of years in which the system is vulnerable for all the water delivery indicator metrics. The portfolio completely eliminates the vulnerability associated with remaining demand above Lower Division States' basic apportionments. For other indicator metrics, nearly identical vulnerability reductions were achieved, relative to the portfolio only addressing system benefits, but at an increased $2.7 billion annualized cost. However, the additional cost eliminates the remaining demands above Lower Division States' basic apportionments vulnerability.

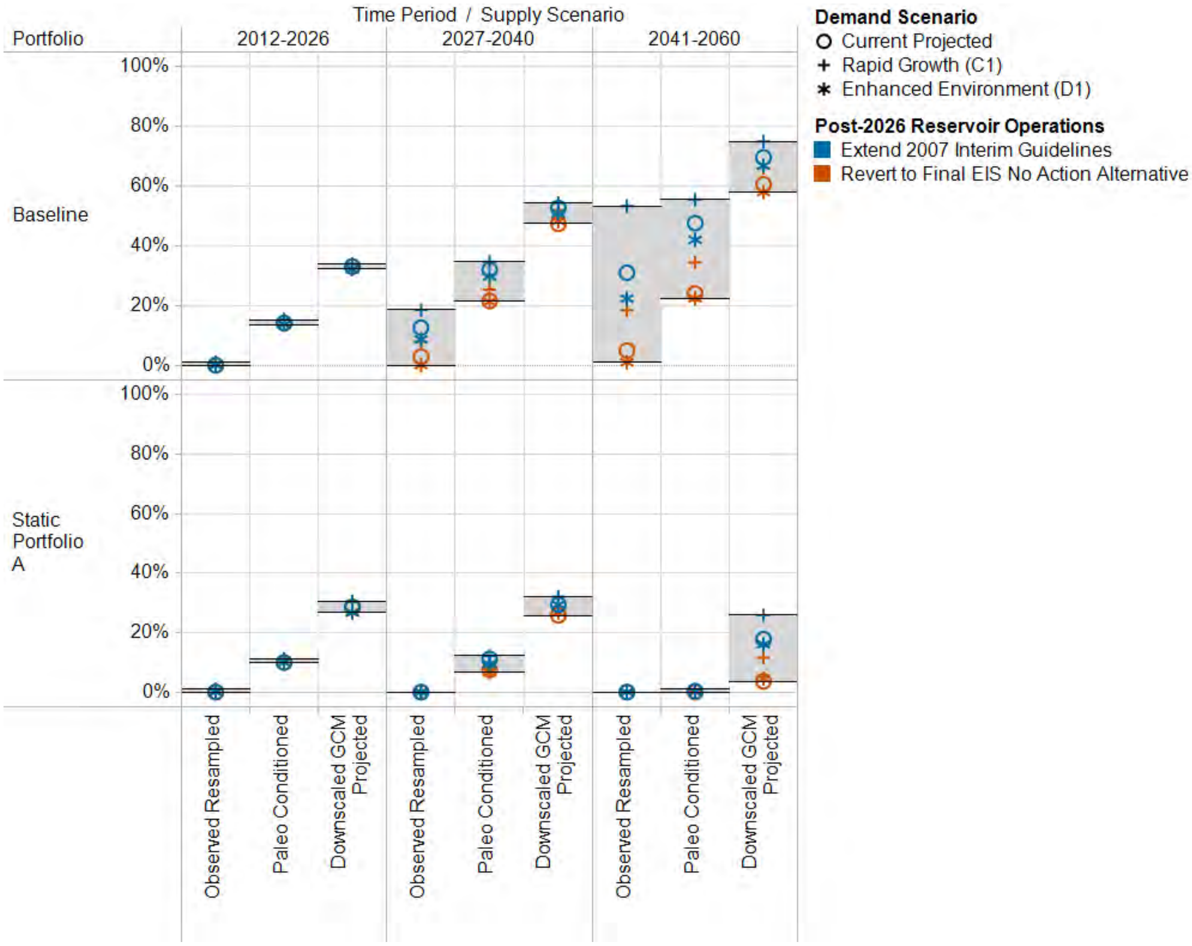
FIGURE G-18
Percent of Vulnerable Years for Each Indicator Metric Across Three Time Periods for the Baseline and *Static Portfolio A*. Includes System and Demands Above Lower Division States' Basic Apportionments Benefits.




Graph reflects a subset of all scenarios evaluated for the portfolio analysis—Supply Scenarios: Observed Resampled, Paleo Conditioned, and Downscaled GCM Projected; Demand Scenarios: Current Projected (A), Rapid Growth (C1), Enhanced Environment (D1); Management Scenarios: Interim Guidelines Continued, Revert to 2007 Interim Guidelines Final EIS No Action Alternative.

To illustrate the static portfolio's effect on outcomes relative to the various demand, supply, and management scenarios, figure G-19 shows the range of traces in which Lake Mead is vulnerable across three time periods for the Baseline case and *Static Portfolio A* across a subset of the demand, supply, and management scenarios. The static portfolio has minimal effect in the first time period, due to the time required to bring on most of the options. In the second period, the portfolio completely eliminates vulnerabilities derived from the Observed Resampled supply scenario, but only modestly reduces vulnerabilities from traces derived from the Downscaled GCM Projected scenario. In the long term, the only remaining vulnerabilities are due to traces from the Downscaled GCM Projected scenario. The vulnerabilities are slightly higher from traces simulated with the Rapid Growth scenario as well as the management scenario in which the 2007 Interim Guidelines (DOI, 2007) are extended past 2026.

FIGURE G-19
Percent of Vulnerable Traces for the Lake Mead Elevation Indicator Metric Across Three Time Periods for the Baseline and *Static Portfolio A*, by Supply and Demand Scenario




Graph reflects a subset of all scenarios evaluated for the portfolio analysis—Supply Scenarios: Observed Resampled, Paleo Conditioned, and Downscaled GCM Projected; Demand Scenarios: Current Projected (A), Rapid Growth (C1), Enhanced Environment (D1); Management Scenarios: Interim Guidelines Continued, Revert to 2007 Interim Guidelines Final EIS No Action Alternative.

This modeling showcases the upper bound of the portfolio's potential to improve vulnerabilities under two assumptions. First, it addresses benefits to the system and demands within Lower Division States' basic apportionment and second, benefits to the system along with remaining demand above Lower Division States' basic apportionments. Both assumptions address vulnerabilities similarly and showed vulnerability could be significantly reduced when applying all options as soon as they are available. To address remaining demands above Lower Division States' basic apportionments, an additional $2.7 billion of options needed to be added. Implementing *Static Portfolio A* implies that all options would need to begin the permitting process immediately. Further, options would be implemented regardless of the system status at the time they are available, creating the potential for over-investment in many cases. The next section describes how the Basin can improve system benefits using portfolios that are dynamic and implement options only under conditions in which they are simulated to be needed. All portfolios benefit system demands within the existing basic apportionments as well as attempt to satisfy demands above Lower Division States' basic apportionments under specific conditions.

## 6.2 Improving System Benefits Through Dynamic Portfolios

### *6.2.1 Dynamic Portfolios*

The Study recognizes that Basin needs will depend upon future conditions that are highly uncertain. Successful strategies for addressing system imbalances must be adaptive and implement new options under future conditions in which they are most likely needed and are most effective for preventing vulnerabilities. Called dynamic portfolios, this approach aims to explore the timing and magnitude of options required to mitigate vulnerabilities on a trace-by-trace basis. The goal of this approach is to better understand the range of investment needs across scenarios and also improve the benefit to system resources given those investments. This affords a quantitative perspective of the magnitude of the overinvestment associated with *Static Portfolio A* (in which no dynamic implementation was considered). The basic principle is to construct model logic such that option implementation is delayed when conditions are favorable while investments are accelerated as vulnerabilities emerge. In order to do this, additional tools, model functionalities, and assumptions were required.

From the option characterization, many options require significant time to plan and construct, which is reflected by their "earliest date available." From a dynamic perspective, one cannot wait for vulnerability to occur before beginning the planning and implementation activities. The result would be a sizeable response lag and likely little improvement with regard to resource vulnerability. Therefore, in order to realize more timely benefits, it is assumed that the planning and construction process for all options begins in 2013. The length of time to conduct feasibility, permitting, and construction was estimated for each option as part of the characterization process (see *Technical Report F – Options and Strategies).* This duration is added to 2013 to estimate the earliest possible operational year. As a result, all options are available by their respective earliest possible dates. With this assumption, during a model simulation, vulnerabilities can now be more effectively addressed by implementing appropriate options from those available in a given year. Obviously it is unrealistic that the planning and construction process for all options would begin effective immediately with the goal to make them available by the earliest possible date. However, by tracking the options implemented and the timing thereof, a trace-by-trace "best case investment" could be hindcast. For example, if only one option was required for a particular trace and it was implemented much later than the earliest possible date, that particular "best case investment" would perhaps be to begin planning for the option, but defer additional significant investment until conditions suggest that it is required. By analyzing the options selected and their timing and cost, across all scenarios, insight can be gained as to how often and when each option might be needed, which is likely to be useful information when faced with making actual Basin investments.

Building upon the assumption and framework discussed above, the most effective way to mitigate vulnerabilities is preemptive option investment to avoid vulnerability instead of simply reacting to it. As a result, the ability to anticipate vulnerability, at some lead time, helps to guide and inform the actual timing of when an option should be implemented to effectively hedge against vulnerability. This capacity is referred to as signposting. For the purpose of the Study, it was assumed that option implementation only occurs to address water supply vulnerabilities. As such, signposts were developed only for specific vulnerabilities that were used to trigger option implementation. Through an objective analysis of system conditions that tend to precede vulnerable events, signposts were developed. When a signpost is observed, options are implemented from those available at that particular time. In taking preemptive steps, the benefit of a single option is allowed to accrue, possibly reducing the need for a larger, more reactive investment. By design, signposts are based on system factors that can change in response to the already implemented options, helping to avoid over-investment. The specifics of each signpost, detailed in table G-11, balance lead time and predictive skill. In the case of the Upper Basin shortage vulnerability, little predictive skill was achieved given the high degree of inter-annual flow variability. Therefore, the signpost is simply one vulnerable event. The lead time is the longest period between the triggering of a signpost and occurrence of a vulnerability that still retained sufficient predictive skill. Appendix G3 provides an illustration of signposts and how they were developed.

TABLE G-11
Definitions of the Vulnerability Signposts Developed for Each Indicator Metric

| Indicator Metric/ Vulnerability | Lead Time (years) | Conditions | | | | |
|---|---|---|---|---|---|---|
| | | Lake Powell | Lake Mead | Natural 5-year Mean Flow at Lees Ferry | Upper Basin Shortage | Lower Division States' Demand Above Basic Apportionments |
| Lee Ferry Deficit | 5 | 3490' | NA | 12.39 maf | NA | NA |
| Lower Basin Shortage (>1 maf over 2 years) | 3 | NA | 1060' | 13.51 maf | NA | NA |
| Lower Basin Shortage (>1.5 maf over 5 years) | 3 | NA | 1075' | 13.51 maf | NA | NA |
| Mead Pool Elevation (< 1,000 feet msl) | 3 | NA | 1040' | 13.35 maf | NA | NA |
| Upper Basin Shortage (>25%) | 0 | NA | NA | NA | 25% | NA |
| Demand Above Lower Division States' Basic Apportionments | Varies | NA | NA | NA | NA | Demand above basic apportionments is within 100 kaf of permissible level |

Driven by the needs of dynamic option implementation, a secondary assessment of each representative option was performed. Specifically, the capacity of an option to address the various water supply vulnerabilities was quantified. This was accomplished by modeling the representative options and monitoring changes in the aforementioned vulnerabilities. The purpose of this is to inform dynamic option selection given the vulnerability at hand. Table G-12 shows the results of this analysis. It should be noted that some judgment was exercised in this process, particularly when vulnerability improvements were found to be marginal or protracted. Note that because Upper Basin shortages are largely agricultural shortages on smaller tributaries, municipal conservation is not likely to reduce shortages.

TABLE G-12
Options that Address Different Vulnerabilities

| Representative Option | Year Available | Vulnerability Addressed by Representative Option | | | | | |
|---|---|---|---|---|---|---|---|
| | | UB Shortage | Lee Ferry Deficit | Mead Pool Elevation | Lower Basin Shortage 1 | Lower Basin Shortage 2 | Lower Division States' Demand Above Basic Apportionments |
| Agriculture (Ag) Conservation | 2016 | X | X | X | X | X | X |
| M&I Conservation | 2016 | X | X | X | X | X | X |
| Local-Rainwater Harvesting | 2016 | X | X | X | X | X | X |
| Reuse-Grey Water | 2021 | X | X | X | X | X | X |
| Reuse-Industrial | 2021 | X | X | X | X | X | X |
| Reuse-Municipal (Steps 1 and 2) | 2021 | X | X | X | X | X | X |
| Reuse-Municipal (Steps 3-5) | 2036 | | | X | X | X | X |
| Desalination (Desal)-Gulf of California (Gulf) | 2028 | | | X | X | X | X |
| Desal-Pacific Ocean-CA | 2031 | | | X | X | X | X |
| Desal-Pacific Ocean-Mexico | 2026 | | | X | X | X | X |
| Desal-Salton Sea Drainwater | 2026 | | | X | X | X | X |
| Desal-Southern California (SoCal) Groundwater | 2021 | | | X | X | X | X |
| Desal-Yuma Area Groundwater | 2021 | | | X | X | X | X |
| Import-Front Range-Missouri | 2041 | X | X | X | X | X | |
| Energy Water Use Efficiency-Air Cooling | 2021 | X | X | | | | |
| Watershed-Dust | 2026 | X | X | | | | |
| Watershed-Tamarisk | 2023 | | X | X | X | X | |
| Watershed-Weather Modification (Weather Mod) | 2016 | X | X | | | | |
| Local-Coal Bed Methane | 2021 | X | X | | | | |

Option and signpost information is passed to the model at the onset of each simulation. Additional model logic was implemented to monitor for the vulnerability signposts. Upon detection of a signpost, options that are 1) available (timing) and 2) address the anticipated vulnerability (quantity) are implemented in accordance with the following logic:

(1) In a single year, no more than four options total may be implemented Basin-wide. This aims to reduce over-investment while ensuring that enough options could be implemented to address all vulnerabilities in a single year, should that be required.

(2) In a single year, additional options are implemented to address the same vulnerability until their total yield equals or exceeds 100 kafy, subject to the limitation described in (1).

(3) If multiple signposts are triggered in the same year, an option is implemented for the first vulnerability. If the selected option(s) do not address the other vulnerabilities, additional options are implemented until all vulnerabilities are addressed, subject to the limitation in (1). This helps to prevent over-investment.

(4) Once an option is implemented, it remains in effect for the remainder of the simulation.

At the conclusion of each model run/simulation, a summary of the selected options and their implementation timing is included in the results output.

For each portfolio, specific data on option implementation such as timing and yield are output on a trace by trace basis, in addition to the standard suite of performance metrics. These data afford the ability to perform numerous analyses such as portfolio impact on system response variables, metrics, and indicator metrics. As an alternate and complementary measure, the improved resiliency can be quantified for a portfolio; for example, given some action taken, how bad of a drought can now be tolerated without incurring a vulnerable event, as compared to the system without options and strategies. When coupled with cost information, the trade-off between capital investment and performance can be considered. Option implementation frequency can also be assessed, both within and across portfolios.

### *6.2.2 Strategies and Study Portfolios*

The Study developed four exploratory portfolios to reflect different strategies for selecting and combining options to address Colorado River imbalances between water supply and water demand, as described in *Technical Report F – Development of Options and Strategies*. Each portfolio consists of a unique selection of options that are considered to address vulnerabilities (e.g., declining Lake Mead pool elevation) that may exist under future combinations of supply and demand. The portfolios were implemented dynamically in CRSS, meaning options were implemented based on the portfolio strategy depending on the timing and nature of the vulnerabilities. Portfolios were then analyzed to assess the effects of the strategy on resolving vulnerabilities to Basin resources. As a result, for a given portfolio, the sequencing and timing of options will be unique to each supply/demand scenario.

Table G-13 describes each of the four strategies and portfolios developed for the Study. Table G-14 summarizes the number and yield of options by 2060 by type for *Portfolios A* and *C*. *Technical Report F* provides additional detail on included options for each portfolio.

TABLE G-13
Strategies and Portfolio Descriptions Explored in the Study

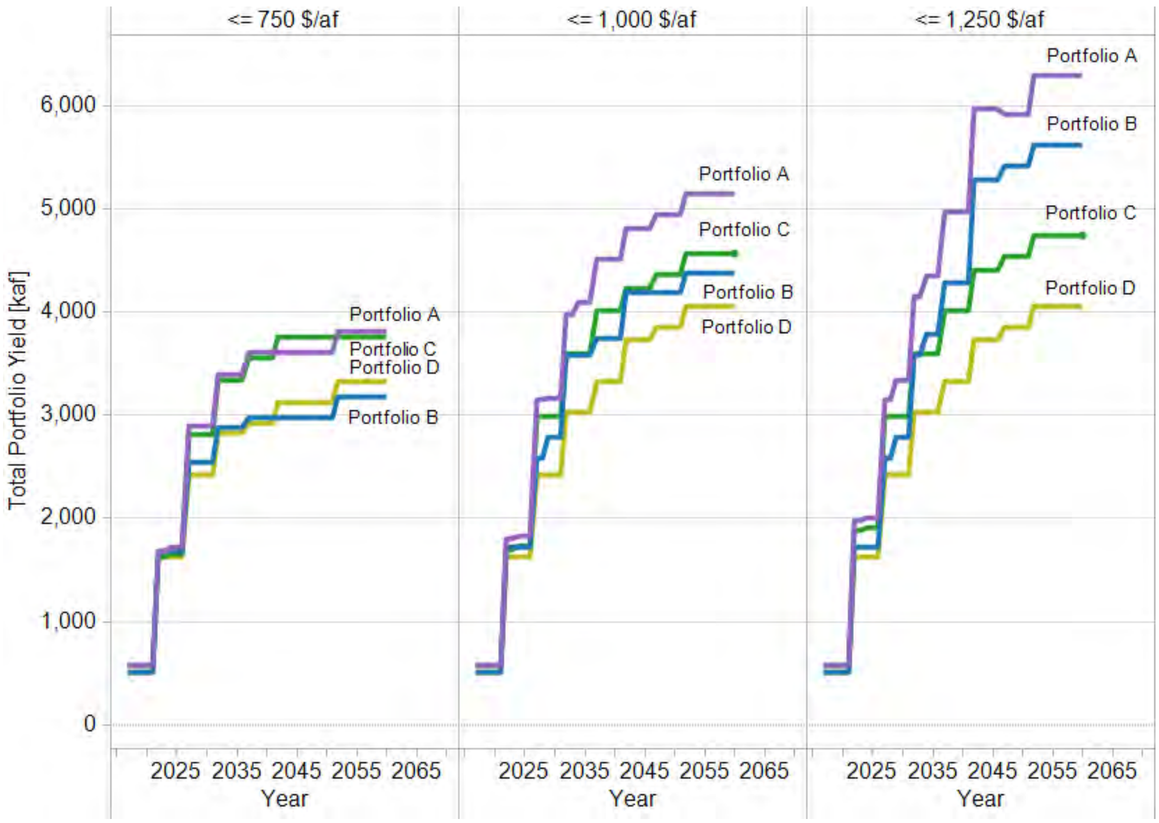
| Strategy and Portfolio Name | Portfolio Description |
|---|---|
| *Portfolio A* | Includes options with high technical feasibility, excludes options with highest permitting, legal, policy, and long-term viability risks. Is the least restrictive in terms of options, and contains all options that are in both Portfolio B and Portfolio C. |
| *Portfolio B* | Includes options with high technical feasibility and high long-term reliability; excludes options with high permitting, legal, or policy risks |
| *Portfolio C* | Includes only options with relatively low energy intensity; includes options that result in increased instream flows; excludes options that have low feasibility or high permitting risk |
| *Portfolio D* | Is the most selective in terms of options and contains only those options that are included in both Portfolio B and Portfolio C |

TABLE G-14
Summary of Included Options for *Portfolios B* and *C*

| Option Category | Option Type | ***Portfolio B*** | | ***Portfolio C*** | |
|---|---|---|---|---|---|
| | | **Number of Options** | **Sum of Yield (kafy)** | **Number of Options** | **Sum of Yield (kafy)** |
| Increase Supply | Desalination | 10 | 1,476 | 5 | 620 |
| | Import | 1 | 600 | 0 | 0 |
| | Local Supply | 1 | 100 | 1 | 75 |
| | Reuse | 6 | 972 | 7 | 1,150 |
| | Watershed Management | 2 | 300 | 5 | 730 |
| | Total | 20 | 3,448 | 18 | 2,575 |
| Reduce Demand | Agricultural Conservation | 5 | 1,000 | 5 | 1,000 |
| | Energy Water Use Efficiency | 1 | 160 | 1 | 160 |
| | M&I Conservation | 5 | 1,000 | 5 | 1,000 |
| | Total | 11 | 2,160 | 11 | 2,160 |
| | **Grand Total** | **31** | **5,608** | **29** | **4,735** |

Figure G-20 shows the potential yield of the four portfolios over time for three different limits on the portfolio average cost. Portfolios are limited by including only those options that keep the average cost of the portfolio below the specified limit. On the right, the portfolios are essentially unconstrained by cost (average costs less than $1,250 per af). Not surprisingly, *Portfolio A* has the highest potential yield (~6.3 maf) and *Portfolio D* has the lowest potential yield (~4.0 maf). *Portfolios B* and *C* yields are similar through 2042. At that point, *Portfolio B* yield increases significantly more than *Portfolio C*. For lower average costs, the differences between the four portfolios are less significant (figure G-20, left), particularly between *Portfolios B* and *C*.

FIGURE G-20
Total Yields over Time for Average Costs for Portfolios
*Less than $750 per af (left), less than $1,000 per af (middle) and less than $1,250/af (right)*




## 6.3 Study Portfolio Evaluation

### *6.3.1 Improvements in System Performance*

The effects of the dynamic portfolios were simulated in CRSS for the entire suite of supply, demand, and management scenarios. This section describes how the portfolios affect the performance of the system across these scenarios. Each figure is composed of five vertical panels. The first panel displays the Baseline runs, which do not include new actions considered in the portfolios. The remaining four panels present results from one of four simulated portfolios discussed above.

The figures present either magnitude and percent of traces with occurrence, or 10th, 50th and 90th percentile results for each of the key system response variables. The percentiles represent a level of non-exceedance for a given percentage of traces—i.e., the 10th percentile indicates the level at which 10 percent of the traces have not exceeded the value shown. In each of the figures, all traces for all combined scenarios are incorporated such that the results represent an ensemble of plausible future conditions.

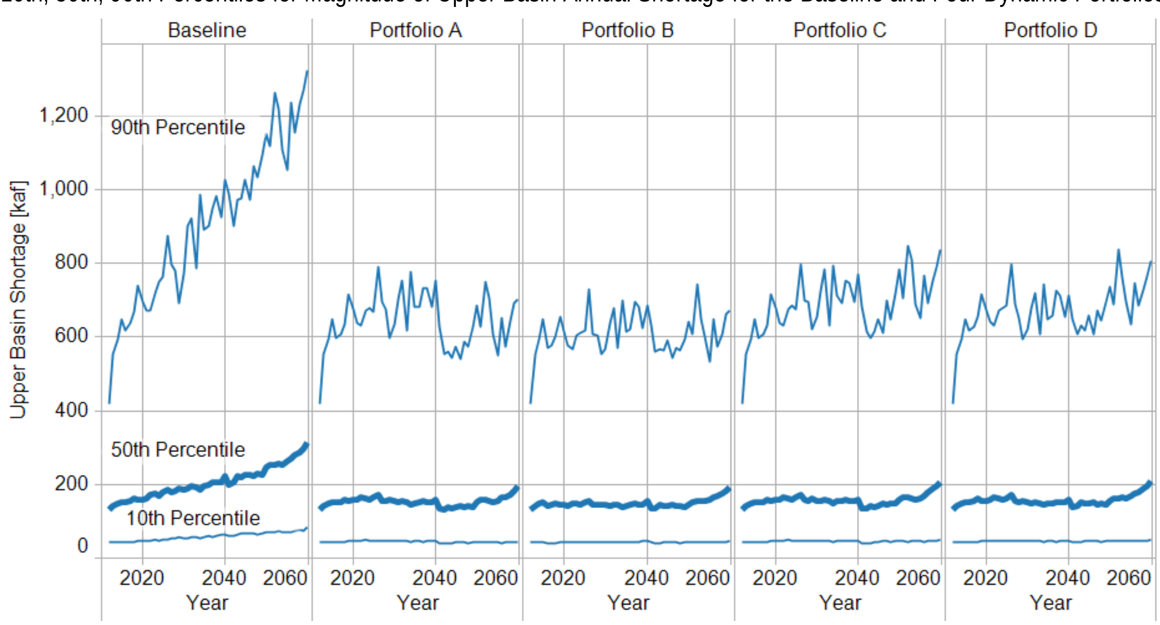
Summaries of system performance across traces presented in this section do not describe probabilistic outcomes. They describe plausible ranges and distributions for the baseline or a portfolio, corresponding to a wide range of plausible hydrologic, demand, and management traces. The underlying traces are the same across all portfolios and as such enable a consistent comparison of outcome differences across the portfolios.

Figure G-21 presents Upper Basin annual shortage as calculated by CRSS, which consistently and significantly underestimates shortages in the Upper Basin. Under the Baseline conditions, median shortage reaches 390 kaf by 2060. Portfolio B reduces 2060 median shortage to 230 kaf, a 40 percent reduction, followed closely by the *Portfolio A* (240 kaf), Portfolio D (250 kaf), and *Portfolio C* (250 kaf) portfolios (a 35 percent reduction).

The 90th percentile results suggest approximately 1.42 maf of Upper Basin shortage in 2060 under the Baseline. These shortages are projected to be reduced by approximately 36 percent in *Portfolio C* and by approximately 49 percent with *Portfolio B*. The other two portfolios fall between these bounds.

Again, this graphic likely overestimates the reduction in Upper Basin shortages under each portfolio, as a result of CRSS-simplified representation of smaller tributaries in the Upper Basin. Because the smaller tributary demand is placed on the mainstem of the larger tributaries (Yampa, Colorado, Gunnison, and San Juan), the model tends to overestimate the ability of many options to reduce the associated shortages. For example, municipal conservation on the Front Range or in large cities along the mainstem Colorado will not increase flow on smaller tributaries where many of the shortages exist.

FIGURE G-21
10th, 50th, 90th Percentiles for Magnitude of Upper Basin Annual Shortage for the Baseline and Four Dynamic Portfolios




Note: In all years under each of the portfolios, a shortage is projected in more than 99 percent of all traces.

Figure G-22 presents Lake Powell end-of-December pool elevation. Under the Baseline, median pool elevation decreased 29 feet by 2060, from 3,643 feet msl in 2012 to 3,614 feet msl by 2060. Implementation of any portfolio reversed this drop. The increase in pool elevation from 2060 Baseline conditions was bound by *Portfolio A* (51-foot increase) and *Portfolio D* (39-foot increase). With *Portfolio B*, pool elevation increased by 49 feet msl and with *Portfolio C* pool elevation increased by 46 feet msl.

The 10th percentile indicated a 218-foot drop in elevation by 2060 under the Baseline. This drop is reduced to 145 feet under *Portfolio D*, 123 feet under *Portfolio C*, 96 feet under *Portfolio B*, and 82 feet under *Portfolio A*. It is noteworthy that even with such an improvement, levels are quite low, indicating that some scenarios still pose a challenge to the system, even with options in place.

FIGURE G-22
10th, 50th, 90th Percentiles for Lake Powell End-of-December Pool Elevation for the Baseline and Four Dynamic Portfolios

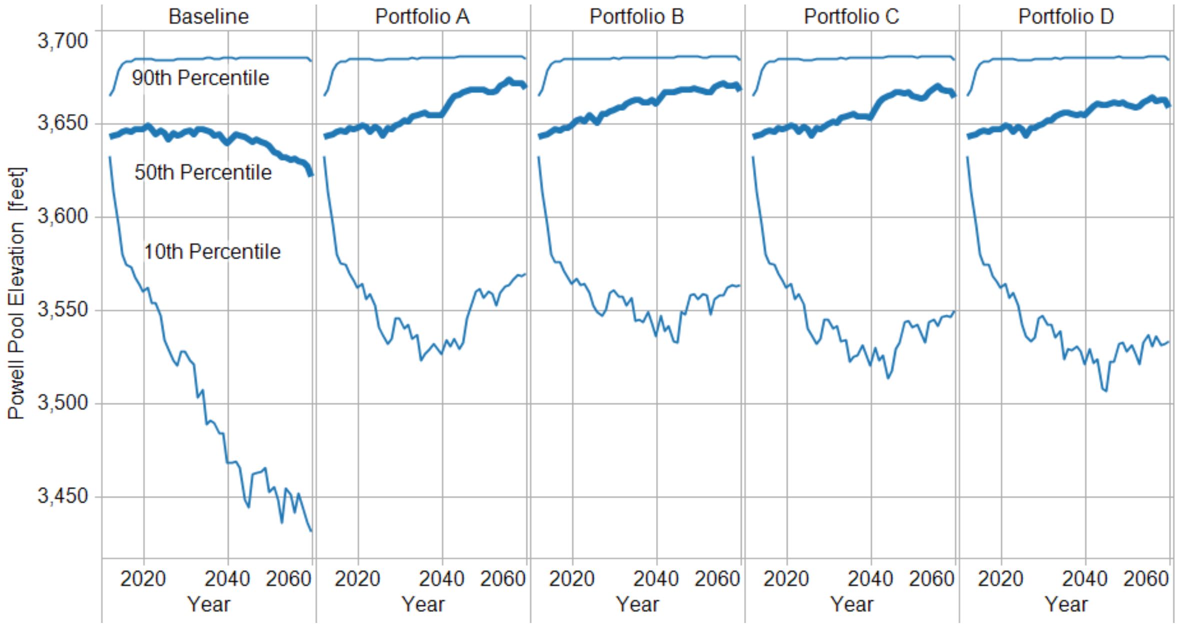



Figure G-23 presents the magnitude (top panel) and percent of traces (bottom panel) with a Lee Ferry Deficit defined as less than 75 maf of flow over 10 years. As was the case with Lake Powell pool elevation, all portfolios show improvements compared to the Baseline. In some cases, the number of traces in which a deficit occurs appears to have stabilized at less than 2 percent. Under the Baseline, the median deficit oscillates between approximately 1 and 3 maf between 2012 and 2040 then stabilizes at approximately 2 maf through 2060. A spike in deficit magnitude after 2050 is a result of reduced natural flows present in the Downscaled GCM Projected supply scenario. This spike is present under all portfolio results. Although the risk of a Lee Ferry Deficit was notably lowered, the median magnitude was impacted less (average magnitude reduction of 5.4 kafy across portfolios). In fact, at the 90th percentile, there appear to be some slight increases in shortage magnitudes. This is likely an artifact of reducing the number of shortage events, particularly those of smaller magnitudes, thereby shifting some of the more-extreme conditions to the 90th percentile. Importantly, the portfolios that stabilize the probability of a Lee Ferry Deficit contain an option for an Upper Basin water bank, with certain assumptions about how a water bank would operate, that is used to help meet Compact delivery obligations when needed. The water bank concept is one of the best ways at reducing vulnerability of the Upper Basin to a Lee Ferry deficit. Because water banking concepts involve large institutional, legal, and policy issues, work must continue with deliberate speed to explore Upper Basin water banking options.

FIGURE G-23
10th, 50th, 90th Percentiles for Lee Ferry Deficit in Years in Which a Deficit Occurs (top) and Percent of Traces (bottom) with a Lee Ferry Deficit for the Baseline and Four Dynamic Portfolios

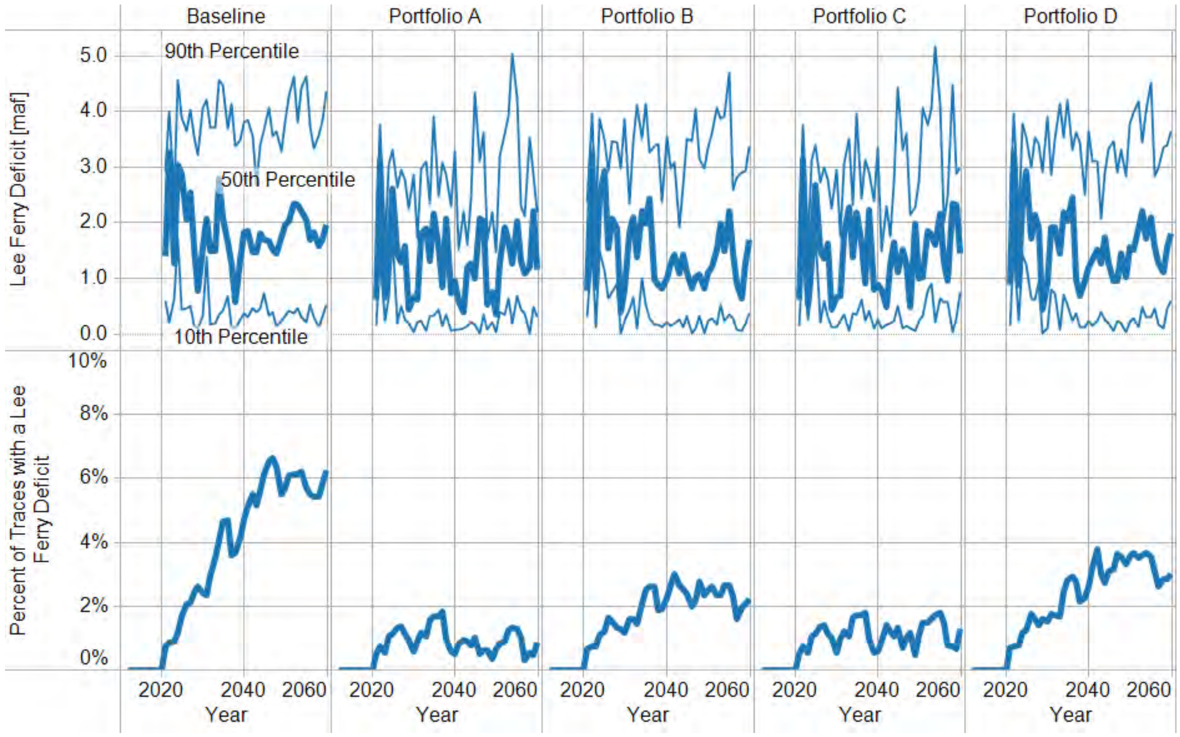



Figure G-24 presents Lake Mead end-of-December pool elevation. Under the Baseline, median pool elevation decreased 69 feet, from 1,135 feet msl in 2012 to 1,066 feet msl by 2060. Pool elevations improved under all portfolios, relative to the Baseline, albeit not as immediate and to a lesser magnitude compared with the results at Lake Powell. The delayed recovery of the median pool elevation is a combination of option availability for implementation and the additional demands above Lower Division States' basic apportionments that were not addressed in the Baseline run. These demands all originate in the Lower Division States, and therefore add demand on Lake Mead by calling for greater releases. In 2060, relative to the Baseline, median pool elevations rose from 60 to 90 feet msl depending on the specific portfolio. Not surprisingly, *Portfolio A*, which has the largest maximum potential yield, saw the largest increase (90 feet), and *Portfolio D*, with smallest maximum potential yield, showed the smallest gains (60 feet). Further, the 10th percentile indicates a 177-foot decline by 2060 under the Baseline. This decline is reduced to 75 feet under *Portfolio D*, 71 feet under *Portfolio C*, 48 feet under *Portfolio B*, and 43 feet under *Portfolio A*. The 90th percentile indicates an approximate 20-foot increase from Baseline conditions by 2060 across all portfolios.

FIGURE G-24
10th, 50th, 90th Percentiles for Lake Mead End-of-December Pool Elevation for the Baseline and Four Dynamic Portfolios

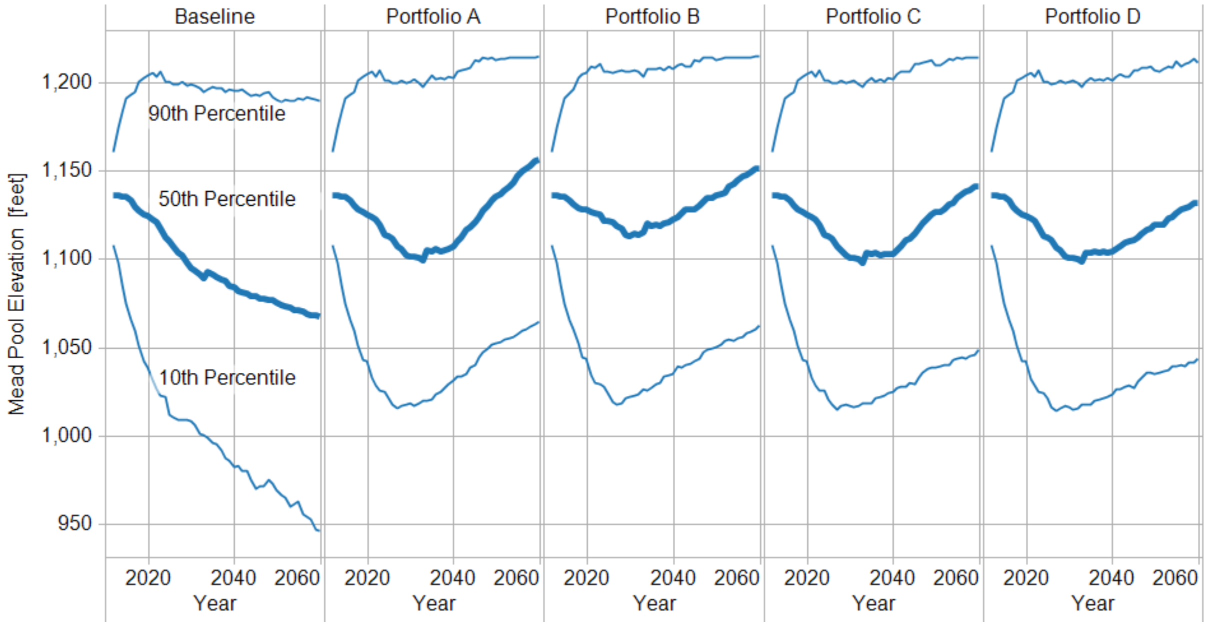



Figure G-25 presents the magnitude (top panel) and percent of traces (bottom panel) with the Lower Basin 2012 through 2060 annual regulatory shortage. Under the Baseline, the Lower Basin median regulatory shortage begins at 400 kaf, indicating 50 percent of traces are under level 1 shortage; raises to 500 kaf by 2019 (level 2 shortage); reaches 600 kaf by 2027 (level 3 shortage); and maintains this through 2060. The 90th percentile shortage increases to 600 kaf by 2018, then jumps to approximately 1.72 maf by 2027, and rises to 1.78 maf by 2060.

With the implementation of portfolios, the availability of options to address Lower Basin regulatory shortage is insufficient until 2032, at which time all portfolios show a drop in median shortage to as low as 241 kaf under *Portfolio C* by 2060. There is also a substantial decrease in shortage at the 90th and 10th percentile levels. At the 90th percentile, *Portfolio A* shows a reduction by 2060 to 584 kaf and the 10th percentile shows a reduction to 88 kaf.

FIGURE G-25
10th, 50th, 90th Percentiles for Lower Basin Annual Shortages (Regulatory plus Hydrologic) Magnitude (top), and Percent of Traces with Lower Basin Shortage (bottom) for the Baseline and Four Dynamic Portfolios

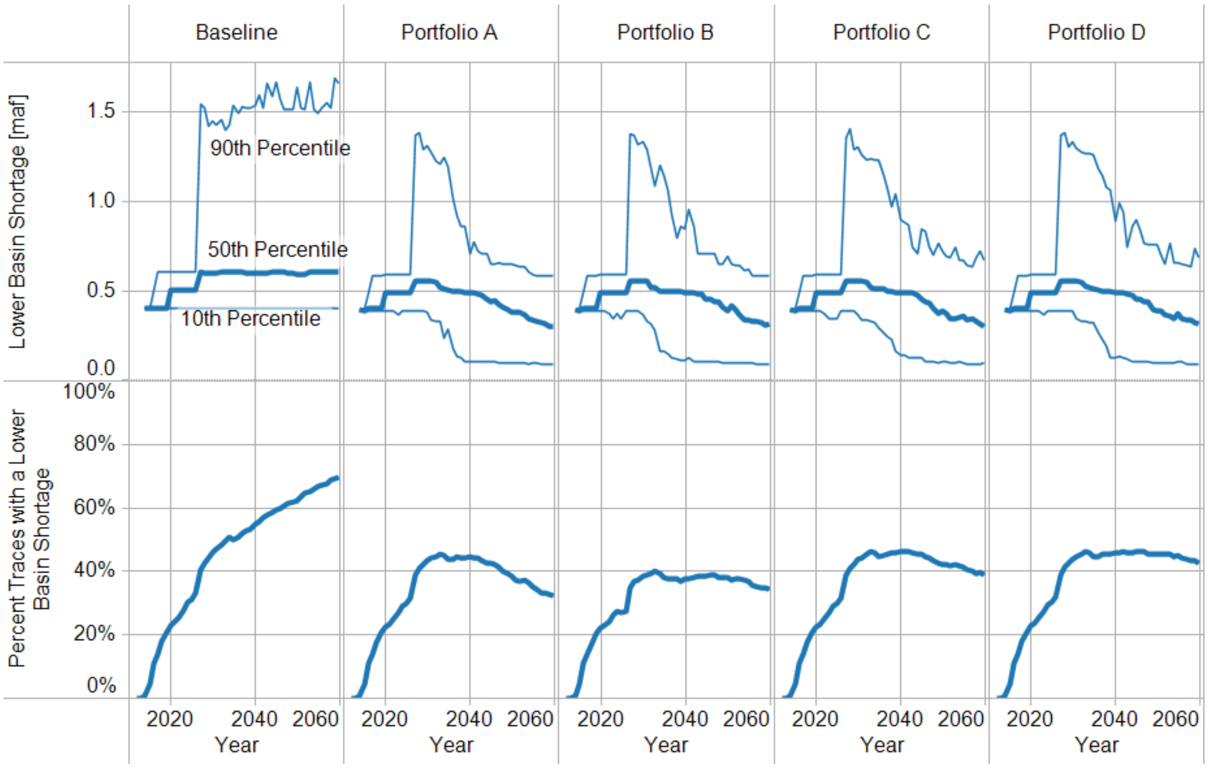



Figure G-26 presents the Lower Basin 2012–2060 annual remaining demands above Lower Division States' basic apportionments as distribution of magnitudes and percent of traces when that occurs. Under the Baseline, median remaining demands above Lower Division States' basic apportionments (top panel) increases from 536 kaf in 2012 to 1,687 kaf by 2060. The 90th percentile increases from 536 kaf in 2012 to 2,507 kaf by 2060, while the 10th percentile begins at 529 kaf in 2012, dips to a low of 0 kaf in 2022, and then grows to a high of 1,168 kaf by 2060. The percent of traces with remaining demands above Lower Division States' basic apportionments in 2012 (bottom panel) begins at 100 percent, dips to 90 percent around 2020, then climbs back to 100 percent by 2044 and remains at that percentage through 2060. This behavior is related to the similar pattern observed at the 10th percentile magnitude. Recall that under the Baseline, the only time Lower Division States' demands above basic apportionments are met is during surplus. The near-term probability of surplus is negligible, so Lower Division States' demands above basic apportionments often goes unmet. As the percent of traces with surplus increases in the near future, the percent of traces in which above basic apportionments are not met drops modestly, as does the remaining demands above basic apportionments magnitude at the 10th percentile. Ultimately, however, the percent of traces returns to 100 percent and the 10th percentile magnitudes begin to increase. This is due to the demands above Lower Division States' basic apportionments increasing with time to a level that cannot be satisfied with surplus conditions alone.

Implementation of any portfolio shows a reduction in magnitude after 2016 and percent of traces after 2030. By 2060, the median remaining demands above Lower Division States' basic apportionments is reduced to 0 kaf under *Portfolio A*, 16 kaf under *Portfolio B*, 77 kaf under *Portfolio D*, and 97 kaf under *Portfolio C*. The percent of traces is reduced to 48 percent under *Portfolio A*, 51 percent under *Portfolio B*, 63 percent under *Portfolio D*, and 66 percent under *Portfolio C*.

FIGURE G-26
10th, 50th, 90th Percentiles for Remaining Demands Above Lower Division States' Basic Apportionments Magnitude (top) and Percent of Traces When This Occurs (bottom) for the Baseline and Four Dynamic Portfolios

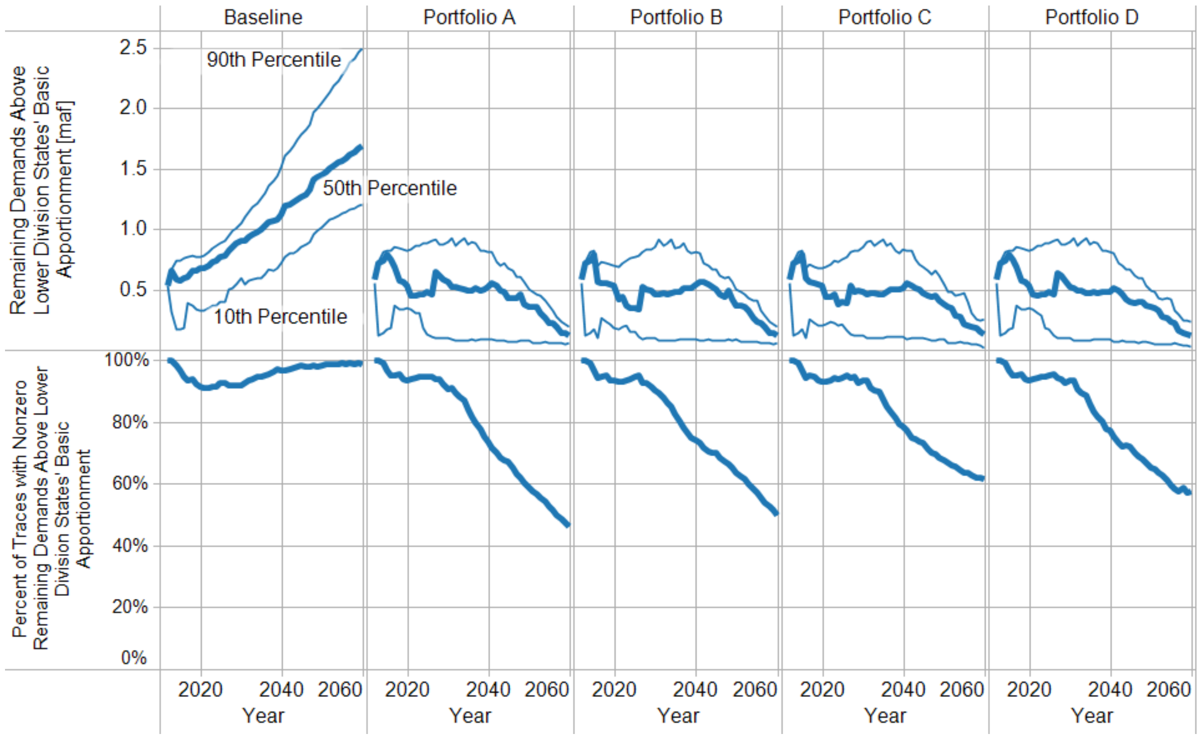
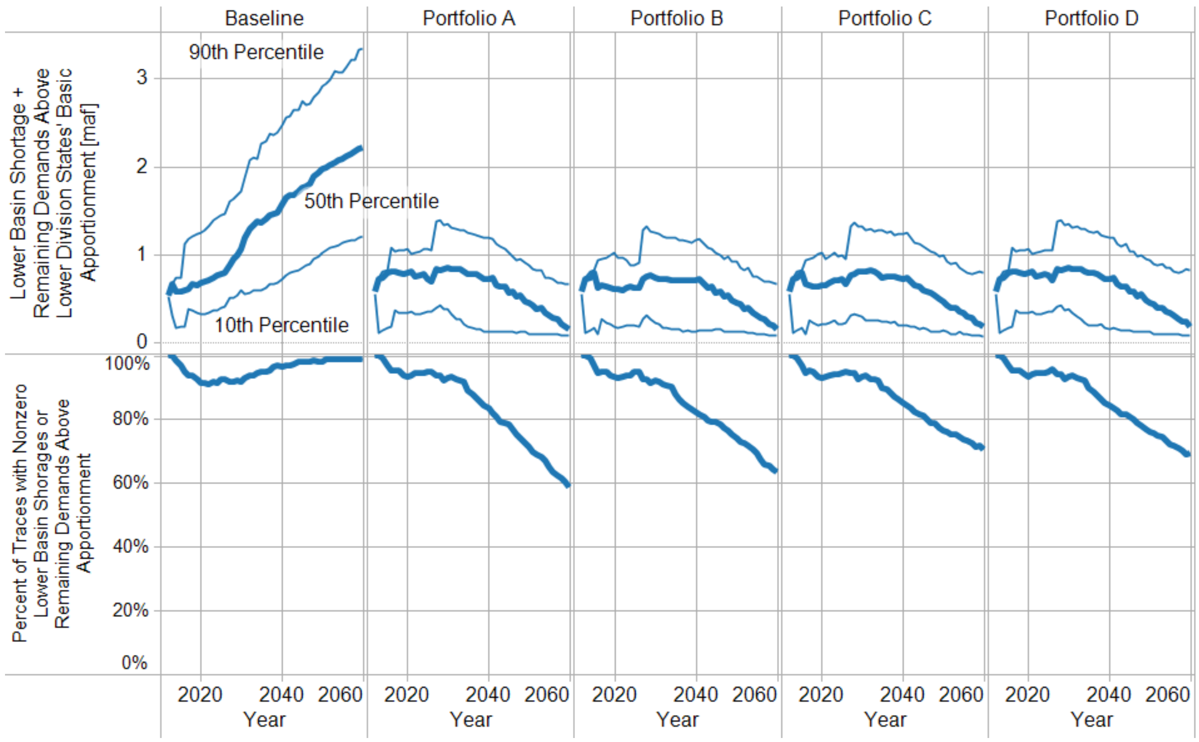



Figure G-27 presents the Lower Basin 2012 through 2060 annual total shortage determined as regulatory and hydrologic shortages plus remaining demands above Lower Division States' basic apportionments. The figure shows the magnitude (top panel) and percent of traces when that occurs (bottom panel). Under the Baseline, median shortage in 2012 is 536 kaf and climbs to 2.274 maf by 2060. The 90th percentile increases to 3.720 maf, while the 10th percentile climbs at a slower rate to 1.167 maf. The percent of traces with shortage begins at 100 percent in 2012, dipping to 90 percent from 2020 through 2024, then climbing back to 100 percent by 2044 and through 2060. This is the same behavior discussed in the previous section. When reservoirs are full (i.e., surplus conditions exist), there are no regulatory shortages and occasionally the surplus is sufficient to satisfy all demands above basic apportionments.

Implementation of portfolios consistently reduces median shortage from 2030 to a magnitude of 150 kaf under *Portfolio A*, 154 kaf under *Portfolio B*, 162 under *Portfolio D*, and 181 kaf under *Portfolio C* by 2060 in all portfolios. The 90th percentile is reduced to about 1 maf by

2060. The percent of traces with shortage in 2060 is reduced to 60 percent under *Portfolio A,* 65 percent under *Portfolio B,* 75 percent under *Portfolio D,* and 76 percent under *Portfolio C.*

FIGURE G-27
10th, 50th, 90th Percentiles for the Sum of Lower Basin Regulatory and Hydrologic Shortages plus Remaining Demands Above Lower Division States' Basic Apportionments for the Baseline and Four Dynamic Portfolios




Improvements in system performance are demonstrated across all portfolios when compared with the Baseline analyses. Comparison of the four portfolios with 2060 Baseline conditions showed:

- Due to CRSS simplification, the reduction in Upper Basin median shortage magnitude is likely overstated. Still, while the magnitude of shortage was reduced, nearly all traces still contained some shortages.
- Lake Powell end-of-December median pool elevation increased between 39 and 51 feet msl under implementation of the dynamic portfolios.
- Lee Ferry median deficit magnitude was reduced by 265 kaf, and the percent of traces with deficit was reduced to between 1 and 4 percent versus 8 percent for the Baseline.
- Lake Mead end-of-December storage shows declines through 2030 in all portfolios, but increases between 60 and 90 feet by 2060 as options are implemented to reduce demand or increase Basin supply.
- Lower Basin regulatory shortage was similar to the Baseline through 2030 then dropped to a low of 241 kaf by 2060, a 60 percent reduction from 2060 Baseline conditions. Similarly, the percent of traces with shortage dropped from a high of 48 percent in 2033 to a low of 32 percent by 2060, compared with 67 percent under the Baseline. Remaining

demand above Lower Division States' basic apportionments showed a steady median decline from a high of 820 kaf in 2015 to between 0 and 100 kaf by 2060. By 2060, the percent of traces with remaining demands above Lower Divisions' States basic apportionments is reduced to between 48 and 66 percent from 100 percent under the Baseline.

### 6.3.2 Changes in Water Delivery Vulnerabilities

Simulation results from the evaluation of portfolios were also used to estimate to what degree these new investments could reduce vulnerability in the Basin across all water delivery indicator metrics. The results of this analysis are shown in the figures following. Shown below are two figures for each resource category: one figure for the percentage of traces and one for the percentage of years in which vulnerability occurs. Each figure shows a barplot with the percentage of traces or years vulnerable, separated by indicator metric and time period. In addition, the results from each dynamic portfolio simulation are shown across the x-axis, with the baseline (no action) simulations shown in the left-most pane and the portfolio simulations shown in sequence to the right.

Figures G-28 and G-29 shown the change in vulnerability for the water delivery indicator metrics with portfolios in place compared with the Baseline. The next section provides these same summary results for the other indicator metrics.

For all metrics shown, vulnerabilities in the first period tend to change little from the Baseline results. This is a combination of often low vulnerability risk in the early period and few options available to address vulnerabilities when they occur. The middle time period is the first period in which results significantly diverge from the Baseline for most indicator metrics. However, this period, in some cases, is also the most vulnerable window, because options may have only been available for a short time and little benefit has yet accrued. As discussed earlier, demands above apportionment were not addressed in the Baseline modeling and therefore show a marked improvement under the portfolios. Also, one might expect *Portfolio A* to show the greatest reduction in vulnerabilities simply by having the greatest yield available to address imbalances. However, this is not always the case. Because this portfolio includes the Upper Basin banking option, water generated by conservation is not immediately available to address vulnerabilities, but is instead "banked" to help hedge against future water use curtailments as specified in the Upper Colorado River Basin Compact.

For this same reason, *Portfolio A* was particularly effective at reducing frequency of Lee Ferry Deficits. It is noteworthy that in general, the relative reduction in percent of years in which vulnerable conditions existed was greater than the reduction in percent of traces vulnerable. For example, with regard to the Lower Basin Shortage indicator metric (1.5 maf per 5 years), percent of years vulnerable in the 2041 through 2060 time period are reduced from about 59 percent to less than 25 percent, whereas percent of traces vulnerable are lowered from 87 percent to about 58 to 66 percent, depending on the portfolio. This indicates that it is difficult to completely eliminate the vulnerability in each trace due to significant hydrologic variability.

FIGURE G-28
Percent of Vulnerable Traces for Each Water Delivery Indicator Metric Across Three Time Periods for the Baseline And Four Simulated Portfolios

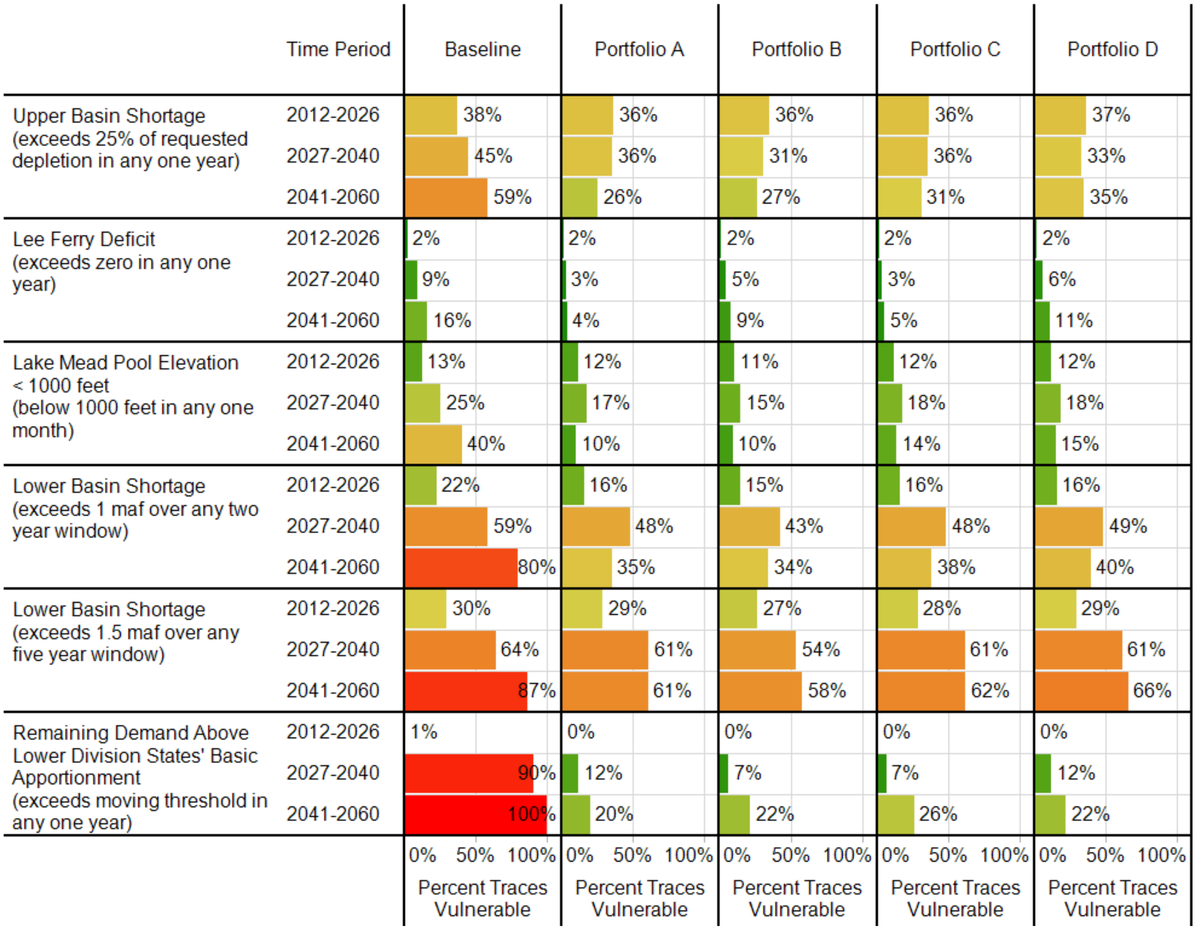
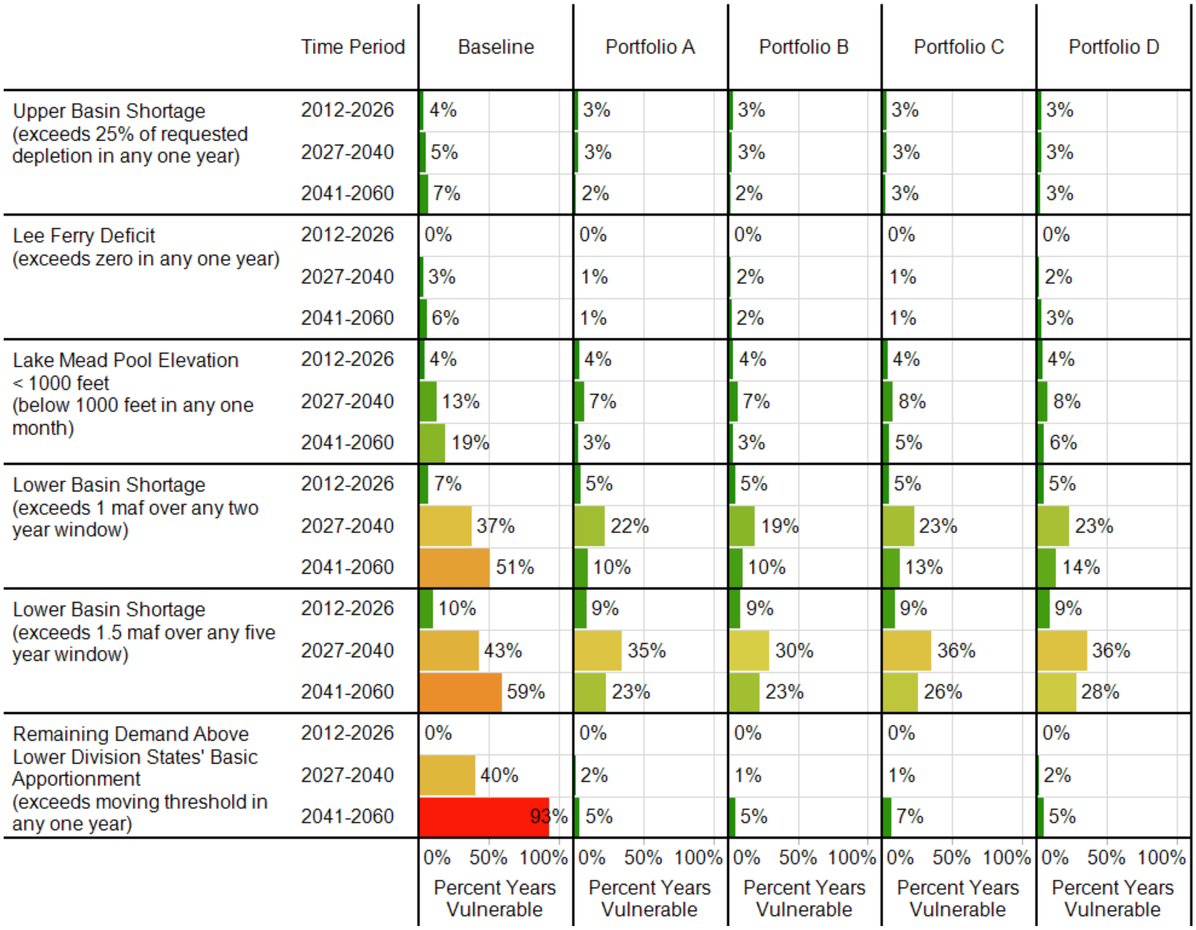


FIGURE G-29
Percent of Vulnerable Years for Each Water Delivery Indicator Metric Across Three Time Periods for the Baseline And Four Simulated Portfolios




The following paragraphs address specific changes in water delivery indicator metric vulnerability with portfolios in place (in order of water delivery metrics listed).

### *Upper Basin Shortage*

Due to CRSS simplification, the reduction in Upper Basin median shortage magnitude is likely overstated. Still, while the magnitude of shortage was reduced, nearly all traces still contained some shortages.

### *Lee Ferry Deficit*

Portfolio investments appear to substantially reduce the occurrence of a Lee Ferry deficit in many simulated traces. In particular, *Portfolios A* and *C*, which include an Upper Basin banking option, reduce the percent of vulnerable traces in the 2041 through 2060 time period from 16 percent to 4 to 5 percent. Similarly, these portfolios reduce the percent of vulnerable years from 6 percent in the final time period to 1 percent with options implemented. *Portfolios B* and *D* also reduce the proportion of traces or years with a Lee Ferry Deficit occurring (vulnerability remains in 9 to 11 percent of traces or 2 to 3 percent of years in the 2041 through 2060 time period).

### *Lake Mead Elevation*

Lake Mead elevation is better maintained above the 1,000-foot vulnerability threshold with portfolios in place. All four dynamic portfolios reduce the proportion of years or traces in which vulnerability occurs, although *Portfolios A* and *B* yield the most substantial vulnerability reduction for this indicator metric. This is due to the inclusion of additional desalination options for the Lower Basin in these portfolios. One note here is that the portfolios do not perform as well in the middle time period (2027 through 2040), generally yielding a larger percent of vulnerable traces and years in the middle period when compared with the final period despite growing vulnerability over time. This result is because the options needed to augment Lake Mead storage levels—particularly additional system water gained by offsetting Lower Basin demand with new coastal desalination—only become available after 2040, resulting in very low Lake Mead levels during the interim decades in 15 to 17 percent of traces (7 percent of years).

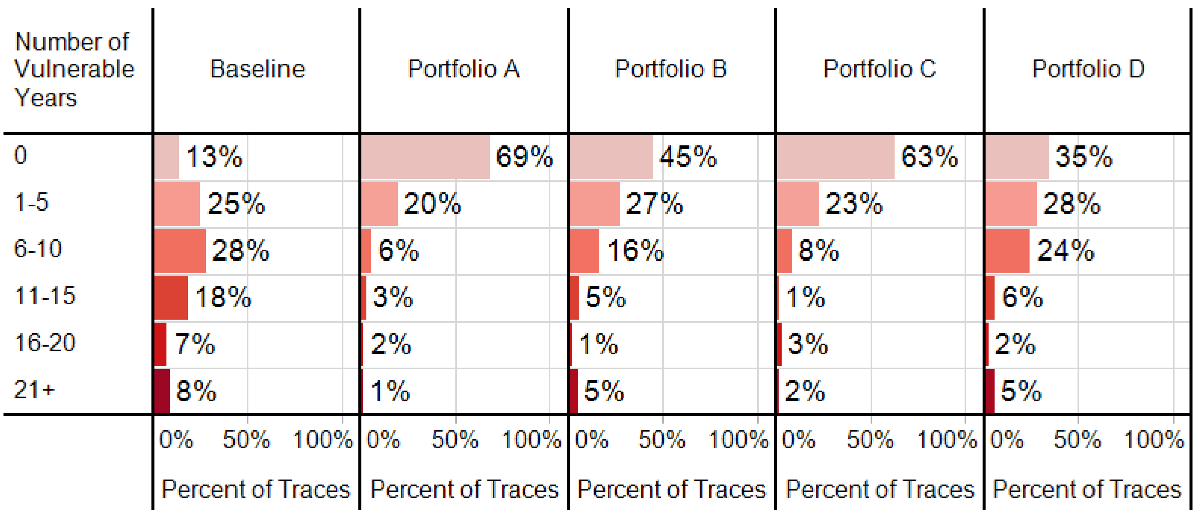
### *Lower Basin Shortage*

The portfolios generally reduce the percent of time in which Lower Basin shortages occur. However, shortages exceeding the vulnerability thresholds specified by Lower Basin users still occur in many traces or years with the portfolios in place. For example, with *Portfolio A* in place, the proportion of traces/years with a shortage exceeding 1 maf over 2 years declines from 80 percent of traces /51 percent of years in the Baseline to 35 percent/10 percent in the 2041 through 2060 time period. When considering a shortage of 1.5 maf over 5 years, alternately, the reduction is from 87 percent of traces/59 percent of years to 61 percent/23 percent with *Portfolio A* in place. In general, the 5-year shortage metric is more sensitive, and shows a larger proportion of vulnerable traces and years both in the Baseline and with dynamic portfolios implemented. As with Lake Mead elevation, for these metrics, a greater reduction in vulnerability is observed in the third time period compared with the first and second periods due to the number of options available and called by the portfolio by this point in time.

Lower Basin shortages are driven by Lake Mead storage levels, so these results reiterate that, despite the improvement in storage levels with the dynamic portfolios, a substantial fraction of traces or years remain in which Lake Mead levels trigger Lower Basin shortages that could exceed users' capacity for short-term adaptation. As noted above, the most significant reduction in vulnerability occurs with remaining demand above basic apportionments in the Lower Division States. Due to increasing demand and the declining moving threshold over time, 100 percent of traces and 93 percent of years are vulnerable for this indicator metric by the 2041 through 2060 time period in the Baseline. With the portfolios implemented, however, the outcome is substantially improved in the middle and final time periods. In particular, in the final period the proportion of vulnerable traces is reduced dramatically (20 to 26 percent with portfolio), as is the proportion of vulnerable years (5 to 7 percent with portfolio). All portfolios help to reduce unmet demand above Lower Division States' basic apportionments, although due to the desalination options, *Portfolios A* and *B* generally yield the greatest reduction in vulnerable traces or years for this metric across all time periods.

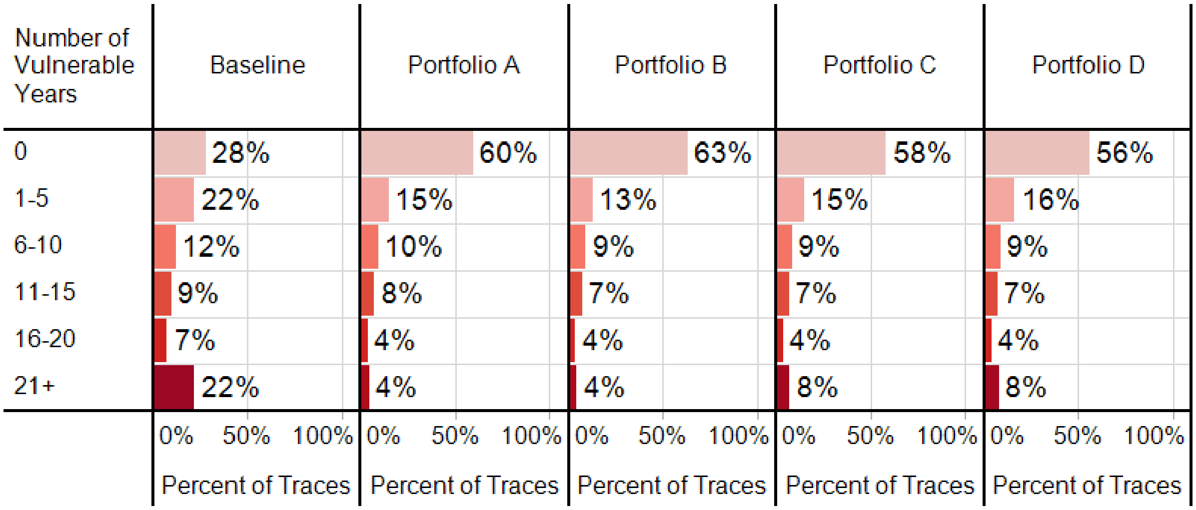
A subset of the traces included in CRSS, particularly those drawn from the Downscaled GCM Projected hydrology, yield a large number of vulnerable years in a given trace. In these cases, portfolio investments may not fully eliminate vulnerable years (i.e., may not yield zero vulnerability in a trace), but may nevertheless reduce the number of years in which a vulnerability occurs. Figure G-30 illustrates this result for the Lee Ferry Deficit indicator metric by showing a histogram with bins for the number of vulnerable years (y-axis) summarized as a proportion of traces (x-axis). As above, this figure shows results from the Baseline (left column) as well as those from the four dynamic portfolios. For further sensitivity, this figure focuses on those traces included in the *low long-term annual average flow below 14 maf and 8-year drought below 11 mafy* vulnerable conditions defined for this metric in the previous section.

FIGURE G-30
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios, Lee Ferry Deficit Indicator Metric, In Vulnerable Conditions (Long-Term Flow < 14 mafy and Drought < 11 mafy)




For traces in this set of vulnerable conditions, 13 percent of traces have no years with a Lee Ferry Deficit in the Baseline from 2012 through 2060. However, 25 percent of traces show a deficit in 1 to 5 years, 28 percent show a deficit in 6 to 10 years, and 33 percent (18 + 7 + 8 percent) have a deficit in 11 or more years. This distribution shifts substantially, however, with the portfolios in place. Implementing *Portfolio A*, for instance, shifts many traces to zero vulnerability (69 percent within the vulnerable condition). Other traces still include at least one vulnerable year, but the upper tail—the proportion of traces with a large number of vulnerable years—is dramatically reduced. Using *Portfolio A* again, the proportion of traces with a deficit in 11 or more years is reduced from 33 percent to 6 percent.

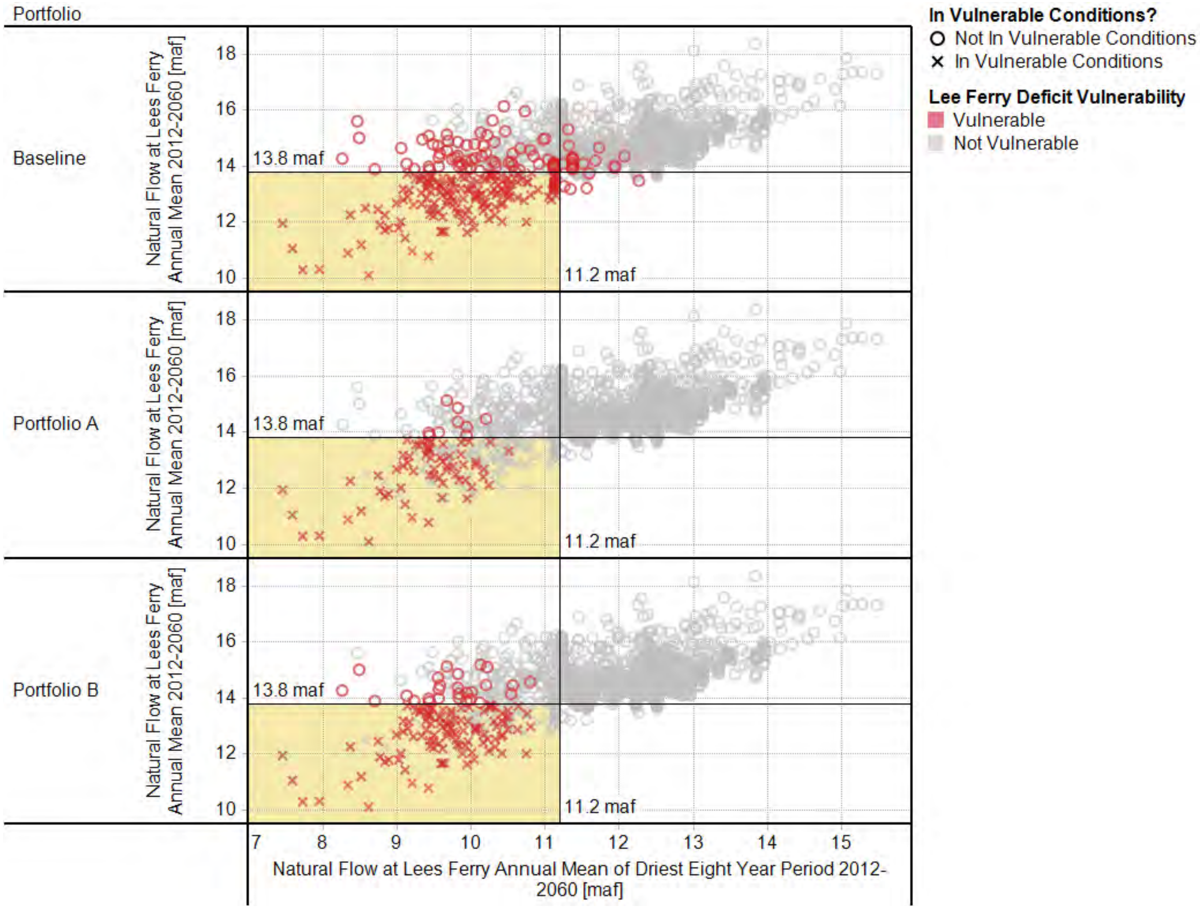
FIGURE G-31
Number of Vulnerable Years Across Traces 2012–2060 for a Subset of All Scenarios, Lake Mead Elevation Indicator Metric, In Vulnerable Conditions (Long-Term Flow < 15 mafy & Drought < 13 mafy)




Similar results can be observed using the *Lake Mead elevation* indicator metric (figure G-31). Once again, the figure shows the subset of traces within the vulnerable conditions previously defined for this metric (*Long-term average flow below 15 mafy and 8-year drought below 13 mafy*). Note that, in this set of vulnerable conditions, a large proportion of traces in the Baseline show Lake Mead elevation below 1,000 feet msl in 11 or more years, with nearly one-quarter of traces (22 percent) showing Lake Mead at critically low levels in 21 or more years. With *Portfolio B* implemented, however, the entire distribution is shifted—from 28 percent to 63 percent of traces with zero vulnerable years at one end, and 22 percent to 4 percent with 21 or more years vulnerable. Although a large fraction of traces with at least one vulnerable year remain within this set of vulnerable conditions (44 percent with the best-performing portfolio), the general pattern is a reduction in the number of vulnerable years and improved performance even in highly adverse traces. Similar results for other water delivery indicator metrics are provided in appendix G3.

Vulnerable conditions were previously defined in order to better understand the external drivers—in this case, what turned out most often to be the hydrologic conditions in the Basin—that most often led to vulnerable outcomes across the Basin. It was previously observed that the portfolios can improve outcomes for the system, either at the median of the distribution of traces or in terms of indicator metric vulnerability. However, another key question is how the portfolios perform in terms of reducing vulnerability within the set of vulnerable conditions defined for each metric. Ideally, a portfolio would shift the definitions or thresholds for vulnerable conditions altogether, yielding a range of conditions that were previously vulnerable under the Baseline but no longer produce vulnerable outcomes with the portfolio implemented. This type of change does in fact occur in the simulated portfolio results for the water delivery metrics. For example, the top pane of figure G-32 below shows the same scatter plot of vulnerable conditions for the Lee Ferry Deficit indicator metric also shown in figure G-15. The axes show the two dimensions that define the vulnerable conditions: long-term average annual natural flow at Lees Ferry (y-axis) and average annual natural flow at Lees Ferry during the lowest 8-year period (x-axis). Each point in the plot shows one trace outcome across the 2012-2060 time span, with vulnerable traces colored red and non-vulnerable traces colored gray. Points within the *low long-term average flow and 8-year drought below 11.2 mafy* vulnerable conditions are marked with X's, and points outside are marked with O's.

FIGURE G-32
Reduction in Vulnerable Traces with Selected Portfolios in Place, Lee Ferry Deficit Indicator Metric




The middle and bottom panes show the same plot with the same vulnerable conditions defined, but with results from *Portfolio A* or *Portfolio B* implemented, respectively, instead of the Baseline. This figure shows that, with the portfolios in place, a large fraction of traces and corresponding region of the vulnerable conditions has changed from red (vulnerable) to gray (not vulnerable). For instance, significantly few traces with a mean flow of 10 mafy or greater during the driest 8-year period are vulnerable with either of these portfolios implemented, whereas in the Baseline traces with average flows during an 8-year drought of 10 to 11.2 mafy were nearly always vulnerable when coupled with a low long-term overall flow. This suggests that the conditions that cause this vulnerability have shifted with the portfolios in place, and the new investments have provided a hedge against vulnerability in plausible simulated futures.

To test the potential shift in vulnerability with a portfolio in place, the vulnerable conditions were re-evaluated for all water delivery indicator metrics with *Portfolio A* in place. The results of this reanalysis are provided in table G-15. In this table, results are provided from the Baseline and also show the change in vulnerability with the portfolio in place. The second column shows the change in the overall proportion of vulnerable traces, while the rightmost columns describe how the vulnerable conditions shift when *Portfolio A* is implemented. In each cell, the blue bars again show the full range of the flow characterization or other quantitative input to the modeling across all scenarios; the red bars show the range of the restriction that helps to define the new vulnerable condition; and the yellow bars (with subscript values) show where the restriction identified for the Baseline simulations was previously defined.

For example, the first row shows the vulnerable conditions for Upper Basin Shortage with the portfolio in place. In the Baseline, 86 percent of traces include at least one vulnerable year during the 2012 through 2060 timeframe, and the vulnerable conditions are defined by a 1-year minimum natural flow at Lees Ferry less than or equal to 8.3 maf. With *Portfolio A* implemented, however, the percentage of vulnerable traces is reduced to 73 percent, and the new threshold for minimum natural flow shifts to 7.0 maf. This indicates that the additional supply and/or reduced demand in the Upper Basin with the portfolio in place provides additional capacity to handle single years with very low natural flows of between 7.0 and 8.3 maf without yielding a shortage of more than 25 percent of requested depletions for Upper Basin users. This result suggests that *Portfolio A* could introduce new resiliency to the system and allow the Upper Basin to better hedge against low-flow years.

With respect to the other water delivery indicator metrics, the following changes in vulnerable conditions with the portfolio implemented are noted:

- The conditions producing a Lee Ferry Deficit shift farther into the tail: with the portfolio implemented, these vulnerabilities most often occur in traces with a long-term flow mean of 13.2 mafy and an 8-year drought mean of 10 mafy, compared with 13.8 mafy and 11.2 mafy in the Baseline, respectively.

- Lake Mead elevation vulnerability shows a similar shift towards the extreme cases, with the long-term flow threshold reduced by about 500 kaf and the drought mean reduced by 700 kaf to 1 maf compared with the Baseline, depending on the post-2026 operation assumption for Lakes Powell and Mead.

- Two different patterns occur in the Lower Basin shortage indicator metrics. First, the “ORs” change to “ANDs,” meaning that within each portfolio the domain of the vulnerable condition is reduced and all conditions across the row must now be met within the vulnerable conditions. By contrast, in the Baseline, meeting either flow condition was sufficient to predict a vulnerable trace. In addition, for both metrics both the long-term mean and 8-year drought mean thresholds shift downwards, but only if management reverts to the 2007 Interim Guidelines Final EIS No Action Alternative (i.e., the 2007 Interim Guidelines (DOI, 2007) expire) after 2026. However, the new vulnerable conditions for these metrics with *Portfolio A* in place still include a large proportion of traces from CRSS simulations, and the long-term mean thresholds remain above the observed historical average of Lees Ferry natural flow.

TABLE G-15
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric for Portfolio A

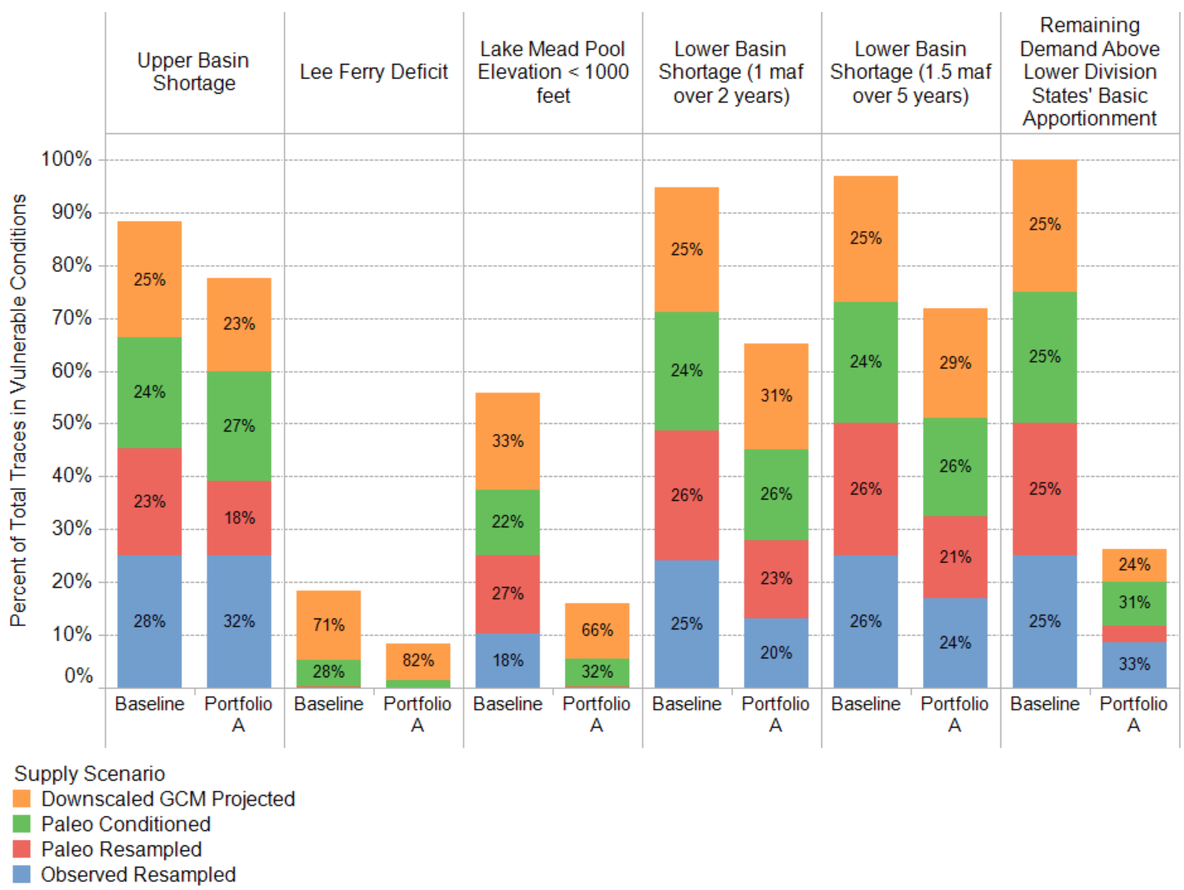
| **Indicator Metric** | **Vulnerable Traces (Baseline → with Portfolio)** | **System Condition** | | | | |
|---|---|---|---|---|---|---|
| | | **Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf]** | | **One Year Minimum Annual Natural Flow at Lee Ferry (2012–2060) [maf]** | | **Post-2026 Operation of Lakes Powell and Mead** |
| Upper Basin Shortage | 86% → 69% | NA | – | 7.0<br>8.3<br>3 12 | – | NA |
| **Indicator Metric** | **Vulnerable Traces (Baseline → with Portfolio)** | **System Condition** | | | | |
| | | **Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf]** | | **Driest 8-Year Period of Annual Mean Natural Flow at Lee Ferry [maf]** | | **Post-2026 Operation of Lakes Powell and Mead** |
| Lee Ferry Deficit | 19% → 6% | 13.2<br>13.8<br>10 18.5 | AND | 10.0<br>11.2<br>7 15.5 | – | NA |
| Lake Mead Pool Elevation | 47% → 24% | 14.5<br>15<br>10 18.5 | AND | 12.0<br>13<br>7 15.5 | AND | 2007 Interim Guidelines |
| | | 14.1<br>14.6<br>10 18.5 | AND | 11.3<br>13<br>7 15.5 | AND | Revert to 2007 Interim Guidelines Final EIS No Action Alternative |
| Lower Basin Shortage (1 maf over 2 years) | 86% → 62% | 15.6<br>15.6<br>10 18.5 | ~~OR~~<br>**AND** | 11.8<br>11.8<br>7 15.5 | AND | 2007 Interim Guidelines |
| | | 15.6<br>16.1<br>10 18.5 | ~~OR~~<br>**AND** | 13.7<br>14.2<br>7 15.5 | AND | Revert to 2007 Interim Guidelines Final EIS No Action Alternative |

TABLE G-15
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric for Portfolio A

| Indicator Metric | Vulnerable Traces (Baseline → with Portfolio) | System Condition | | | | |
|---|---|---|---|---|---|---|
| | | Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf] | | One Year Minimum Annual Natural Flow at Lee Ferry (2012–2060) [maf] | | Post-2026 Operation of Lakes Powell and Mead |
| Lower Basin Shortage (1.5 maf over 5 years) | 92% → 83% | 16.0<br>10 16.0 18.5 | ~~OR~~<br>**AND** | 12.8<br>7 11.6 15.5 | AND | 2007 Interim Guidelines |
| | | 16.5<br>10 16.1 18.5 | ~~OR~~<br>**AND** | 12.1<br>7 14.2 15.5 | AND | Revert to 2007 Interim Guidelines Final EIS No Action Alternative |
| **Indicator Metric** | **Vulnerable Traces** | **System Condition** | | | | |
| | | **Annual Mean Natural Flow at Lee Ferry (2012–2060) [maf]** | | **Average Annual Lower Basin Demand 2041–2060 [maf]** | | **Post-2026 Operation of Lakes Powell and Mead** |
| Remaining Demand Above Lower Division States' Basic Apportionment | 100% → 26% | 15.2<br>10 NA 18.5 | OR | 9.7<br>9 NA 11 | AND | 2007 Interim Guidelines |
| | | 15.4<br>10 NA 18.5 | OR | 10.2<br>9 NA 11 | AND | Revert to 2007 Interim Guidelines Final EIS No Action Alternative |

In general, portfolio implementation narrows the range of conditions that typically produced vulnerability when projecting plausible future water delivery reliability using CRSS simulations. Although vulnerability is not eliminated, the additional resiliency introduced by *Portfolio A* reduces the risk of future vulnerabilities under current operational assumptions in many plausible futures. Figure G-33 includes the baseline vulnerable condition results of figure G-16 and the new vulnerable conditions associated with the *Portfolio A* results. It shows the distribution of traces and total number of traces in vulnerable conditions broken out by supply scenario. As to be expected, the number of traces in vulnerable conditions was reduced for all indicator metrics. Most notable were reductions in the number of traces in the Lake Mead and Lower Division States' demand above basic apportionments vulnerable conditions. Interestingly, for Upper Basin shortage, overall reductions were moderate, and all supply scenarios contribute a roughly equally number of traces. This is likely because most traces have at least one low-flow year, which is the condition for Upper Basin vulnerability. Further, when comparing the distribution of traces within vulnerable conditions, between the Baseline and with *Portfolio A*, a higher percentage tends to be from the Downscaled GCM Projected supply scenario. This is particularly noteworthy for the Lake Mead vulnerable conditions.

FIGURE G-33
Percentage of Each Supply Scenario Within Each Set of Vulnerable Conditions with Portfolio A in Place, by Water Delivery Indicator Metric



### *6.3.3 Changes in Electrical Power Resource Vulnerabilities*

Figures G-34 (percent of traces) and G-35 (percent of years) shown the change in vulnerability for the electric power indicator metrics with portfolios in place compared with the Baseline. Electric power resources exhibited moderate performance improvements, as were seen in the water delivery indicator metrics. As more options are implemented, increased flow helps to raise pool elevations and in some cases, greater downstream demand requires larger releases. This combination is a two-fold benefit to hydropower.

FIGURE G-34
Percent of Vulnerable Traces for Each Electric Power Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

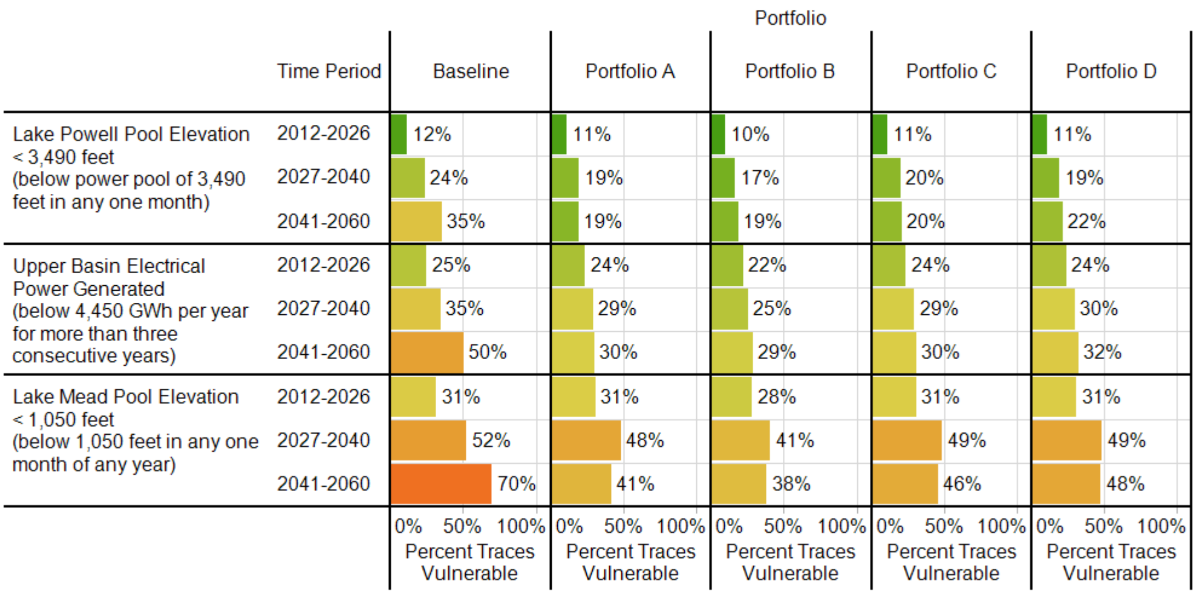
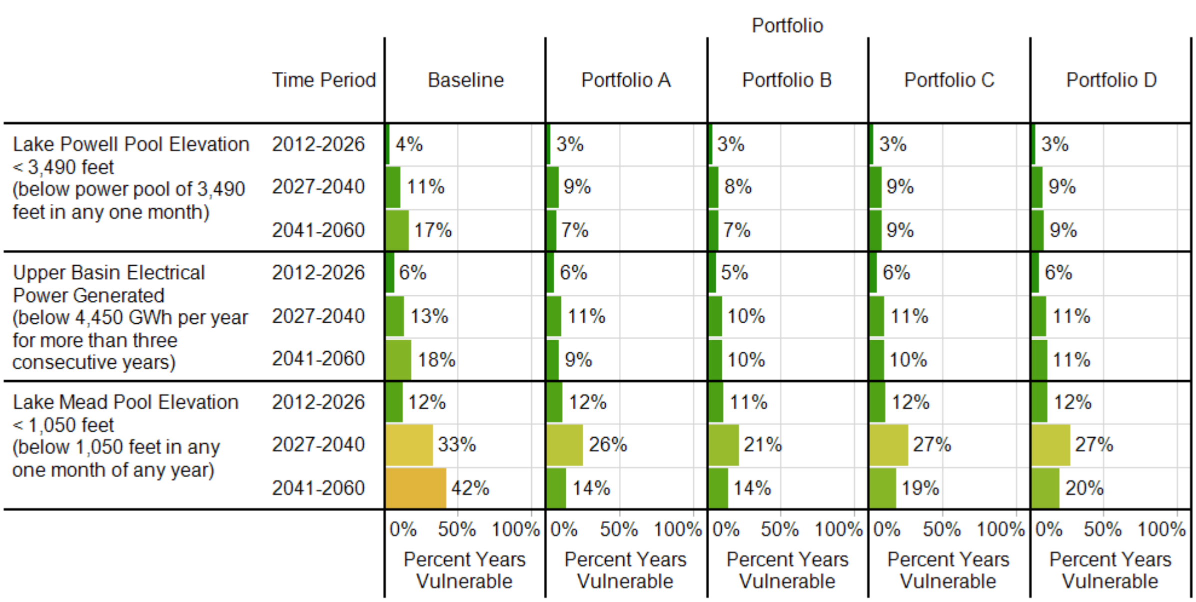



FIGURE G-35
Percent of Vulnerable Years for Each Electric Power Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios



### 6.3.4 Changes in Flood Control Vulnerabilities

Figures G-36 and G-37 show the change in vulnerability for the flood control indicator metrics with portfolios in place and compared with the Baseline. Under the Baseline modeling, flood control vulnerabilities were few and actually decreased over time due to the increase in available storage associated with growing demand. Under the various portfolios, the vulnerability incidence rate remained low, but did increase slightly. This is a direct result of option benefit increasing pool elevations, which in turn, reduces capacity to absorb extreme flow events. Logically, these increased risks are most notable in the third time window, when the most options have been implemented. These increases are considerably more notable in the percent of traces vulnerable view (figure G-36) compared to the percent of years vulnerable (figure G-37).

FIGURE G-36
Percent of Vulnerable Traces for Each Flood Control Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

| | Time Period | Baseline | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|---|
| Lake Mead Downstream Safe Channel Capacity (flow greater than 28,000 cfs in any one month) | 2012-2026 | 17% | 18% | 19% | 18% | 17% |
| | 2027-2040 | 16% | 20% | 24% | 19% | 20% |
| | 2041-2060 | 14% | 35% | 35% | 32% | 29% |
| | | 0% 50% 100%<br>Percent Traces Vulnerable | 0% 50% 100%<br>Percent Traces Vulnerable | 0% 50% 100%<br>Percent Traces Vulnerable | 0% 50% 100%<br>Percent Traces Vulnerable | 0% 50% 100%<br>Percent Traces Vulnerable |

FIGURE G-37
Percent of Vulnerable Years for Each Flood Control Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

| | Time Period | Baseline | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|---|
| Lake Mead Downstream Safe Channel Capacity (flow greater than 28,000 cfs in any one month) | 2012-2026 | 2% | 2% | 2% | 2% | 2% |
| | 2027-2040 | 2% | 2% | 3% | 2% | 2% |
| | 2041-2060 | 1% | 4% | 4% | 3% | 3% |
| | | 0% 50% 100%<br>Percent Years Vulnerable | 0% 50% 100%<br>Percent Years Vulnerable | 0% 50% 100%<br>Percent Years Vulnerable | 0% 50% 100%<br>Percent Years Vulnerable | 0% 50% 100%<br>Percent Years Vulnerable |

### 6.3.5 Changes in Water Quality Resource Vulnerabilities

Due to model constraints, the metric for the Water Quality Resource category, salinity below Parker Dam, is only available in the Observed Resampled and Paleo Resampled supply scenarios. With options enacted, across the available supply scenarios, salinity below Parker Dam does not violate the numeric criteria.

### *6.3.6 Changes in Recreational Resource Vulnerabilities*

Figures G-38 through G-41 shown the change in vulnerability for the recreational indicator metrics with portfolios, compared to the Baseline. Specifically, the metrics in figures G-38 and G-39 are river boating vulnerabilities, and those in figures G-40 and G-41 pertain to reservoir recreation. River boating indicator metrics are based on the shift in long-term average availability of PBO-based flows deemed acceptable (total days) and optimal (optimal days). Between the total and optimal flow metrics, the optimal were consistently more vulnerable. This is because the window for optimal flows is more stringent and thus more sensitive to changes in flow. All portfolios demonstrate improvements in the number of vulnerabilities for the boating indicator metrics. However, *Portfolios A* and *C* showed the most improvement. This is due to the Upper Basin banking option, found in both, which shepherds conserved water from across the major tributaries to the bank in southern Utah. By shepherding the conserved water, resources that depend on in-stream flows tend to benefit, including river boating recreation.

For reservoir recreation, Flaming Gorge performs notably well, even under the Baseline simulations. This is due to a combination of increases in streamflow projections in the Upper Green and slower growth relative to other regions. On the other hand, Blue Mesa and Navajo show significant vulnerability and little improvement even with portfolios. Based on their respective vulnerability definitions, both locations experienced multiple vulnerable years in the historical record. Therefore, it is not surprising that with increasing demands, vulnerabilities would continue and be challenging to mitigate in these locations, compared to other sites. Reductions to vulnerabilities at other locations in the Upper Basin are largely due to conservation and weather modification options. These options serve to either increase reservoir inflow or reduce the required release.

FIGURE G-38
Percent of Vulnerable Traces for Each Recreational (Boatable Days) Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

| | Time Period | Baseline | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|---|
| Colorado River Optimal Boating Flow Days (below 10th percentile of control run) | 2012-2026 | 38% | 35% | 35% | 35% | 38% |
| | 2027-2040 | 59% | 51% | 53% | 50% | 57% |
| | 2041-2060 | 76% | 58% | 63% | 63% | 68% |
| Green River Optimal Boating Flow Days (below 10th percentile of control run) | 2012-2026 | 30% | 27% | 27% | 27% | 30% |
| | 2027-2040 | 53% | 43% | 46% | 43% | 51% |
| | 2041-2060 | 68% | 51% | 56% | 51% | 62% |
| San Juan River Optimal Boating Flow Days (below 10th percentile of control run) | 2012-2026 | 23% | 19% | 22% | 19% | 23% |
| | 2027-2040 | 44% | 28% | 40% | 28% | 43% |
| | 2041-2060 | 57% | 39% | 50% | 40% | 52% |
| Colorado River Acceptable Boating Flow Days (below minimum of control run) | 2012-2026 | 25% | 20% | 19% | 20% | 24% |
| | 2027-2040 | 48% | 33% | 32% | 33% | 40% |
| | 2041-2060 | 68% | 34% | 37% | 36% | 43% |
| Green River Acceptable Boating Flow Days (below minimum of control run) | 2012-2026 | 5% | 3% | 4% | 3% | 5% |
| | 2027-2040 | 15% | 5% | 11% | 5% | 12% |
| | 2041-2060 | 24% | 8% | 16% | 8% | 18% |
| San Juan River Acceptable Boating Flow Days (below minimum of control run) | 2012-2026 | 9% | 7% | 8% | 7% | 9% |
| | 2027-2040 | 20% | 6% | 16% | 7% | 18% |
| | 2041-2060 | 30% | 13% | 23% | 15% | 26% |
| | | 0% 50% 100% Percent Traces Vulnerable | 0% 50% 100% Percent Traces Vulnerable | 0% 50% 100% Percent Traces Vulnerable | 0% 50% 100% Percent Traces Vulnerable | 0% 50% 100% Percent Traces Vulnerable |

FIGURE G-39
Percent of Vulnerable Years for Each Recreational (Boatable Days) Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

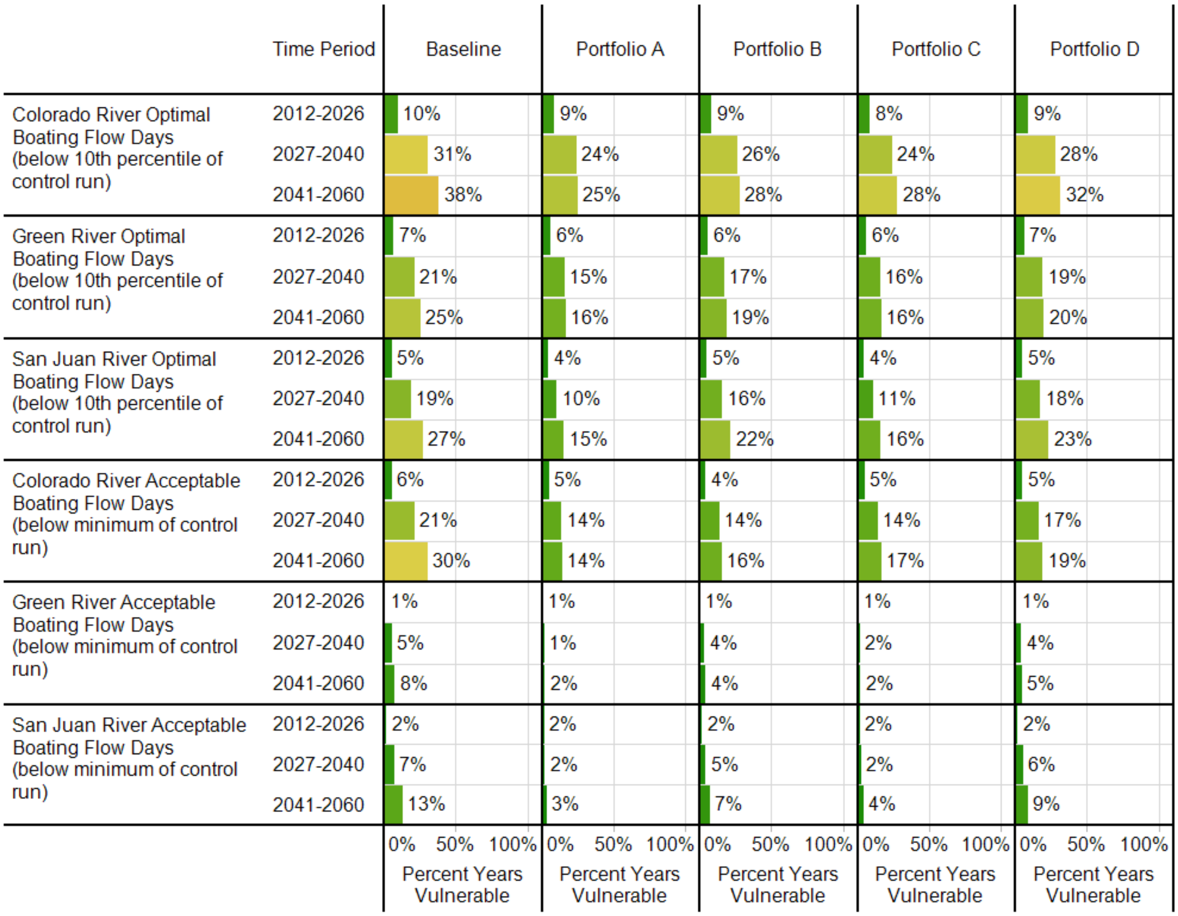


FIGURE G-40
Percent of Vulnerable Traces for Each Recreational (Shoreline Facilities) Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

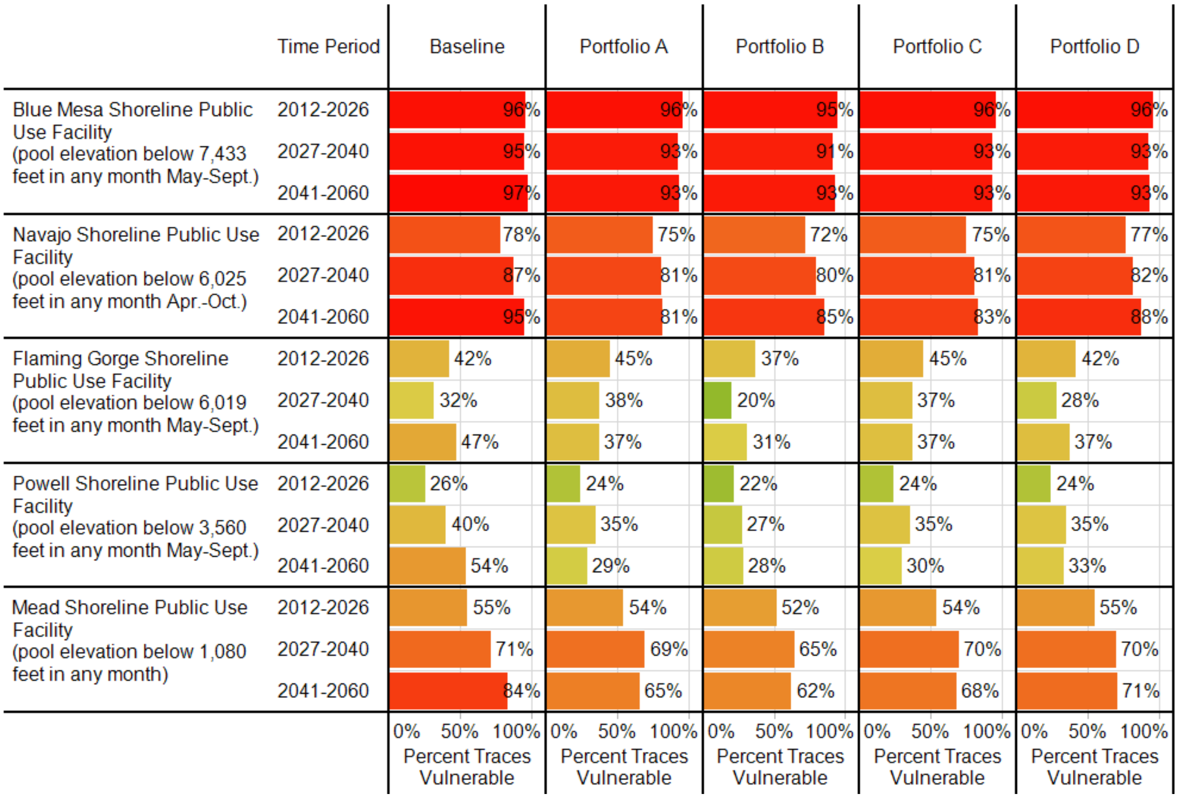
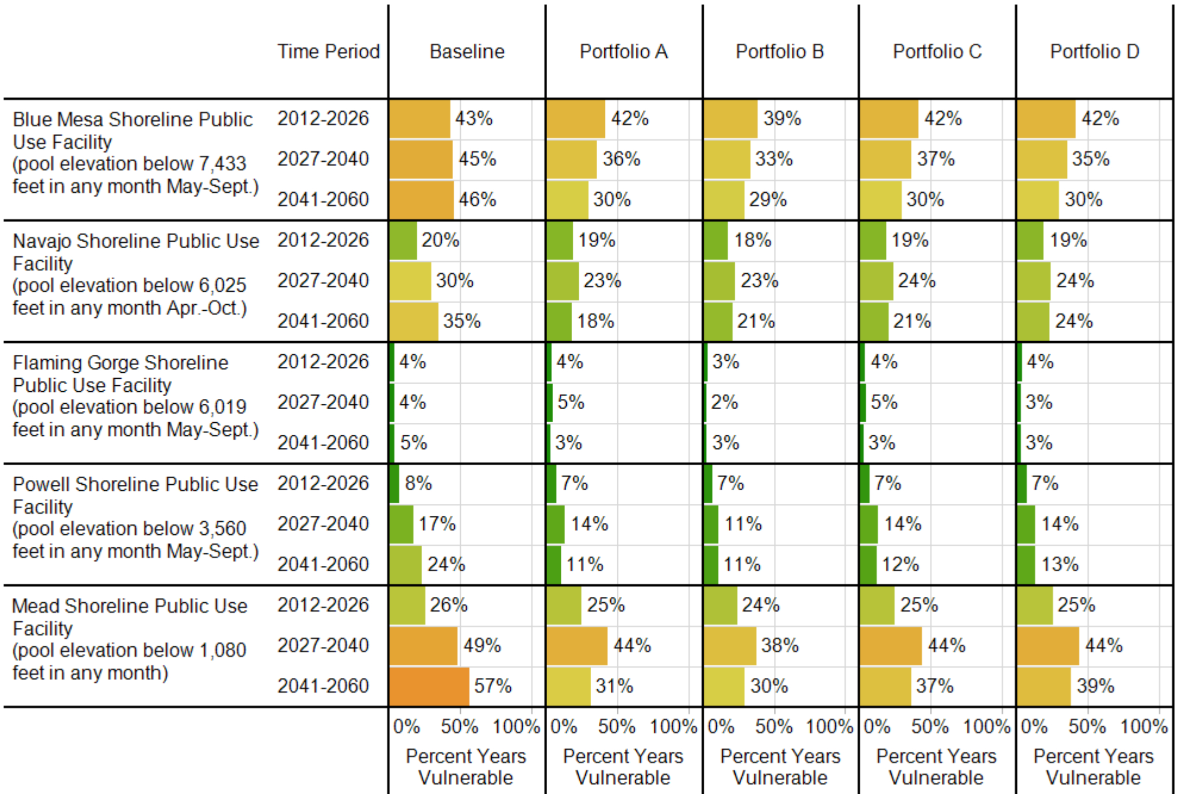


FIGURE G-41
Percent of Vulnerable Years for Each Recreational (Shoreline Facilities) Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios




## 6.3.7 *Changes in Ecological Resource Vulnerabilities*

Figures G-42 and G-43 show the change in vulnerability for the ecological resource indicator metrics within portfolios, compared with the Baseline. Based on the discussion of river boating vulnerabilities, it would be logical to expect that the portfolios with the Upper Basin Banking option and associated shepherding of flows would benefit ecological resources more so than other portfolios. In the case of the Yampa and San Juan rivers, this is exactly the case. However, for the Green and Upper Colorado rivers, the improvements are largely commensurate with other portfolios. This is due to the particular PBO-based flow recommendations at those sites. The Green River and Colorado River flow prescriptions are specific with regard to timing and volume. As such, increases in flow as a result of shepherding water to the bank may not help to resolve vulnerabilities if the transfer is not managed consistently with the flow recommendations. Coordinated shepherding and re-regulation may be required to achieve the maximum benefit to those more-detailed flow requirements.

FIGURE G-42
Percent of Vulnerable Traces for Each Ecological Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios

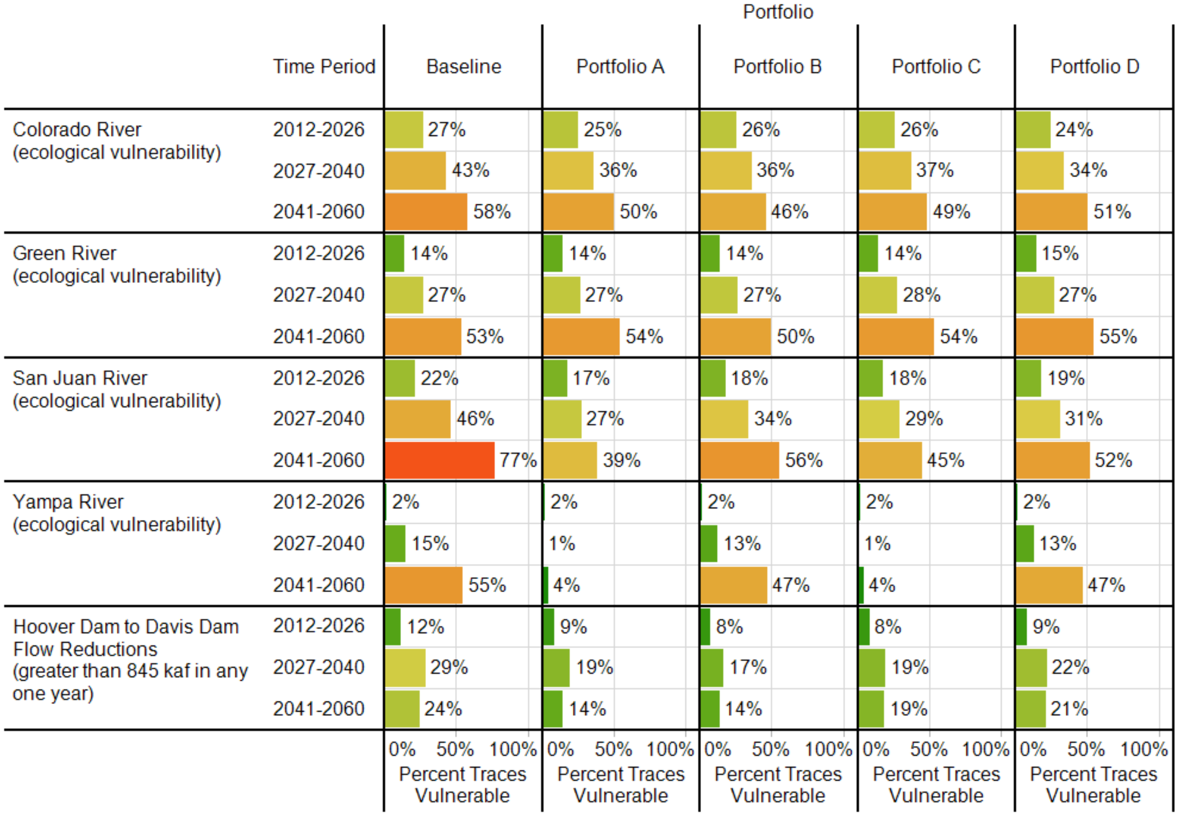
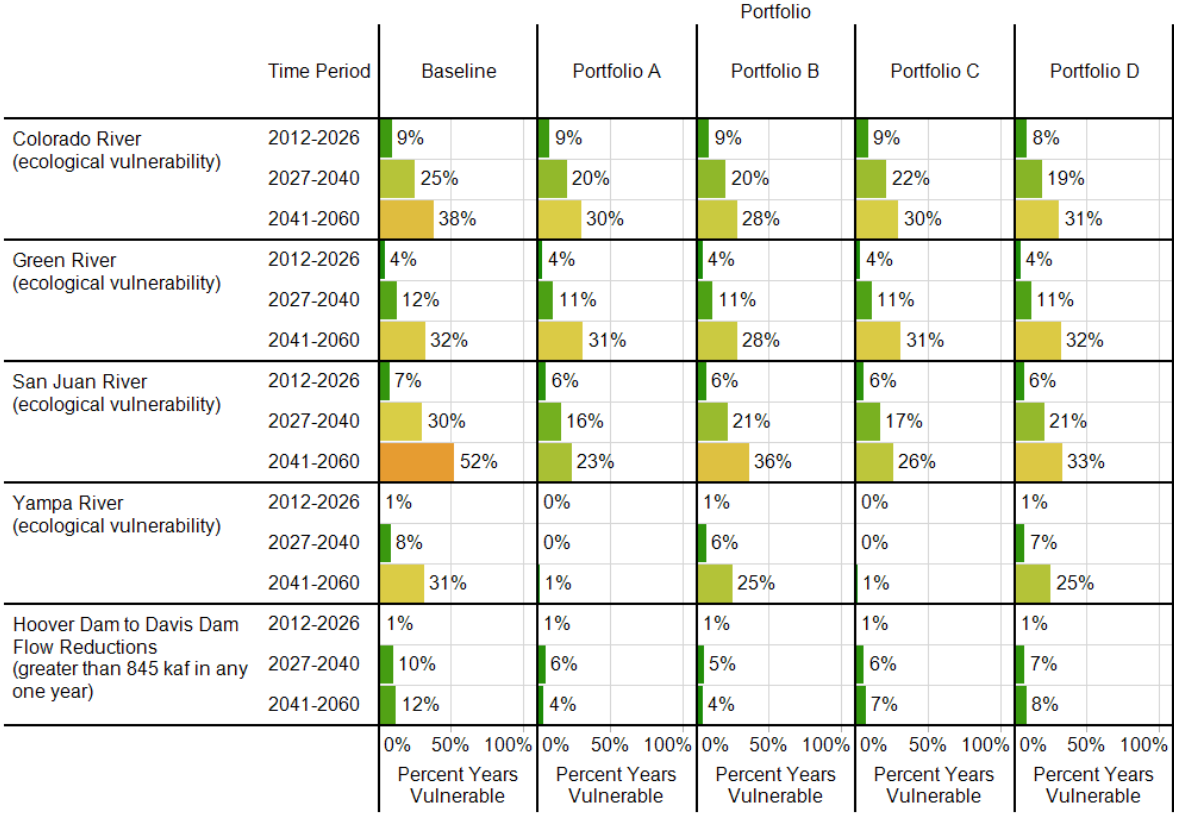


FIGURE G-43
Percent of Vulnerable Years for Each Ecological Indicator Metric Across Three Time Periods for the Baseline and Four Simulated Portfolios




### 6.3.8 *Summary of System Reliability Results*

Table G-16 summarizes the system reliability results with the four portfolios in place. As shown in the table, portfolios are projected to improve the ability to meet Basin resources needs (reduction in vulnerabilities). The vulnerabilities related to critical Upper Basin and Lower Basin water delivery metrics—Lee Ferry Deficit and Lake Mead pool elevation below 1,000 feet msl—were reduced by 50 percent or more. The results for metrics related to electrical power, water quality, recreation, and ecological resources demonstrate reductions of a similar percentage in vulnerabilities. Only the metric related to flood control below Hoover Dam shows a slight increase in vulnerability due to the potential for higher reservoir storage (and higher likelihood of high release) when portfolios were included.

TABLE G-16
Summary of System Reliability Outcomes (Percent of Years Vulnerable) for Baseline and Portfolios for All Scenarios, 2041–2060 Period

| Resource | System Vulnerability | Baseline | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|---|
| Water Delivery | Lee Ferry Deficit (Upper Basin Reliability) | **7%** | 2% | 2% | 3% | 3% |
| | Lake Mead pool elevation below 1,000 feet msl (Lower Basin Reliability) | **19%** | 3% | 3% | 5% | 6% |
| Electrical Power | Upper Basin Generation (below 4,450 gigawatts per hour per year for 3 consecutive years) | **18%** | 9% | 10% | 10% | 11% |
| | Lower Basin Generation (Lake Mead pool elevation below 1,050 feet msl) | **42%** | 14% | 14% | 29% | 20% |
| Flood Control | Critical River Stage below Hoover Dam (greater than 28,000 cfs) | **1%** | 4% | 4% | 3% | 34% |
| Water Quality | Salinity below Parker Dam (greater than numeric criteria)[1] | **0%** | 0% | 0% | 0% | 0% |
| Recreation | Colorado River Boating (days less than control run) | **30%** | 14% | 16% | 17% | 19% |
| | Powell Shoreline Facilities (pool elevation less than 3,560 feet msl) | **24%** | 11% | 11% | 12% | 13% |
| | Mead Shoreline Facilities (pool elevation less than 1,080 feet msl) | **57%** | 31% | 30% | 37% | 39% |
| Ecological | Colorado River Flow (less than reference value) | **38%** | 40% | 28% | 28% | 31% |
| | Lake Mead to Lake Mohave Flow (annual flow change greater than 845 kaf) | **12%** | 4% | 4% | 7% | 8% |

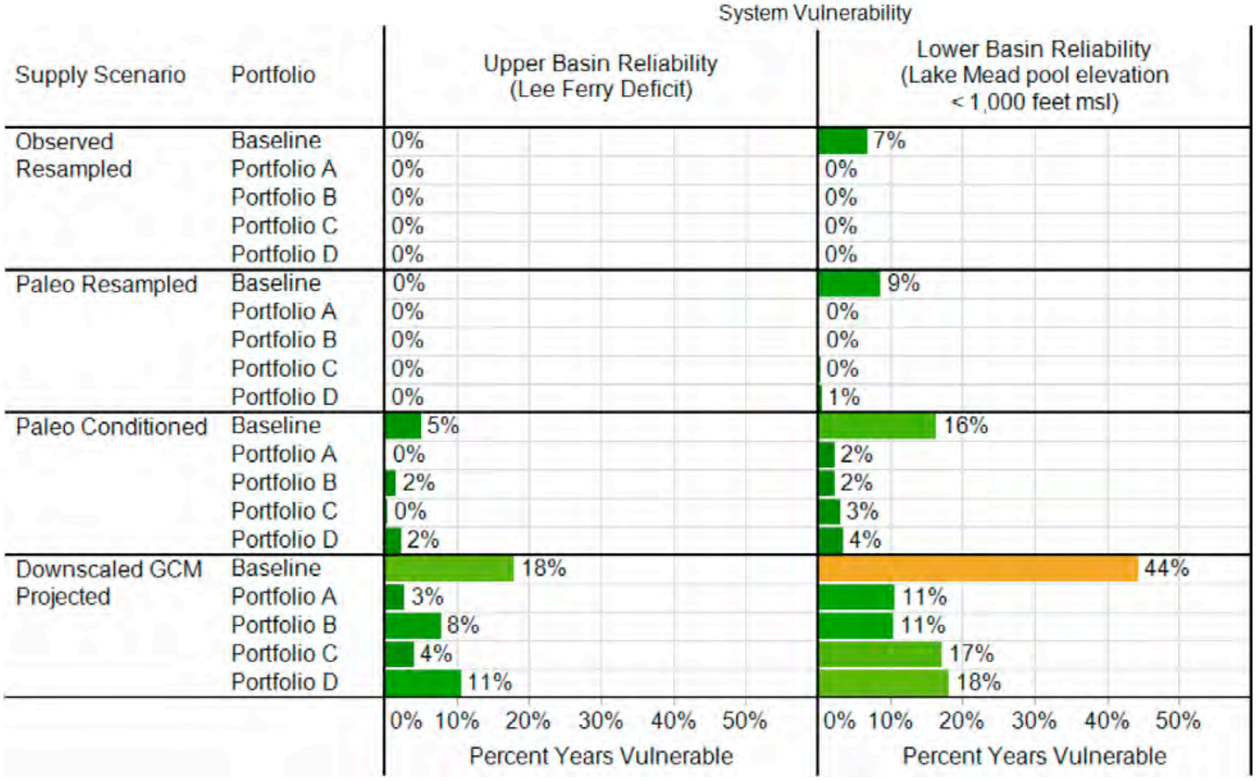
[1] Due to modeling limitations, results reported do not include results from the Downscaled GCM Projected scenario.

Although the portfolio analysis successfully demonstrated that system reliability can be improved, it is not without significant cost and performance tradeoffs. Figure G-44 illustrates the performance across portfolios by supply scenario in terms of addressing the Upper Basin water delivery reliability and Lower Basin water delivery reliability vulnerabilities.

*Portfolio B* favors options believed to have higher certainty of available water supply once implemented. As shown in figure G-44 (on the right), this portfolio performs as well or better than all the other portfolios for addressing the Lower Basin reliability vulnerability shown in table 4 across all supply scenarios. The portfolio is less effective than *Portfolios A* and *C* for the Upper Basin reliability vulnerability (figure G-44, left), particularly in the Downscaled GCM Projected supply scenario (bottom row).

*Portfolio C*, while focused on options that favor lower energy needs and less environmental impacts, is more dependent on shifting social values towards additional conservation and reuse. Choosing to implement options characterized as having low energy needs (as a surrogate for potential environmental impacts) might come at the expense of having a less certain long-term water supply. However, this portfolio performs well for addressing the Upper Basin reliability vulnerability (figure G-44, left) and is particularly effective under the Downscaled GCM Projected supply scenario (figure G-44, bottom row). The effectiveness of this portfolio for addressing Upper Basin reliability vulnerabilities is largely attributable to the inclusion of an Upper Basin water bank that specifically targets this vulnerability. *Portfolio C* is less effective, however, at addressing the Lower Basin reliability vulnerabilities (figure G-44, right).

FIGURE G-44
Percent of Years Vulnerable for Upper Basin Reliability (left) and Lower Basin Reliability (right) in 2041–2060 with Portfolios Implemented, by Supply Scenario



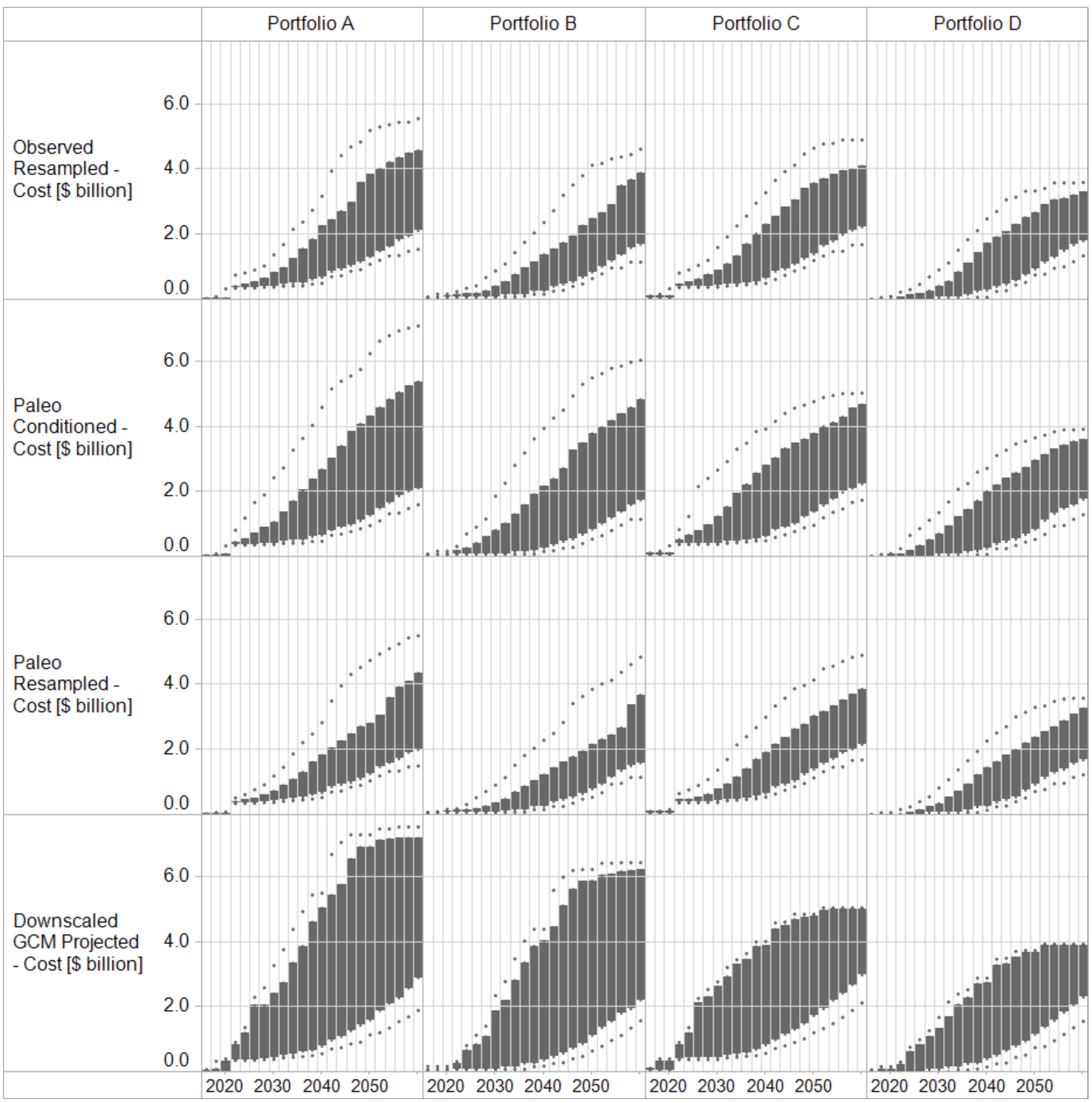

## 6.3.9 Costs and Other Characteristics of Implemented Options

The costs of addressing the Basin's vulnerabilities differ across portfolios and traces, and depend on which options are implemented. Figures G-45 through G-48summarize the total annual cost ($) and average annual cost per unit of water ($ per af) across different subsets of traces over time. Total annual cost is calculated as the sum of the annual costs associated with each of the options implemented up to that point in time. Annual costs reflect capital and operation and maintenance costs in 2012 dollars, using 4.125 percent interest over the beneficial life of the option. Average cost per unit of water is computed as the quotient of annual cost and average annual yield. One set of figures summarizes across the traces within the four scenarios (figures G-45 and G-47). The other set (figures G-46 and G-48) summarizes across traces inside and outside two vulnerable conditions—those vulnerable for Lake Mead pool elevation < 1,000 feet msl and the Lee Ferry Deficit.

Total annual costs increase over time for all portfolios and supply scenario (figure G-45). The costs across the traces diverge significantly over time. In 2060, the 25th to 75th percentile costs range between about $2 billion to $5 billion for the Observed Resampled, Paleo Conditioned, and Paleo Resampled supply scenarios, and increases to potentially $7.0 billion under the GCM Projected scenario. *Portfolio A* is the most costly due to the inclusion of the greatest number of options and *Portfolio D* is the least costly due to the inclusion of the least number of options. These wide ranges of costs reflect the large differences in types of conditions evaluated for each supply scenario. For example, about

25 percent of the traces within the Downscaled GCM Projected scenario require only modest investment, and costs generally do not exceed $3 billion per year for all portfolios. Reciprocally, 25 percent of the traces require much more investment in options, pushing costs to as high as $5 billion for *Portfolio C* and more than $6 billion for the *Portfolios A* and *B*. *Portfolio C* is similar in cost range to *Portfolio B* except under the GCM Projected scenario, where it is less expensive largely due to exclusion of some options that are only triggered under more–challenging water supply conditions within *Portfolio A* and *Portfolio B.* The range of costs for *Portfolio C* is lower for the Downscaled GCM Projected scenario than the costs for *Portfolio B*, largely due to the exclusion of some option that are only triggered under more challenging water supply conditions within *Portfolio A* and *Portfolio B*, and the inclusion of focused-options such as the water bank, that more cost effectively address severe regional conditions.

FIGURE G-45
Total Annual Cost by Supply Scenario Resulting from Implementation of the Dynamic Portfolios Over Time



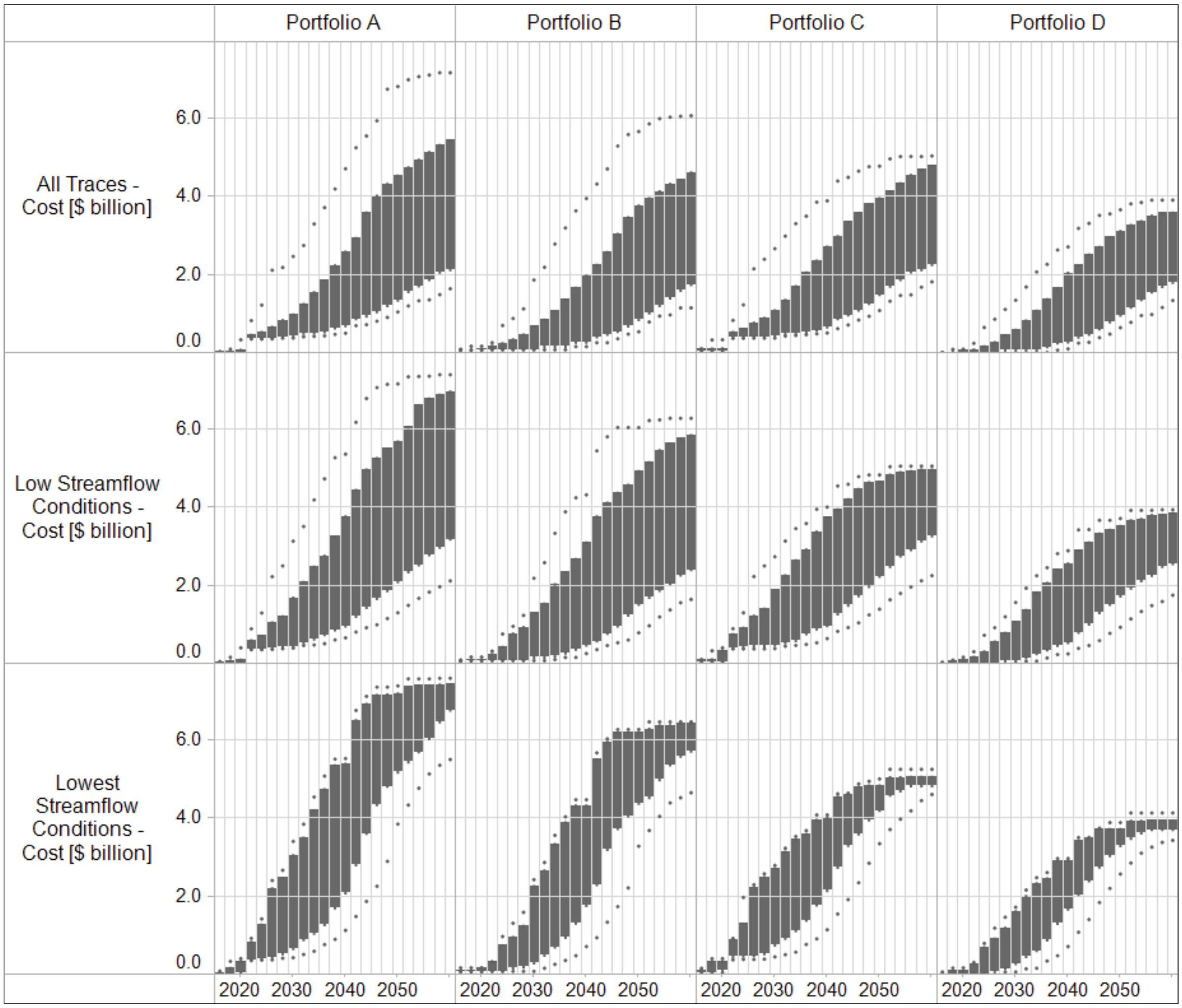

The spread between the 25th and 75th percentile is indicated by shading. The 10th and 90th percentile values are indicated by the 'x's.

The total annual costs are also summarized across all traces and those within the vulnerable conditions (figure G-46). This shows more clearly how stressing conditions lead to higher costs across all portfolios. In general the Lake Mead Pool Elevation vulnerable conditions describe low streamflow conditions and the Lee Ferry Deficit vulnerable conditions describe even lower streamflow conditions (table G-8):

- **Lake Mead vulnerable conditions**: Long-term average flow below 15 mafy and 8-year drought below 13 mafy—or "Low Streamflow" conditions.
- **Lee Ferry Deficit vulnerable conditions**: Long-term average flow below 13.8 maf and 8-year drought below 11.2 mafy—or "Lowest Streamflow" conditions.

Recall that the Lee Ferry Deficit vulnerable conditions are more stressing conditions than the Lake Mead pool elevation < 1,000 feet msl vulnerable conditions. As expected, for all portfolios, costs are significantly lower and grow more slowly over time when considering all traces. For traces within vulnerable conditions, however, costs increase more rapidly in the early and middle periods as available options are quickly brought on line. Again, *Portfolio C* is less costly for the Lowest Streamflow conditions (i.e., traces with Long-Term Flow < 14 mafy and Drought Below 11 mafy) than *Portfolios A* and *B*. Note that the wide range in costs for traces within the Lowest Streamflow conditions reflects the mixture of very stressing and moderately stressing traces.

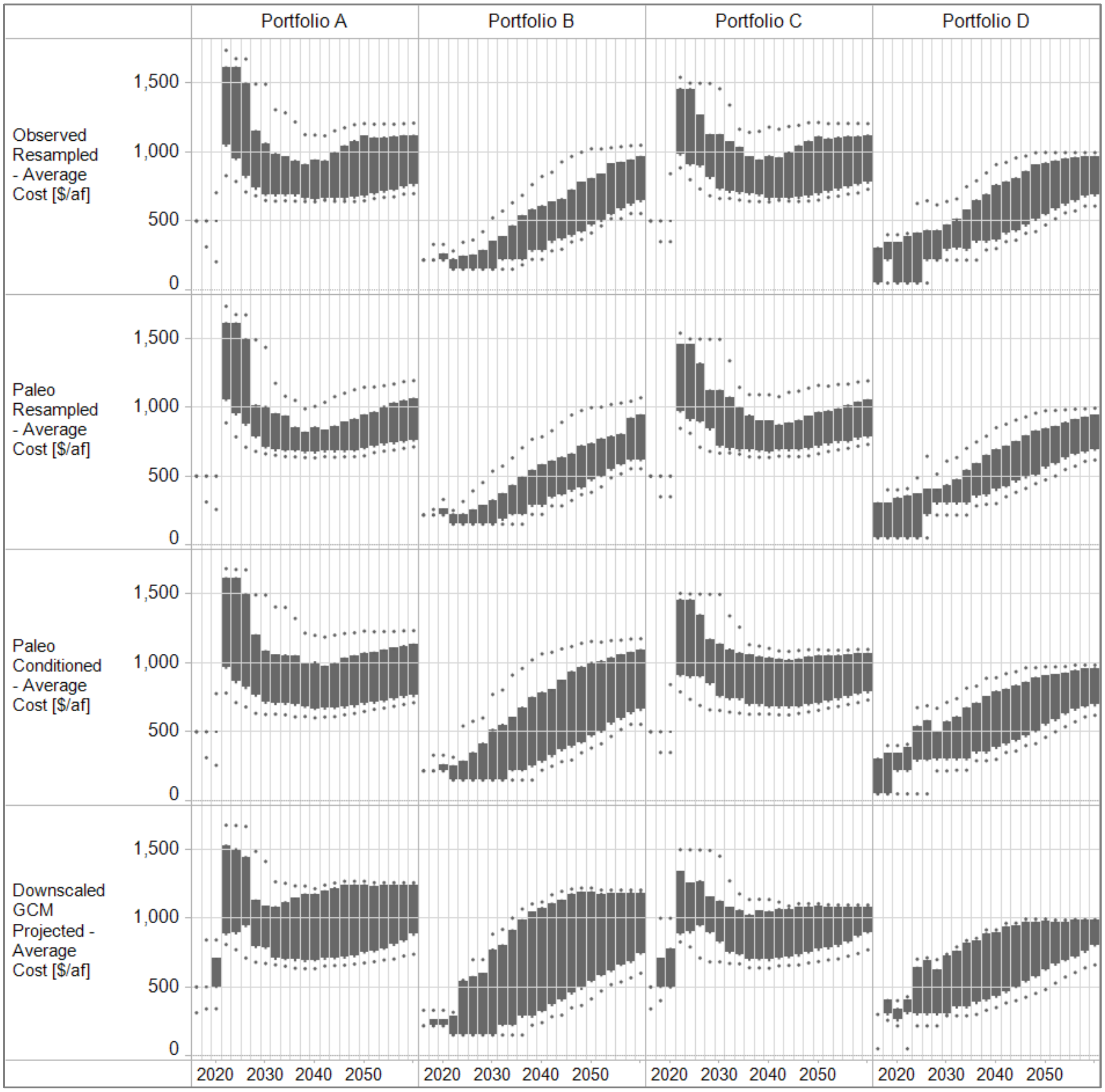
FIGURE G-46
Total Annual Cost for All Traces and Low Streamflow and Lowest Streamflow Conditions Resulting from Implementation of the Dynamic Portfolios over Time




The spread between the 25th and 75th percentile is indicated by shading. The 10th and 90th percentile values are indicated by the 'x's. Low Streamflow conditions are those in which long-term mean natural flows are less than 15 mafy and the 8-year dry period flows are less than 13 mafy. Lowest Streamflow conditions are those in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.

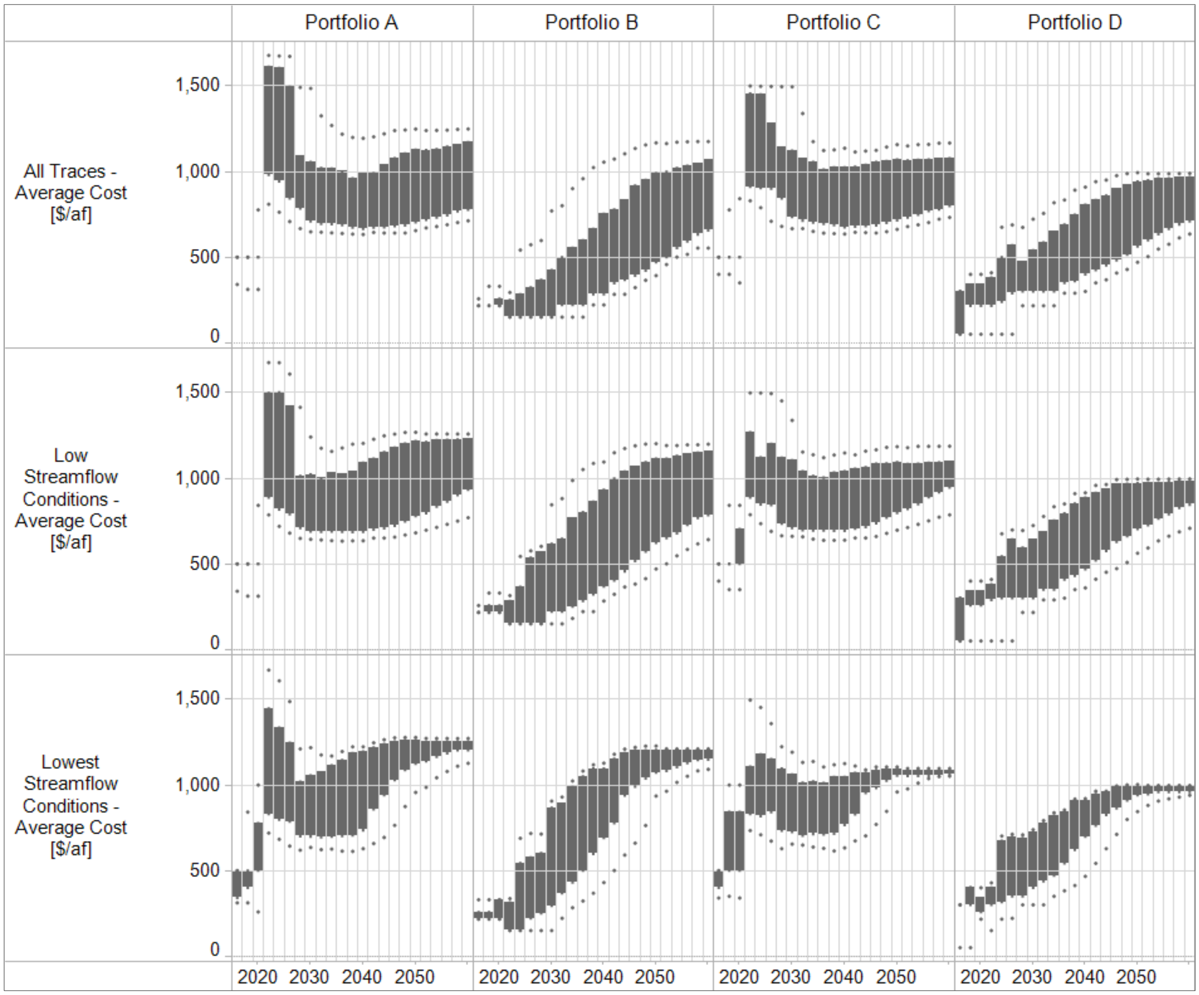
The next two figures show the distribution of average costs over time for the four portfolios and the scenarios (figure G-47) and the vulnerable conditions (figure G-48). Across all groups of traces, the pattern of average costs for the *Portfolios A* and *C* is distinct from *Portfolios B* and *D*. Specifically, the former portfolios lead to markedly higher costs in the near term. These higher costs are due to the relatively high cost of the Energy Sector Conservation option ($2,000 per af) and some of the later increments of M&I Conservation ($700 to $950 per af), which are specified to be implemented when available. Average costs for all portfolios are roughly similar by 2060, ranging from about $750 to $1,250 per af for the Observed Resampled traces (top panels, figure G-47) and from $1,000 to $1,250 per af for the Lee Ferry Deficit vulnerable traces (bottom panels, figure G-48).

FIGURE G-47
Average Annual Cost by Supply Scenario Resulting From Implementation of the Dynamic Portfolios over Time




The spread between the 25th and 75th percentile is indicated by shading. The 10th and 90th percentile values are indicated by the ‘x’s.

FIGURE G-48
Average Annual Cost for All Traces and Low Streamflow and Lowest Streamflow Conditions Resulting from Implementation of the Dynamic Portfolios over Time




The spread between the 25th and 75th percentile is indicated by shading. The 10th and 90th percentile values are indicated by the 'x's. Low Streamflow conditions are those in which long-term mean natural flows are less than 15 mafy and the 8-year dry period flows are less than 13 mafy. Lowest Streamflow conditions are those in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.

The options implemented within the portfolios also vary in terms of their characteristics (see the individual options section). Figures G-49 and G-50 summarize the range across the traces of yield in 2060 by each of the five characteristics ratings (A through E) for two groupings of criteria. These two criteria groups are representative of the overall strategy used to develop the portfolios. The Reliability group, which includes Technical Feasibility, Long-Term Viability, and Implementation Risk criteria, is used to represent the technical feasibility and long-term reliability preferences of *Portfolio B*. Similarly, the Environment group, comprising Energy Needs, Permitting, and Other Environmental Factors criteria, is used as a surrogate for reduced potential environmental impacts that are preferred in *Portfolio C*. For each grouping, the total yield by options with scores of A through C and D through E are summed for each three criteria and divided by three.

Figure G-49, for example, shows that *Portfolio B* implements mostly options with reliability characteristics of A, B, or C. *Portfolio C*, however, provides a modest about of yield using options that score D or E on these criteria.

FIGURE G-49
Amount of Annual Yield with Reliability Group Characteristics Scores A–E for Each Portfolio in 2060

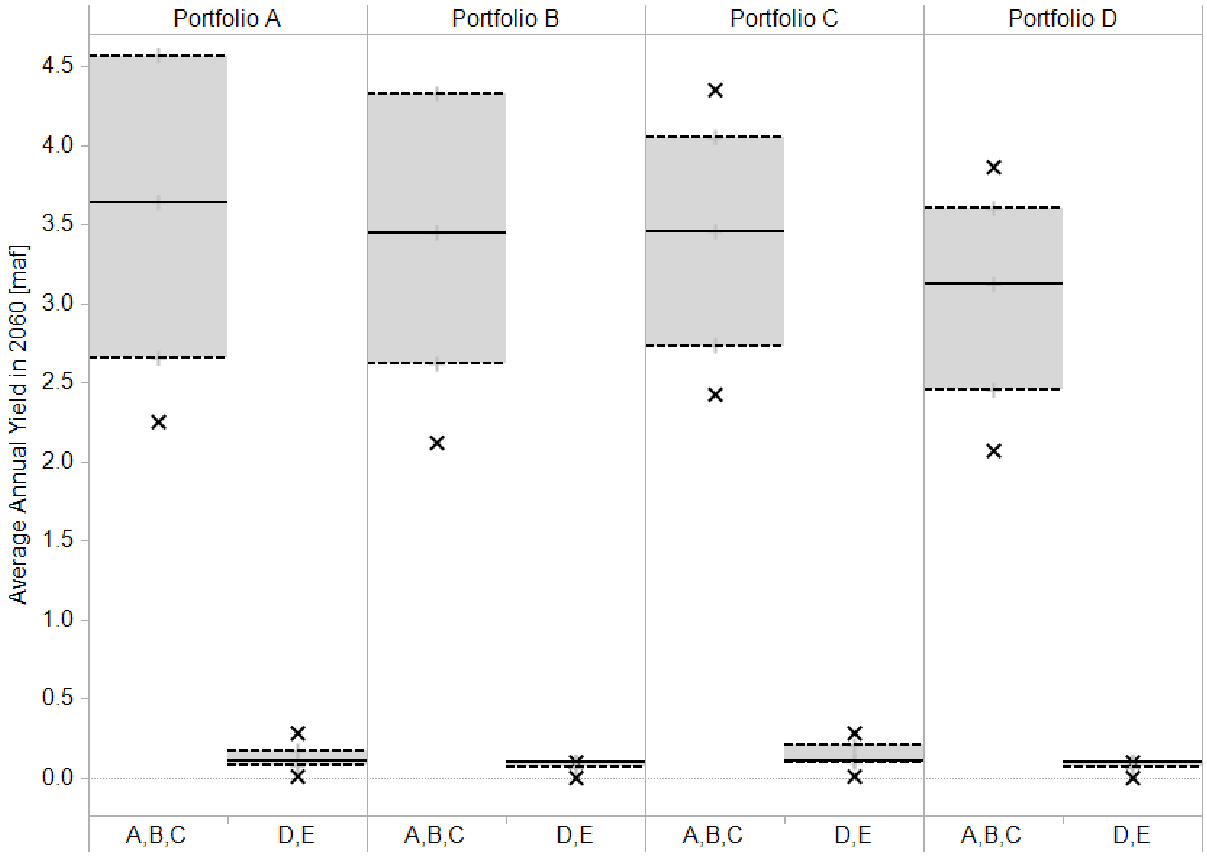
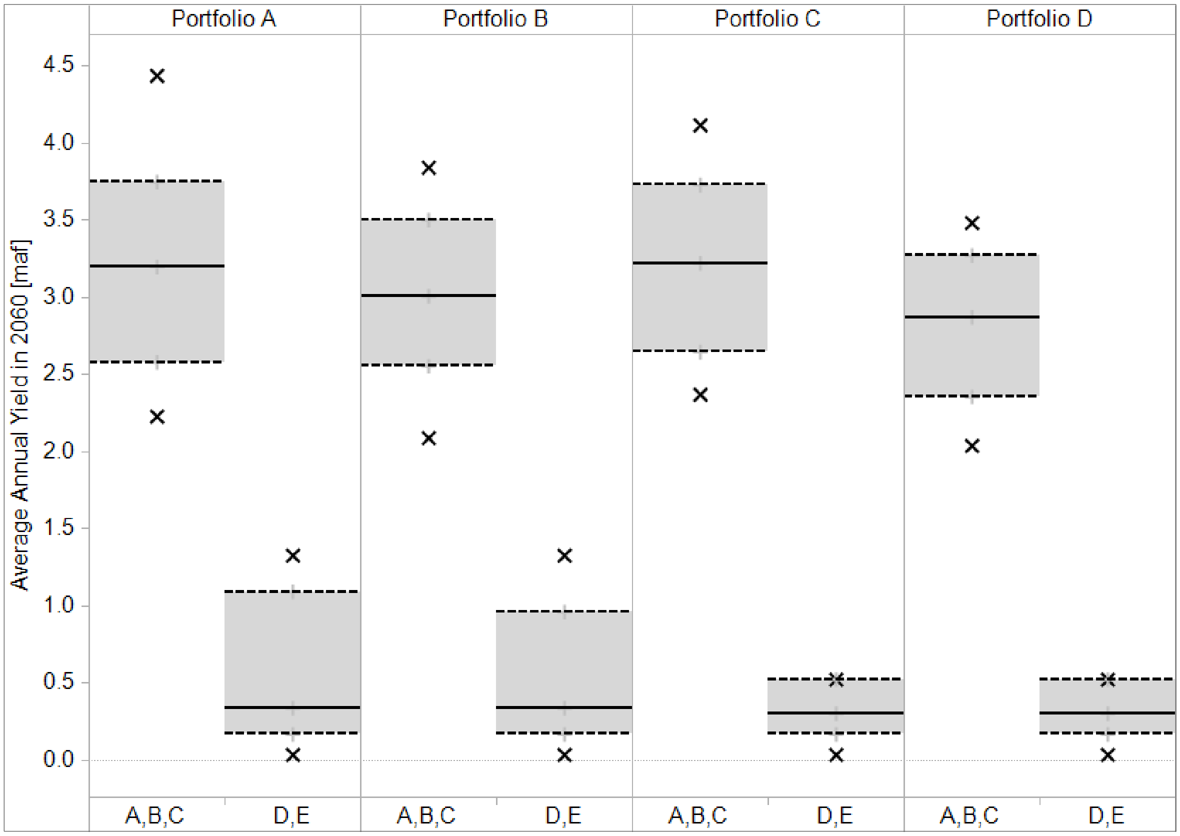



Figure G-50 shows that *Portfolio B* implements up to about 1.5 maf of options that received either a D or E score in terms of energy needs for some traces. *Portfolio C*, in contrast, provides less yield through options that received a D or an E score for the Environment group characteristics.

FIGURE G-50
Amount of Annual Yield with Environment Group Characteristics Scores A–E for Each Portfolio In 2060




In summary, there is much similarity across the portfolios in terms of the costs incurred across the traces and the characteristics of the options. Some modest differences are summarized in table G-17.

TABLE G-17
Summary of Costs and Option Characteristics Differences Among Portfolios

| | ***Portfolio A*** | ***Portfolio B*** | ***Portfolio C*** | ***Portfolio D*** |
|---|---|---|---|---|
| **Costs** | Highest cost | Higher annual costs in later years | High average cost in early years, lower cost, particularly for more stressing traces, in later years | Lowest cost |
| **Option characteristics** | Use of broadest range in terms of characteristics of options | Options with higher reliability | Fewer energy-intensive options | No low reliability options; fewer energy-intensive options |

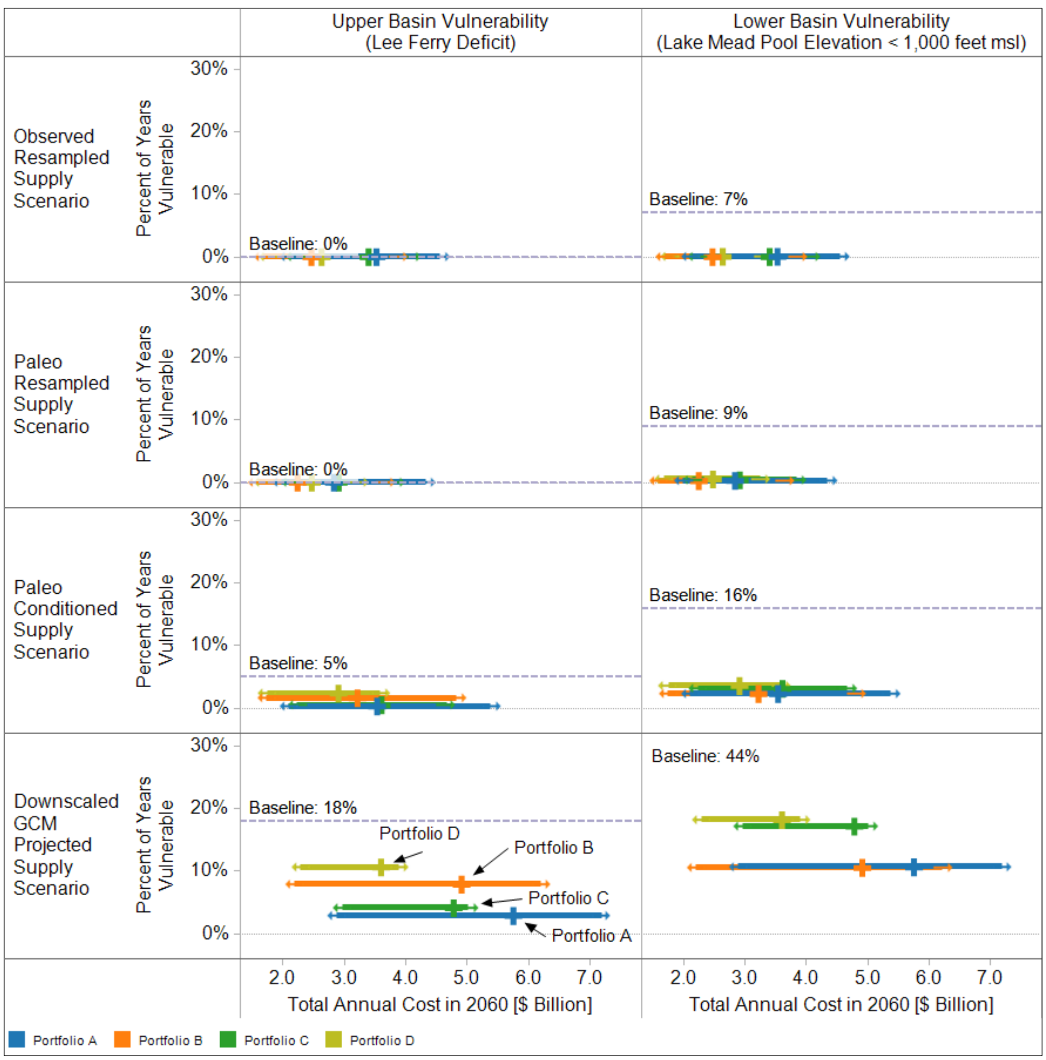
### *6.3.10 Vulnerability Reduction Versus Cost Tradeoffs*

It is important to consider the costs of implementing portfolios in relationship to their effects on reducing basin vulnerabilities. Figures G-51 and G-52 combines the information presented in figure G-29 (percent of vulnerable years for each water delivery indicator metric) and figure G-45 (total annual cost by vulnerable condition) for different groups of traces.

As shown in figure G-51 (top row) the annual cost, in 2012 dollars, for implementing the portfolios ranges from approximately $2.5 billion to $3.5 billion in the year 2060 when considering the median of the Observed Resampled supply sequences, and from $3.6 billion to $5.8 billion when considering the median of the Downscaled GCM Projected supply sequences. The inter-quartile ranges of cost are significantly larger. However, because of the appraisal-level option cost estimating used in the Study, the cost values contain additional uncertainty not directly reflected in these estimates.

Across the top three supply scenarios (Observed Resampled, Paleo Resampled, and Paleo Conditioned), one can see that Portfolios B and D are generally less costly than Portfolios A and C. For the Downscaled GCM Projected water supply scenario tradeoffs begin to become apparent. Specifically, Portfolio C leads to fewer vulnerable years with respect to Upper Basin reliability than Portfolios A and B, with an upper range of costs that is also lower than those for Portfolios A and B. Conversely, Portfolio A generally leads to the fewest vulnerable years with respect to Lower Basin reliability than other portfolios.

FIGURE G-51
Percent of Years Vulnerable for Upper Basin and Lower Basin Vulnerabilities from 2041–2060 and Range In Total Annual Cost In 2060 Across Supply Scenarios for Four Portfolios

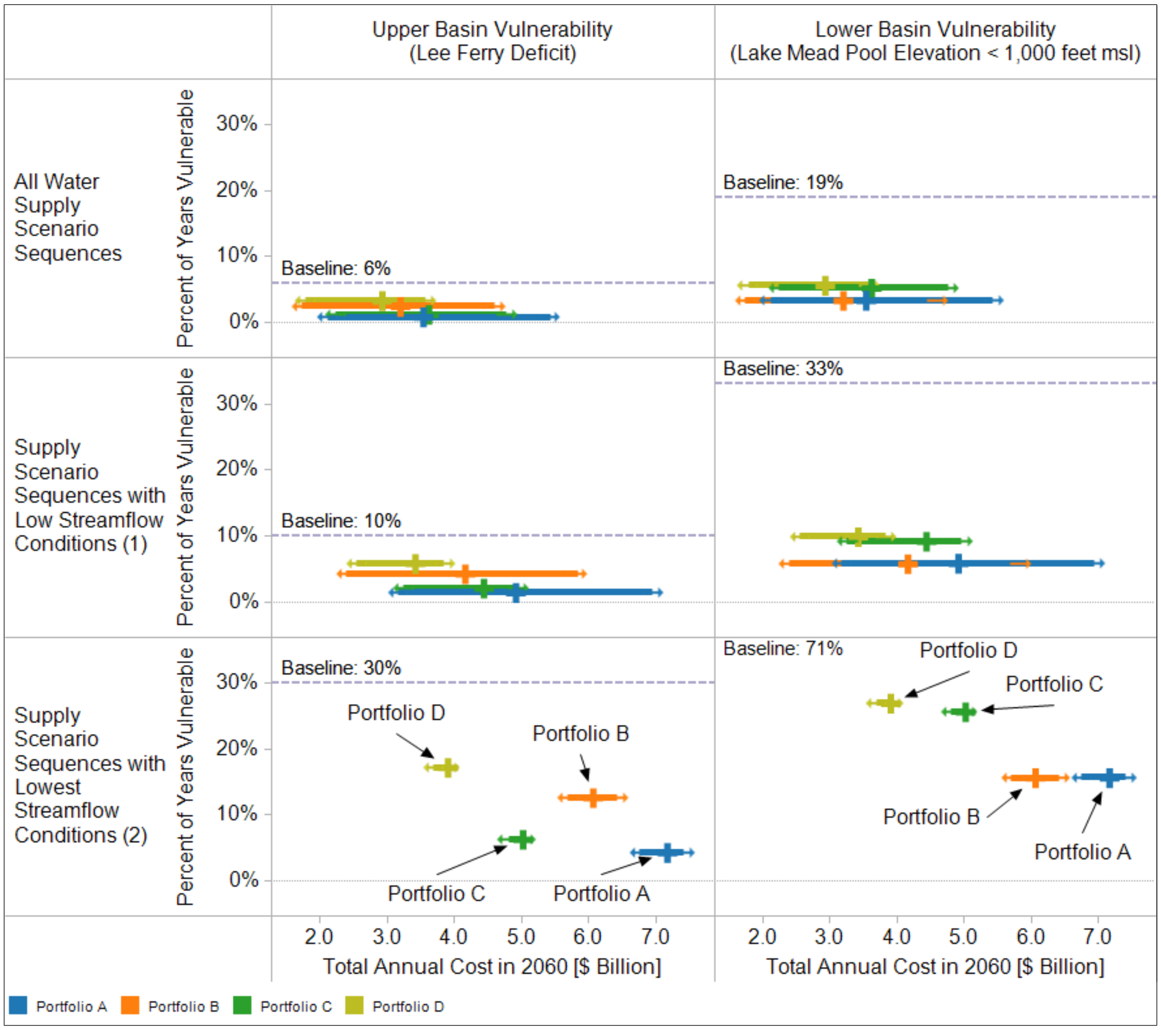


The differences among the portfolios become even more apparent in terms of costs and ability to reduce vulnerability as one focuses on the future conditions that are particularly stressing to the basin. Figure G-52 shows that across all traces, each portfolio reduces the years in which the Basin is vulnerable similar amounts. As was seen in figure G-45, the 2060 cost ranges are wide, reflecting the diversity of conditions across all traces.

For sequences that are less favorable, such as in the “Low Streamflow” conditions, tradeoffs among the portfolios more pronounced. For the Lower Basin Vulnerability (Lake Mead Pool Elevation < 1,000 feet msl) (right column), *Portfolios A* and *B* are the most effective in reducing vulnerability, yet the range in costs are lower for the former. In this case, *Portfolio B* could be considered more favorable to the others in terms of these two dimensions. For the Upper Basin Vulnerability (Lee Ferry Deficit) (left column), however, the portfolios that reduce vulnerability more, lead to higher ranges in cost. Note, however, that *Portfolio C* reduces vulnerabilities more than the *Portfolios B* and *D*, and has a lower high cost range than *Portfolio B*.

When considering the “Lowest Streamflow” subset of sequences (figure G-52, bottom row), two distinct tradeoffs between reduction in vulnerability and cost across the portfolios are seen. For the Upper Basin Reliability system vulnerability, *Portfolio C* both performs better than *Portfolios B* and *D* in terms of reducing this vulnerability and has a lower range of costs than *Portfolios A* and *B*. For the Lower Basin Reliability System Vulnerability, however, *Portfolio B* reduces vulnerability more than *Portfolios C* and *D* and also results in lower costs than *Portfolio A*.

FIGURE G-52
Percent of Years Vulnerable from 2041–2060 and Range In Total Annual Cost In 2060 for all water supply sequences (top), sequences with Low Streamflow Conditions (middle), and sequences with Lowest Streamflow conditions (bottom) across Upper Basin and Lower Basin Vulnerabilities, for Four Portfolios




(1) Conditions in which long-term mean natural flows are less than 15 mafy and the 8-year dry period flows are less than 13 mafy.

(2) Conditions in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.

### *6.3.11 Implemented Options for Different Portfolios*

The four portfolios evaluated in the Study represent different approaches for addressing the projected imbalances between water supply and demand and associated vulnerabilities. These portfolios were developed as exploratory strategies and should not be considered as individual suggestive pathways. Rather, they were developed to explore the range of options, different preferences for option characteristics, and different levels of option inclusion. Analysis of the frequency and timing of option implementation in the dynamic portfolios provides insight toward development of long-term strategies for the Basin.

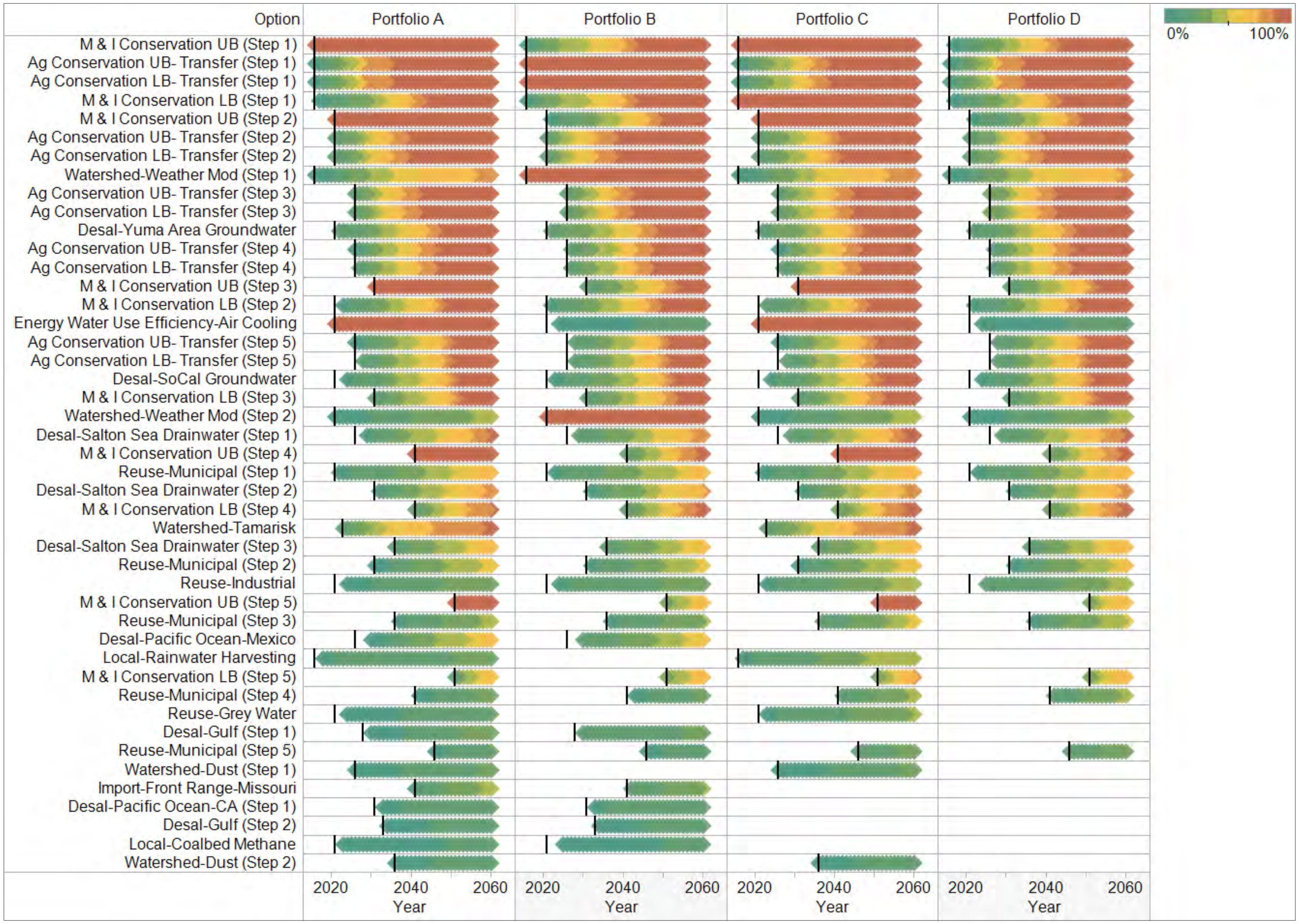
Successful strategies for the Basin will need to consider near-term actions, conditions that should be monitored over time, and options that can be implemented contingent on future conditions. The results presented in this section can be analyzed to identify for which options implementation should begin soon, and which options may be necessary only if conditions warrant them. The vulnerable conditions described in this report can provide a starting point for developing a monitoring approach to inform future investment needs. However, some actions have sufficiently long implementation timelines that action will need to be taken well in advance of the shorter-duration monitoring metrics. Some options are needed soon after availability only in futures consistent with the vulnerable conditions identified in the Study. In such cases, implementation of such options would hedge against the possible vulnerable conditions. Last, due to the particularly severe nature of some scenarios, the elimination of all vulnerabilities is not possible given the current range of options and the extreme nature of certain hydrologic futures.

Evaluation of options across the range of uncertain futures and exploratory portfolios considered in the Study can be summarized in terms of three main outcomes:

- **The percentage of traces in which an option is implemented**: The higher percentage of traces, the less contingent the need for the option is on future conditions.
- **The time delay between when individual options could be available and when they are implemented in CRSS simulations**: Options with no or little time delay require planning to begin soon.
- **The differences in implementation percentage and delay across portfolios and vulnerable conditions**: Options with similar implementation percentage and delay across the portfolios represent common groups between the preferences behind the different portfolios; options implemented soon in vulnerable conditions represent potential hedging actions.

CRSS implements options according to the ordering defined by the portfolio preferences and cost effectiveness (described in *Technical Report F – Development of Options and Strategies*) and in response to vulnerable conditions, according to defined signposts. Some options, therefore, are implemented by all four portfolios, whereas other options are only implemented in some of the portfolios. Within each portfolio, options are implemented more frequently and at different timing depending on the particular trace conditions. Figure G-53 shows the frequency of option implementation for all four portfolios by year. The black vertical line indicates the first year in which an option could be available. Green diamonds indicate years in which those options are implemented in few traces, and yellow and red diamonds indicate years in which options are increasingly implemented within the traces. Note that these results aggregate results across all the supply, demand, and management scenarios.

FIGURE G-53
Percent of Traces in Which Options are Implemented over Time for Each Portfolio




Note: Color indicates percentage of traces in which options are implemented. Vertical lines indicate year in which options are available.
Ag=agricultural, UB=Upper Basin, LB=Lower Basin, M&I=Municipal and Industrial, Mod=Modification, Desal=Desalination, SoCal=Southern California.

Several key observations can be made from this figure:

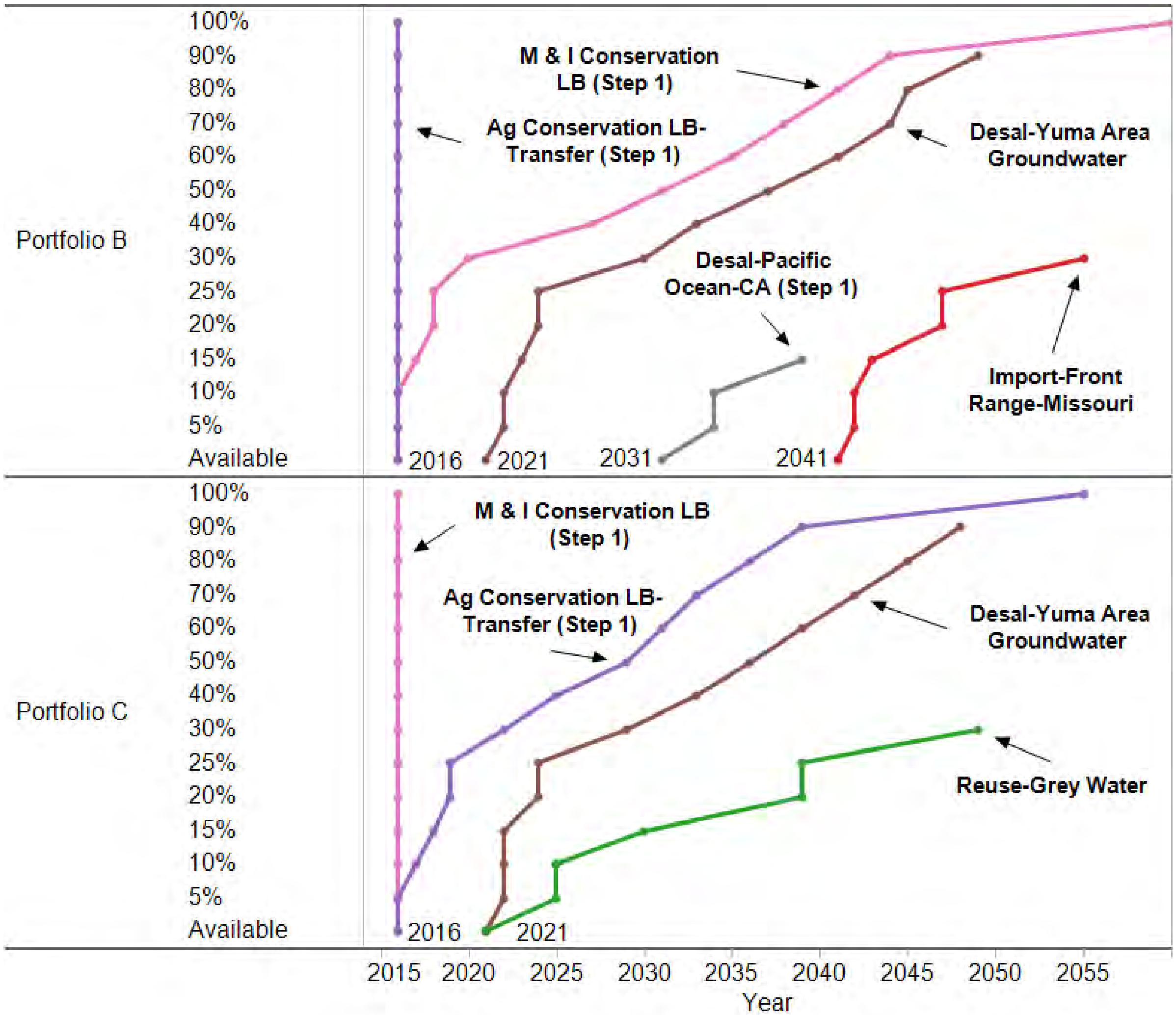
- Almost all of the conservation options are implemented in nearly all traces by 2060, although *Portfolios A* and *C* implement these options more frequently, and earlier in the Study period. The exception is the fifth step of M&I conservation, which is only implemented in some traces by 2060 in *Portfolio B*.
- The only options that are always implemented the year in which they are available are those that are specified to begin immediately by portfolio design—e.g., M&I Conservation UB, which is part of the specified water bank in *Portfolios A* and *C*; Watershed-Weather Mod (Steps 1 and 2) for *Portfolio B*; and Energy Sector Conservation for *Portfolio C* and *Portfolio A*.
- The *Portfolios A* and *B*, in general, implement more options than the other two portfolios in some traces, largely due to the greater availability of options in these portfolios to meet stressing traces.

*Common options* can be defined as those that are frequently selected for implementation across the range of scenarios included in the Study. Similarly, *short delay options* can be described as those that are implemented at or near the earliest dates that they are assumed to be available. *Common, short delay* options are then those that are frequently selected for implementation and which are implemented soon after they are available. The implementation of these options suggest that feasibility may need to be investigated soon. *Common, long delay* options are those that are implemented in most traces, but only after a delay from the time in which they are available. A delay in feasibility assessment of these options may be warranted in these cases. Last, *contingency options* are those that are implemented in only some traces.

To identify common, short delay options; common, long delay options; and contingency options, the percent of traces in which an option is implemented and the delay in option implementation is evaluated for each portfolio. The percent of traces in which the option is implemented is computed by considering all traces in all scenarios. The option implementation delay is computed as the median difference between the dynamic implementation timing and the year in which the option is assumed to be available in traces where the option is on. The implementation delay threshold between short and long delay options was 5 years.

Figure G-54 expands on figure G-53 for a few select options in *Portfolios B* and *C* to show the timing in which options are implemented at increasing frequency. Options in which this relationship is vertical are needed in most traces immediately and are common, short delay options. Options with a more sloped relationship are only required soon in some traces, and for other traces the options are not needed until later. These are either common, long delay or contingency options. For example, M&I Conservation (Step 1) is implemented in all traces immediately after it is available in *Portfolio C*. However, it is only implemented in 25 percent of the traces by 2018 and in 100 percent of the traces by 2060 for Portfolio B. This option is a common, short delay option for *Portfolio C* and a common, long delay option for *Portfolio B*. The Desal-Pacific Ocean-CA (Step 1) and Import-Front Range-Missouri portfolios, in contrast, are contingency options—they are only needed in about 15 percent and 30 percent of the traces evaluated, respectively.

FIGURE G-54
Percentage of Traces (vertical axis) Implemented by year (horizontal axis) for Select Options with Portfolio B and Portfolio C




To summarize these results for all options, table G-18 shows the percent implemented by 2060 (color and label) and the minimum delay (across options) between availability and median implementation (size) for eight representative option groups. Large, red squares indicate option groups in which options are implemented frequently across the sequences and have a short delay (e.g., Ag Conservation, M&I Conservation, and Weather Mod for *Portfolio B*). These groups include common, short delay options. Smaller red squares indicate option groups in which options are implemented in most traces by 2060, but only after a long delay from availability. These groups include common, long delay options. Large green squares include options that are less frequently implemented and have a short delay. Small green squares include options that are less frequently implemented and have a long delay (e.g., Local-Coal Bed Methane). These are contingency options.

TABLE G-18
Percent of Traces in Which Options are Implemented from Option Group (label and color) and the Minimum Delay (across the options) Between Availability and Median Implementation Delay (size)

| Option Category | Option Group | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|
| Ag. Conservation | Ag Conservation with Transfers | 100% | 100% | 100% | 100% |
| Desalination | Desal-Groundwater | 99% | 99% | 99% | 99% |
| | Desal-Gulf of California | 28% | 27% | | |
| | Desal-Pacific Ocean-California | 16% | 17% | | |
| | Desal-Pacific Ocean-Mexico | 66% | 63% | | |
| | Desal-Salton Sea | 78% | 76% | 85% | 81% |
| | Desal-Yuma | 100% | 100% | 100% | 100% |
| Energy WUE | Energy Water Use Efficiency | 100% | 19% | 100% | 20% |
| Import | Import Front Range | 42% | 39% | | |
| Local Supply | Local-Coalbed Methane | 16% | 16% | | |
| | Local-Rain | 29% | | 48% | |
| M & I Conservation | M&I Conservation | 95% | 93% | 97% | 93% |
| Reuse | Reuse-Grey Water | 25% | | 39% | |
| | Reuse-Industrial | 35% | 33% | 44% | 42% |
| | Reuse-Municipal | 47% | 44% | 54% | 53% |
| Watershed Management | Watershed-Brush Control | 89% | | 88% | |
| | Watershed-Dust Control | 23% | | 24% | |
| | Watershed-Weather Mod | 60% | 100% | 62% | 59% |

Implementation: 0% – 100%
Minimum Delay (years): 0, 5, 10, 15, ≥ 21

Interpretation of common, short delay options is straightforward. These options were found by CRSS to be most effective in addressing system imbalances in most traces, and would need to be implemented soon to meet Basin needs. There is more ambiguity about options identified to be long delay or contingency options (those implemented soon after availability in a smaller percentage of traces).

To better understand whether implementation of long delay or contingency options should proceed soon, looking to the vulnerable conditions identified earlier can provide insight. Identifying options that are needed soon after availability within the vulnerable conditions provides guidance on options to invest in to increase the system's resilience to these conditions. Tables G-18 and G-19 show similar information as table G-18 but based on only those within *Low Streamflow* conditions (table G-19) and within *Lowest Streamflow* conditions (table G-20).

Table G-18 shows that several more option groups include common, short delay options. For example, Ag Conservation with Transfers is a short delay option for all portfolios, not just *Portfolio B*. Reuse-Municipal is also implemented in most traces across all traces with short delays. Many option groups show more options becoming common, long delay options.

Desal-Pacific Ocean-Mexico is now implemented in about 90 percent of traces in the Long-Term Reliability and *Portfolio A*. Watershed-Weather Mod projects also move to a long delay option, being implemented in between 66 and 100 percent of traces across the four portfolios.

TABLE G-19
Percentage of Traces within *Low Streamflow* conditions In which Options are Implemented from Option Group (label and color) and the Minimum Delay (across options) between Availability and Median Implementation Delay (size)

| Option Category | Option Group | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|
| Ag. Conservation | Ag Conservation with Transfers | 100% | 100% | 100% | 100% |
| Desalination | Desal-Groundwater | 100% | 100% | 100% | 100% |
| | Desal-Gulf of California | 47% | 44% | | |
| | Desal-Pacific Ocean-California | 26% | 27% | | |
| | Desal-Pacific Ocean-Mexico | 84% | 81% | | |
| | Desal-Salton Sea | 90% | 88% | 93% | 92% |
| | Desal-Yuma | 100% | 100% | 100% | 100% |
| Energy WUE | Energy Water Use Efficiency | 100% | 33% | 100% | 35% |
| Import | Import Front Range | 62% | 58% | | |
| Local Supply | Local-Coalbed Methane | 28% | 28% | | |
| | Local-Rain | 45% | | 70% | |
| M & I Conservation | M&I Conservation | 95% | 92% | 96% | 93% |
| Reuse | Reuse-Grey Water | 41% | | 60% | |
| | Reuse-Industrial | 55% | 52% | 67% | 65% |
| | Reuse-Municipal | 65% | 61% | 72% | 72% |
| Watershed Management | Watershed-Brush Control | 98% | | 98% | |
| | Watershed-Dust Control | 37% | | 39% | |
| | Watershed-Weather Mod | 66% | 100% | 70% | 67% |

Implementation: 0% – 100%
Minimum Delay (years): 0, 5, 10, 15, 21

Low Streamflow conditions are those in which long-term mean natural flows are less than 15 mafy and the 8-year dry period flows are less than 13 mafy.

When considering the within *Lowest Streamflow* conditions, even more option groups become short delay (table G-20). For example, more desalination options are implemented in most traces, although not immediately after availability. Reuse and watershed management options are also implemented in most traces within this vulnerability.

TABLE G-20
Percentage of Traces within *Lowest Streamflow* conditions in which Options are Implemented from Option Group (label and color) and the Minimum Delay (across options) between Availability and Median Implementation Delay (size)

| Option Category | Option Group | Portfolio A | Portfolio B | Portfolio C | Portfolio D |
|---|---|---|---|---|---|
| Ag. Conservation | Ag Conservation with Transfers | 100% | 100% | 100% | 100% |
| Desalination | Desal-Groundwater | 100% | 100% | 100% | 100% |
| | Desal-Gulf of California | 92% | 94% | | |
| | Desal-Pacific Ocean-California | 53% | 59% | | |
| | Desal-Pacific Ocean-Mexico | 100% | 100% | | |
| | Desal-Salton Sea | 99% | 99% | 100% | 100% |
| | Desal-Yuma | 100% | 100% | 100% | 100% |
| Energy WUE | Energy Water Use Efficiency | 100% | 87% | 100% | 93% |
| Import | Import Front Range | 91% | 91% | | |
| Local Supply | Local-Coalbed Methane | 77% | 78% | | |
| | Local-Rain | 93% | | 100% | |
| M & I Conservation | M&I Conservation | 96% | 96% | 98% | 98% |
| Reuse | Reuse-Grey Water | 91% | | 99% | |
| | Reuse-Industrial | 97% | 98% | 100% | 99% |
| | Reuse-Municipal | 92% | 92% | 95% | 96% |
| Watershed Management | Watershed-Brush Control | 100% | | 100% | |
| | Watershed-Dust Control | 89% | | 93% | |
| | Watershed-Weather Mod | 98% | 100% | 99% | 99% |

Implementation: 0% – 100%
Minimum Delay (years): 0, 5, 10, 15, 21

Lowest Streamflow conditions are those in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.

Planning for short delay options across all traces should ideally begin immediately because these actions will be necessary to meet future challenges. If Basin planners believe that the vulnerable conditions are likely to occur, planning for the short delay options in the vulnerable conditions should also begin immediately. With long delay options, Basin planners can monitor signpost conditions and begin implementation if conditions degrade.

## 6.4 Summary of System Reliability with Options and Strategies

Several key findings emerge from the modeling and analysis discussed in this section:

- The modeling of a single static portfolio (*Static Portfolio A*) shows that significant system improvements are possible given the set of options characterized in the Study. These improvements led to a substantial reduction in vulnerabilities for most, but not all scenarios. Not all vulnerabilities could be mitigated for some extreme scenarios.
- Four dynamic portfolios helped determine a more realistic range of action across the wide variety of supply/demand scenarios quantified. These results indicate that full investment in

the *Static Portfolio A* is not required for many scenarios in order to effectively mitigate a large number of vulnerabilities. Of the traces that the system is still vulnerable with the implementation of portfolios, most are from the Downscaled GCM Projected supply scenario.

- A comparison of dynamic portfolio model simulations revealed several relationships. In many traces, portfolios with more available options improved system performance at higher costs. For some indicator metrics and traces, different portfolios were both more effective at reducing vulnerabilities and containing costs. The portfolio analysis also showed the differences in reliability and environmental characteristics of the options used to address vulnerabilities across the portfolios.

This section provided insight into which options are common across traces and implemented with only short delays after availability. Table G-21 summarizes these findings by classifying which representatives option have short or long delay in more than 75 percent of the traces by 2060. These results are calculated for all traces and by vulnerable conditions. The implementation delay threshold between short and long delay options was 5 years. The coloring in the table indicates the number of portfolios that are short or long delay (Darker reds indicate short delay for more portfolios; darker greens indicate longer delay for more portfolios.)

Table G-19 highlights the following key findings:

- **Options that are always short delay**: M&I Conservation (for all portfolios); Ag conservation and Weather Mod (for Portfolio B); Energy Water Use Efficiency (for *Portfolios A* and *B*)—implementation of these options now, per preferences for different portfolios, is most consistent to the findings of this analysis.

- **Additional short delay options in Low Streamflow conditions (Long-Term Flow < 15 mafy and Drought < 13 mafy)**: Desal-Salton Sea; Ag Conservation (all portfolios); Reuse Municipal (*Portfolio C* and *D*)—these options would need to be implemented soon in order to hedge against these challenging conditions.

- **Additional short delay options in Lowest Streamflow conditions (Long-Term Flow < 14 mafy and Drought < 11 mafy)**: Desal-Yuma; Import-Front Range (*Portfolios A* and *B*)—near-term implementation of these options would be required only to hedge against the more severe conditions.

- **Key contingent options within Low Streamflow conditions (Long-Term Flow < 15 mafy and Drought < 13 mafy) include:** Desal-Gulf of California, Desal-Pacific Ocean-California, Reuse-Grey Water, and Watershed-Dust Control, and Local-Coal Bed Methane—implementation of these options can wait and be triggered in response to signposts anticipating these challenging conditions.

TABLE G-21

Portfolios in Which Option Groups Have Short Delay and Long Delay Options Across All Traces (Left Two Columns)

*Darker reds and darker greens indicate more portfolios with specified delay.*

| Option Category | Option Group | Common Across All Traces | | Common Across *Low Streamflow* Conditions[1] | | Common Across *Lowest Streamflow* Conditions[2] | |
|---|---|---|---|---|---|---|---|
| | | Short Delay | Long Delay | Short Delay | Long Delay | Short Delay | Long Delay |
| Ag Conservation | Ag Conservation with Transfers | B | A, C, D | **A, B, C, D** | | **A, B, C, D** | |
| Desalination | Desal-Groundwater | | **A, B, C, D** | | **A, B, C, D** | | **A, B, C, D** |
| | Desal-Gulf | | | | | | A, B |
| | Desal-Pacific Ocean-California | | | | | | |
| | Desal-Pacific Ocean-Mexico | | | | A, B | | A, B |
| | Desal-Salton Sea | | **A, B, C, D** | **ALL** | | **A, B, C, D** | |
| | Desal-Yuma | | **A, B, C, D** | | **A, B, C, D** | **A, B, C, D** | |
| Energy WUE | Energy Water Use Efficiency | A, C | | A, C | | A, C | B, D |
| Import | Import Front Range | | | | | A, B | |
| Local Supply | Local-Coal Bed Methane | | | | | | A, B |
| | Local-Rain | | | | | | A, C |
| M&I Conservation | M&I Conservation | **A, B, C, D** | | **A, B, C, D** | | **A, B, C, D** | |
| Reuse | Reuse-Grey Water | | | | | | A, C |
| | Reuse-Industrial | | | | | | **A, B, C, D** |
| | Reuse-Municipal | | | | | **A, B, C, D** | |
| Watershed Management | Watershed-Brush Control | | A, C | A | C | A, C | |
| | Watershed-Dust Control | | | | | A, C | |
| | Watershed-Weather Mod. | B | | B | | B | A, C, D |

[1] Low Streamflow conditions are those in which long-term mean natural flows are less than 15 mafy and the 8-year dry period flows are less than 13 mafy.

[2] Lowest Streamflow conditions are those in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.

# 7.0 Summary

The results of the system reliability analysis without options and strategies indicate the potential for continued and significant stress on Basin resources. Lake Mead and Lake Powell storage was shown to be declining. With declining lake levels, resources such as hydropower and shoreline recreation are affected, while the probability of water delivery shortages is increased. Flow in many key tributaries decreased based on projections of reduced r reduced natural flow and growing demands, which had implications for flow-dependent resources such as boating recreation and ecological needs. These findings fully support the need to develop and evaluate options for balancing future supply and demand.

Based on additional analysis of modeling results without options and strategies, it was found that no single combination of water supply, water demand, and operational assumptions is responsible for the aforementioned challenges. In fact, most combinations have the capacity to stress at least some Basin resources. However, more noteworthy is the relative importance of various vulnerability drivers depending on a particular combination of water supply, water demand, and operational assumptions and the time period. For the first period in the Study horizon (2012–2026), all scenarios follow the operational policies established by the 2007 Interim Guidelines (DOI, 2007). At the same time, demands are not appreciably different across the scenarios. Therefore, the largest driver of vulnerability in the early time period is associated with projections of water supply. In the later two time periods, assumptions for the operation of Lakes Powell and Mead and demand scenarios are increasingly important with regard to vulnerability rates. In fact, by the third time window, some resources show roughly equal vulnerability caused by the water supply, water demand, and operational assumptions. The exception to this observation is the Downscaled GCM Projected water supply scenario. The increased variability and declining trend in flow in this scenario increase are substantial enough that vulnerability is elevated under these hydrologic conditions, regardless of the demand and operational assumptions. In most cases, the lowest vulnerability for scenarios with the Downscaled GCM Projected supply is still greater than any other supply, demand, operational assumption combination.

System modeling with options and strategies demonstrated that all portfolios have capacity to reduce vulnerabilities across resources and in doing so, making a sizeable reduction in the supply-demand imbalance. In the 2012 through 2026 period, reductions in vulnerabilities tend to be small, owing to generally low risks early on, even in the baseline and also, in some cases, a lack of options available to address vulnerabilities that may occur. In the latter two time windows, vulnerability reductions of 50 percent or more (relative to Baseline results) are seen in all resource categories. The one exception is the flood control indicator metric. A consequence of increased Basin yield and greater storage in reservoirs is a slight increase in flood control vulnerabilities. These events remain fairly infrequent; reaching a maximum frequency of 5 percent of years in the later period, when the most options have been implemented.

These reductions in vulnerability are encouraging, but vulnerabilities are never completely eliminated, even when every option considered is implemented as soon as it becomes available. Further, given the uncertainty of future conditions, it is impossible to predict the actual vulnerability distribution.  Because of this, the percent of years or traces that are vulnerable does not translate to a future probability of occurrence. Rather the suite of projections of future conditions was used to evaluate the effectiveness of various portfolios for reducing vulnerabilities. The effectiveness of the portfolios are summarized for two subsets of the scenarios considered: by water supply scenario and by specific conditions that tend to accompany certain vulnerabilities. In the case of a Lee Ferry Deficit, an 8-year drought with average flow less than or equal to 11.2 mafy (natural flow at Lees Ferry) was one of the conditions that was found to accompany that particular vulnerability. When repeated for results with portfolios, the 8-year drought magnitude associated with a Lee Ferry Deficit was found to be as low as 10 mafy in some cases. This provides a quantitative assessment of portfolio performance by defining the change in severity of conditions that can be tolerated.

Of the four strategies and associated portfolios considered, notable differences extend beyond portfolio performance. As discussed earlier, portfolios differ based on the options used to address supply/demand imbalances. From analysis of the characterization criteria, the portfolios differentiate most notably on cost, environmental effects, and long-term reliability. Portfolio cost is largely driven by the total potential yield considered in the portfolio, the unit cost of the options, and the water supply and water demand conditions for which the portfolio was evaluated. As such, by 2060, annual portfolio costs range from approximately $2 billion to $5 billion, but could increase to potentially $7 billion under the GCM Projected scenario. The differences in cost across portfolios result from the preference of option types versus increased ability to reduce vulnerabilities. Two examples of this are portfolio preferences for options with higher long-term reliability and preferences for lower environmental impacts. By choosing to only consider options that were characterized as moderate to high long-term viability, lower unit cost alternatives may be excluded, but the options increased the total potential yield. In contrast, options characterized as having lower potential environmental impacts may come at the expense of yield certainty. The purpose of exploring these differences is not to identify a “best” portfolio or strategy, but to acknowledge that there are various approaches to address the future supply and demand imbalance and that each has associated implications that must be considered in the decision making process.

Although the portfolios explored in the Study address Basin imbalances differently, they also have commonalities. For example, all portfolios incorporate significant agricultural water conservation, M&I water conservation, energy water use efficiency, and some levels of weather modification because they are available relatively early in the Study horizon and address many of the vulnerabilities. However, some options were implemented more frequently in response to challenging water supply conditions. For example, ocean and brackish water desalination, wastewater reuse, and importation options were implemented for the most challenging water supply conditions in portfolios. It is also important to note that option selection and implementation depends upon the option characterization process and results. As a result, it is possible that of two similar options, one may be relied on often while the other is almost never implemented due to cost differences, permitting difficulty, technical feasibility, or other factors. Robust planning requires careful consideration with regard to timing, location and magnitude of anticipated future Basin needs in addition to the frequency with which options are implemented as suggested in the Study.

The Study confirms that without action, the Colorado River system will become increasingly challenged to sustain the communities and resources that rely on Colorado River system water supply.  The Study demonstrates that many of the Basin imbalances and resulting vulnerabilities to Basin resources can be greatly improved or mitigated through option and portfolio implementation. However, due to the particularly severe nature of some projected scenarios, the elimination of all vulnerabilities was not possible given the range of options considered and the extreme nature of certain plausible hydrologic futures. This raises significant questions regarding the acceptable levels of risks to Basin resources and the appropriate trade-offs in terms of options, costs, resources, and other implications to achieve those acceptable levels. Even though these questions are beyond the scope of the current effort, they will need to be addressed as part of the implementation of options as well as in subsequent planning efforts.

# 8.0 References


Dessai, S. and M. Hulme. 2007. "Assessing the Robustness of Adaptation Decisions to Climate Change Uncertainties: A Case Study on Water Resources Management in the East of England." *Global Environmental Change* 17(1), 59–72.

Groves, D. G. and R. J. Lempert. 2007). "A New Analytic Method for Finding Policy-Relevant Scenarios." Global Environmental Change, 17: 73–85.

Groves, D. G., D. Yates, C. Tebaldi. 2008. "Developing and Applying Uncertain Global Climate Change Projections for Regional Water Management Planning." *Water Resources Research*, 44 (W12413).

Lempert, R. and D. G. Groves. 2010. "Identifying and Evaluating Robust Adaptive Policy Responses to Climate Change for Water Management Agencies in the American West, Technological Forecasting and Social Change." 77: 960–974.

Lempert, R. J., S. W. Popper and S. C. Bankes. 2003. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-term Policy Analysis*.

McAda, C. 2003. *Flow Recommendations to Benefit Endangered Fishes in the Colorado and Gunnison Rivers*.

Ouarda, T., J.W. Labadie, and D.G. Fontane.1997. "Index sequential hydrologic modeling for hydropower capacity estimation." *Journal of the American Water Resources Association*, 33(6), 1337–1349.

Prairie, J., Nowak, K., Rajagopalan, B., Lall, U., Fulp, T. 2008. "A Stochastic Nonparametric Approach for Streamflow Generation Combining Observational and Paleoreconstructed Data." *Water Resources Research* Volume 44, W06423, DOI: 10.1029/2007WR006684.

Bureau of Reclamation (Reclamation). 2007. *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement.* November 2.

Bureau of Reclamation (Reclamation). 2006. *Navajo Reservoir Operations Environmental Impact Statement*. Final. April.

Bureau of Reclamation (Reclamation). 2005. *Operation of Flaming Gorge Dam Environmental Impact Statement*. Final. September.

Reclamation. 2004. Bureau of Reclamation, U.S. Fish and Wildlife Service, and The Metropolitan Water District of Southern California. *Lower Colorado River Multi-Species Conservation Program. Volume I: Programmatic Environmental Impact Statement/Environmental Impact Report*. Final. December 17.

U.S. Department of the Interior (DOI), 2007. *Record of Decision for Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lakes Powell and Mead.*

U.S. Fish and Wildlife Service (USFWS). 2008. *Rationale for Management of Water Releases from the Elkhead Reservoir Endangered Fish Pool to Augment August–October Base Flows in the Yampa River*. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Upper Colorado River Endangered Fish Recovery Program.

Zagona, E., T. Fulp, R. Shane, T. Magee, and H. Goranflo. 2001. "RiverWareTM: A Generalized Tool for Complex Reservoir Systems Modeling." *Journal of the American Water Resources Association*. 37(4):913–929.

# Disclaimer

The Colorado River Basin Water Supply and Demand Study (Study) is funded jointly by the Bureau of Reclamation (Reclamation) and the seven Colorado River Basin States (Basin States). The purpose of the Study is to analyze water supply and demand imbalances throughout the Colorado River Basin and those adjacent areas of the Basin States that receive Colorado River water through 2060; and develop, assess, and evaluate options and strategies to address the current and projected imbalances.

Reclamation and the Basin States intend that the Study will promote and facilitate cooperation and communication throughout the Basin regarding the reliability of the system to continue to meet Basin needs and the strategies that may be considered to ensure that reliability. Reclamation and the Basin States recognize the Study was constrained by funding, timing, and technological and other limitations, and in some cases presented specific policy questions and issues, particularly related to modeling and interpretation of the provisions of the Law of the River during the course of the Study. In such cases, Reclamation and the Basin States developed and incorporated assumptions to further complete the Study. Where possible, a range of assumptions was typically used to identify the sensitivity of the results to those assumptions.

Nothing in the Study, however, is intended for use against any Basin State, any federally recognized tribe, the federal government or the Upper Colorado River Commission in administrative, judicial or other proceedings to evidence legal interpretations of the Law of the River. As such, assumptions contained in the Study or any reports generated during the Study do not, and shall not, represent a legal position or interpretation by the Basin States, any federally recognized tribe, federal government or Upper Colorado River Commission as it relates to the Law of the River. Furthermore, nothing in the Study is intended to, nor shall the Study be construed so as to, interpret, diminish or modify the rights of any Basin State, any federally recognized tribe, the federal government, or the Upper Colorado River Commission under federal or state law or administrative rule, regulation or guideline, including without limitation the Colorado River Compact (45 Stat. 1057), the Upper Colorado River Basin Compact (63 Stat. 31), the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande, Treaty Between the United States of America and Mexico (Treaty Series 994, 59 Stat. 1219), the United States/Mexico agreement in Minute No. 242 of August 30, 1973 (Treaty Series 7708; 24 UST 1968), or Minute No. 314 of November 26, 2008, or Minute No. 318 of December 17, 2010, or Minute No. 319 of November 20, 2012, the Consolidated Decree entered by the Supreme Court of the United States in Arizona v. California (547 U.S 150 (2006)), the Boulder Canyon Project Act (45 Stat. 1057), the Boulder Canyon Project Adjustment Act (54 Stat. 774; 43 U.S.C. 618a), the Colorado River Storage Project Act of 1956 (70 Stat. 105; 43 U.S.C. 620), the Colorado River Basin Project Act of 1968 (82 Stat. 885; 43 U.S.C. 1501), the Colorado River Basin Salinity Control Act (88 Stat. 266; 43 U.S.C. 1951) as amended, the Hoover Power Plant Act of 1984 (98 Stat. 1333), the Colorado River Floodway Protection Act (100 Stat. 1129; 43 U.S.C. 1600), the Grand Canyon Protection Act of 1992 (Title XVIII of Public Law 102-575, 106 Stat. 4669), or the Hoover Power Allocation Act of 2011 (Public Law 112-72). In addition, nothing in the Study is intended to, nor shall the Study be construed so as to, interpret, diminish or modify the rights of any federally recognized tribe, pursuant to federal court decrees, state court decrees, treaties, agreements, executive orders and federal trust responsibility. Reclamation and the Basin States continue to recognize the entitlement and right of each State and any federally recognized tribe under existing law, to use and develop the water of the Colorado River system.