Appendix G3
Additional Methodology and Results

Appendix G3 — Additional Methodology and Results

1.0 Introduction

This appendix provides additional methodology discussion and results related to the system reliability analysis presented in *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*. The appendix structure largely follows that of Technical Report G . A complete suite of system response variable results is provided, indicator metrics and vulnerability are further explored, and definitions and associated vulnerability thresholds are detailed, followed by a full set of indicator metric vulnerability figures without options and strategies. Also pertaining to vulnerability, a discussion of additional vulnerable condition methodology is presented that includes an example, and vulnerable condition results for all water supply indicator metrics are provided. This appendix supplements the methods and results for system reliability presented in the main report with options and strategies. Therein, modeling assumptions are discussed, including signpost selection methods. Following that, results with options and strategies for all system response variables and indictor metric vulnerable conditions are provided.

2.0 Evaluation of System Reliability without Options and Strategies

2.1 System Response Variables

System response variables describe Colorado River Basin (Basin) conditions for the various scenarios. These are primarily direct model trace results such as pool elevations, hydropower generation, or flow. This output provides a gross estimate of possible future trends and operational ranges for major Basin components. System response variables (listed in table G-1 of the main report) are a first step in investigating system performance under plausible future conditions; however, they are not tailored to assess specific Basin resources and may lack a frame of reference for readers seeking to review a particular Basin resource.

Colorado River Simulation System (CRSS) simulations provide thousands of trace results used to estimate the system reliability across scenarios without options and strategies revealing a wide range of outcomes. This section presents either magnitude and percent of traces with occurrence or statistics that specify the level that a particular percentage of results has not 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, but as the central tendency of the distribution of these results.

These variables are presented for each supply and demand scenario and either of two assumptions regarding Lakes Powell and Mead operations beyond 2026 to explore differences. Figures G3-1 to G3-7, G3-9 to G3-15, and G3-17 show time series of 10th, 50th and 90th percentiles for the following types of system response variables: river flow, reservoir storage, reservoir release, reservoir pool elevation, shortage, surplus, and energy production. In addition, figures G3-8, G3-16, and G3-18 use cumulative distribution functions to further explore energy production results.Select scenarios are highlighted for reference.

FIGURE G3-1
10th, 50th, 90th Percentiles for Annual Flow of Green River at Green River, Utah, by Scenario, Without Options and Strategies

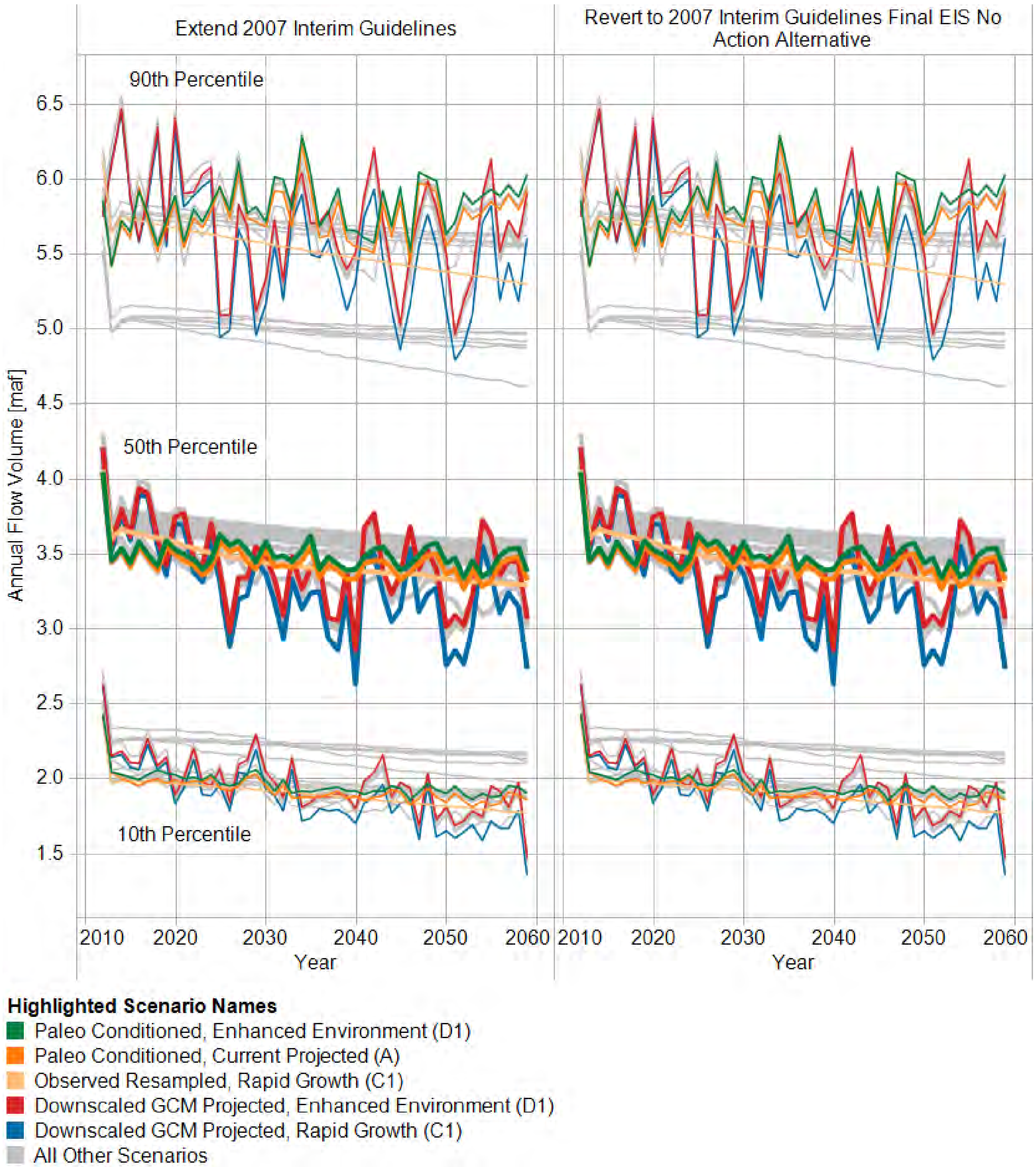


FIGURE G3-2
10th, 50th, 90th Percentiles for Annual Flow of Colorado River near Cisco, Utah, by Scenario, Without Options and Strategies

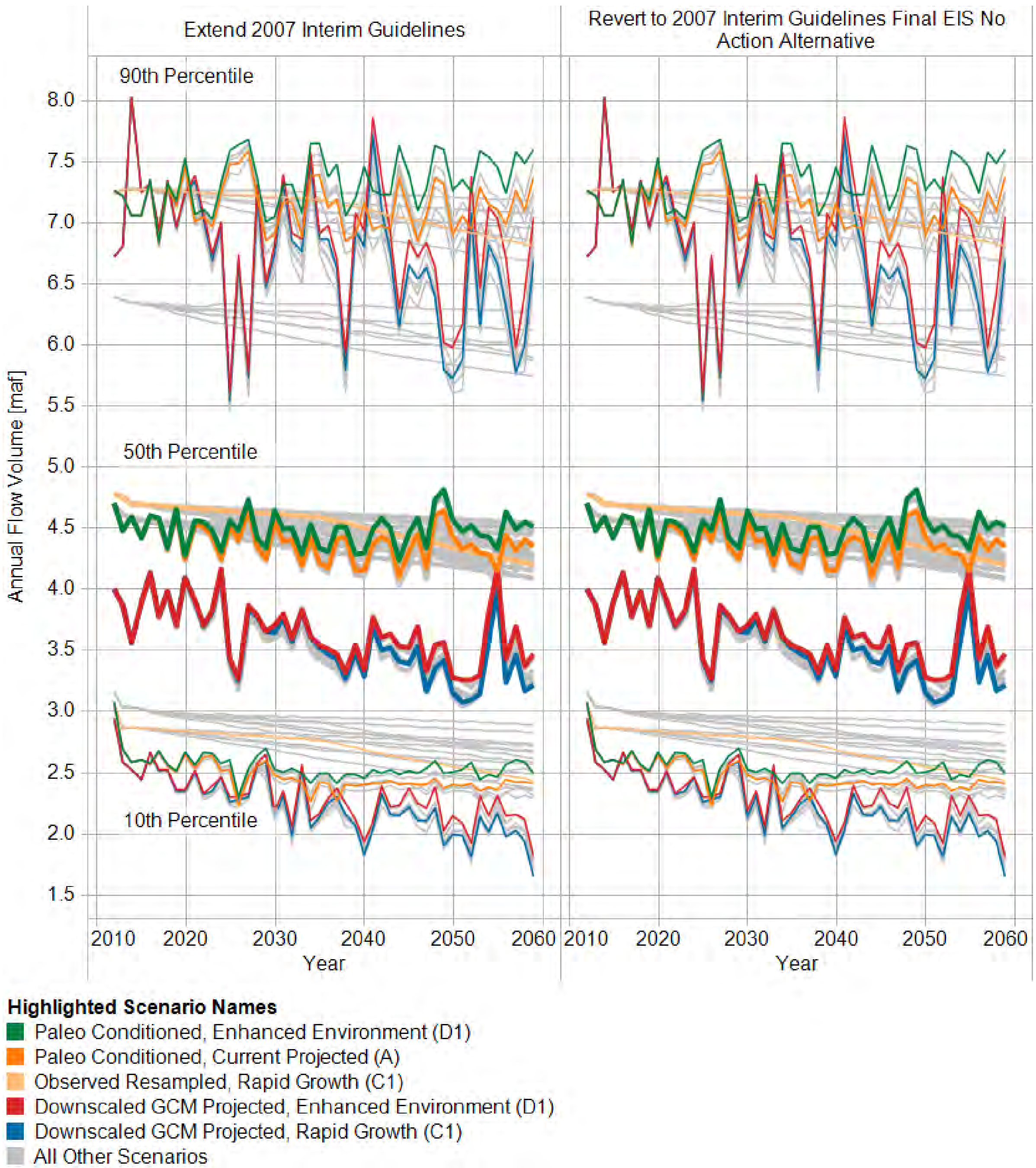


FIGURE G3-3
10th, 50th, 90th Percentiles for Annual Flow of San Juan River near Bluff, Utah, by Scenario, Without Options and Strategies

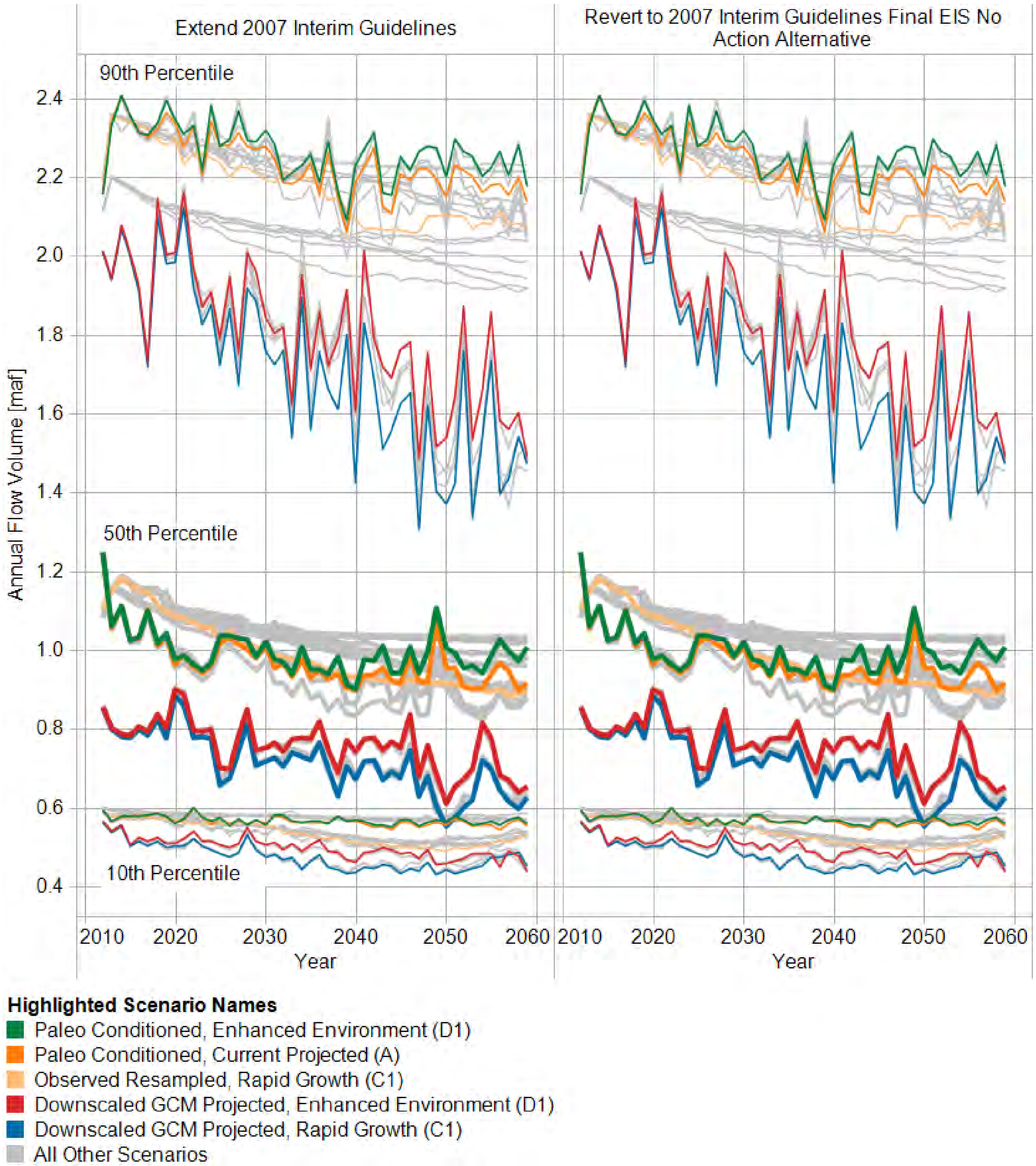


FIGURE G3-4
10th, 50th, 90th Percentiles for Total Storage Above Lake Powell by Scenario, Without Options and Strategies

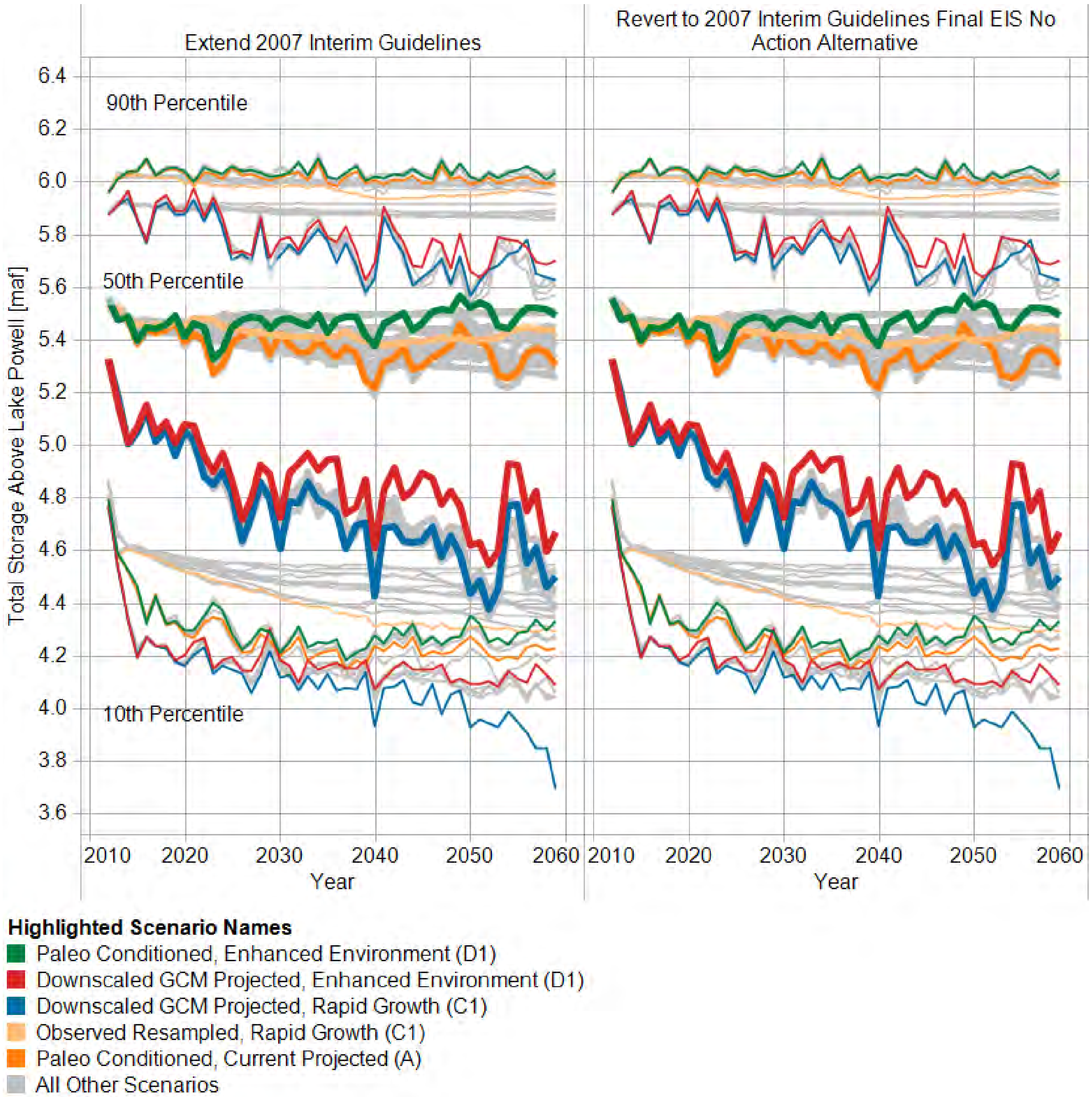


FIGURE G3-5
10th, 50th, 90th Percentiles for Upper Basin Annual Shortage by Scenario, Without Options and Strategies

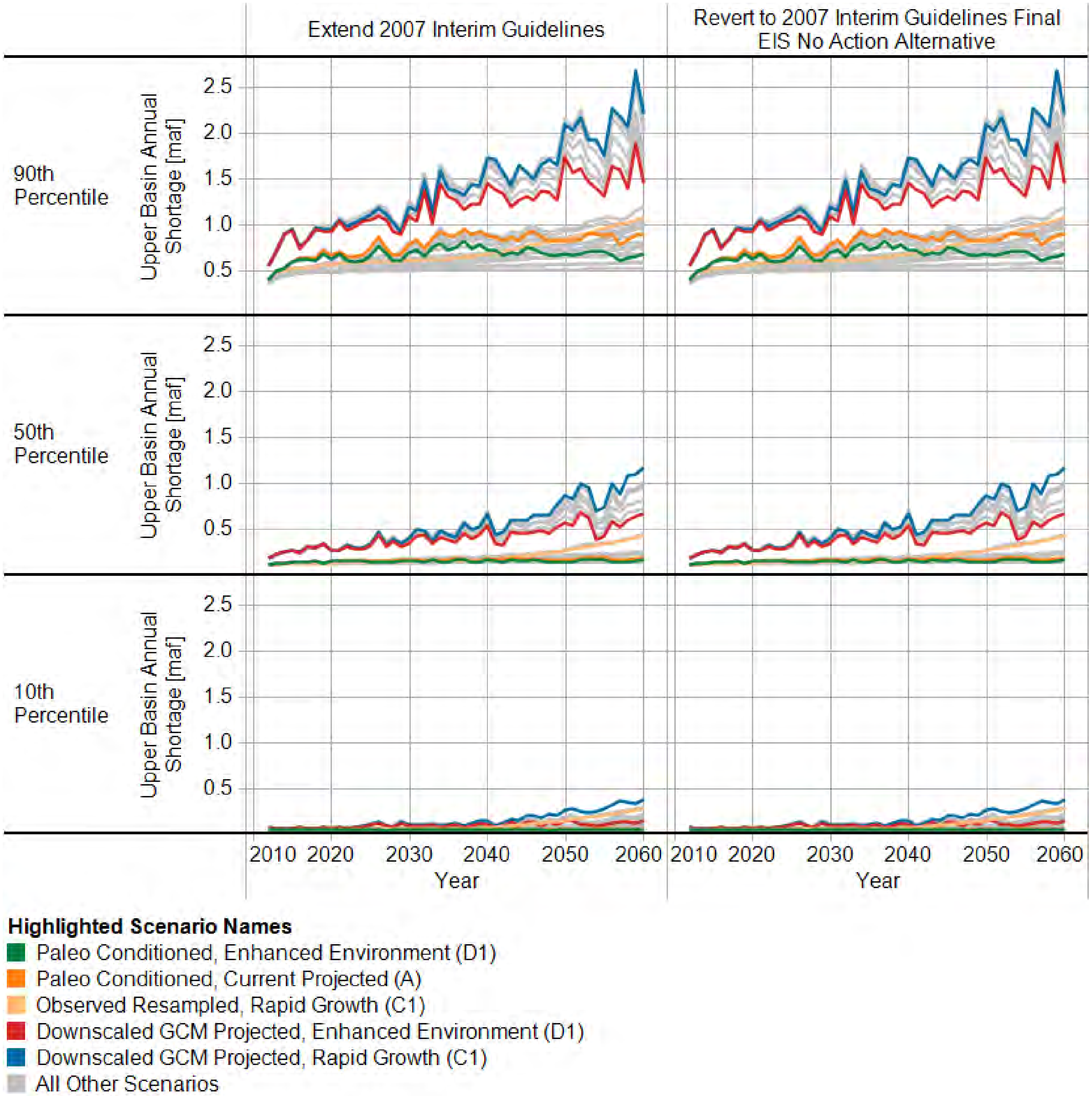


FIGURE G3-6
10th, 50th, 90th Percentiles for Lake Powell Pool Elevation by Scenario, Without Options and Strategies

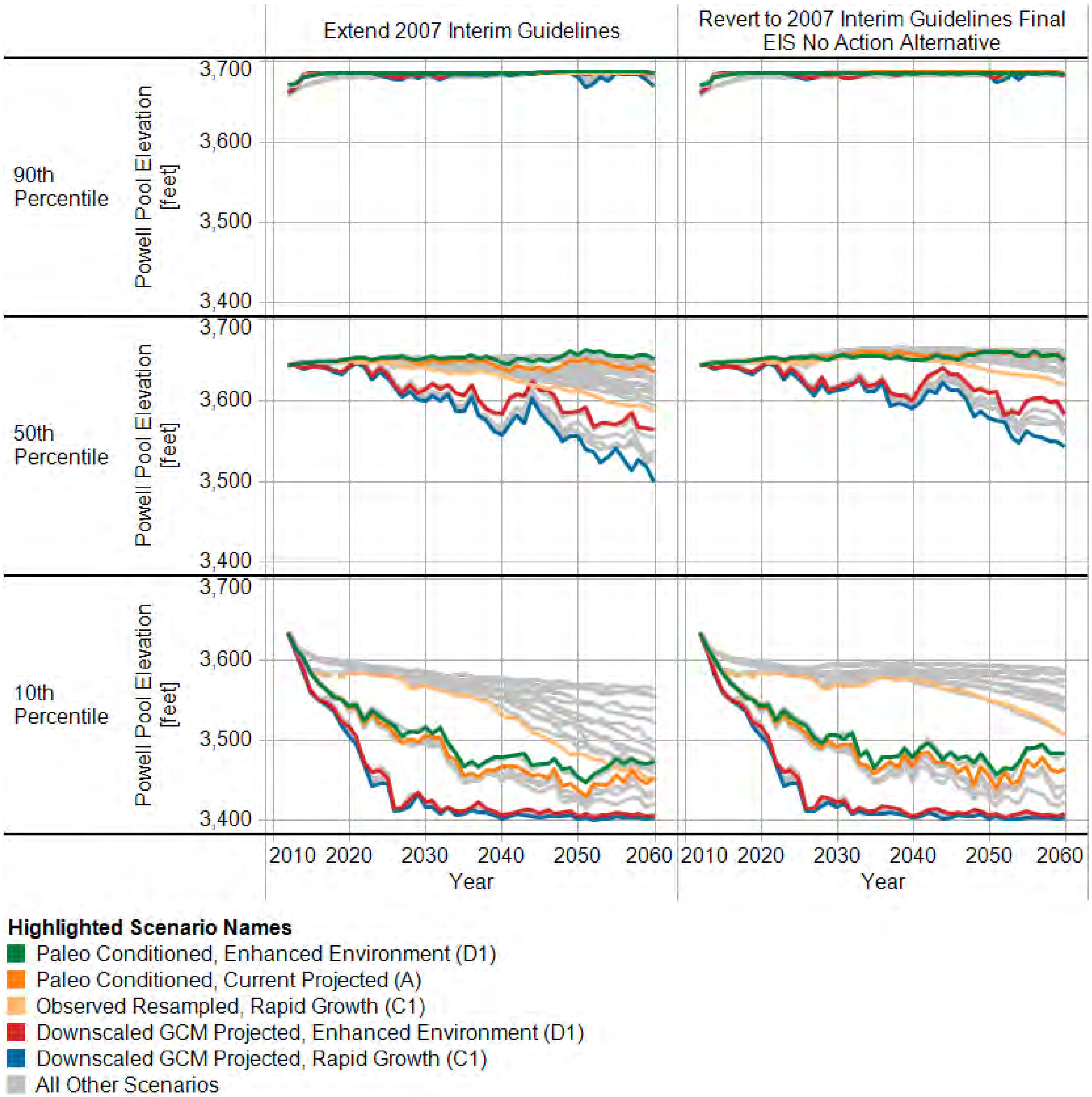
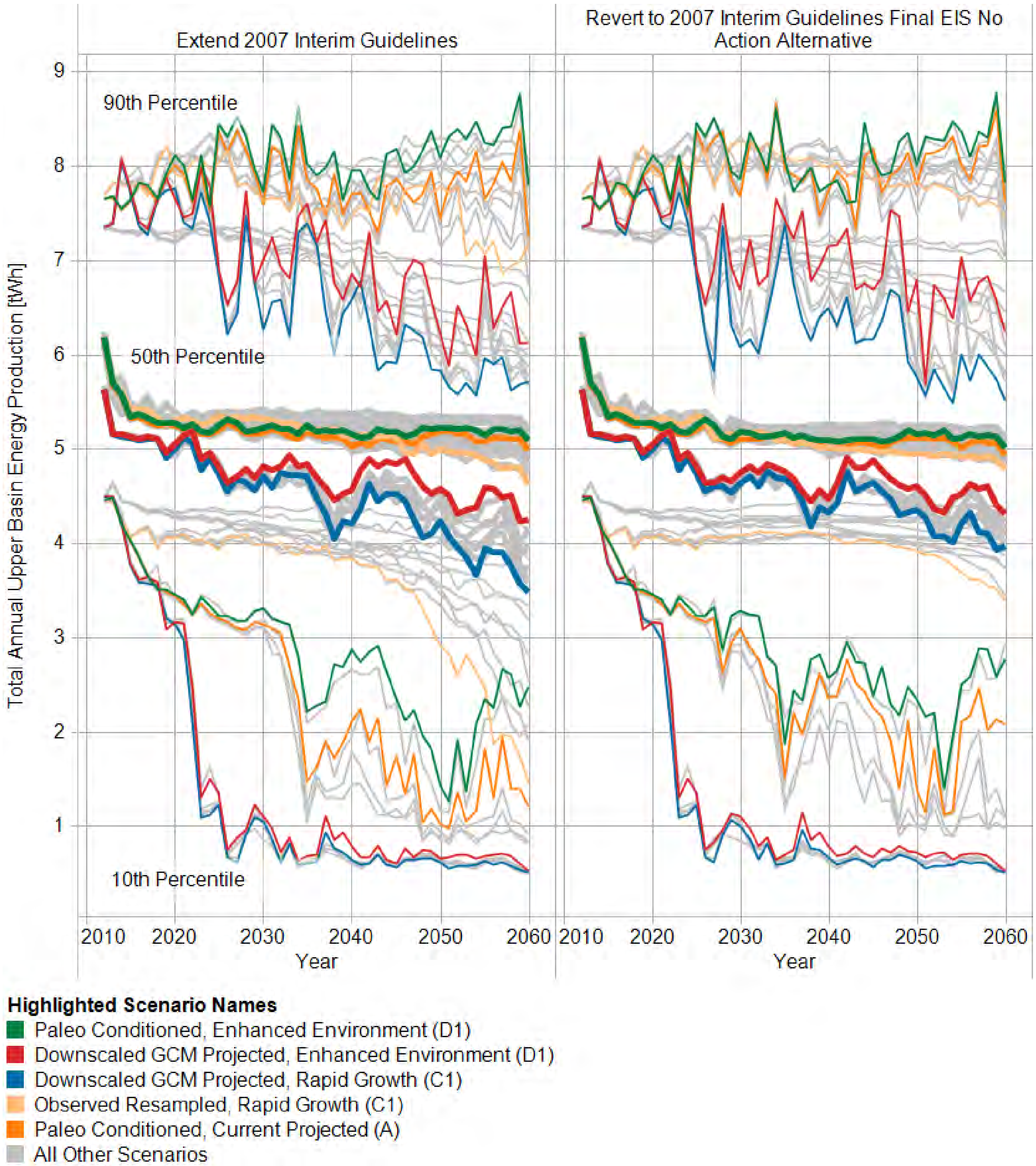


FIGURE G3-7
10th, 50th, 90th Percentiles for Total Upper Basin Energy Production by Scenario, Without Options and Strategies



terawatt hour (tWh)

FIGURE G3-8
Cumulative Density Function for Total Upper Basin Energy Production by Scenario, Without Options and Strategies

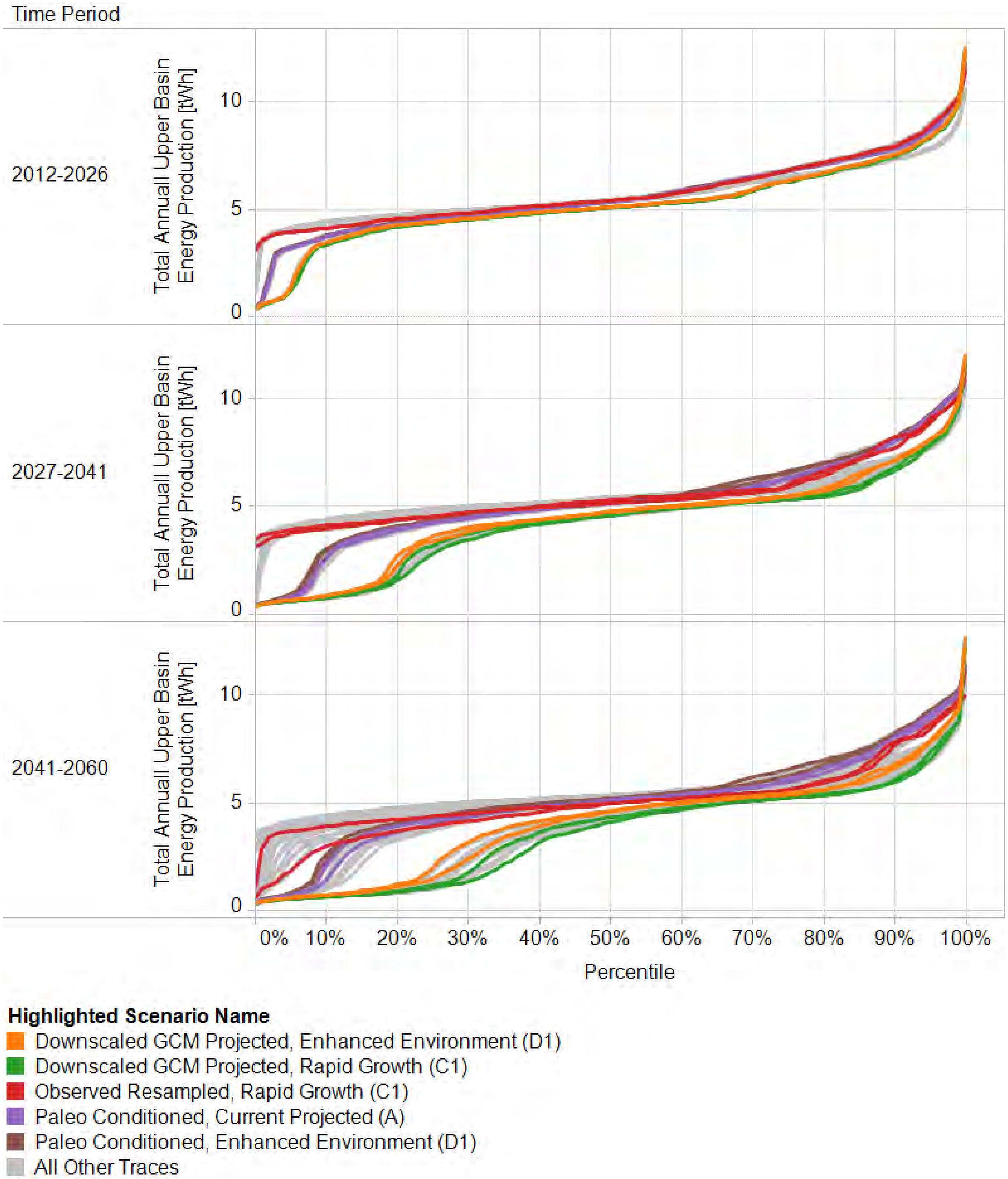


FIGURE G3-9
10th, 50th, 90th percentiles for Lake Powell Water Year Release by Scenario, Without Options and Strategies

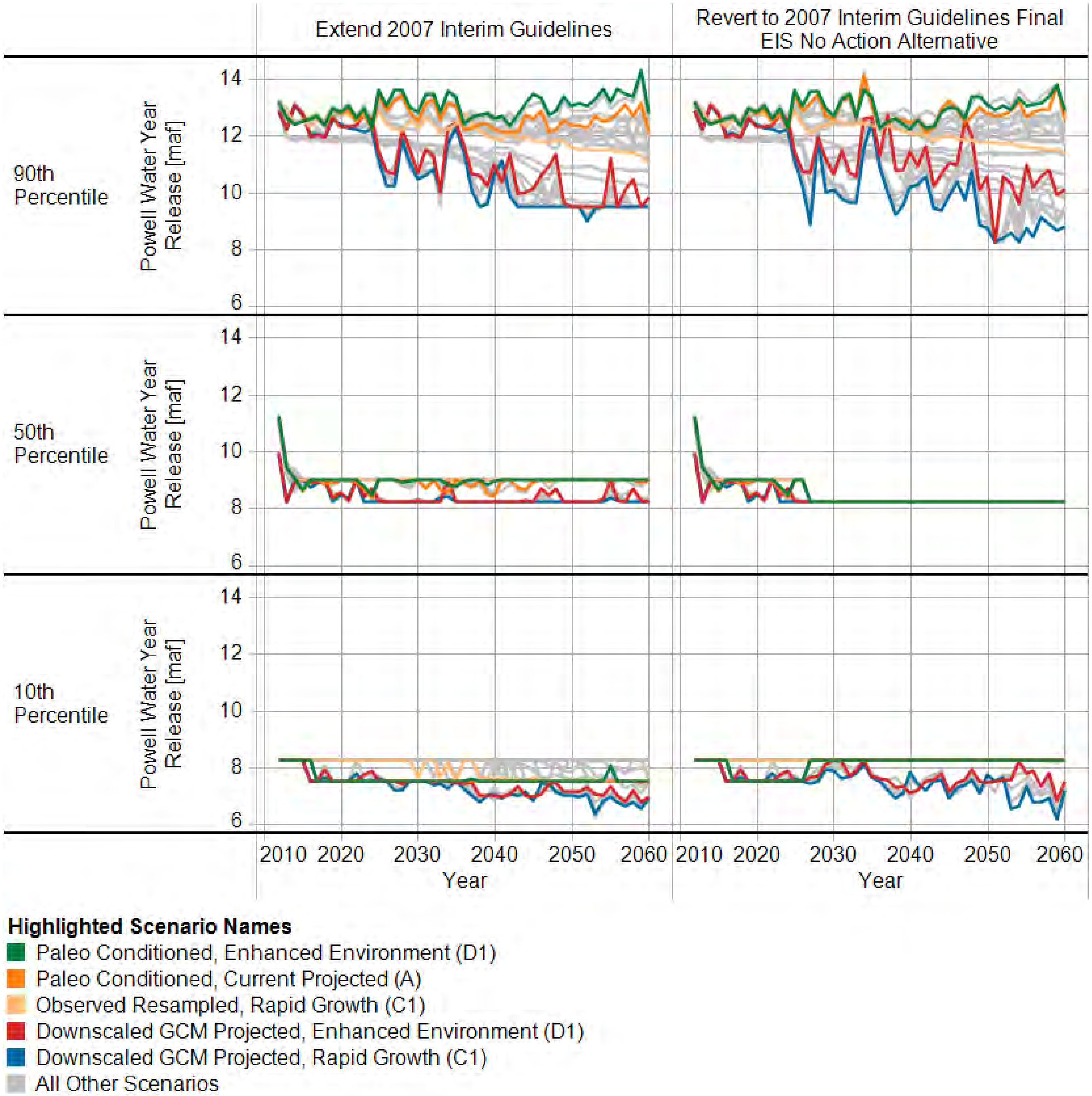


FIGURE G3-10
Percent Traces and 10th, 50th, and 90th Percentiles for Lee Ferry Deficit by Scenario, Without Options and Strategies

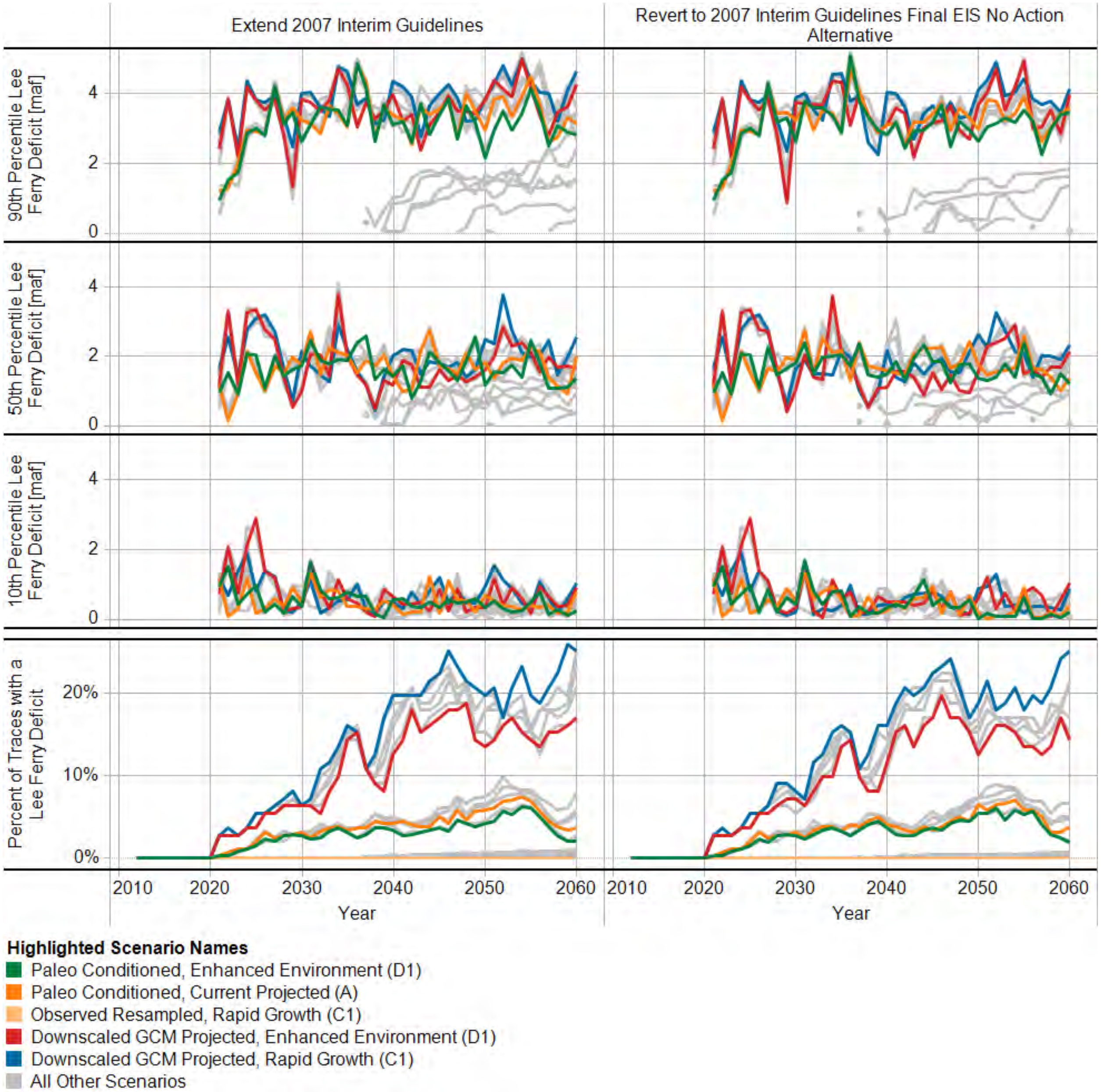


FIGURE G3-11
10th, 50th, 90th Percentiles for Lake Mead Pool Elevation by Scenario, Without Options and Strategies

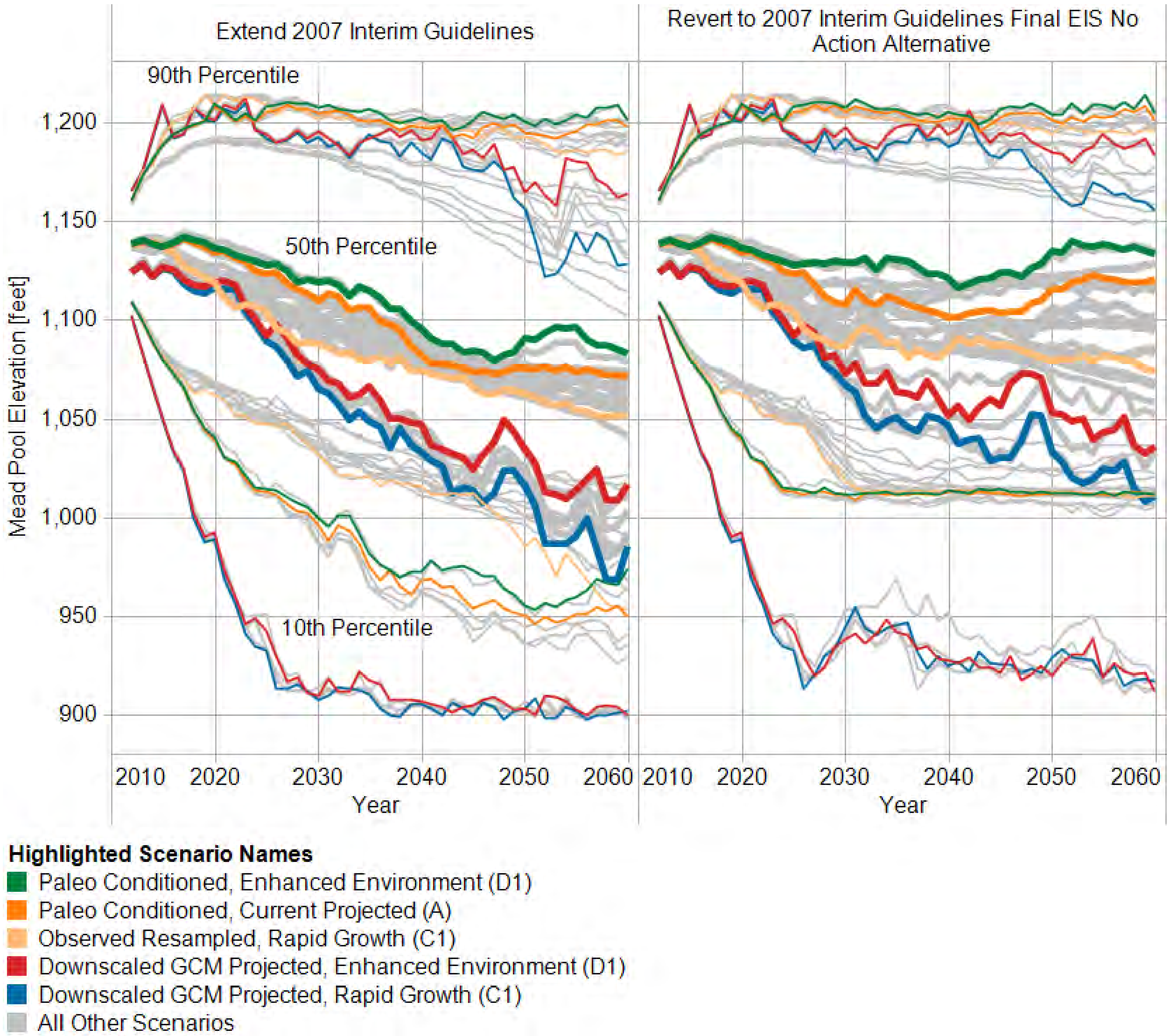


FIGURE G3-12
Percent Traces and 10th, 50th, and 90th Percentiles for Lower Basin Annual Total Shortage (including remaining demands above Lower Division States' basic apportionments) by Scenario, Without Options and Strategies

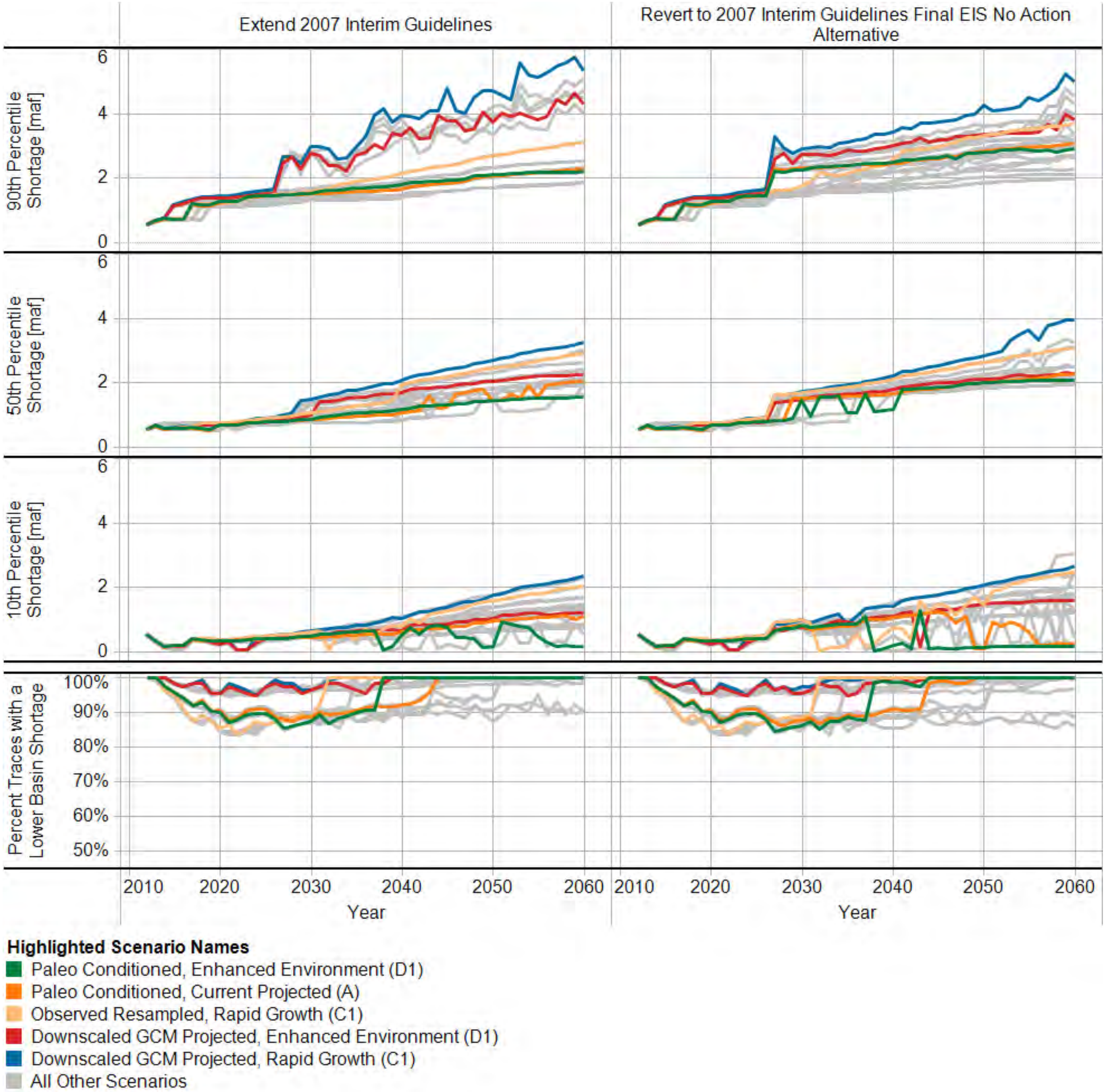


FIGURE G3-13
Percent Traces and 10th, 50th, and 90th Percentiles for Lower Basin Annual Regulatory Shortage by Scenario, Without Options and Strategies

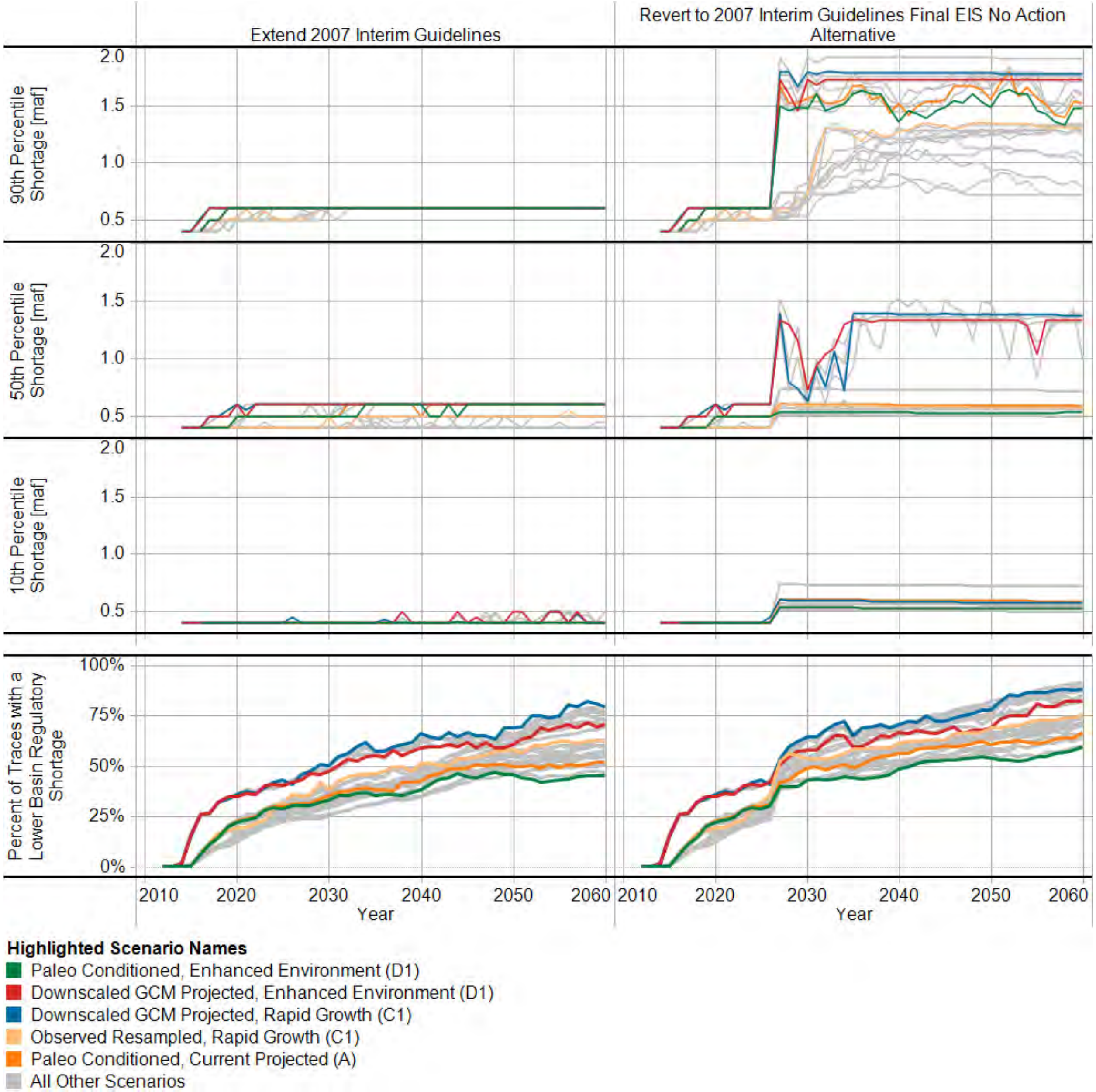


FIGURE G3-14
Percent Traces with a Lower Basin Surplus by Scenario, Without Options and Strategies

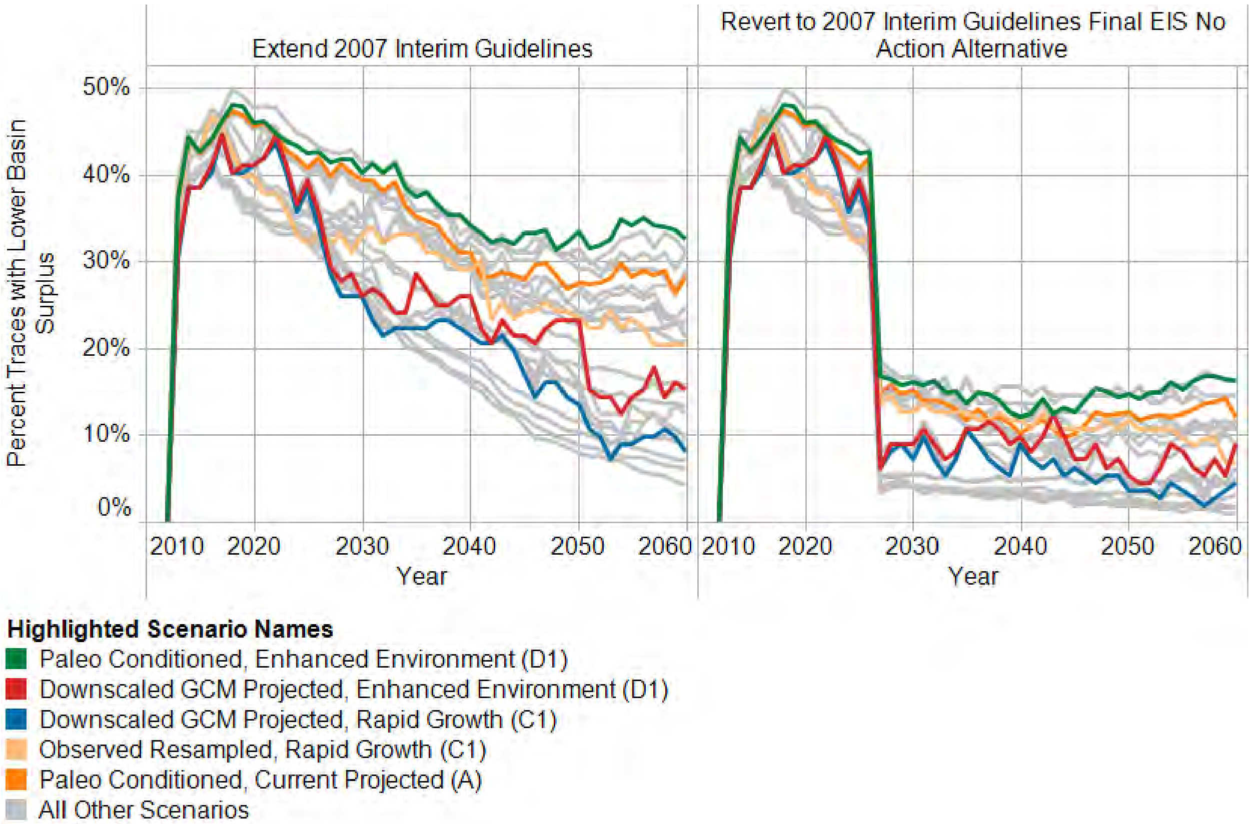


FIGURE G3-15
10th, 50th, 90th Percentiles for Hoover Dam Energy Production by Scenario, Without Options and Strategies

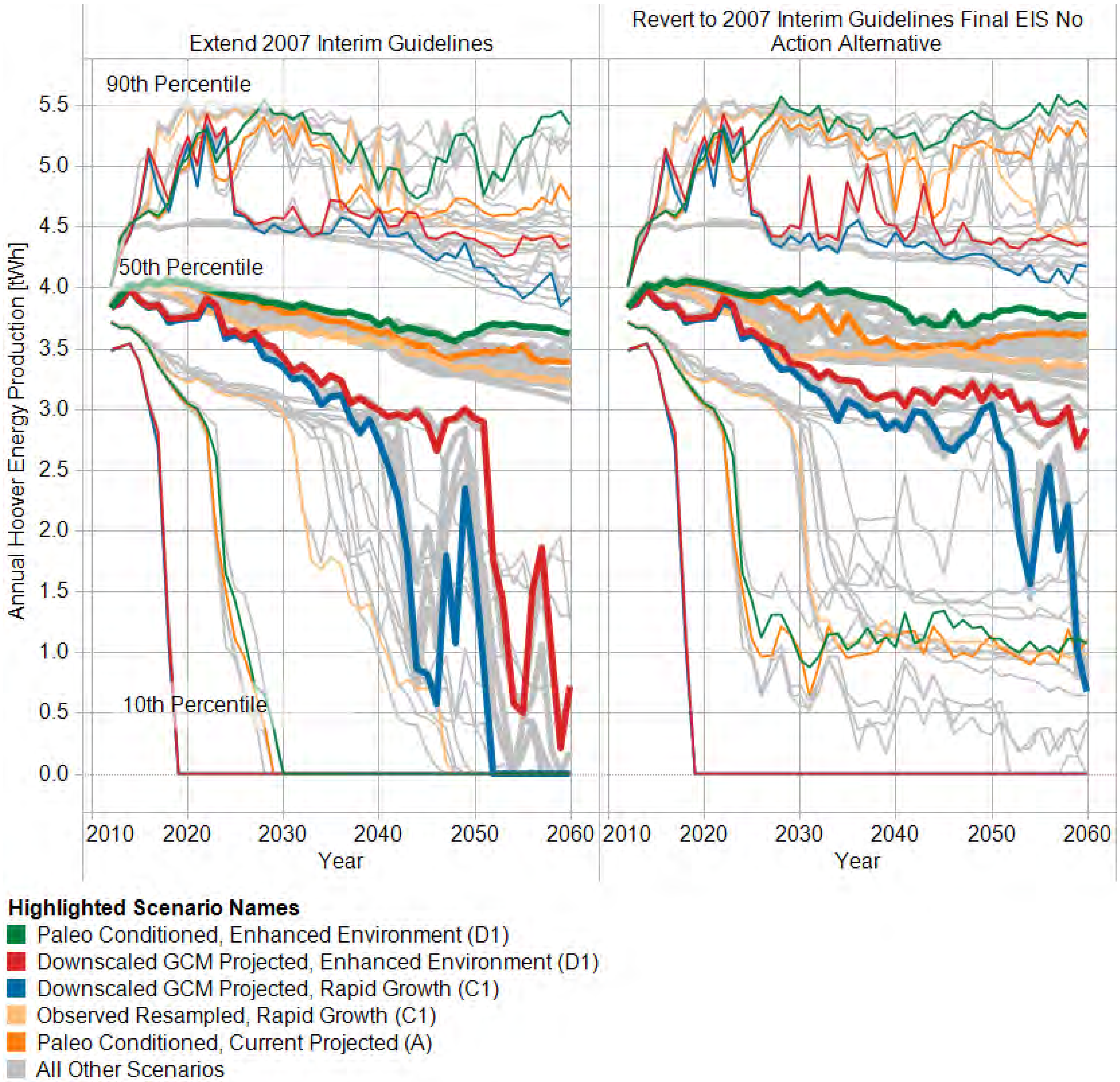


FIGURE G3-16
Cumulative Density Function for Hoover DamEnergy Production by Scenario, Without Options and Strategies

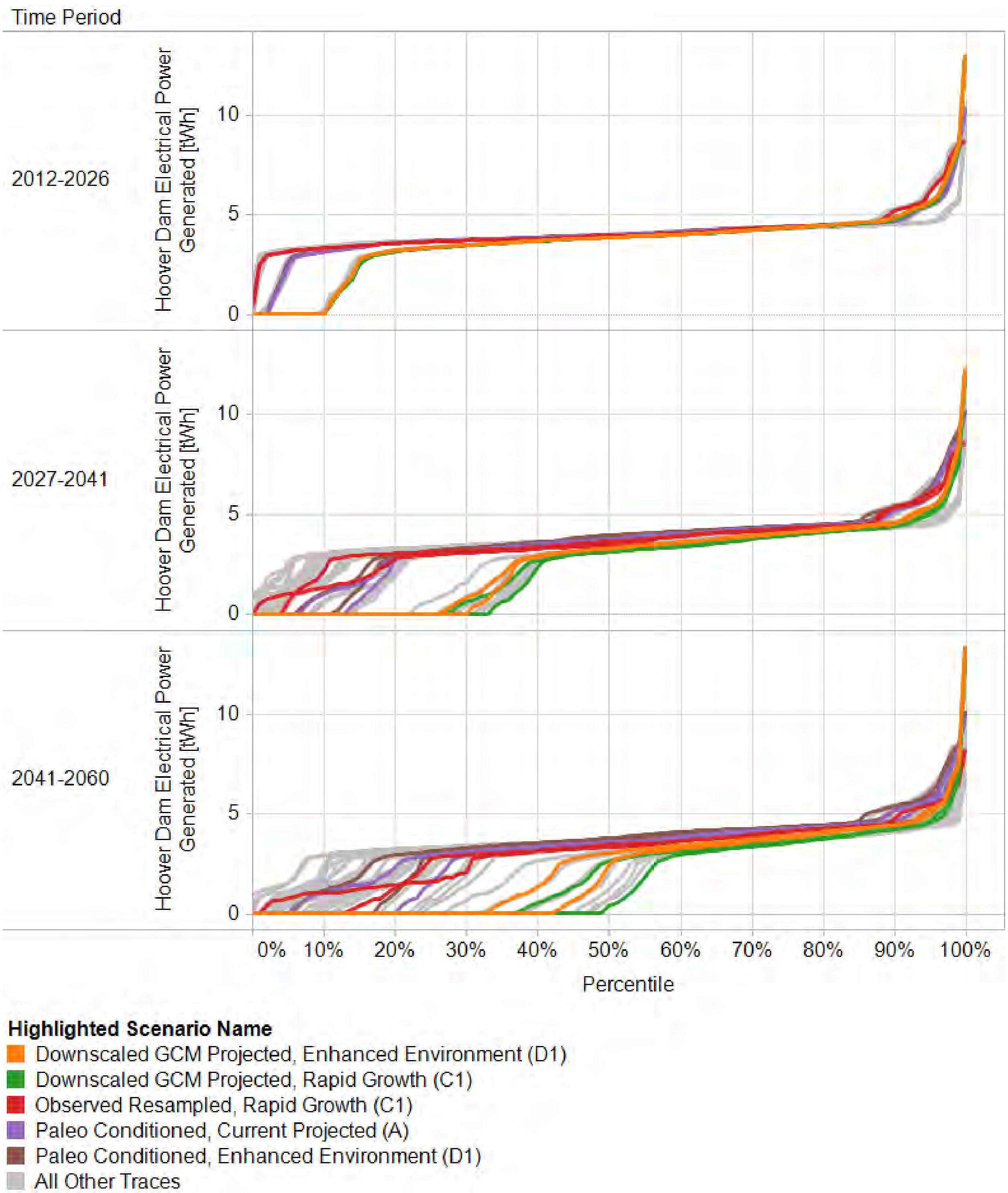


FIGURE G3-17
10th, 50th, 90th Percentiles for Parker Dam and Davis Dam Energy Production by Scenario, Without Options and Strategies

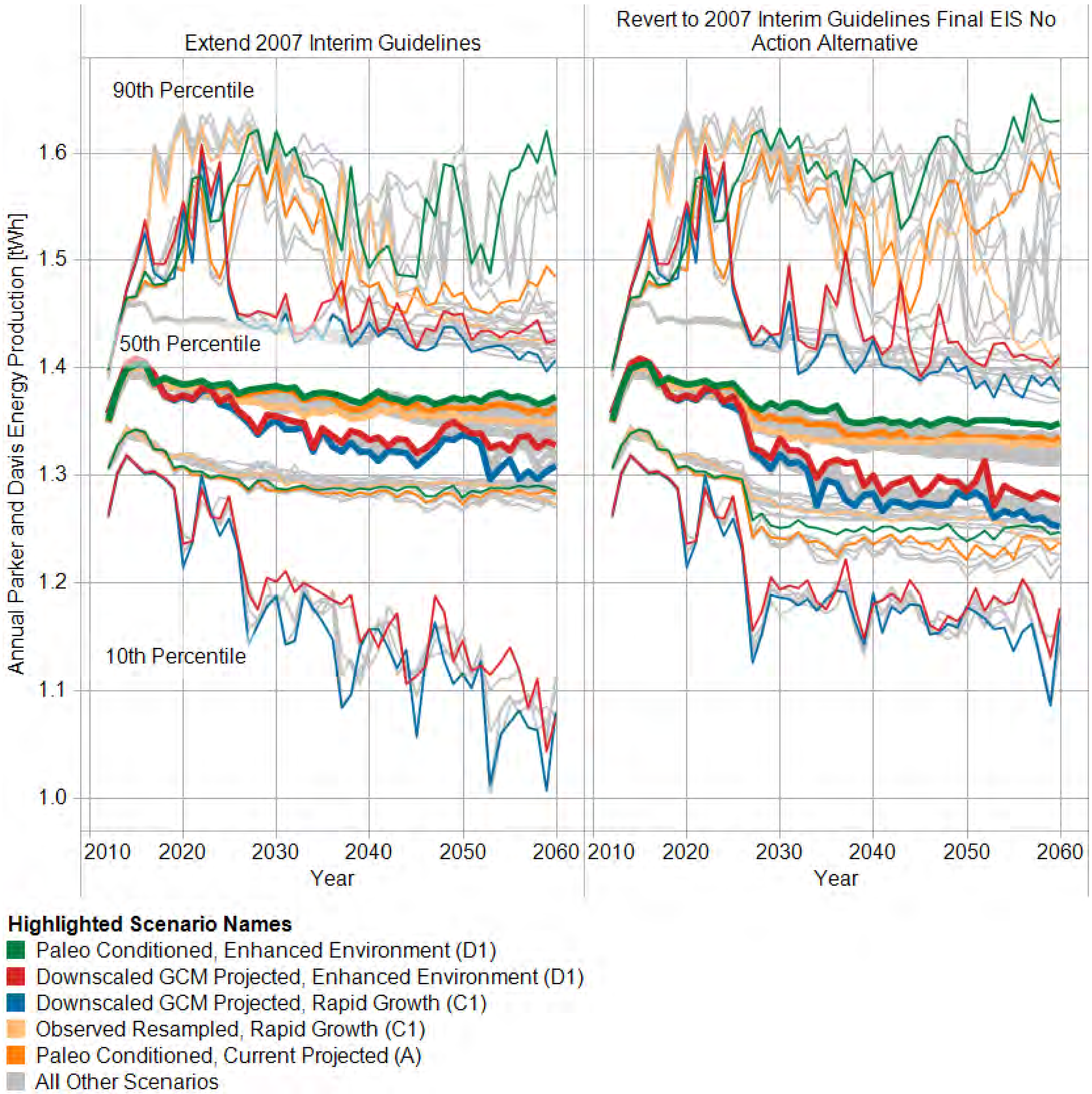
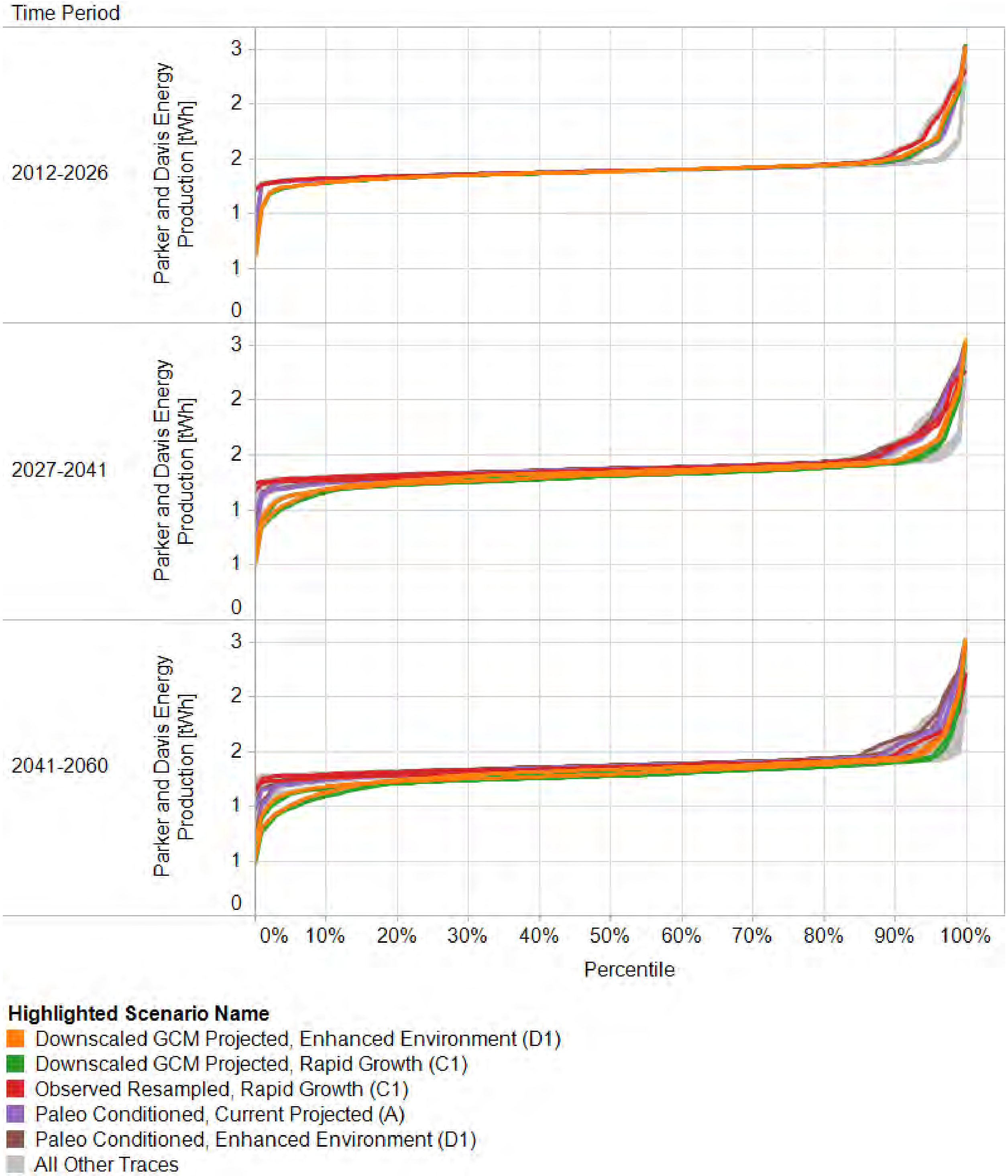


FIGURE G3-18
Cumulative Density Function for Parker Dam and Davis Dam Energy Production by Scenario, Without Options and Strategies



3.0 Defining Vulnerable Outcomes and Vulnerable Conditions

3.1 Vulnerability Definitions

3.1.1 Indicator Metric Vulnerability

This section provides additional information regarding the indicator metric definitions and associated vulnerability thresholds described in *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*. Some of the selected indicator metrics required additional assumptions and/or additional processing in order to generate a suitable indicator for vulnerability. Field and resource experts were consulted in developing vulnerability thresholds and were instrumental in the process. Because vulnerability is unique to each resource/location combination, the thresholds and associated methods varied. Generally, the approach was to capture a condition that would result in a significant degradation for the resource and/or require sizeable capital/infrastructure investment to mitigate. The rationale, assumptions, and methods for these metrics are described below.

Water Delivery

Water delivery indicator metrics were developed with the Modeling Sub-Team. Flow at Lee Ferry was selected as an indicator metric; vulnerability was defined as flow less than an aggregate of 75 million acre-feet (maf) over any 10-year period. Lake Mead's pool elevation was also was selected as an indicator metric. Elevation 1,000 feet above mean sea level (msl) in Lake Mead is important to water deliveries for multiple reasons. This is significant both in terms of deliveries to the Southern Nevada Water Authority and is of importance in the 2007 Interim Guidelines. For these reasons, vulnerability was defined as any month in which pool elevation falls below that threshold.

Delivery shortages are of considerable concern and unique to the various regional water users throughout the Basin.The following indicator metrics were developed to reflect this geographic heterogeneity: (1) Upper Basin shortage as percent of requested depletion, (2) Lower Basin 2-year moving window shortage volume sum, and (3) Lower Basin 5-year moving window shortage volume sum. Drawing from expertise of the Modeling Sub-Team, respective vulnerabilities were selected to be (1) annual shortage volume greater than 25 percent of requested depletion, (2) cumulative shortage volume exceeding 1 maf in any 2-year window, and (3) cumulative shortage volume exceeding 1.5 maf in any 5-year window. From *Technical Report C – Water Demand Assessment*, demand exists for Colorado River water in excess of Lower Divison States' basic apportionments. Because this is a considerable portion of the overall Lower Division States' demand in several scenarios, annual demand above Lower Division States' basic apportionment was also selected as a water delivery indicator metric. Vulnerability for this indicator was developed based on estimated sustainability of existing and identified future supplies that could be used to meet those demands. Through this effort, it was decided that, for the period of 2012 to 2035, demand above Lower Division States' basic apportionment up to 1 maf would not indicate a vulnerability, but exceeding this threshold would indicate a vulnerability. For the period 2035 to 2060, the non-vulnerable demand above Lower Division States' basic apportionment decreased linearly from 1 maf to 0.25 maf, reflecting reduced availability of other supplies. As was the case for the first period, any year in which the demand above Lower Division States' basic apportionment exceeded its corresponding threshold value was deemed vulnerable.

Electric Power

Electric power indicator metrics and associated vulnerabilities were developed with guidance from Western Area Power Administration. Based on key facilities, power markets and contracts, three indicator metrics were developed. Owing to the relationship between head and generation capacity, two of the indicator metrics are pool elevation at Lakes Powell and Mead. The third indicator developed was annual aggregate Upper Basin generation (defined as the sum of Blue Mesa, Morrow Point, Crystal, Flaming Gorge, Fontenelle, and Glen Canyon). For the Lake Powell indicator metric, vulnerability was defined as pool elevation below power pool in any month (pool elevation less than 3,490 feet msl. For Lake Mead, vulnerability was defined as pool elevation below 1,050 feet msl, which is the turbine rough water threshold. For the Upper Basin aggregated indicator metric, vulnerability was defined as 3 consecutive years with generation less than 4,450 gigawatt-hours (GWh) per year. This threshold was developed by Western Area Power Administration, taking into consideration its power contracts in markets served by Upper Basin facilities and its capacity to secure supplemental power from other sources.

Flood Control

The flood control indicator metric was selected to be Hoover Dam release. Because substantial downstream infrastructure and agriculture are close to the river and floodplain, this area has potential for considerable damages should the safe channel capacity (28,000 cubic feet per second [cfs]) be exceeded (Bureau of Reclamation [Reclamation], 2000). Given the aforementioned consequences of flow exceeding the critical river stage, vulnerability was defined as any month in which the Hoover Dam release violates that threshold.

Recreation

Recreation indictor metrics were developed for (1) shoreline public use facilities and (2) river and whitewater boating. Metrics pertaining to shoreline public use facilities were developed in conjunction with appropriate federal and state management agencies. The thresholds are pool elevations that would necessitate relocation or infrastructure work (e.g., siltation removal or boat ramp extension) to maintain viability of major shoreline public use facilities during the high-use season. Because reservoir conditions vary considerably across the Upper Basin, locations in the three major tributaries (Green, Upper Colorado, and San Juan basins) were selected in addition to Lakes Powell and Mead.

For the Green River Basin, pool elevation at Flaming Gorge Reservoir during May to September served as the indicator of shoreline public facilities in that region. The resource is deemed vulnerable when pool elevation drops below 6,019 feet msl during that period. According to *Operation of Flaming Gorge Dam Final Environmental Impact Statement* (Reclamation, 2005), over 75 percent of visitation occurs from May to September. Further, in appendix 4 of the aforementioned Flaming Gorge Final Environmental Impact Statement, the low-end threshold for most recreation was identified as a pool elevation of 6,017 feet msl; the vulnerability threshold selection was informed by this, but ultimately chosen to be slightly higher (6,019 feet msl) to reflect the point at which the first major boat ramp would no longer be useable.

In the Upper Colorado Basin, the largest reservoir is Blue Mesa on the Gunnison River. From the *Aspinall Unit Operations Final Environmental Impact Statement* (Reclamation, 2012), the peak visitation season is very similar to that of Flaming Gorge, making the indicator metric May to September pool elevation. Through discussions with the National Park Service at Curecanti National Recreation Area, the vulnerability threshold was chosen to be 7,440 feet msl; this is the current minimum elevation at which Lake Fork Marina/boat ramp can operate (Stahlnecker, 2012). The Lake Fork Marina/boat ramp would be the first of the three major public use facilities at Blue Mesa to be significantly impacted by declining reservoir levels.

Navajo Reservoir is the major shoreline recreation destination in the San Juan Basin. As described in the 2006 *Navajo Reservoir Operations Final Environmental Impact Statement* (Reclamation, 2006), the recreation season generally extends from April to October. As such, the San Juan Basin Shoreline Public Use Facility indicator metric is Navajo pool elevation during that period. One of the three major marina/boat ramp facilities at the reservoir, Two Rivers Marina near Arboles, Colorado, was constructed with a concrete boat ramp serviceable to pool elevations as low as 5,978 feet msl (Reclamation, 2006). However, over the years, due to shifts in the main river channel and substantial siltation, considerable work would be required to maintain usability below 6,025 feet. Therefore, the vulnerability threshold for this indictor metric is pool elevation below 6,025 feet msl; other Navajo shoreline public use facilities still provide recreation access at this elevation. The selection was guided by discussion with Colorado State Park staff at Navajo State Park in Arboles (Secrist, 2012) Further; this is supported by the New Mexico State Park description of boating at elevations below 6,030 feet msl as being in the lowest-quality tier.[1]

Lake Powell receives considerable year-round visitation; however, like the other Upper Basin reservoirs, the majority of recreational use occurs during the summer months—approximately 75 percent during the May-to-September window—sothe indicator metric for Lake Powell is pool elevation during that period. The majority of shoreline public use facilities are currently serviceable to pool elevations as low as 3,560 feet msl; below that point, additional infrastructure would be required to maintain most public boat ramps. Further, all major marinas would face sizeable challenges to maintain operation below a pool elevation of 3,555 feet msl (Reclamation, 2000). Therefore, the vulnerability threshold is defined as pool elevation below 3,560 feet msl.

Recreation at Lake Mead occurs year-round; therefore, the indicator metric is pool elevation in all months. Over the past decade, due to declining lake levels some shoreline public use facilities have been relocated or closed. Given the economic reliance of surrounding communities on shoreline access-centric industry, selecting a vulnerability threshold for the entire resource is particularly tenuous. From discussions with the National Park Service, the majority of shoreline public use facilities offering lake access and recreation in 2012 have capacity to operate to a pool elevation of 1,080 feet msl; many facilities have plans to enable operation at lower levels. However, a considerable portion of these strategies require non-trivial infrastructure investment (e.g., moving marinas or extending boat ramps). Owing to the prospect of significant restructuring to maintain recreation opportunities commensurate with current access below 1,080 feet msl, this was chosen as the vulnerability threshold (Turner, 2012).

Metrics pertaining to river and whitewater boating estimate the number of days per month with flows that are below acceptable, acceptable low, optimal, acceptable high and above acceptable for supporting river boating recreation (see *Technical Report D – System Reliability Metrics, Appendix D2 – Boating Flow Days Metrics*). From these results, two indicator metrics were

[1] Available at: http://www.emnrd.state.nm.us/SPD/BOATINGWeb/NavajoLake.html.

developed for each major Upper Basin tributary (Green, Colorado, and San Juan rivers). The first deals exclusively with optimal boating flow days and the second captures total boating flow days (sum of acceptable low, optimal, and acceptable high days). In both cases, the indicator metric aggregates across all metric locations within a particular basin to give, for example, total optimal boating flow days in the Green River Basin. As was the case with the shoreline public facility use attribute of interest, each of the three regions captured by boating flow days indicator metrics have peak seasons. In the Green River Basin, based on a review of commercially offered boating activities and the *Operation of Flaming Gorge Dam Final Environmental Impact Statement* (Reclamation, 2005), the key months were found to be May to September. For the Colorado mainstem, a similar review of commercially scheduled trips indicated the same peak season. The San Juan River, due to its more southerly location, has a slightly longer river recreation season; March to October, confirmed by the *Navajo Reservoir Operations Final Environmental Impact Statement* (Reclamation, 2006) and commercial trip offerings. Therefore, for each sub-basin, a peak season aggregation of optimal and total boating flow days was produced, offering a condensed view of the monthly five flow tiers at eight locations across the Upper Basin.

Working with representatives from American Whitewater, a framework for indicator metric vulnerability threshold criteria was developed. The foundation of this concept is that boating recreation would become vulnerable if the future number of boating flow days deviates substantially from historical levels. Unfortunately, boating flow days computed from gage data are not appropriate for comparison with model projected future conditions due to model biases and reservoir construction or reoperation over time. To capture the spirit of estimating historical levels of boating flow days, a modeling control run was proposed. For the control run, the Study model, CRSS, was run with the historical Observed Resampled supply scenario and demands static at the 2015 Current Projected (A) scenario levels. The result of this run is an approximation of historical boating flow days, driven by observed hydrologic variability and present-day demands, which lends itself to comparison with future projected conditions. Due to considerable inter-annual hydrologic variability in the Basin, simulation results from the control run were compared with future projected conditions based on 10-year running averages. In the case of the total boating flow days indicator metrics, vulnerability was defined as a future period for which the 10-year average boating flow days is below the control run minimum 10-year average. For the optimal boating flow days indicator metric, vulnerability was defined as a future period for which the 10-year average falls below the 10th percentile of the respective control run results. The optimal boating flow days vulnerability threshold is more rigorous, compared with the total boating flow days threshold, because optimal flow days afford the most recreation opportunities and therefore have the greatest value.

Ecological

A wide range of ecological metrics were developed and discussed in *Technical Report D – System Reliability Metrics*. Due to the number and complexity of these metrics, it was not feasible to develop an indicator metric that encompasses several locations within a particular region. As a result, a single metric was selected as an indicator for four regions in the Upper Basin: Yampa, Colorado mainstem, Green, and San Juan. The locations selected tend to be more downstream in their respective regions to offer some aggregation of upstream conditions. Further descriptions of these metrics and the development of vulnerability thresholds follows in the sections below.

For the Yampa River near Maybell, the flows to support threatened and endangered species calls for maintaining a baseflow of 120 cfs at all times (U.S. Fish and Wildlife Service, 2008). Similar to earlier discussion regarding recreation, comparing a flow recommendation derived from gage data with model-simulated flows may not always be appropriate. Further, the development of an ecologically based vulnerability threshold is beyond the scope of the Study, so the control run comparison approach for establishing vulnerability was employed. In this control run, modeled Yampa River flow near Maybell was first checked against the 120 cfs to identify years in which the recommendation was violated. Following, for each trace, a running percent of years with a violation was computed (i.e., if the first year in a trace violated the recommendation but years two and three did not, the percent of years with a violation would be 100 percent in year one, 50 percent in year two and 33 percent in year three). From these data, the annual maxima of percent violation across all control run traces were selected, thereby defining a time series threshold for permissible frequency of flow recommendation violations. The same percent of years with a violation statistic was computed for each model projected future trace. If the value in a given year exceeded the threshold derived from the control run, it was deemed vulnerable.

For the Green and Colorado rivers, the flow recommendations are more complex. At those sites, flow recommendations are monthly and tied to year type categories (Reclamation, 2005; McAda, 2003). For example, during a dry year type, lower flows are targeted while higher flows are prescribed for average or wet years. Further, there is a target distribution for the year types. For the purpose of developing indicator metrics, these were distilled into three components: (1) year type distribution, (2) April to July peak flow compliance, and (3) September baseflow compliance. For the same reasons discussed above, the control run approach was employed for these locations in developing indicator metric vulnerability thresholds. Changing monthly and seasonal flow recommendations and year type distribution targets made this more complicated than the Yampa modeling, but the concept of quantifying some permissible frequency of non-compliance remains the same. The procedure described below examines each of the aforementioned flow recommendation components individually, and should any one of the three components perform worse than observed in the control run, the year is deemed vulnerable.

The target year-type distribution specifies the percent of years that should be classified in each category. Using the control run results, the year-type distribution variability was first quantified to establish a unit-less measure of deviation from the target distribution. For each year, the percent of years falling into each category up to that year were computed. These values were then compared with the target percentages and summarized by taking the sum of the absolute differences. The following is an example calculation for a hypothetical target distribution that specified three year types and equal occurrence frequency (i.e., 0.33 for each). Consider the tenth year of a trace; at this point, 2 years have been classified as wet; 3 years have been average; and 5 years have been dry. The corresponding frequencies would be 0.20, 0.30, and 0.50, with the respective absolute differences being 0.13, 0.03, and 0.17, and the index (sum of absolute differences) would be 0.33. As the trace evolves over time, with more values contributing to the distribution, the expectation is that the percentages converge toward the targets and the index values become smaller and smaller. With this completed for all traces in the control run, the annual maxima were computed, establishing a maximum permissible deviation from the target distribution time series. The index computation was performed for all model projected future traces, and any year that exceeded the threshold derived from the control run was deemed vulnerable.

The success of meeting flow recommendations associated with each year type was quantified in a similar manner to the distribution of year types. As mentioned earlier, the two aspects of the flow recommendations examined were the peak flow period (April through July) and the September baseflow. For each year in the control run results, the number of years falling into each year type category were computed, as was done for the target distribution. Next, the peak flow and September baseflow values for each year were analyzed to assess which year-type flow was actually seen in each of those years. The result is two lists – one of year types that should have been met and a second of the year type flows that were actually met. Subsequently, for each year in those two lists, the percent of years up to that point in each classification was calculated. The average of the absolute differences (by percent of year types, actual versus classified) was computed as a unitless measure of flow recommendation non-compliance. With this completed for all traces in the control run, the annual maxima were computed, thus establishing a maximum permissible flow recommendation non-compliance time series for peak and September flows. The index computation was performed for all model projected future traces with regard to both peak and September flow recommendations, and any year that exceeded either threshold derived from the control run was deemed vulnerable.

The flow recommendation to benefit threatened and endangered species on the San Juan near Bluff, Utah, is similar to those previously discussed; it has peak and base flow targets, in addition to year-type frequencies (Reclamation, 2006). However, the flow targets are not tied to year-type classification; instead the four tiers of flow magnitude-duration combinations are given occurrence frequencies and maximum intervals between occurrence. The baseflow recommendation is static and applies for each month. Hence, three aspects were also identified for this site: (1) baseflow compliance, (2) frequency of magnitude-duration, and (3) tiers interval between tier occurrence. Using the control run results, thresholds for each of these were developed. The baseflow component was evaluated in the same manner as was done for the Yampa baseflow prescription. Flow tier frequency compliance was analogous to the Green/Colorado target distribution calculation. The unique aspect of the Bluff recommendation was the maximum interval between tier occurrence. This index was developed by first computing the compliance for each tier; a year within the permissible interval was flagged as compliant, and each year exceeding the permissible interval was flagged as in violation. The result for each trace was four time series of violation/compliance. To summarize a single trace, for each year, the average number of violations across all tiers up to that point was computed. Last, as was done for all of the previously described indices, for each year, the annual maxima across all control run traces was computed, giving a maximum permissible interval violation. These indices were computed for all model projected future traces, and any year that exceeded one of the thresholds derived from the control run was deemed vulnerable.

Water Quality

In order to comply with the Clean Water Act, the Colorado River Basin Salinity Control Forum develops numeric salinity criteria below Hoover and Parker Dams and at Imperial Dam. The water quality indicator metric was selected to be the numeric salinity criterion below Parker Dam. Parker Dam was chosen because of the three locations on the lower Colorado River where annual salinity criteria have been established, the Parker Dam location has historically shown the highest damages resulting from salinity (e.g., early replacement of household water heaters, reduced agricultural production). Average annual salinity concentrations and salt loads were determined on a flow-weighted basis. The flow-weighted average annual salinity concentration is calculated by dividing the flow-weighted average annual salt load passing a measuring station by the total annual volume of water passing the same point during a calendar year. The flow-weighted average annual salt load is calculated by first multiplying the daily salinity concentration values by the daily flow rates. These values are then summed over a calendar year. The total annual volume of water is calculated by calculating the sum of the daily flow rate. Below Parker Dam the numeric salinity criteria is 747 milligrams per liter.

Exceedance of the flow-weight average annual salinity criteria defines vulnerability. Unlike other resource categories, salinity vulnerably can only be defined for a given year across traces or a specified time period (e.g., 2012 through 2026) and not for an individual trace. At Parker Dam, if 50 percent of the traces in any one year for a given period (e.g., 2012 through 2026) exceeds 747 milligrams per liter, the period was vulnerable.

3.1.2 Vulnerability Results Without Options and Strategies

Technnical Report G provides vulnerability results without options and strategies, summarized across all scenarios, for all indicator metrics. These results are broken out by scenario and described in further detail in figures G3-19 through G3-70. Each figure shows the simulation results for one indicator metric, with each point representing the median result from one scenario. The figures are disaggregated by time period, supply scenario (columns), demand scenario (symbols), and whether the *Record of Decision for Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (2007 Interim Guidelines) (U.S. Department of Interior [DOI], 2007) are extended after 2026 (colors). For sites above Lake Powell, post 2026 reservoir operations do not impact results. As such, there will be no difference between results for the extend 2007 Interim Guidelines (DOI, 2007) and revert to the No Action Alternative options presented in the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead Final Environmental Impact Statement* (2007 Interim Guidelines Final EIS) (Reclamation, 2007). For each supply scenario subset (column), the gray region shows range and the black bar the scenario median.

FIGURE G3-19
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Upper Basin Shortage Indicator Metric (exceeds 25% of requested depletion in any 1 year)

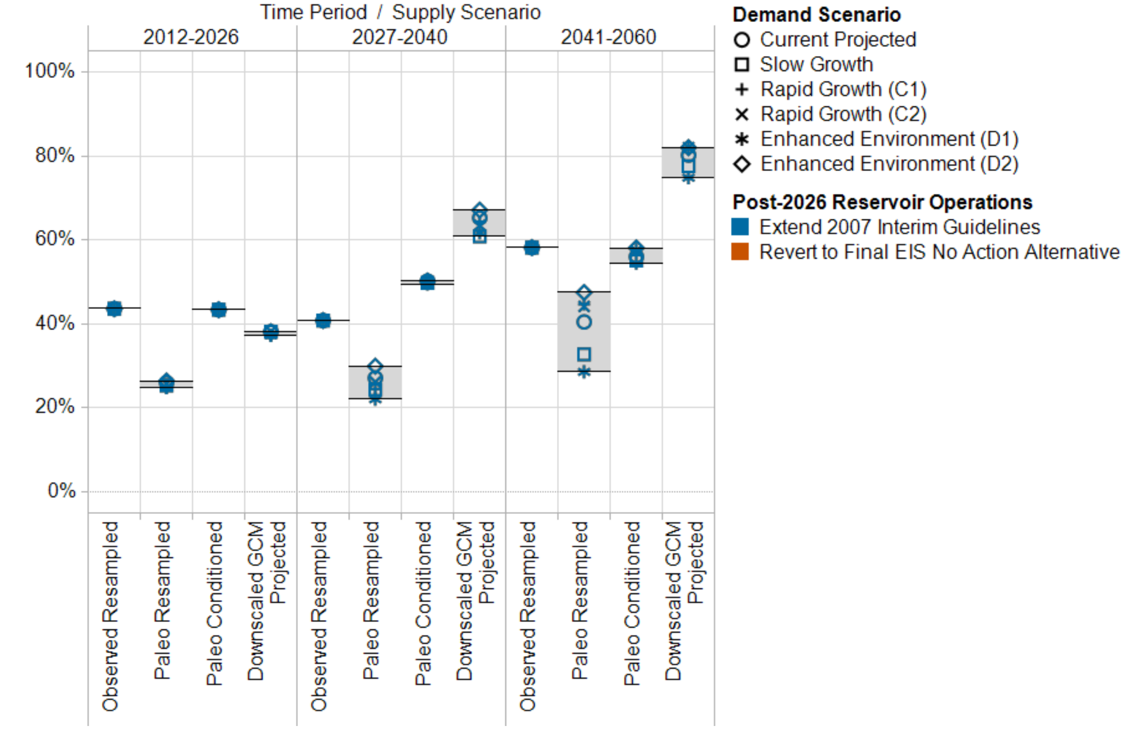


FIGURE G3-20
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Upper Basin Shortage Indicator Metric (exceeds 25% of requested depletion in any 1 year)

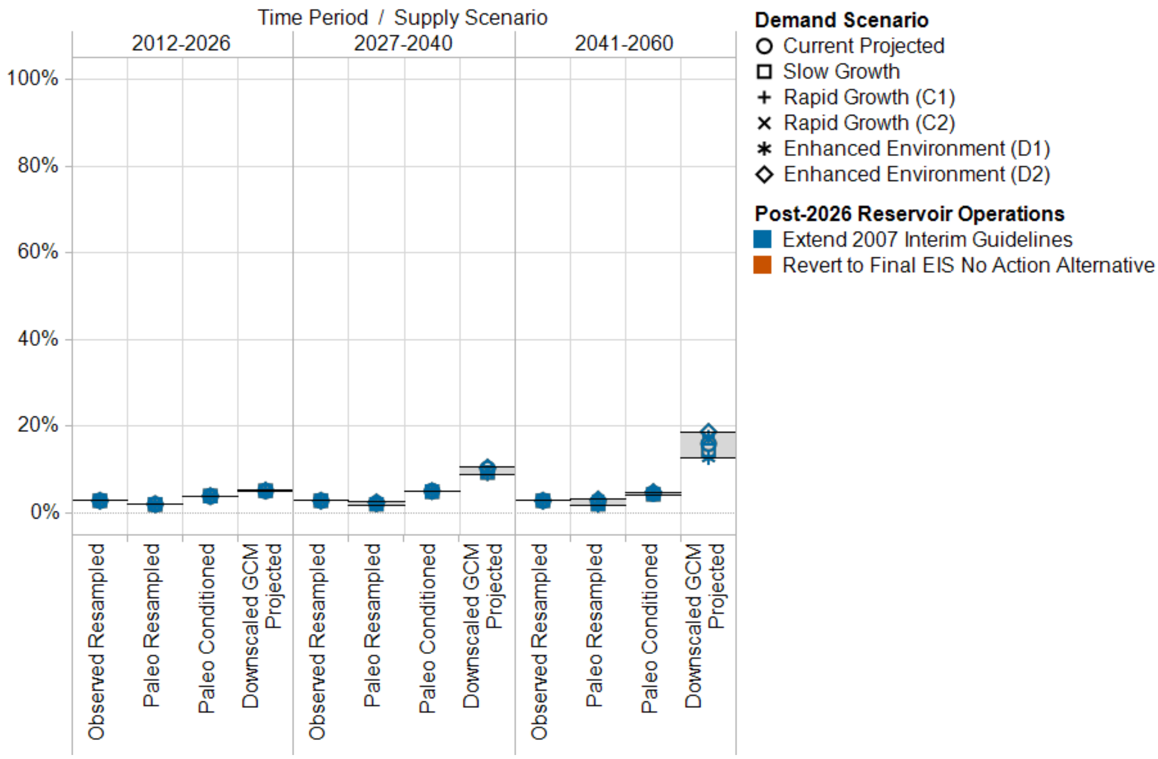


FIGURE G3-21
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Lee Ferry Deficit Indicator Metric (exceeds zero in any 1 year)

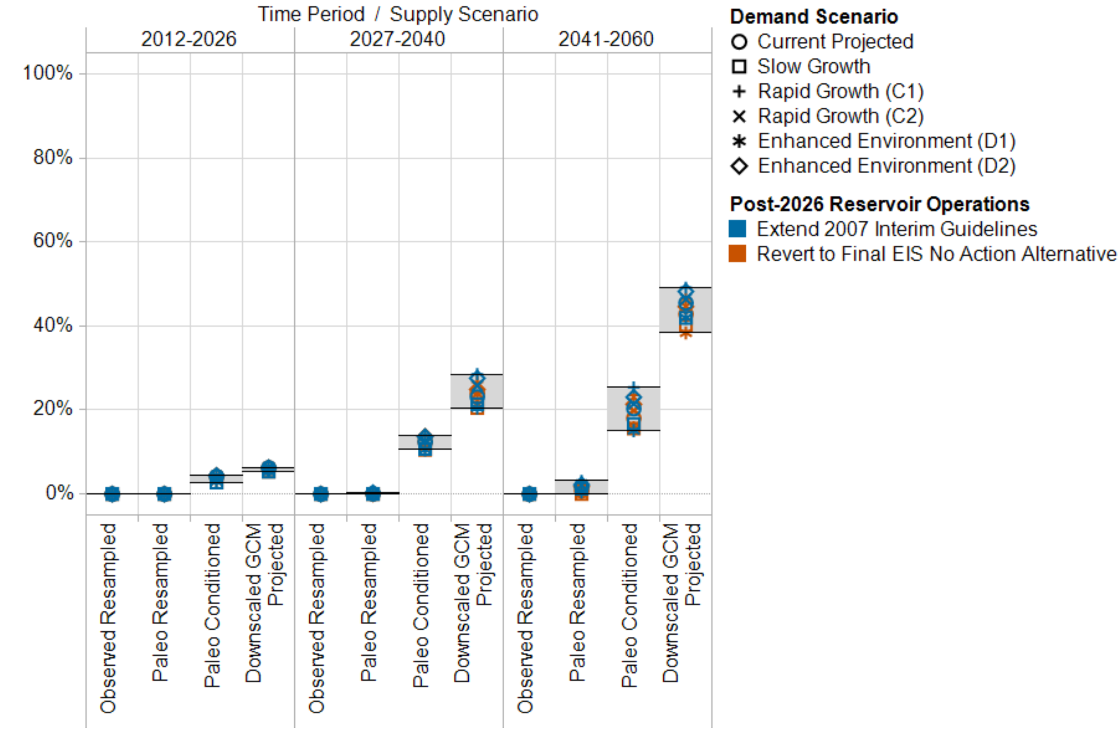


FIGURE G3-22
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Lee Ferry Deficit Indicator Metric (exceeds zero in any 1 year)

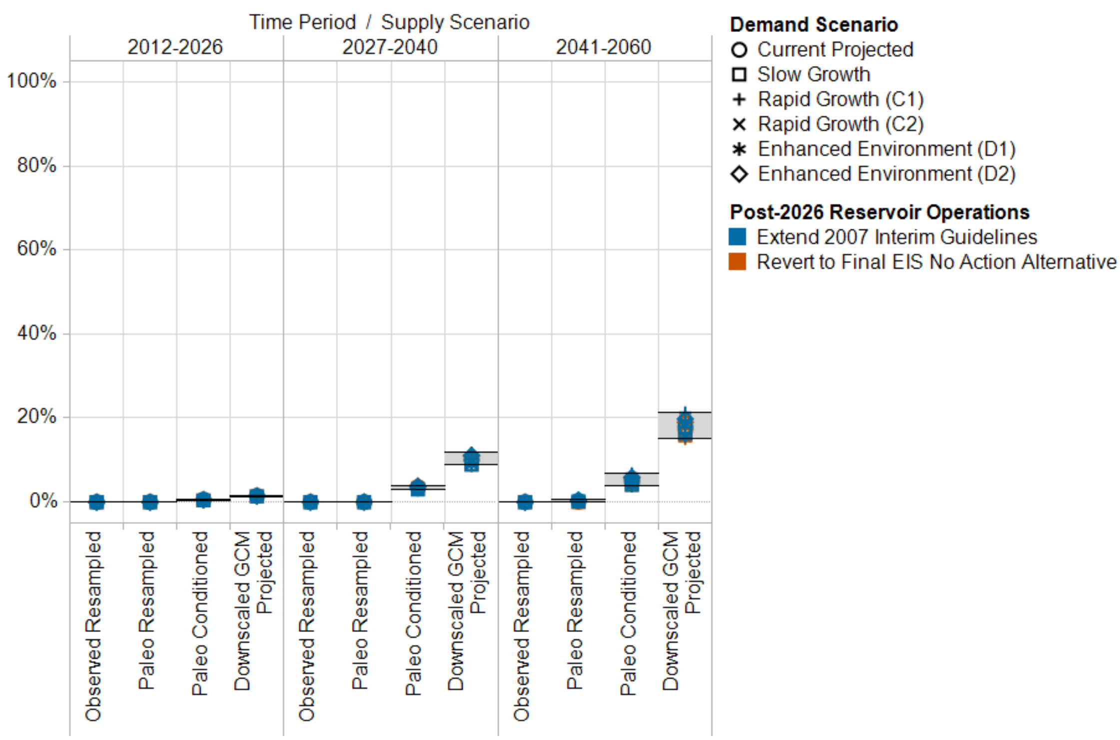


FIGURE G3-23
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Lake Mead Pool Elevation <1,000 feet msl Indicator Metric (below 1,000 feet msl in any 1 month)

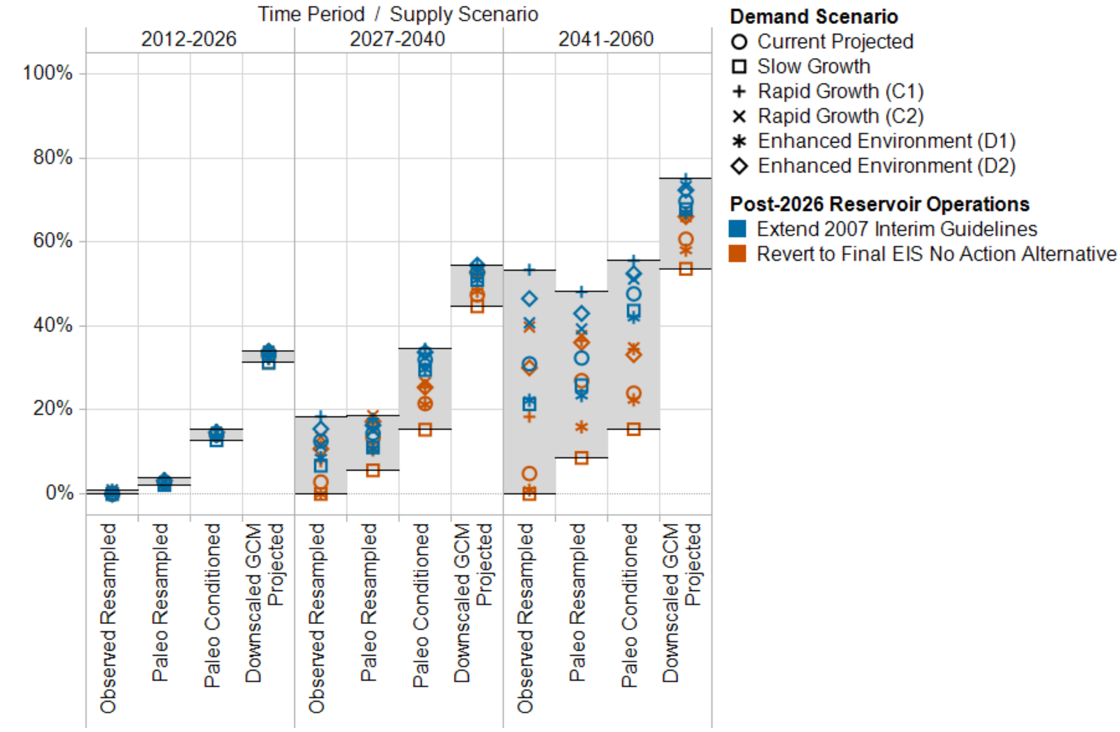


FIGURE G3-24
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Lake Mead Pool Elevation <1,000 feet msl Indicator Metric (below 1,000 feet msl in any 1 month)

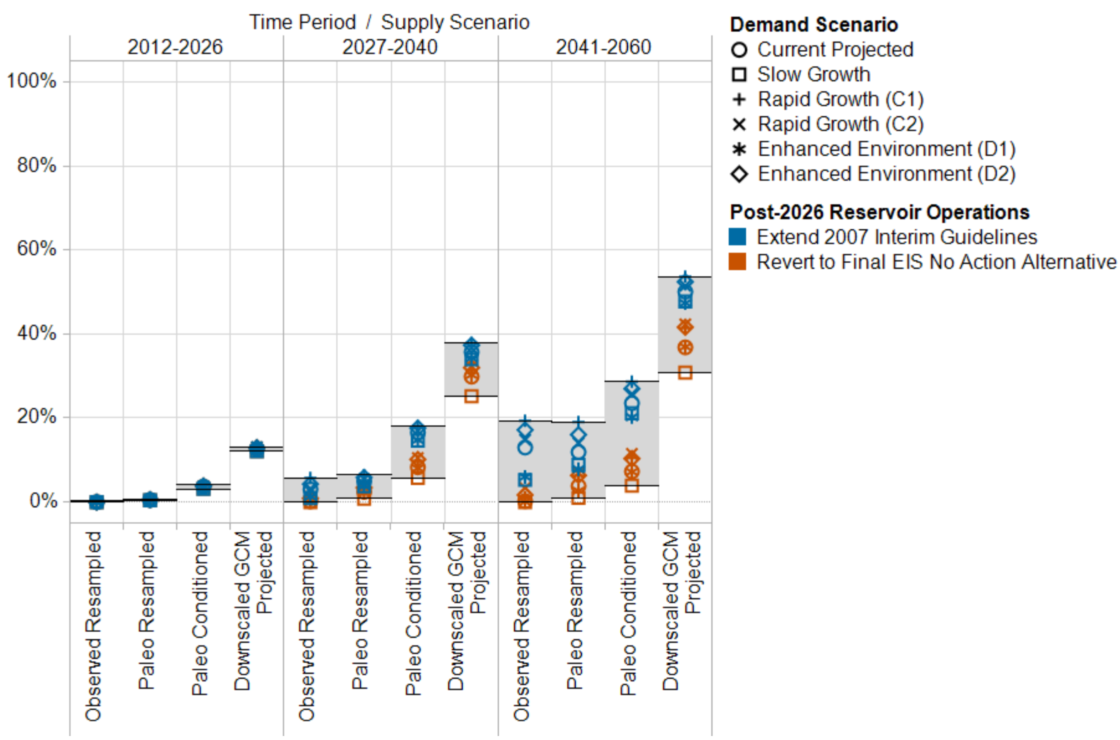


FIGURE G3-25
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Lower Bain Shortage Indicator Metric (exceeds 1 maf over any 2-year window)

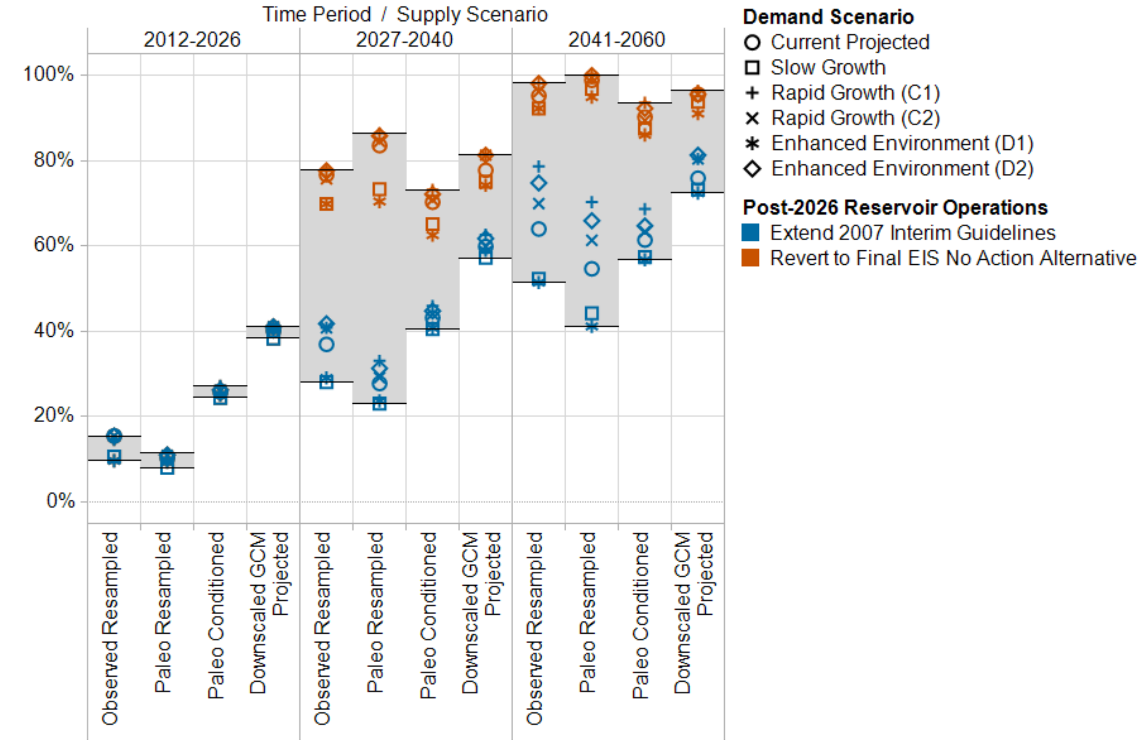


FIGURE G3-26
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Lower Basin Shortage Indicator Metric (exceeds 1 maf over any 2-year window)

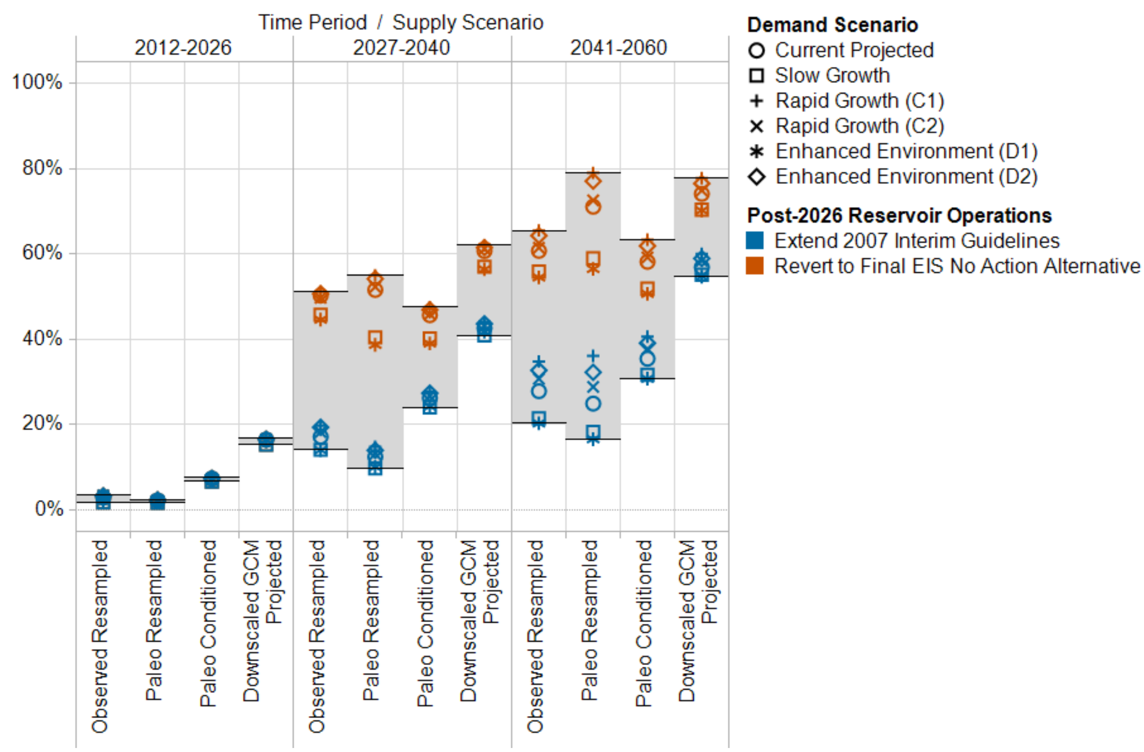


FIGURE G3-27
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Lower Bain Shortage Indicator Metric (exceeds 1.5 maf over any 5-year window)

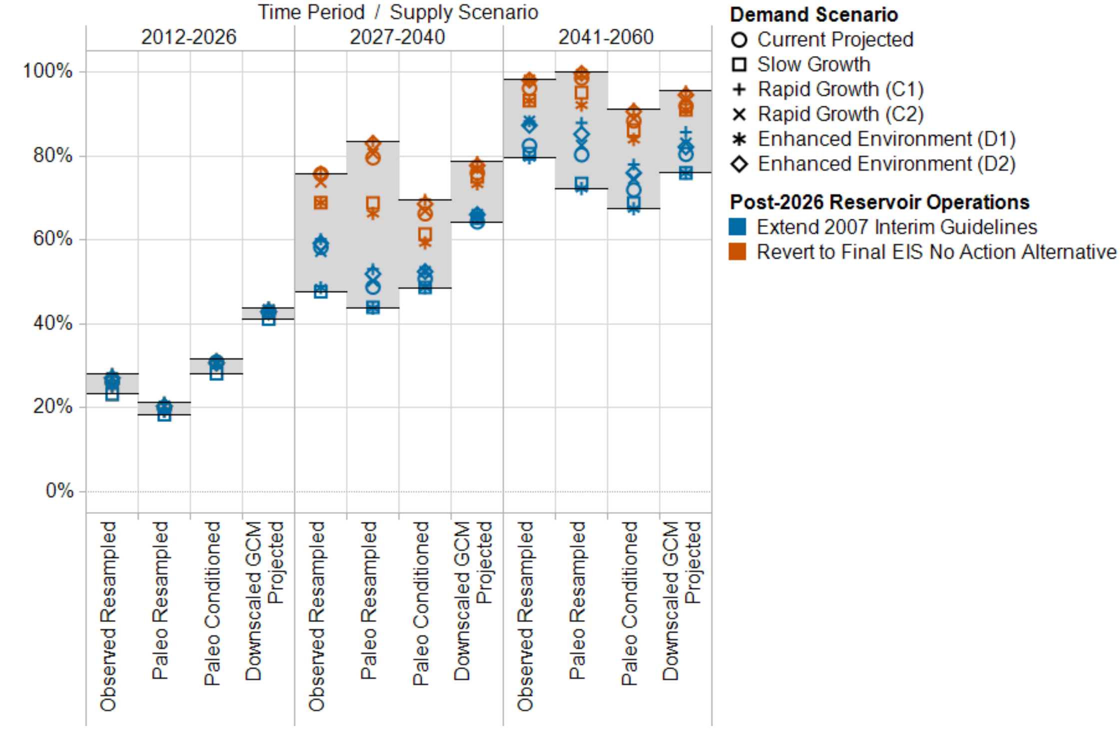


FIGURE G3-28
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Lower Basin Shortage Indicator Metric (exceeds 1.5 maf over any 5-year window)

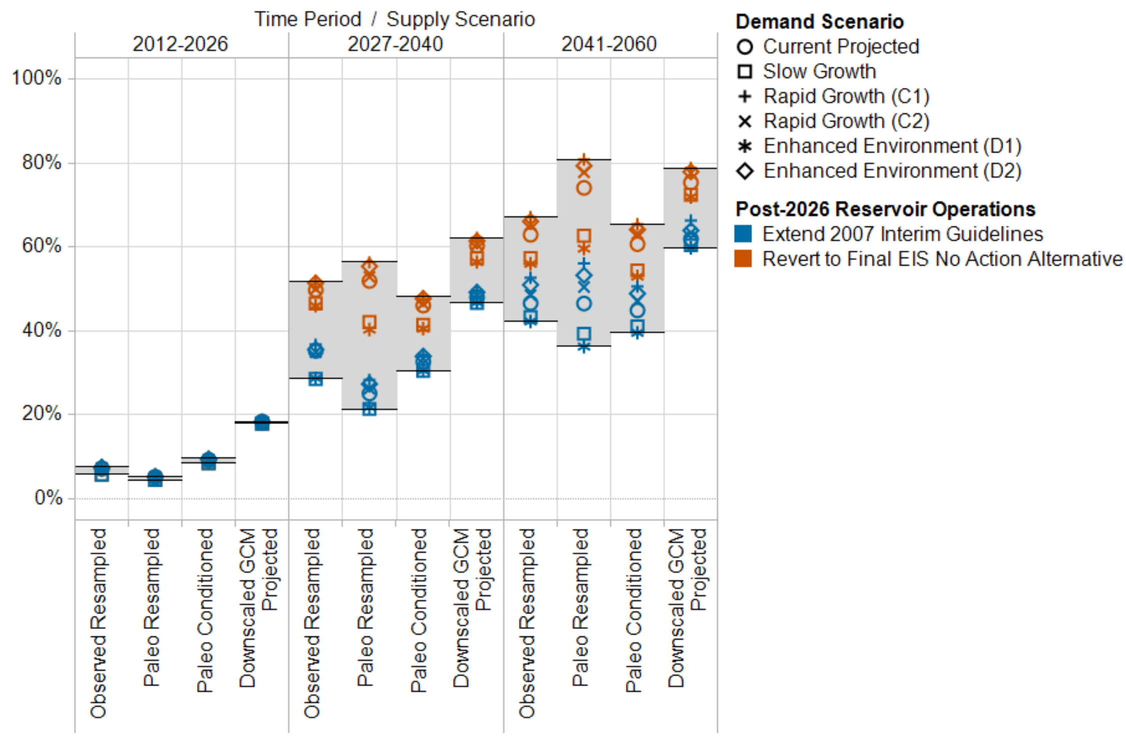


FIGURE G3-29
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Remaining Demand Above Lower Division States' Basic Apportionment Indicator Metric (exceeds moving threshold in any one year)

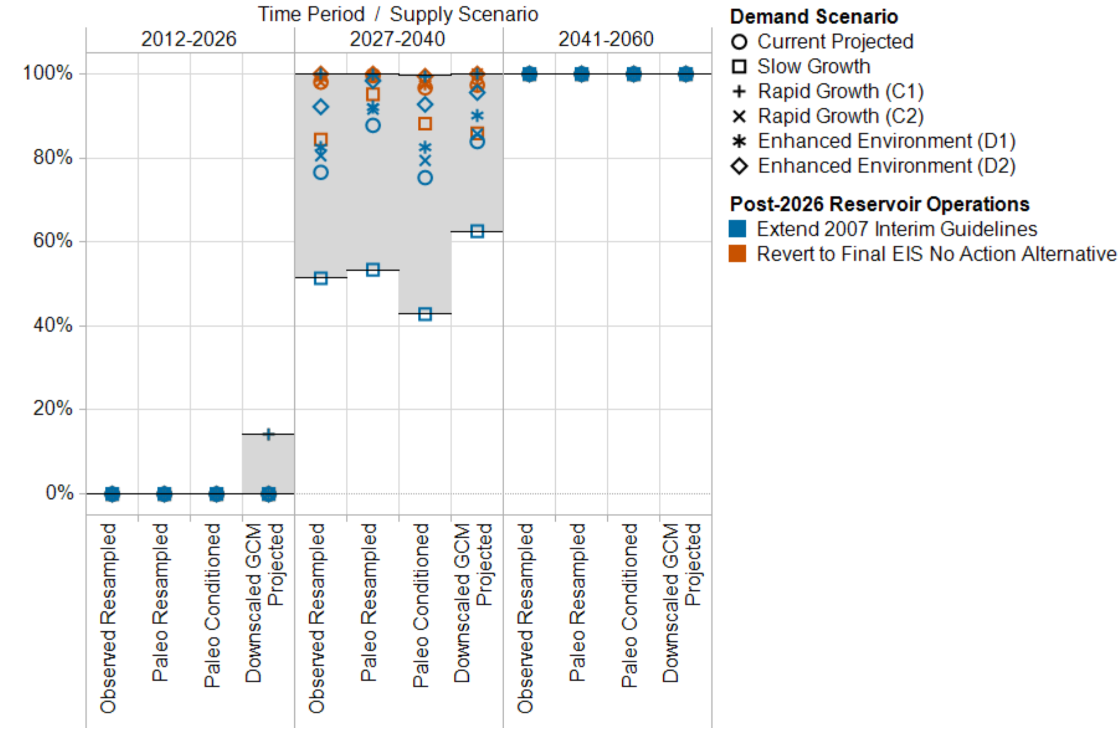


FIGURE G3-30
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Remaining Demand Above Lower Division States' Basic Apportionment Indicator Metric (exceeds moving threshold in any one year)

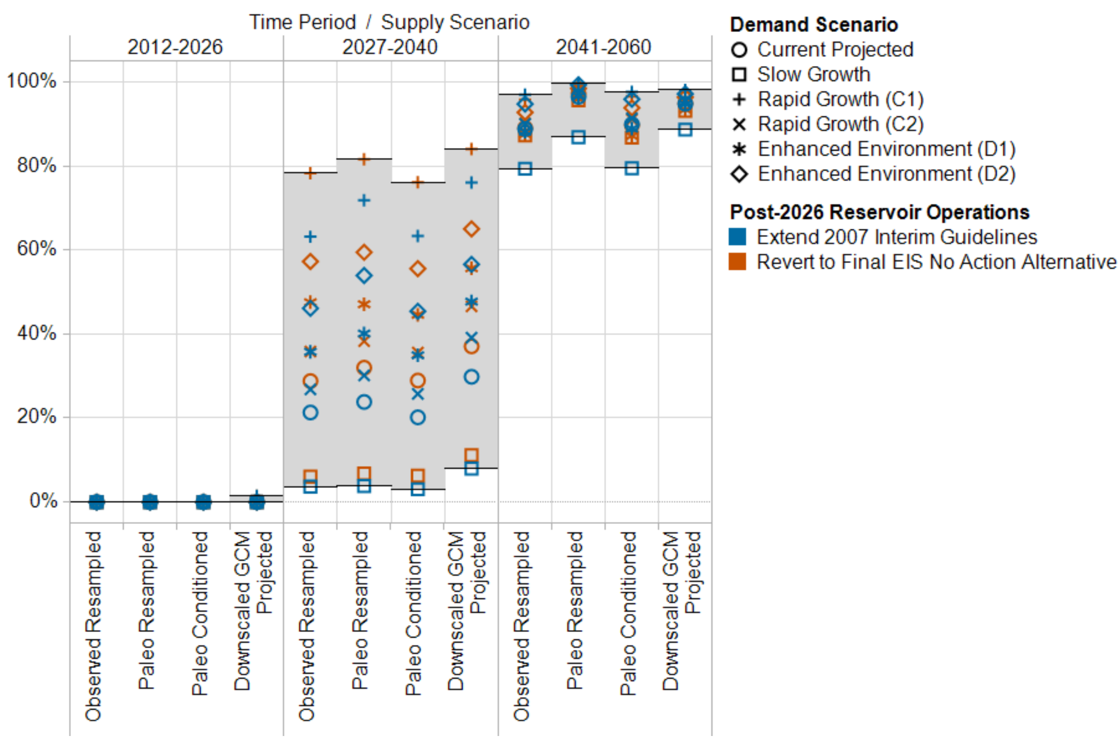


FIGURE G3-31
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Lake Powell Pool Elevation < 3,490 Indicator Metric (below power pool of 3,490 feet in any 1 month)

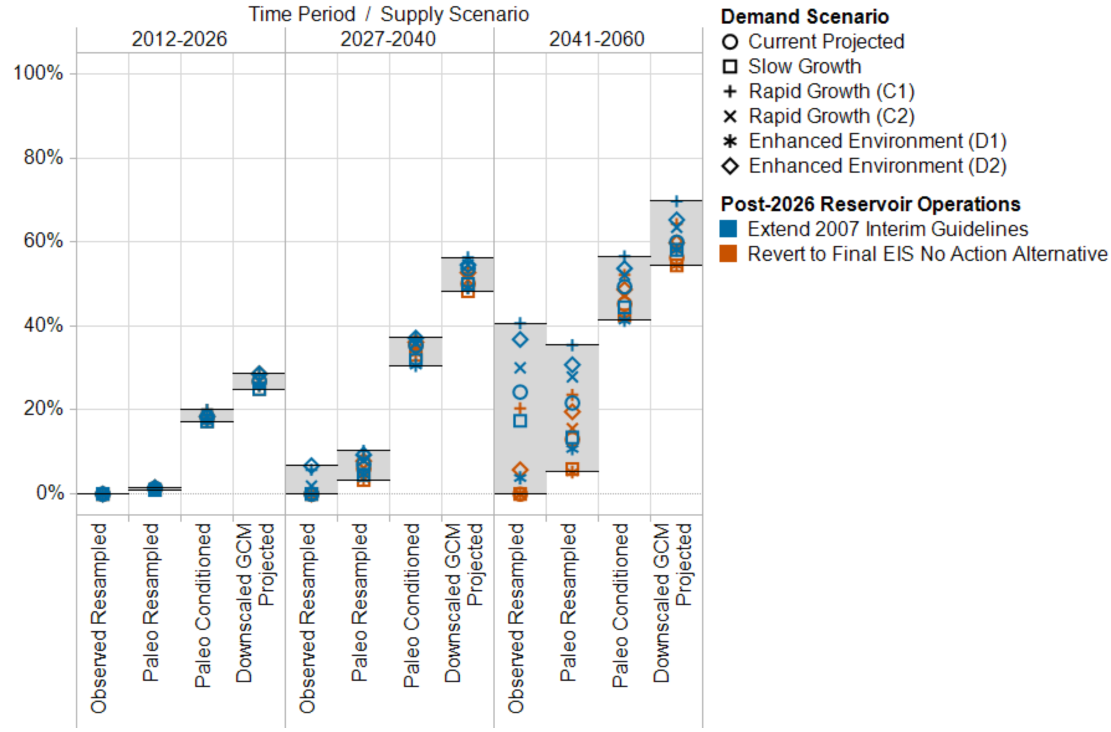


FIGURE G3-32
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Lake Powell Pool Elevation < 3,490 Indicator Metric (below power pool of 3,490 feet msl in any 1 month)

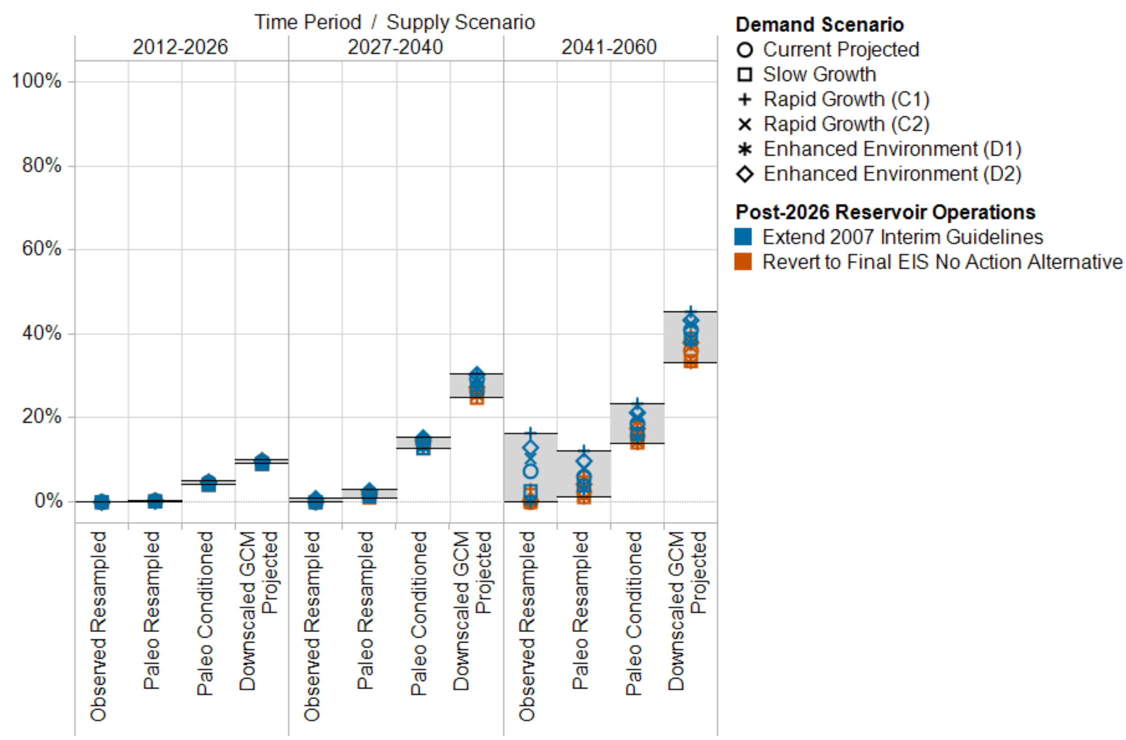


FIGURE G3-33
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Upper Basin Electrical Power Generated Indicator Metric (below 4,450 GWh per year for more than three consecutive years)

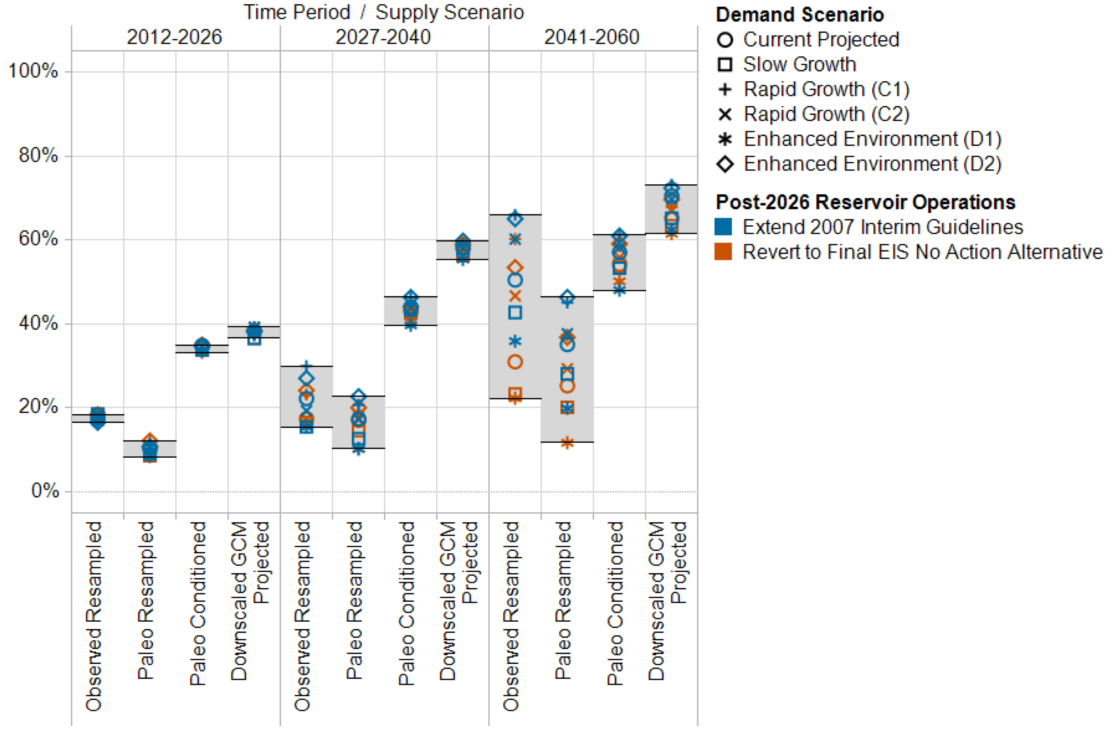


FIGURE G3-34
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Upper Basin Electrical Power Generated Indicator Metric (below 4,450 GWh per year for more than three consecutive years)

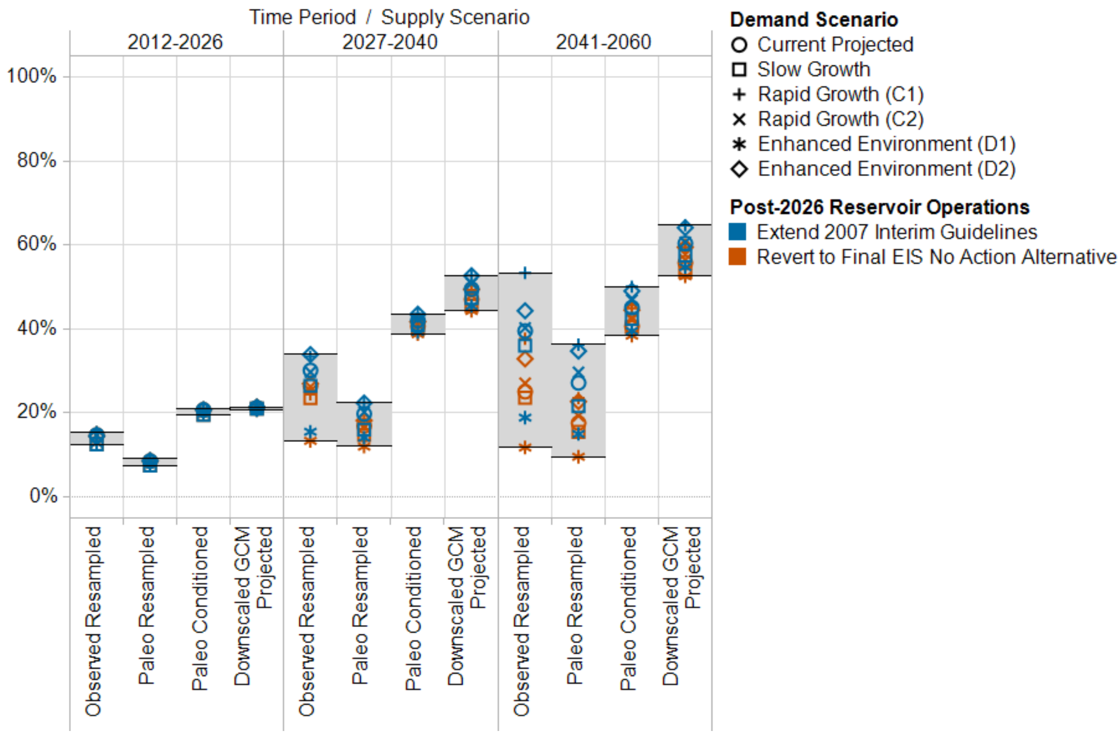


FIGURE G3-35
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Lake Mead Pool Elevation <1,050 feet Indicator Metric (below 1,050 feet in any 1 month of any year)

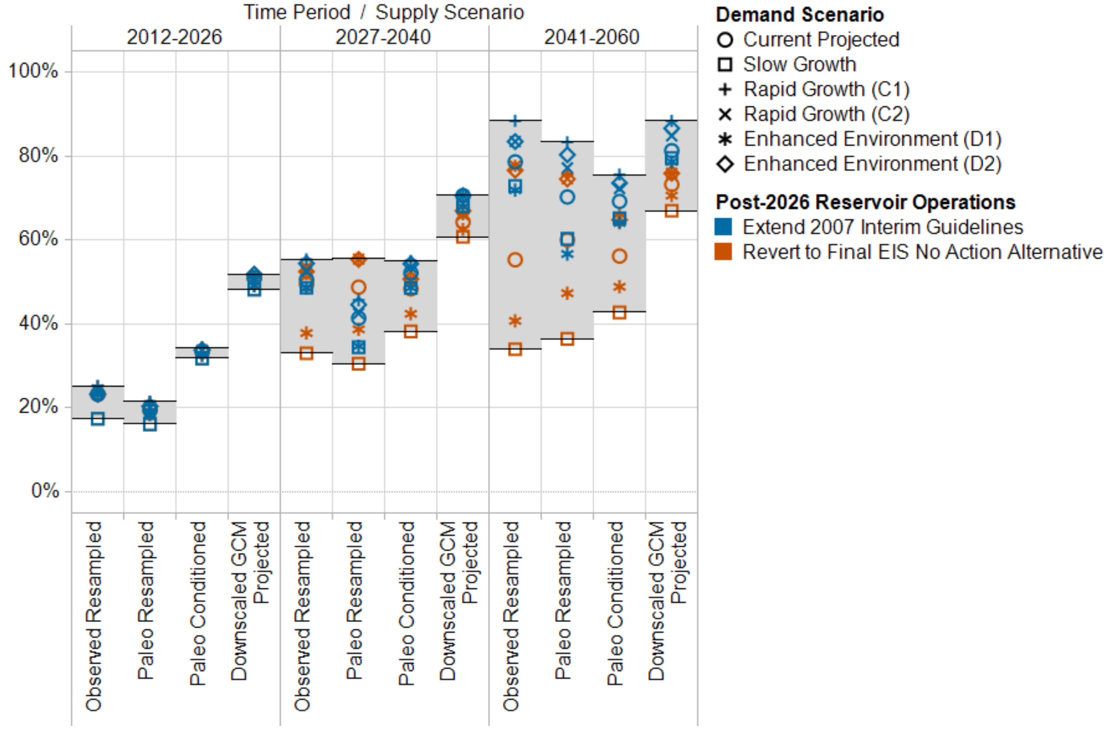


FIGURE G3-36
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Lake Mead Pool Elevation <1,050 feet Indicator Metric (below 1,050 feet in any 1 month of any year)

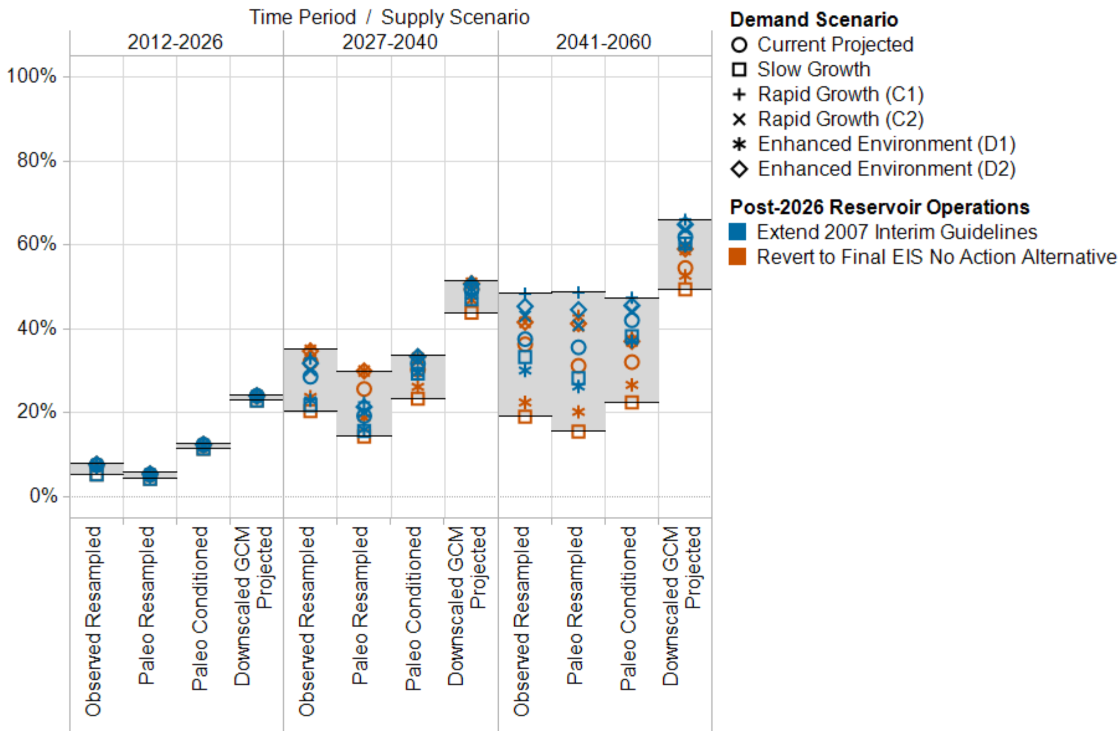


FIGURE G3-37
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Lake Mead Downstream Safe Channel Capacity Indicator Metric (flow greater than 28,000 cfs in any 1 month)

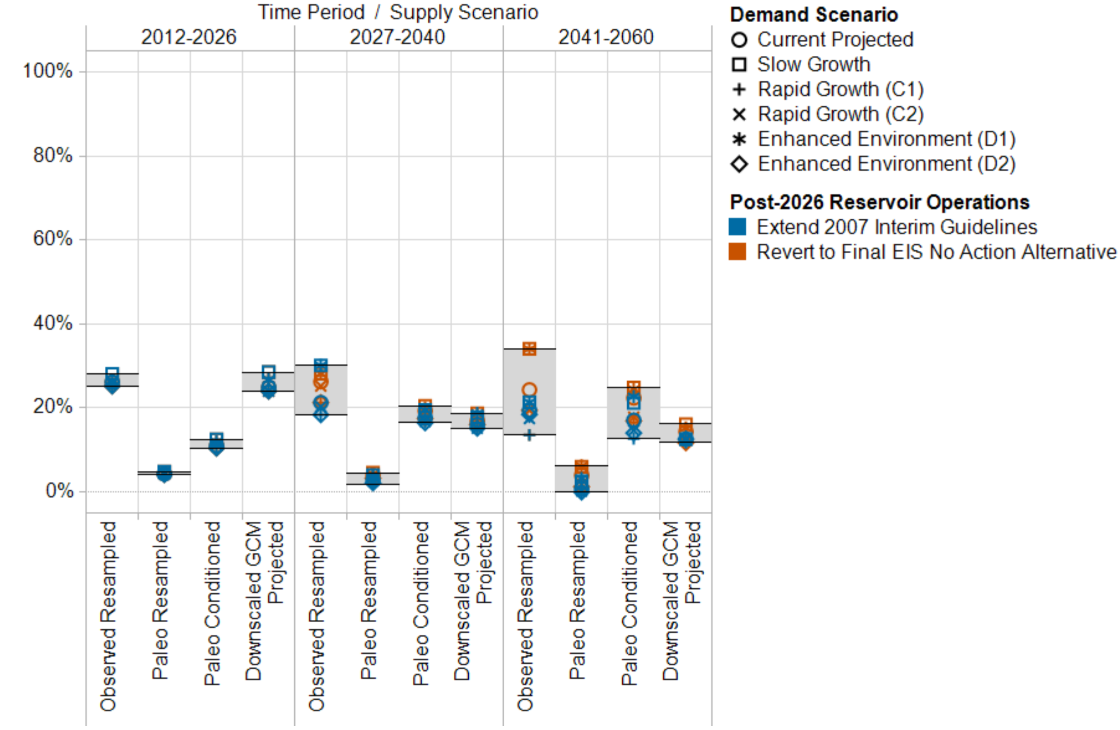


FIGURE G3-38
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Lake Mead Downstream Safe Channel Capacity Indicator Metric (flow greater than 28,000 cfs in any 1 month)

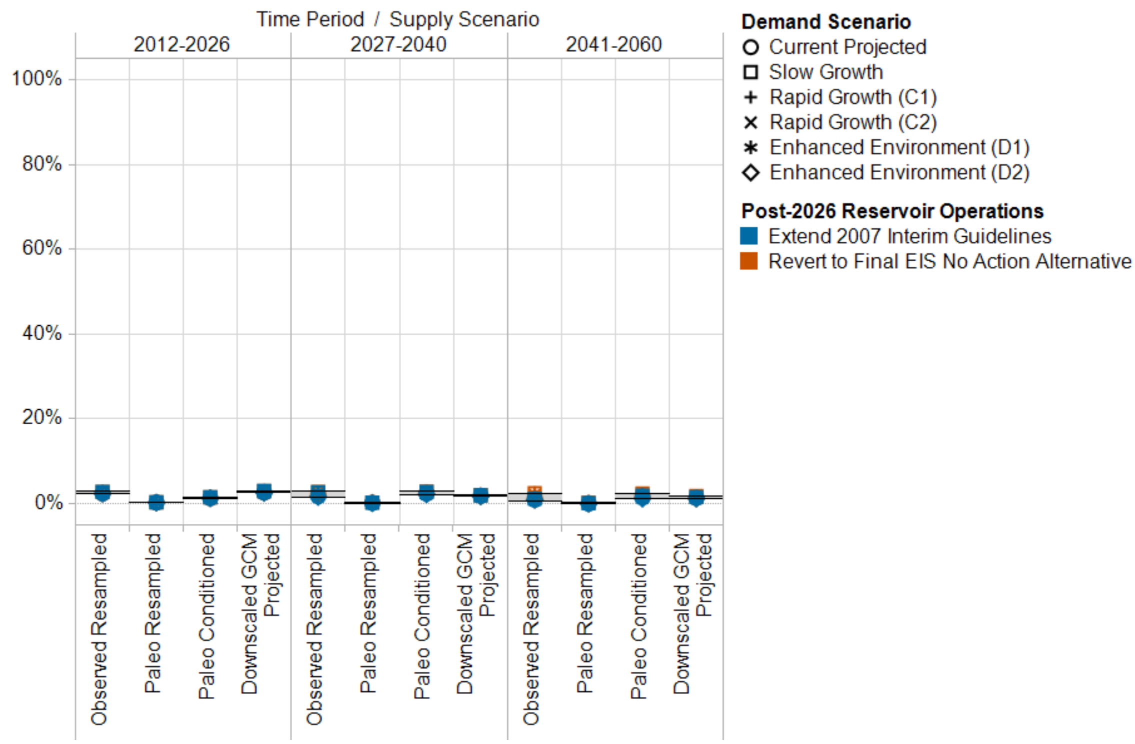


FIGURE G3-39
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Colorado River Optimal Boating Flow Days Indicator Metric (below 10th percentile of control run)

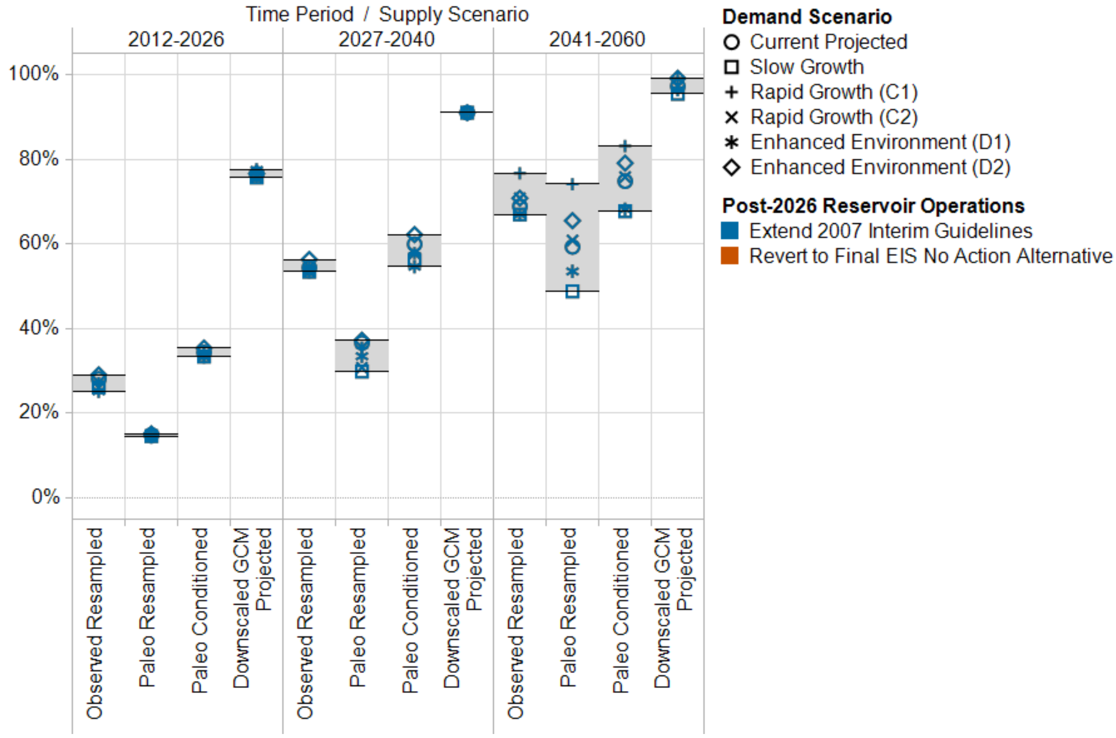


FIGURE G3-40
Percent of Year Vulnerable Without Options and Strategies by Scenario and Time Period,
Colorado River Optimal Boating Flow Days Indicator Metric (below 10th percentile of control run)

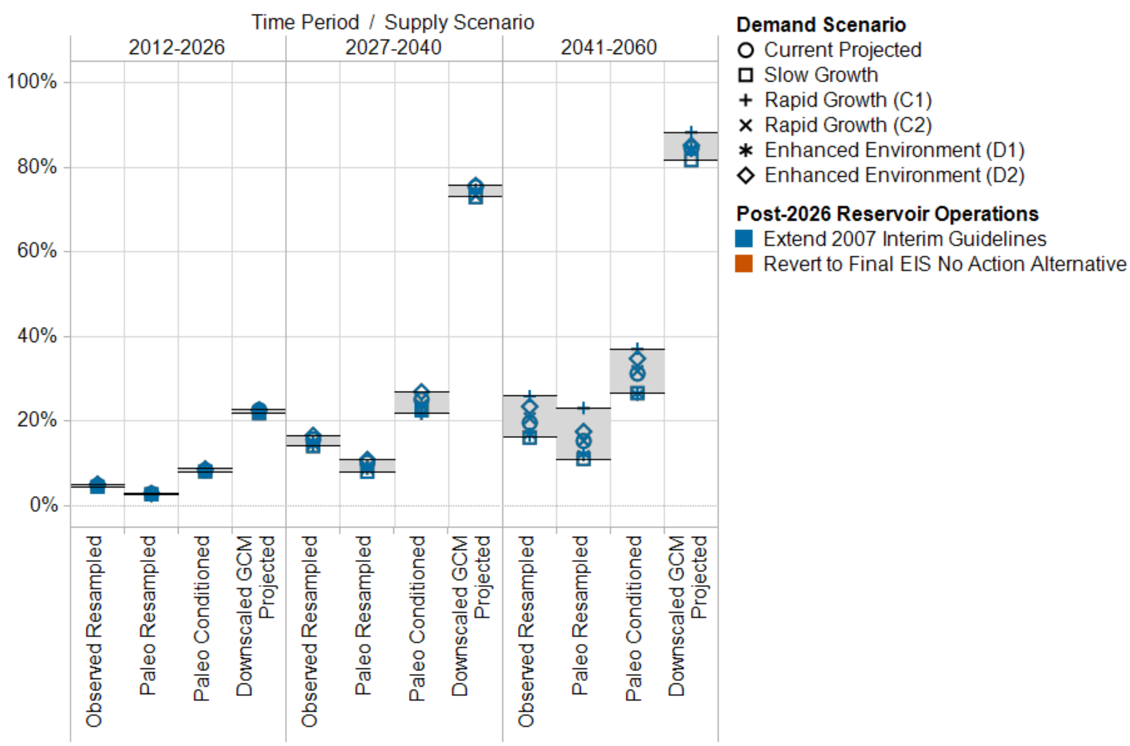


FIGURE G3-41
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Green River Optimal Boating Flow Days Indicator Metric (below 10th percentile of control run)

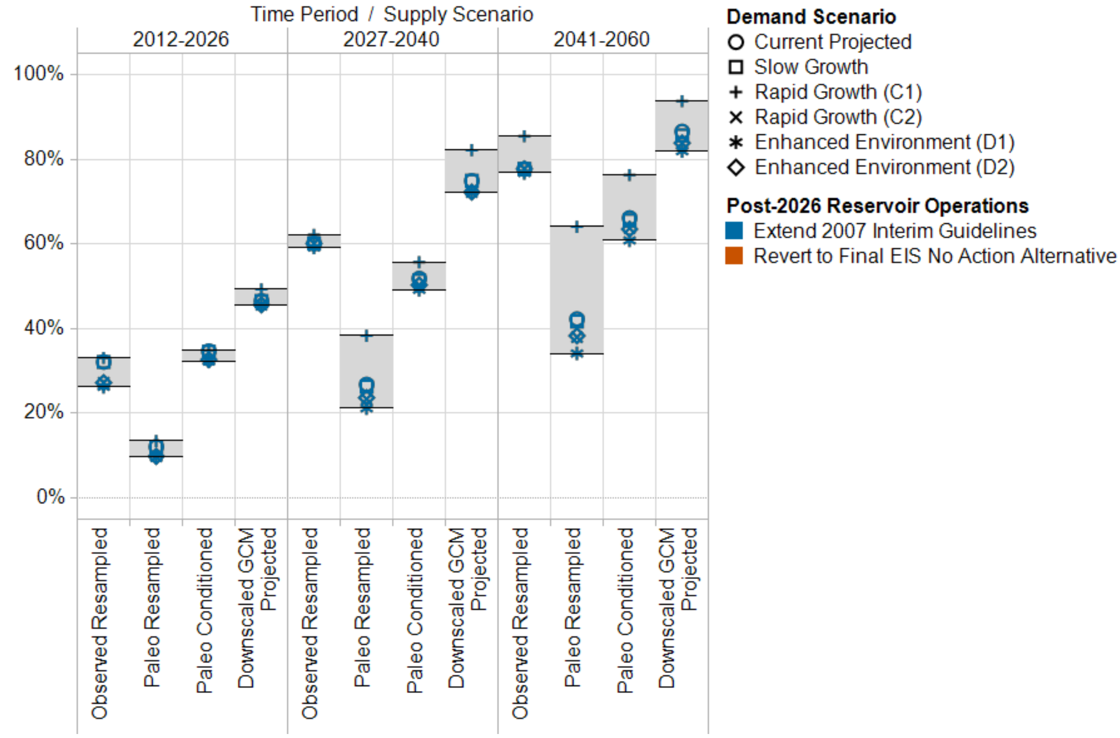


FIGURE G3-42
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Green River Optimal Boating Flow Days Indicator Metric (below 10th percentile of control run)

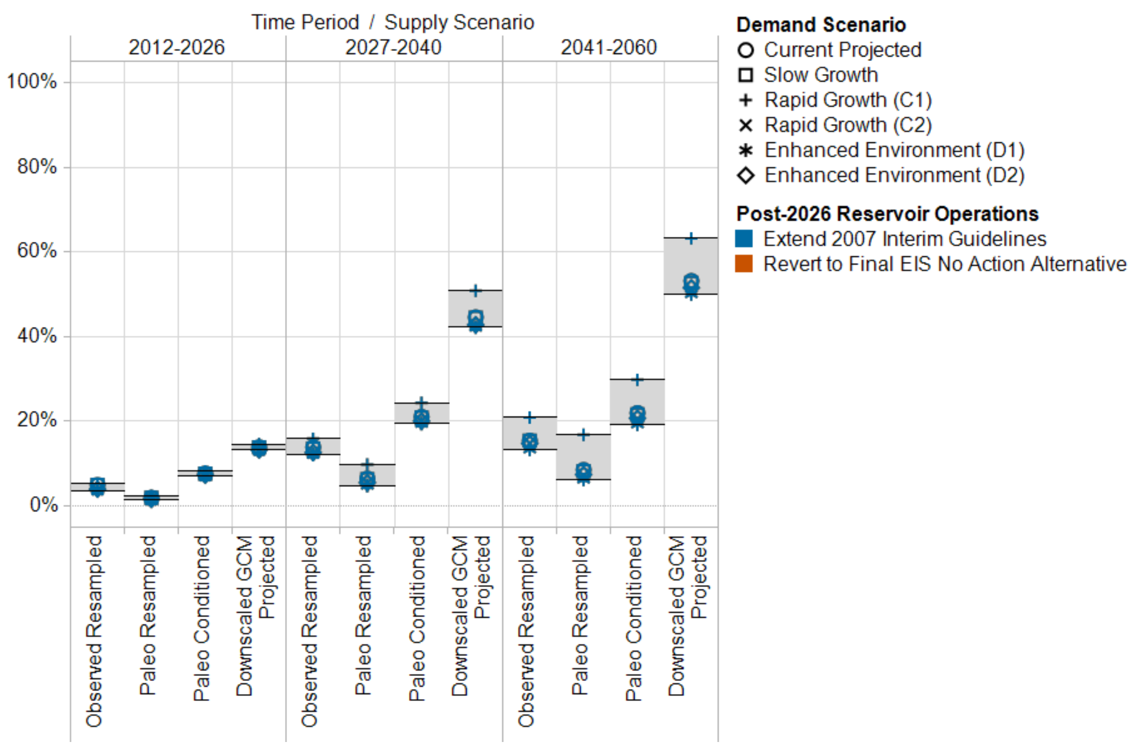


FIGURE G3-43
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, San Juan River Optimal Boating Flow Days Indicator Metric (below 10th percentile of control run)

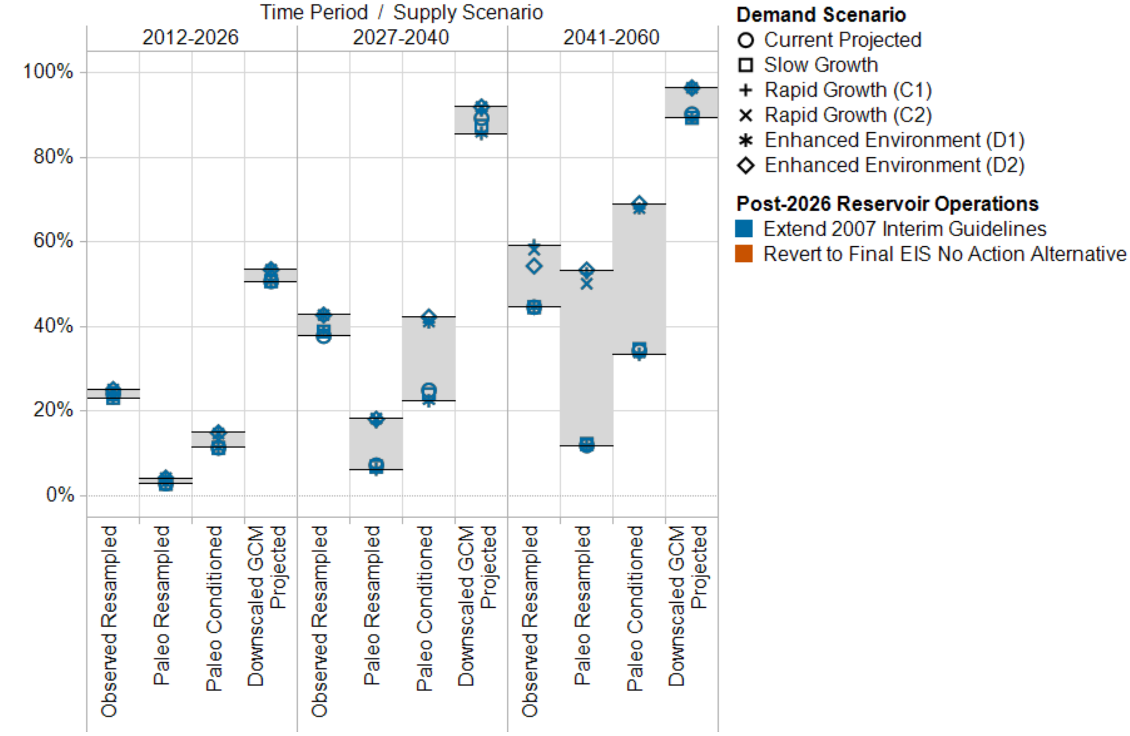


FIGURE G3-44
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, San Juan River Optimal Boating Flow Days Indicator Metric (below 10th percentile of control run)

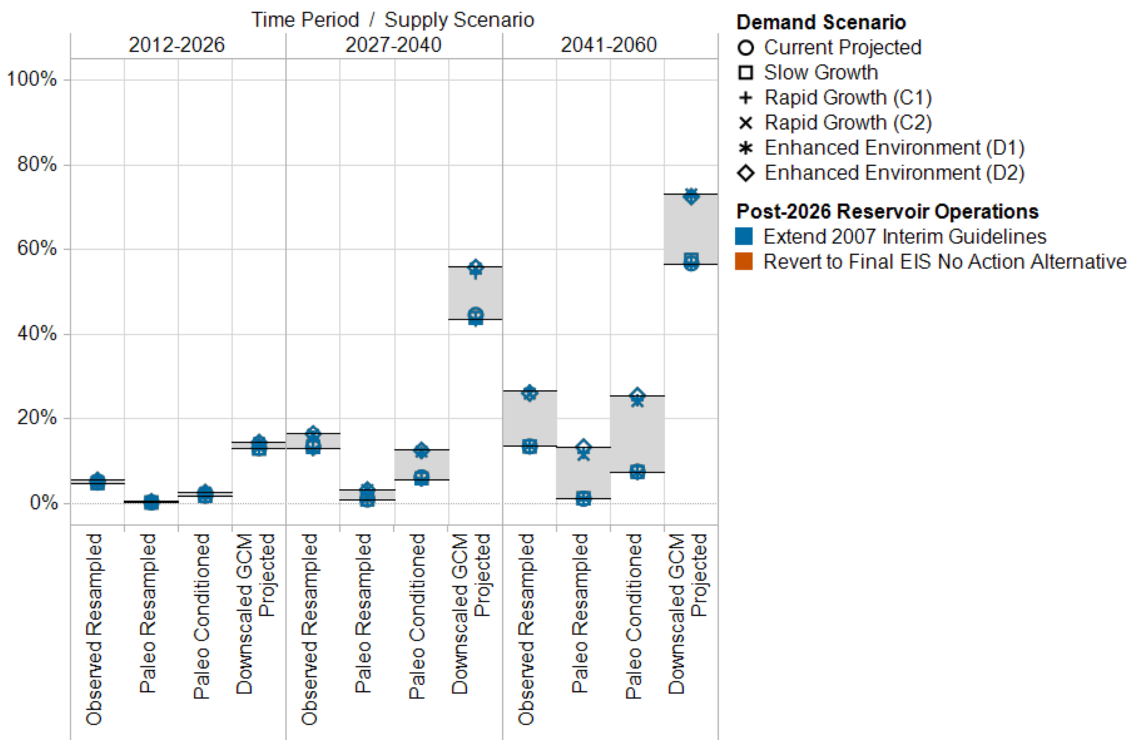


FIGURE G3-45
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Colorado River Acceptable Boating Flow Days Indicator Metric (below minimum of control run)

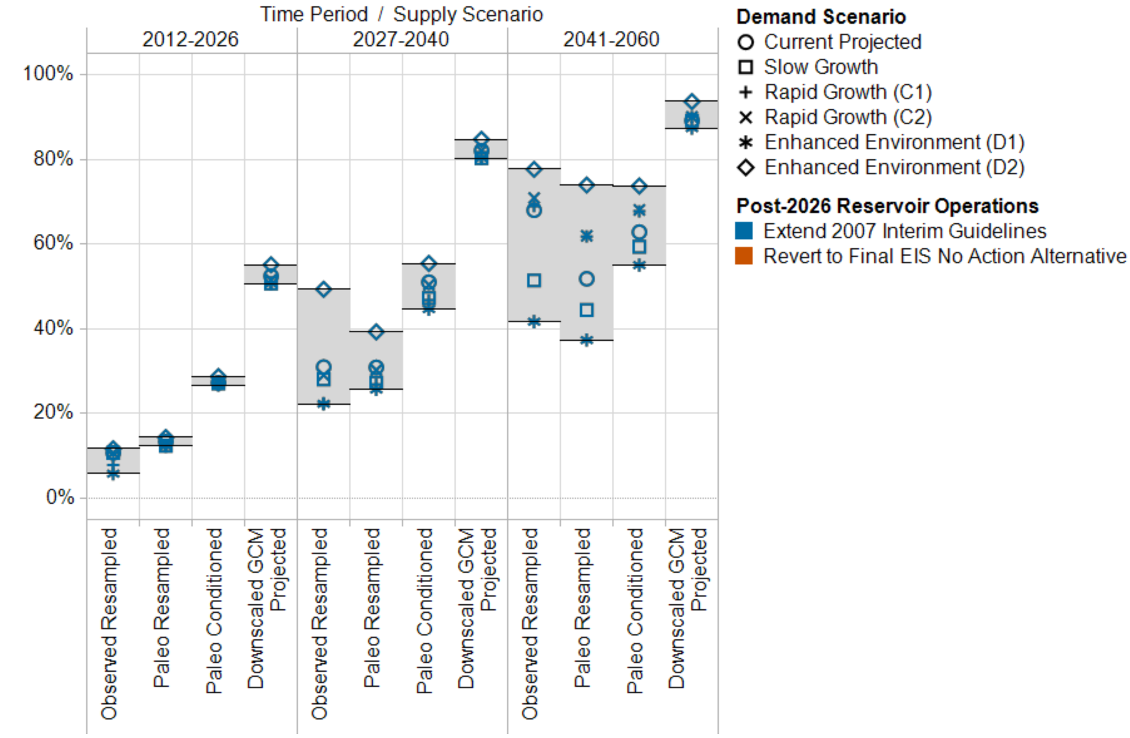


FIGURE G3-46
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Colorado River Acceptable Boating Flow Days Indicator Metric (below minimum of control run)

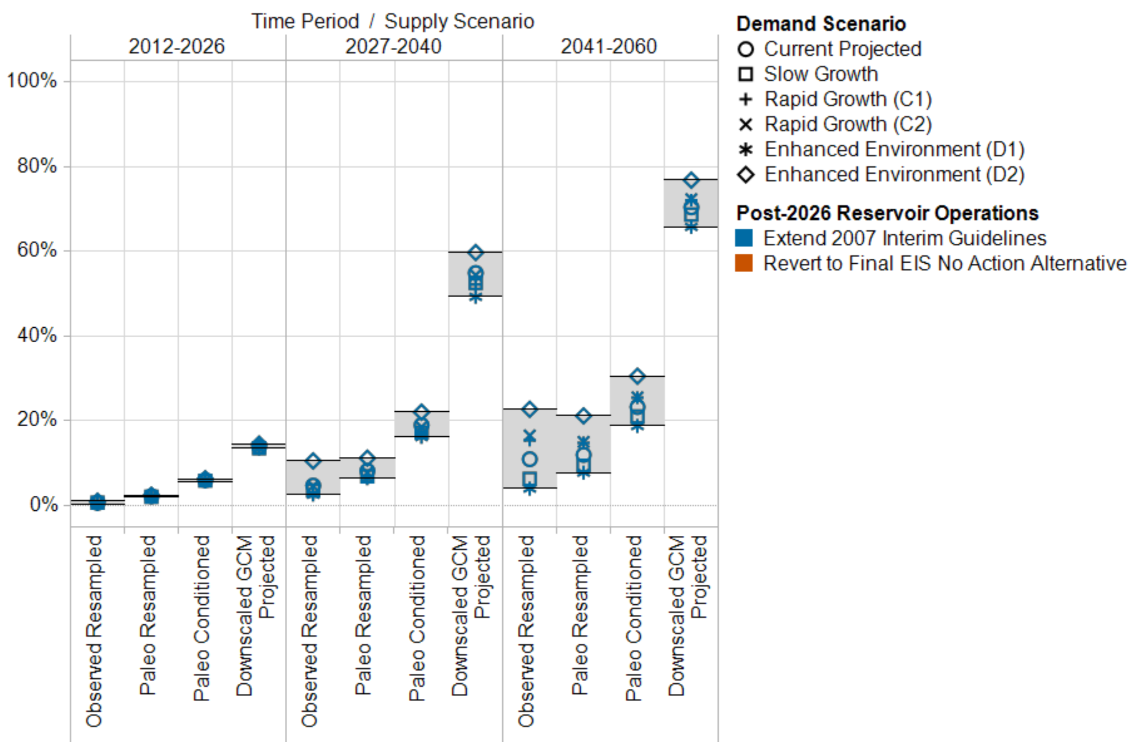


FIGURE G3-47
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Green River Acceptable Boating Flow Days Indicator Metric (below minimum of control run)

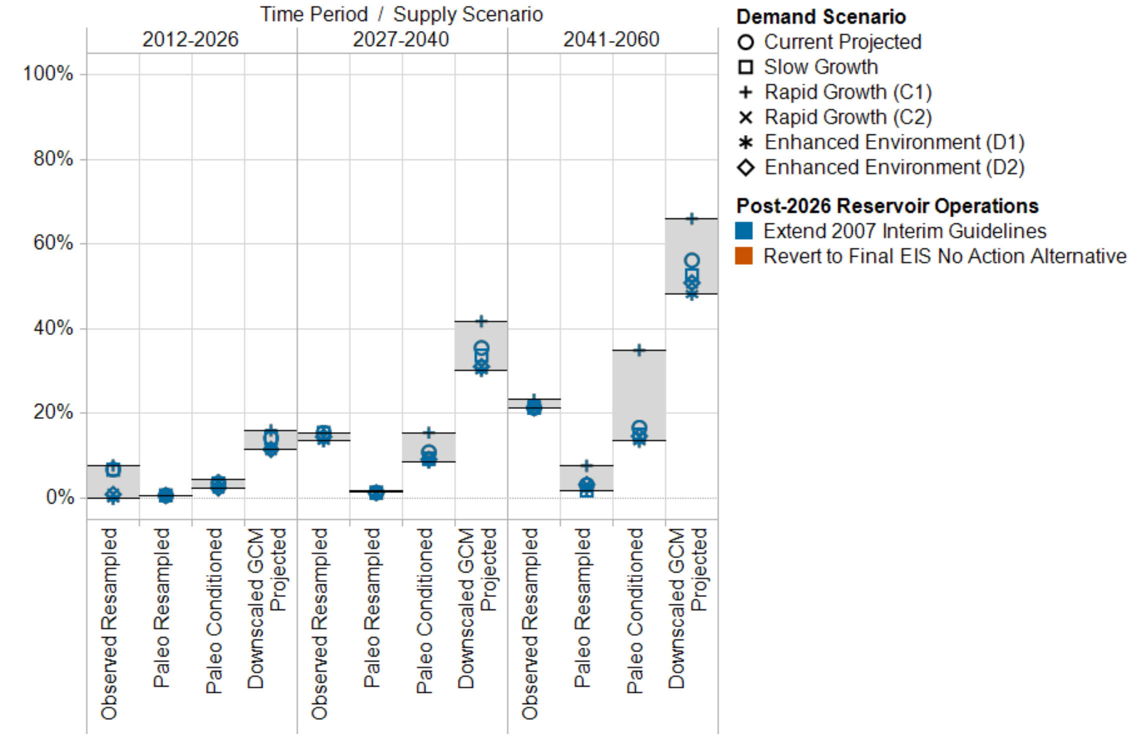


FIGURE G3-48
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Green River Acceptable Boating Flow Days Indicator Metric (below minimum of control run)

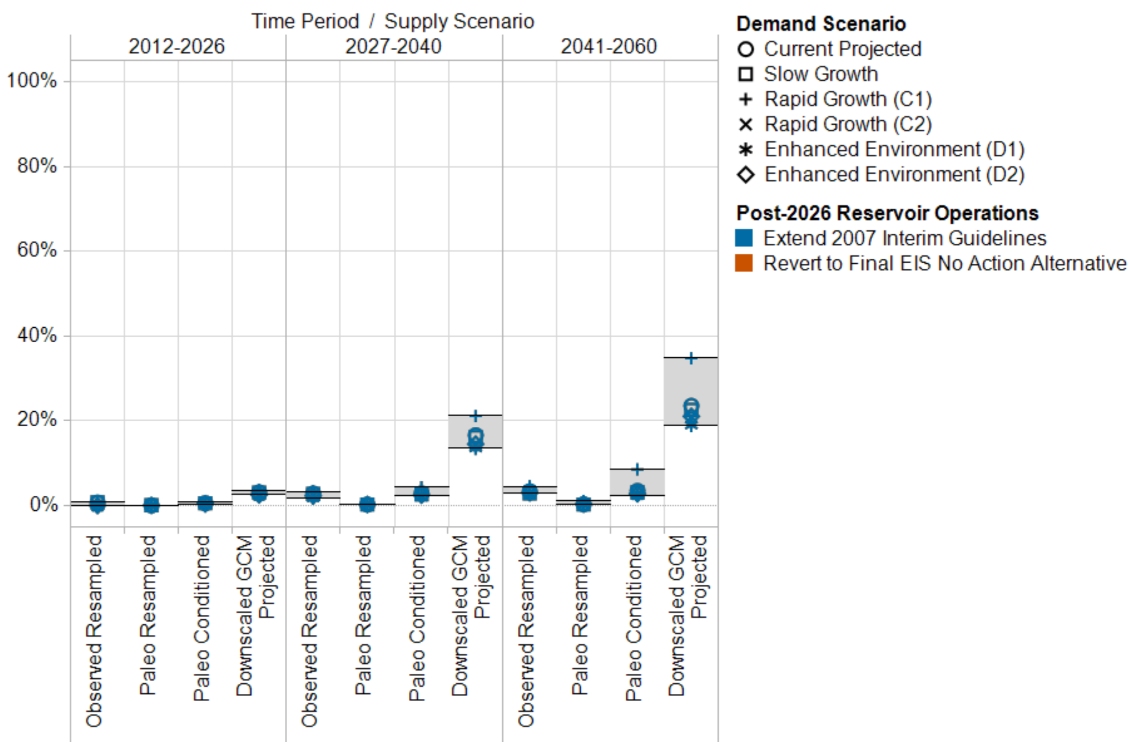


FIGURE G3-49
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, San Juan River Acceptable Boating Flow Days Indicator Metric (below minimum of control run)

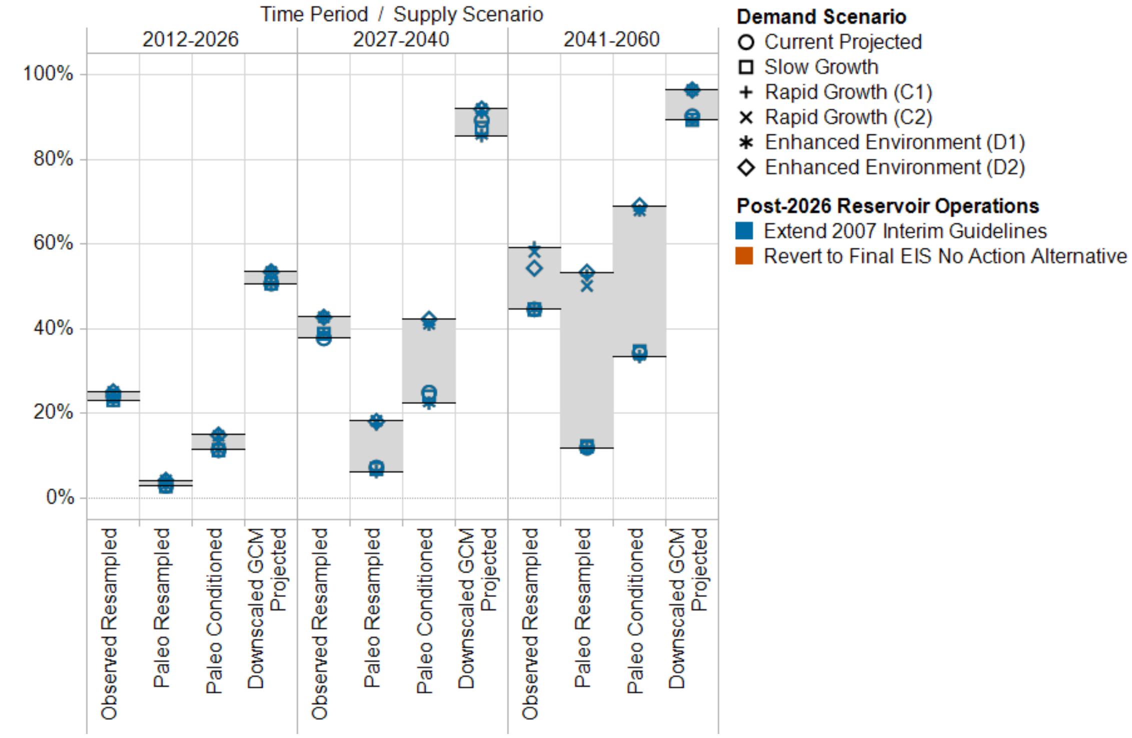


FIGURE G3-50
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, San Juan River Acceptable Boating Flow Days Indicator Metric (below minimum of control run)

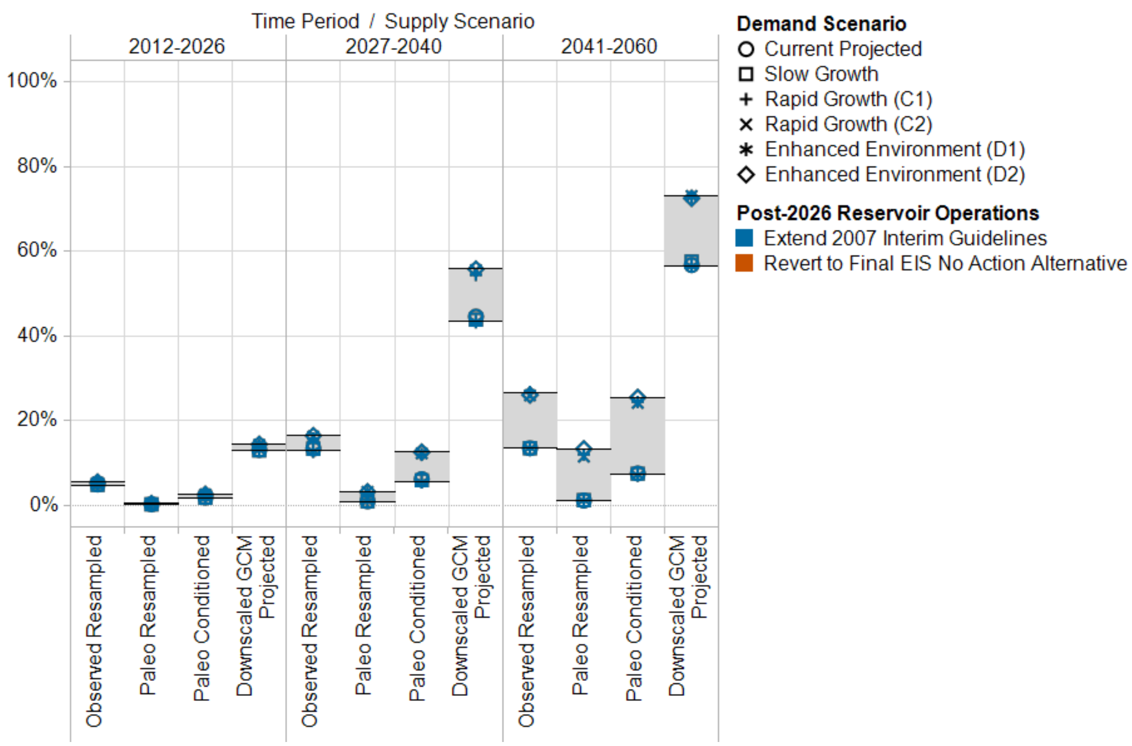


FIGURE G3-51
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Blue Mesa Shoreline Pubic Use Facility Indicator Metric (pool elevation below 7,433 feet in any 1 month May through Sept)

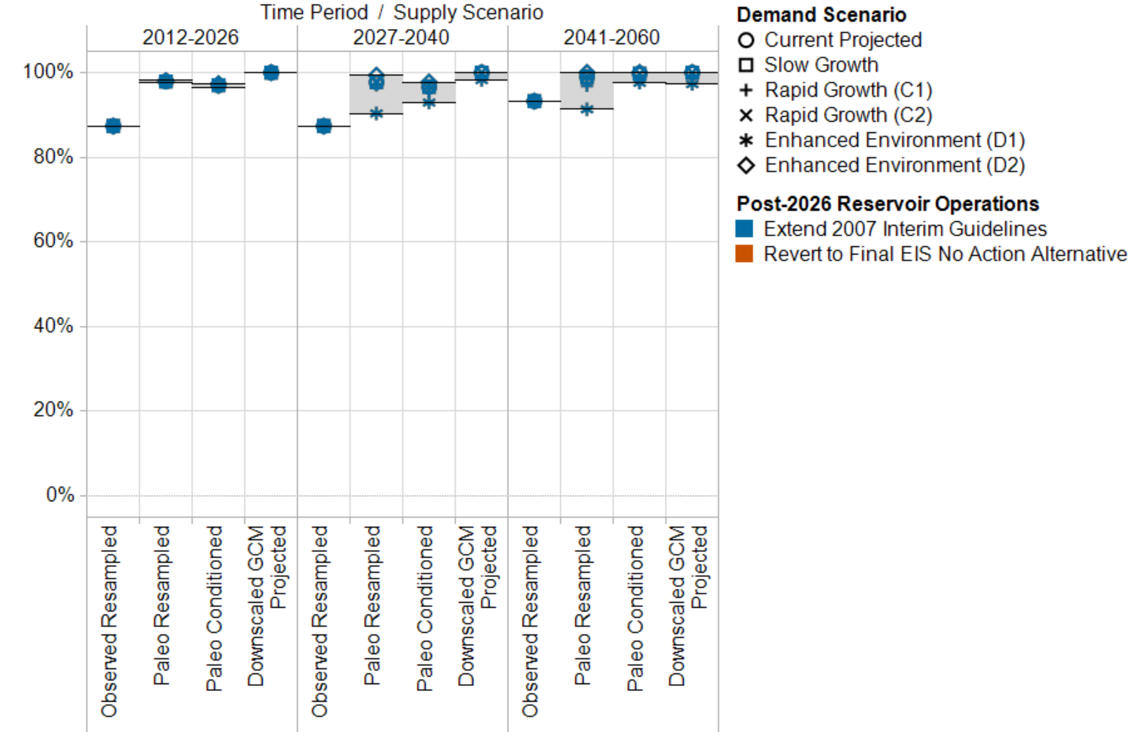


FIGURE G3-52
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Blue Mesa Shoreline Pubic Use Facility Indicator Metric (pool elevation below 7,433 feet in any 1 month May through Sept)

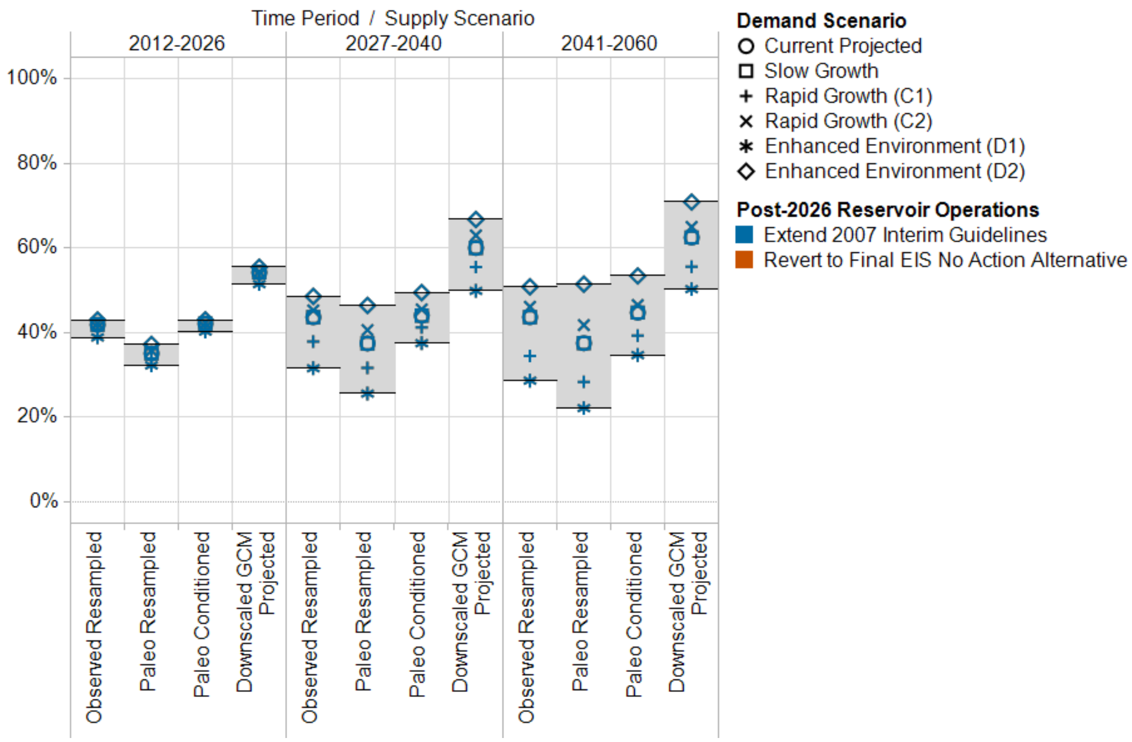


FIGURE G3-53
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Navajo Shoreline Public Use Facility Indicator Metric (pool elevation below 6,025 feet in any 1 month April through Oct)

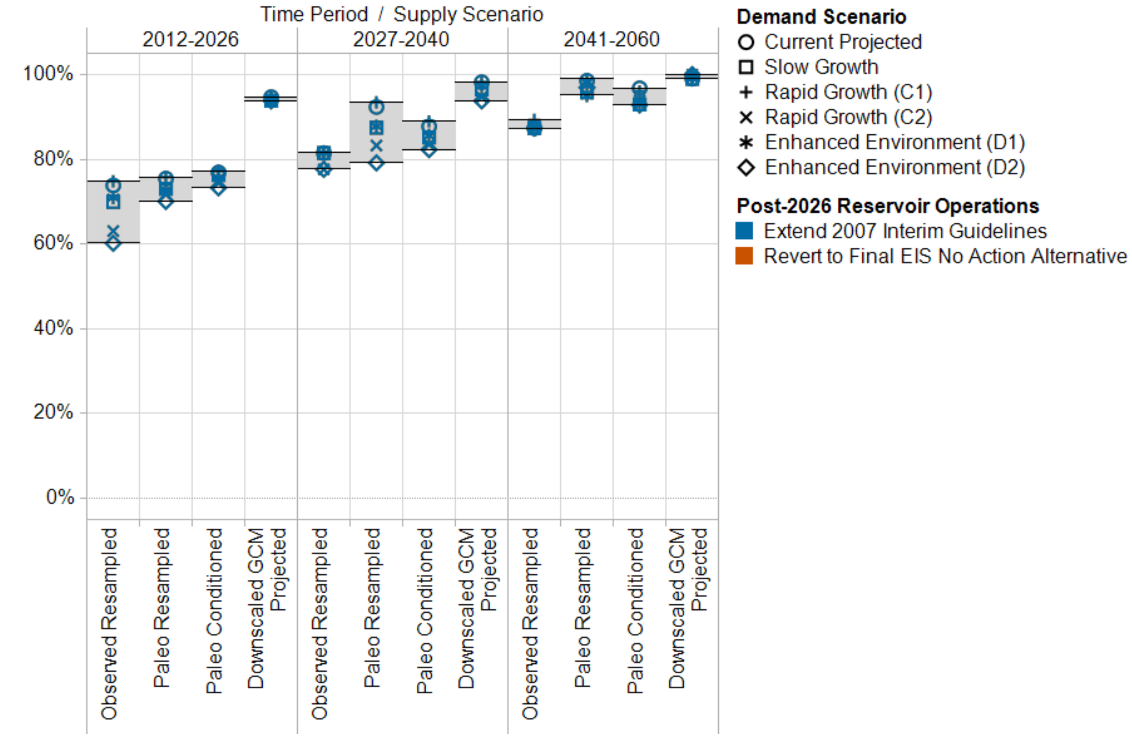


FIGURE G3-54
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Navajo Shoreline Public Use Facility Indicator Metric (pool elevation below 6,025 feet in any 1 month April through Oct)

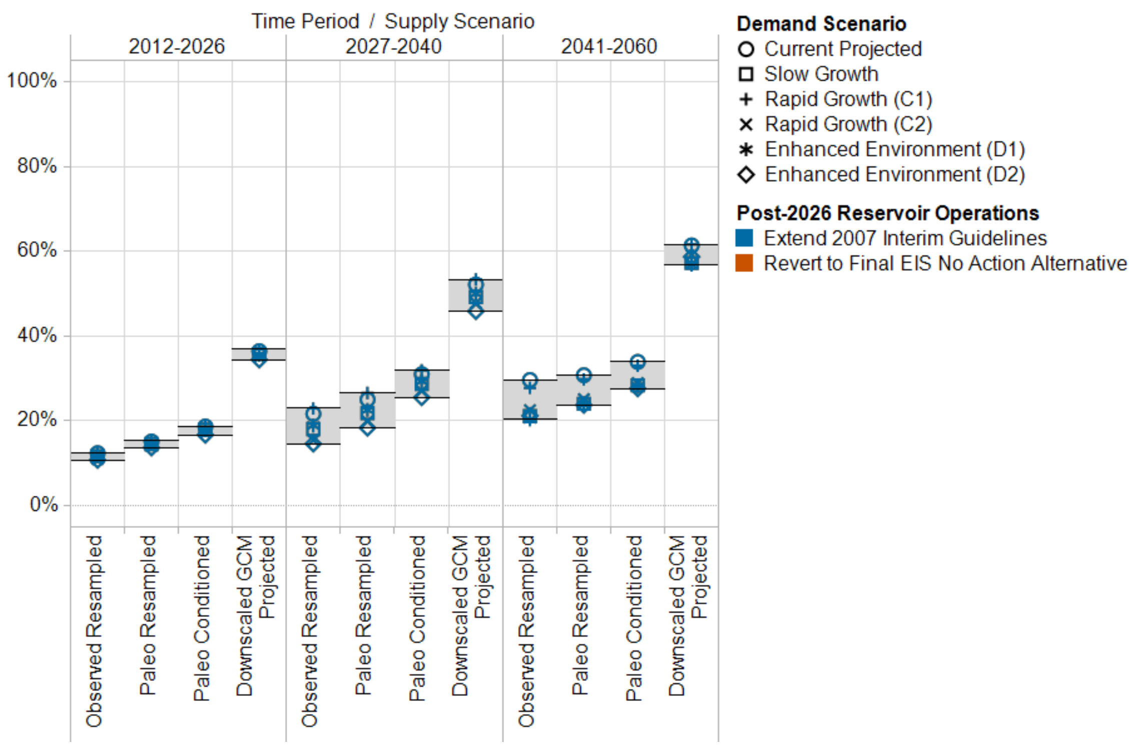


FIGURE G3-55
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Flaming Gorge Shoreline Public Use Facility Indicator Metric (pool elevation below 6,019 feet in any 1 month May through Sept)

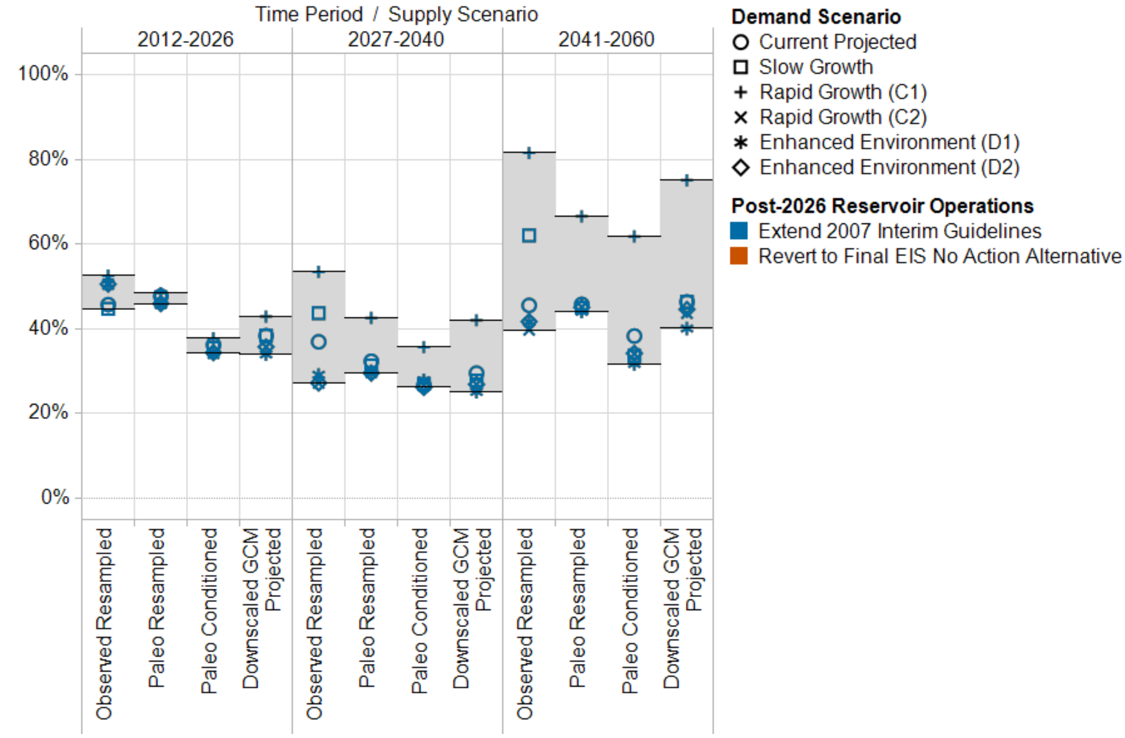


FIGURE G3-56
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Flaming Gorge Shoreline Public Use Facility Indicator Metric (pool elevation below 6,019 feet in any 1 month May through Sept)

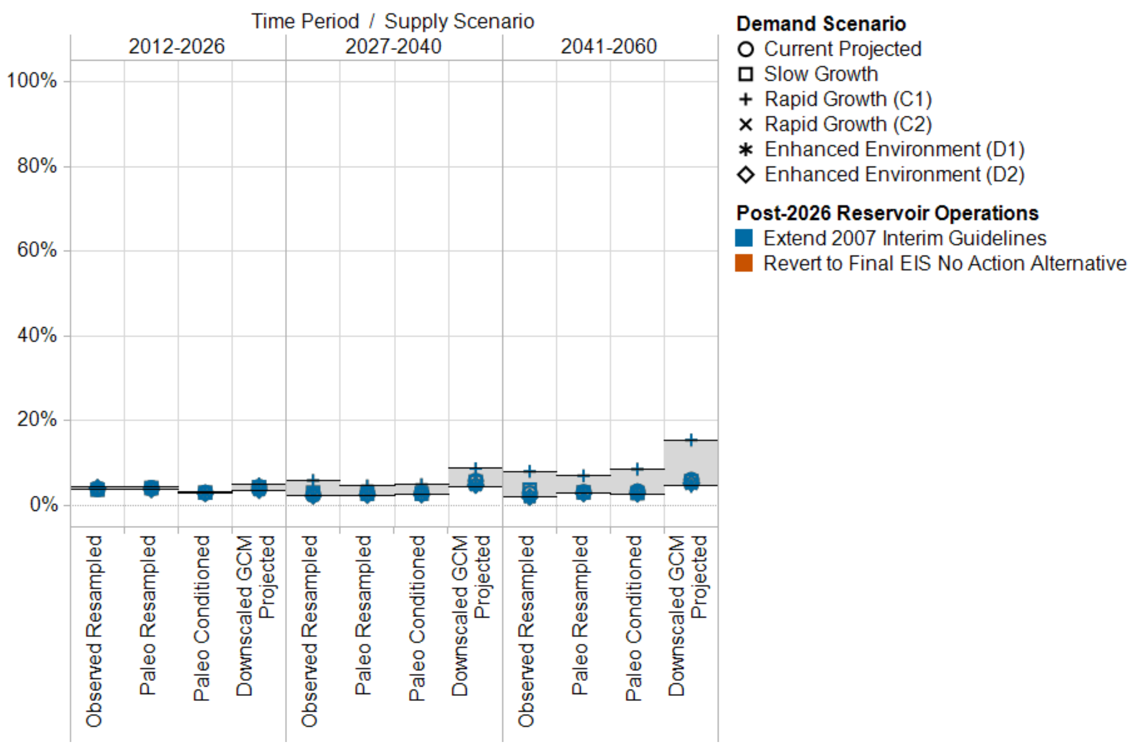


FIGURE G3-57
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Powell Shoreline Public Use Facility Indicator Metric (pool elevation below 3,560 feet in any 1 month May through Sept)

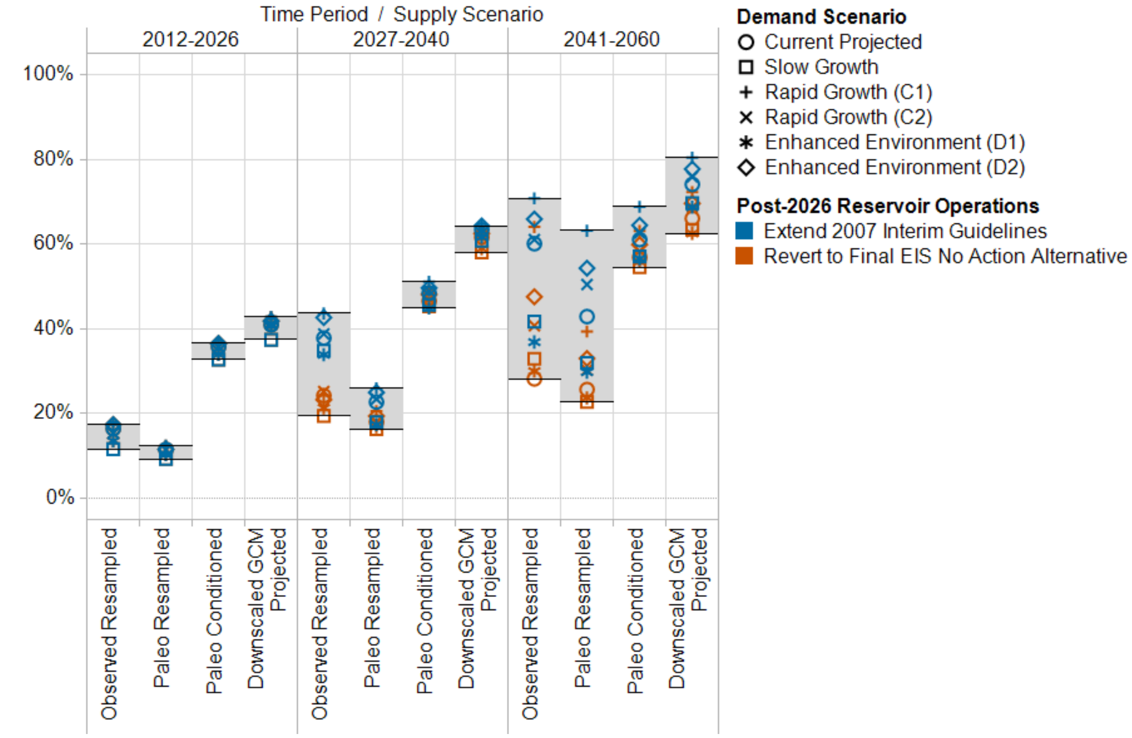


FIGURE G3-58
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Powell Shoreline Public Use Facility Indicator Metric (pool elevation below 3,560 feet in any 1 month May through Sept)

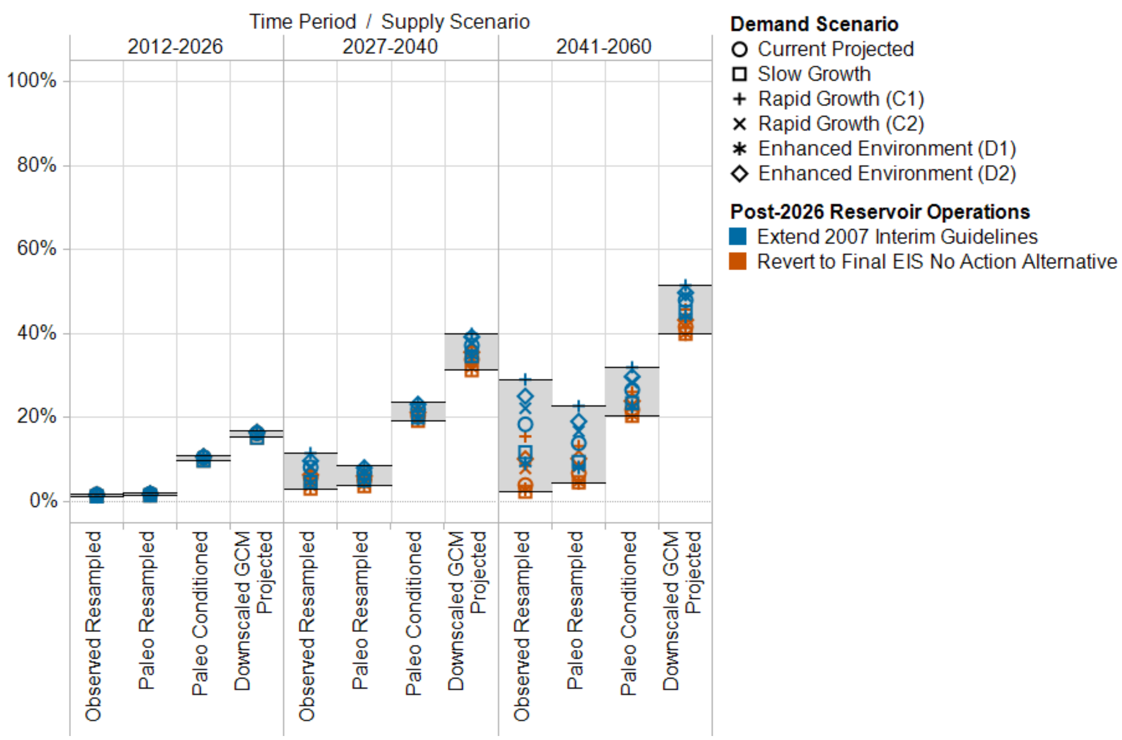


FIGURE G3-59
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Mead Shoreline Public Use Facility Indicator Metric (pool elevation below 1,080 feet in any 1 month)

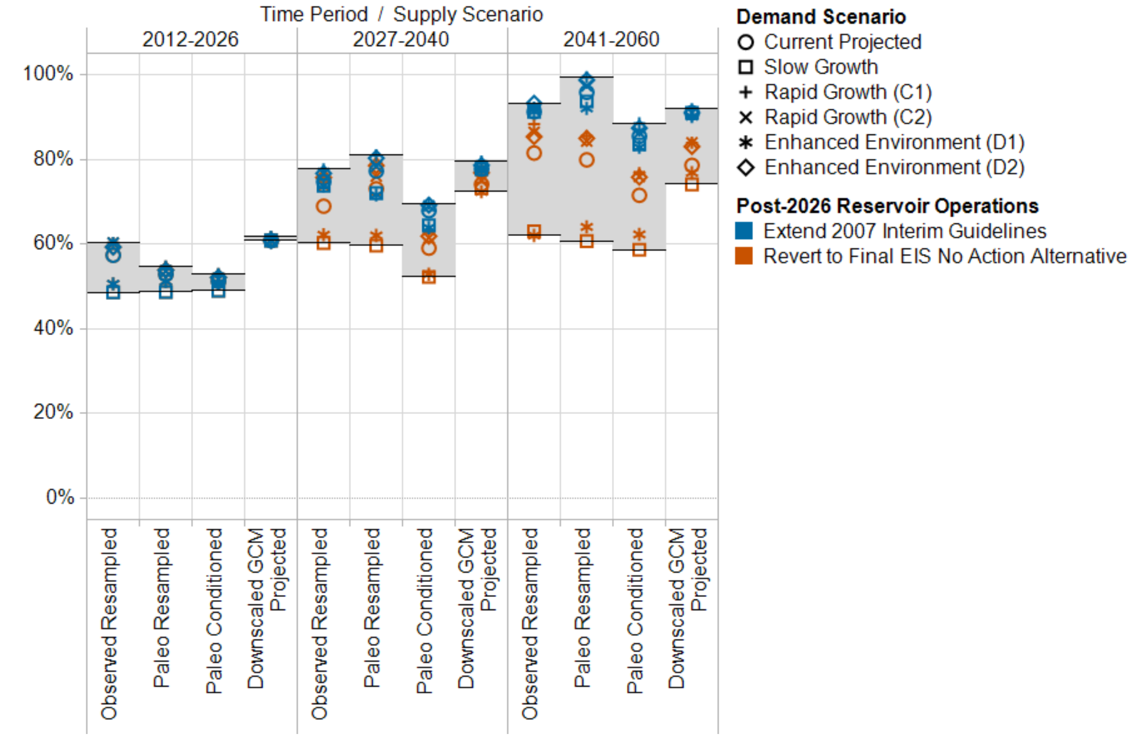


FIGURE G3-60
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Mead Shoreline Public Use Facility Indicator Metric (pool elevation below 1,080 feet in any 1 month)

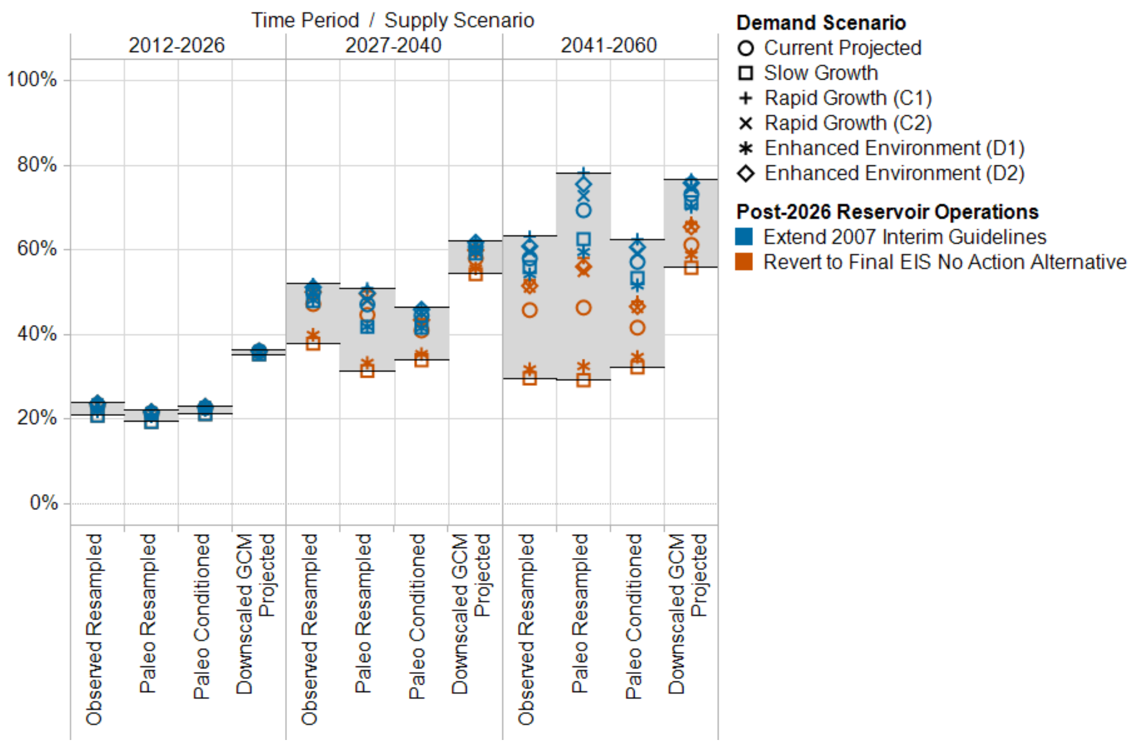


FIGURE G3-61
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Colorado River Indicator Metric (ecological vulnerability)

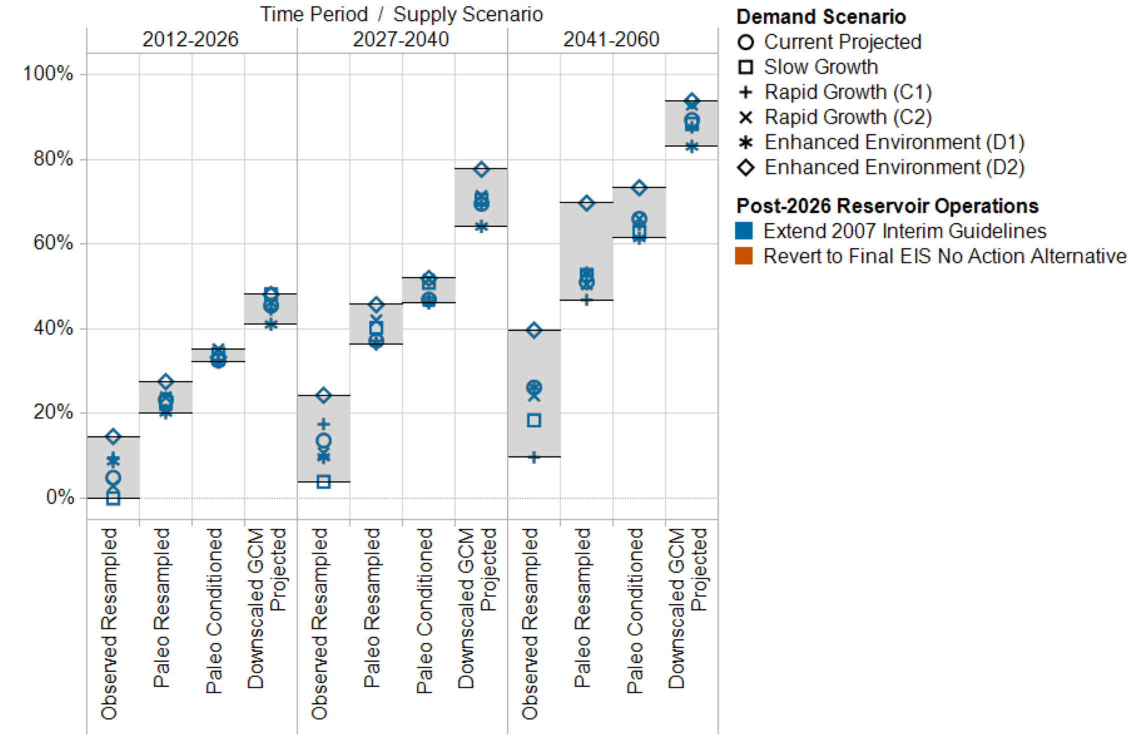


FIGURE G3-62
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Colorado River Indicator Metric (ecological vulnerability)

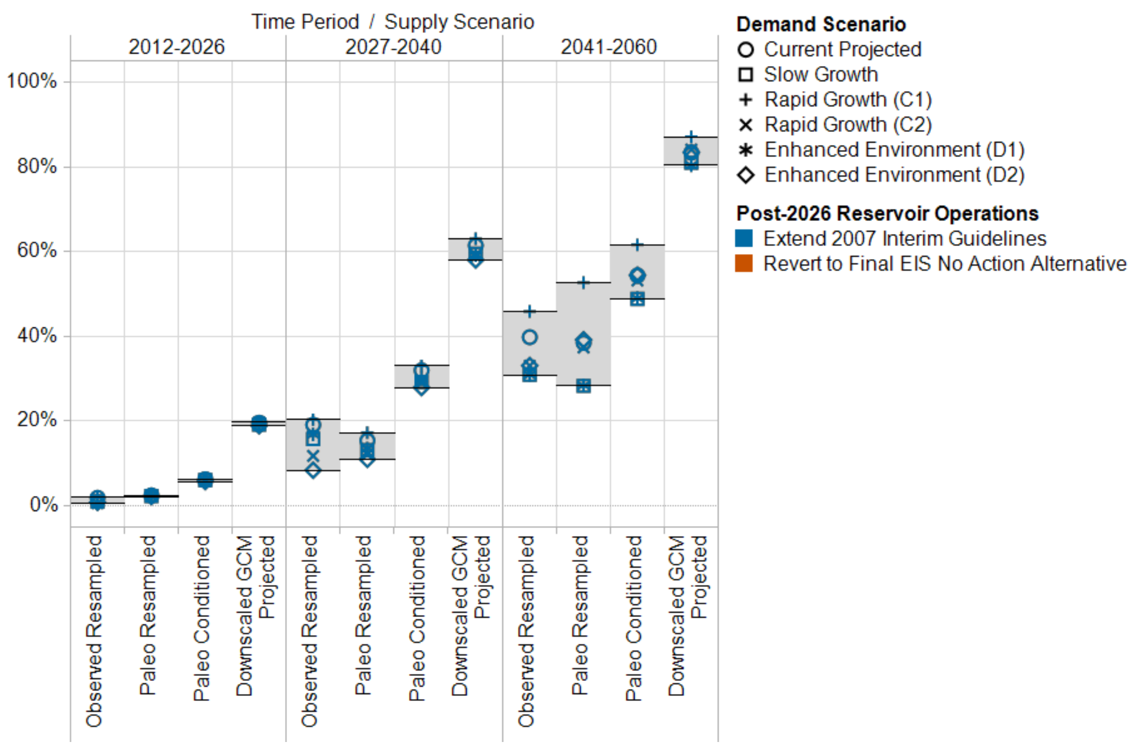


FIGURE G3-63
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Green River Indicator Metric (ecological vulnerability)

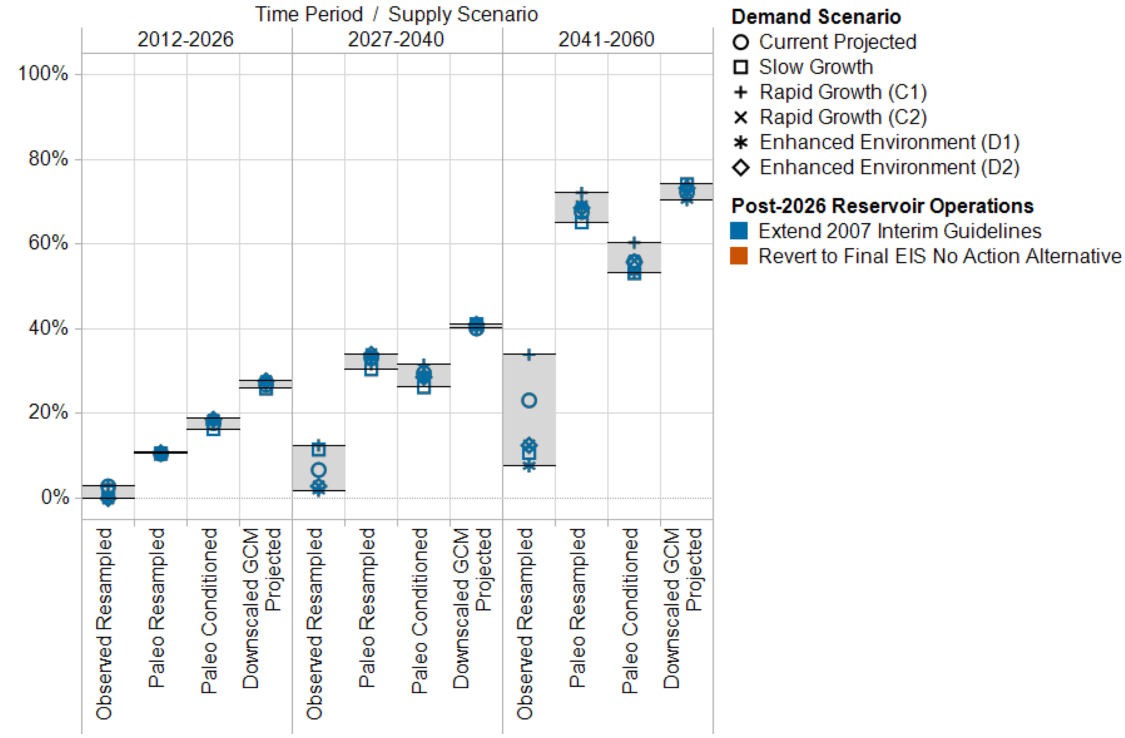


FIGURE G3-64
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Green River Indicator Metric (ecological vulnerability)

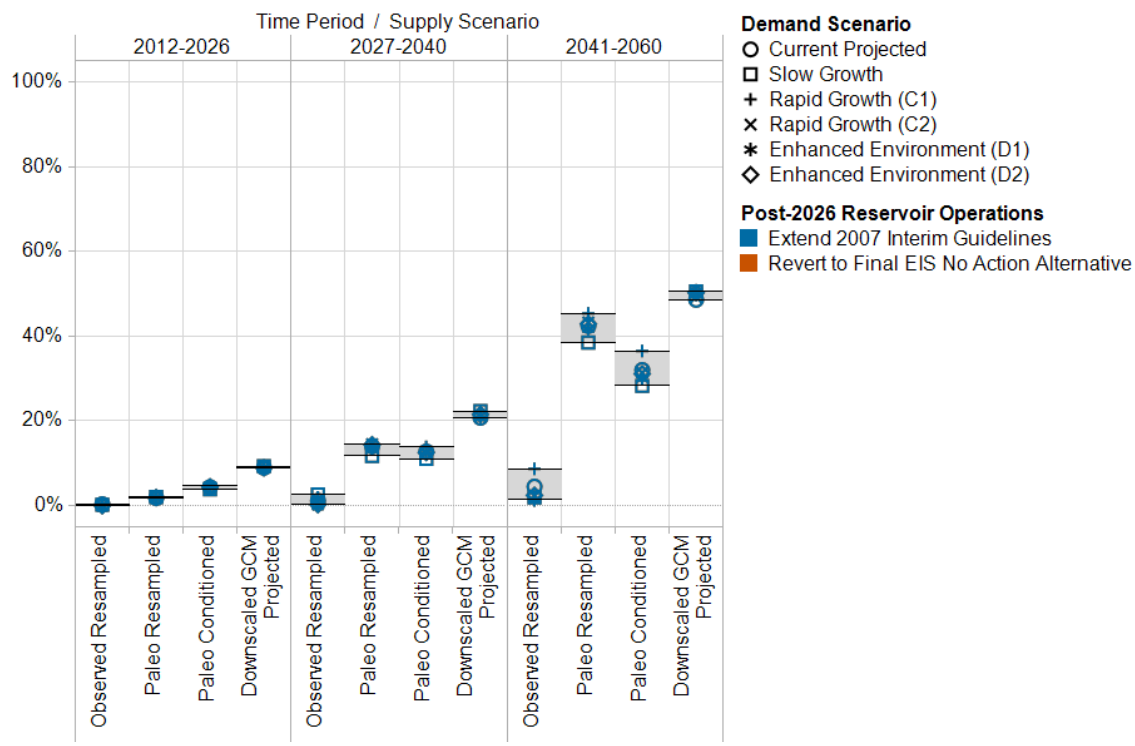


FIGURE G3-65
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, San Juan River Indicator Metric (ecological vulnerability)

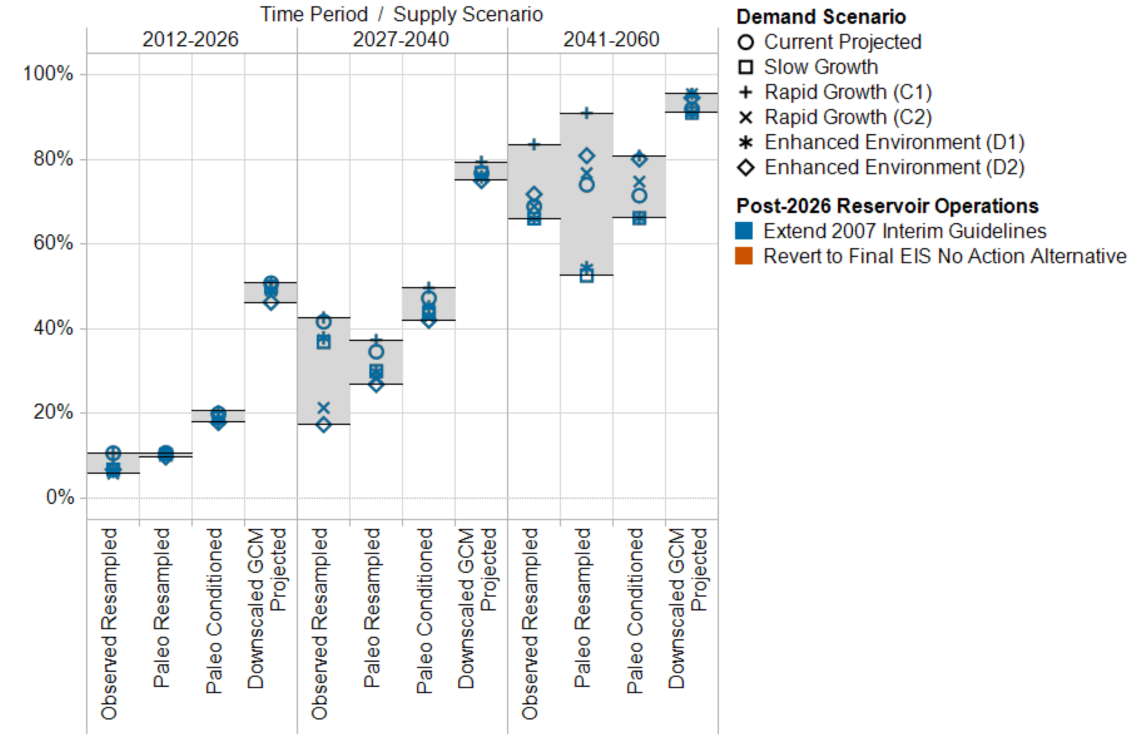


FIGURE G3-66
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, San Juan River Indicator Metric (ecological vulnerability)

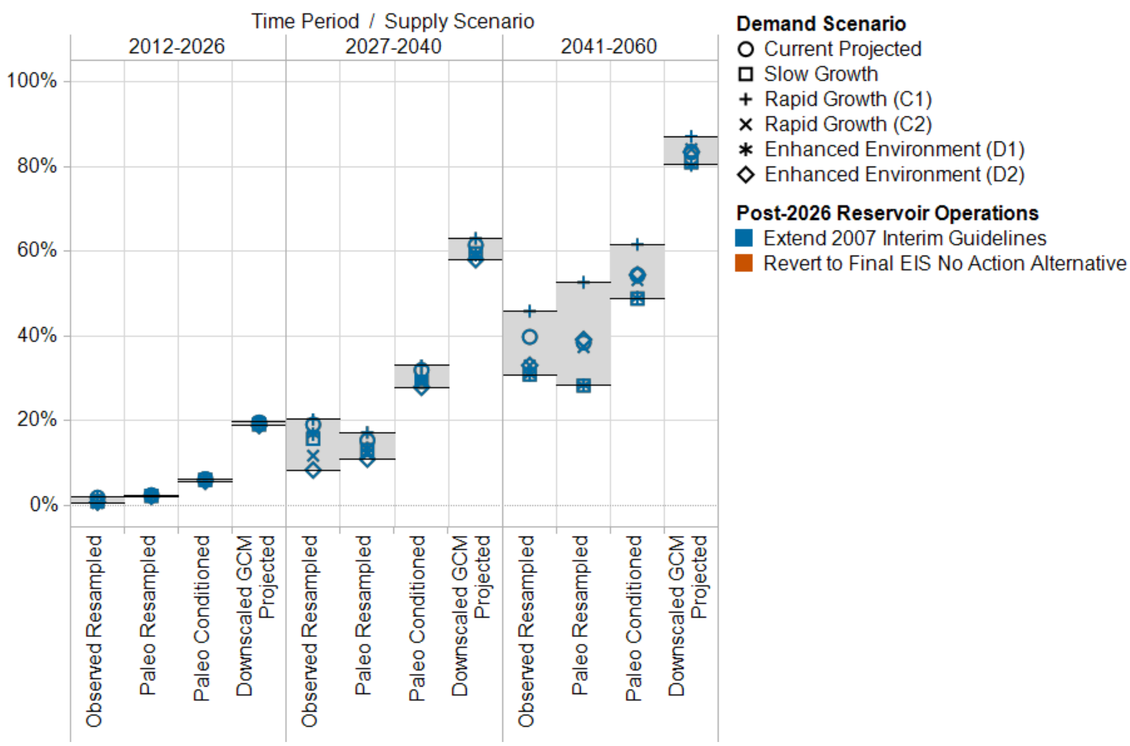


FIGURE G3-67
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period, Yampa River Indicator Metric (ecological vulnerability)

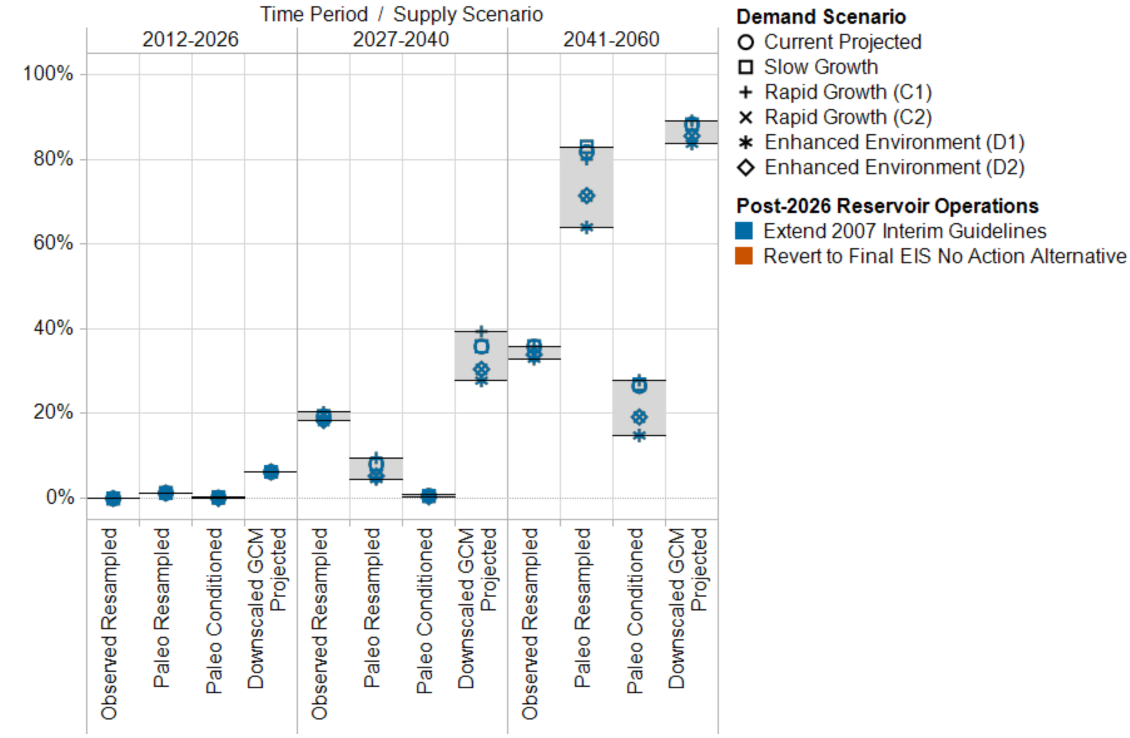


FIGURE G3-68
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period, Yampa River Indicator Metric (ecological vulnerability)

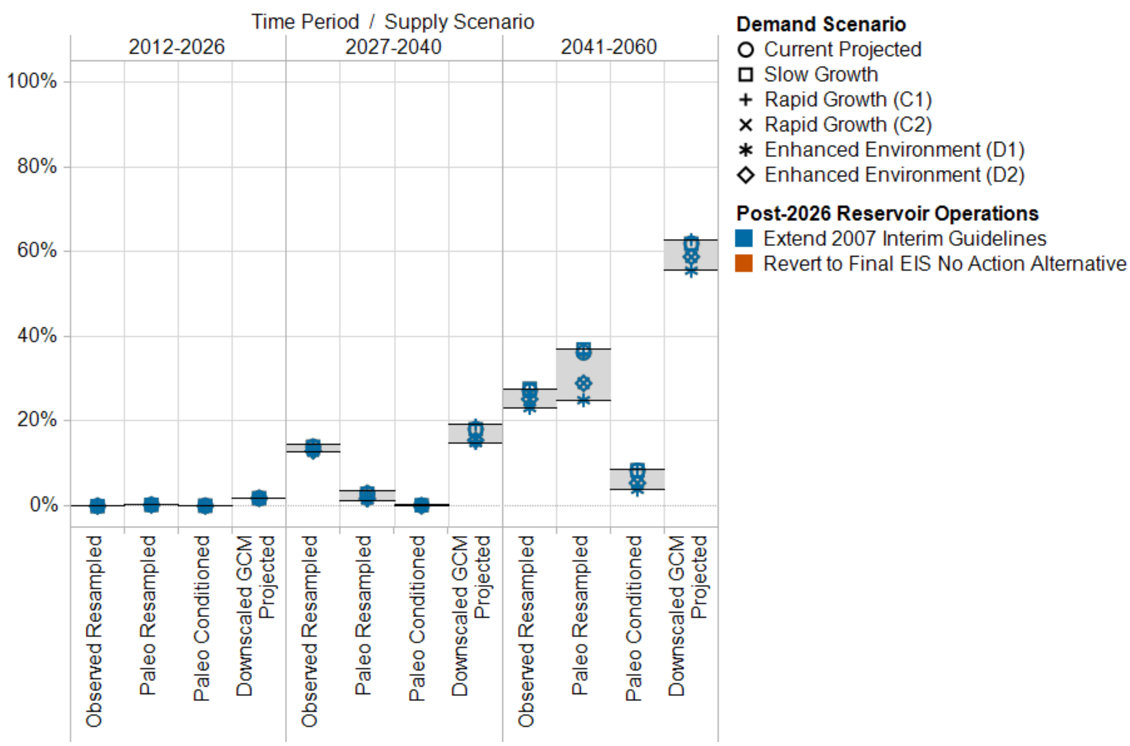


FIGURE G3-69
Percent of Traces Vulnerable Without Options and Strategies by Scenario and Time Period,
Hoover Dam to Davis Dam Flow Reductions Indicator Metric (greater than 845 thousand acre-feet (kaf) in any 1 year)

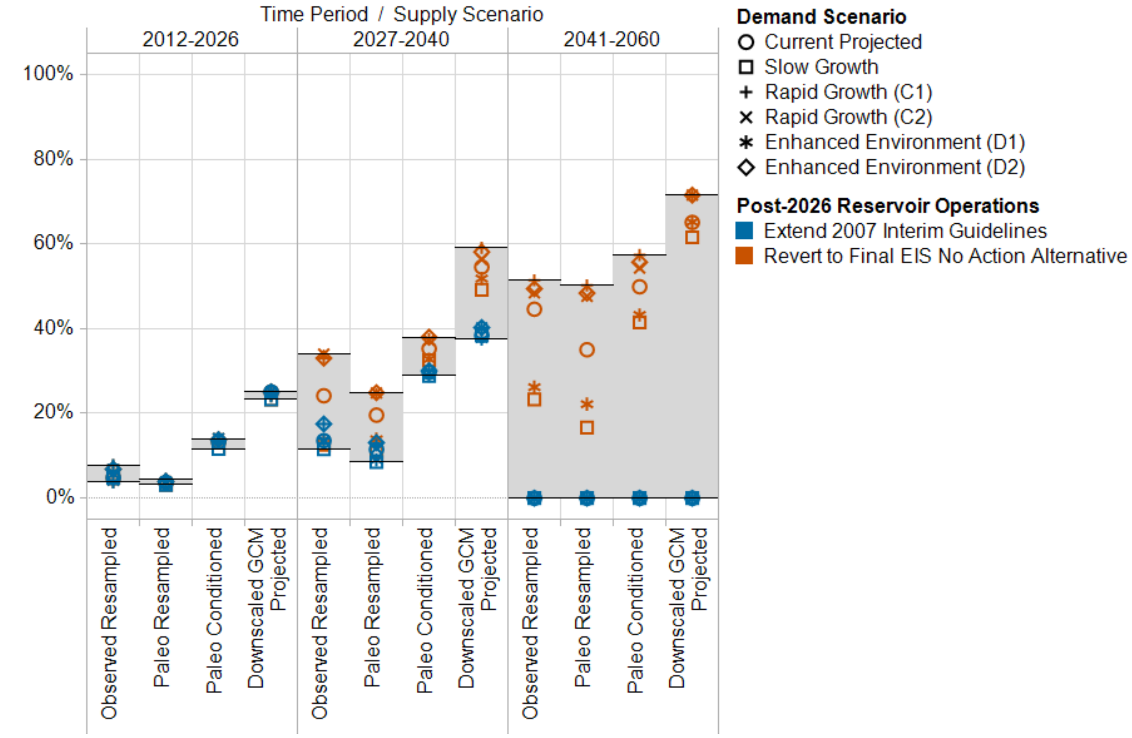
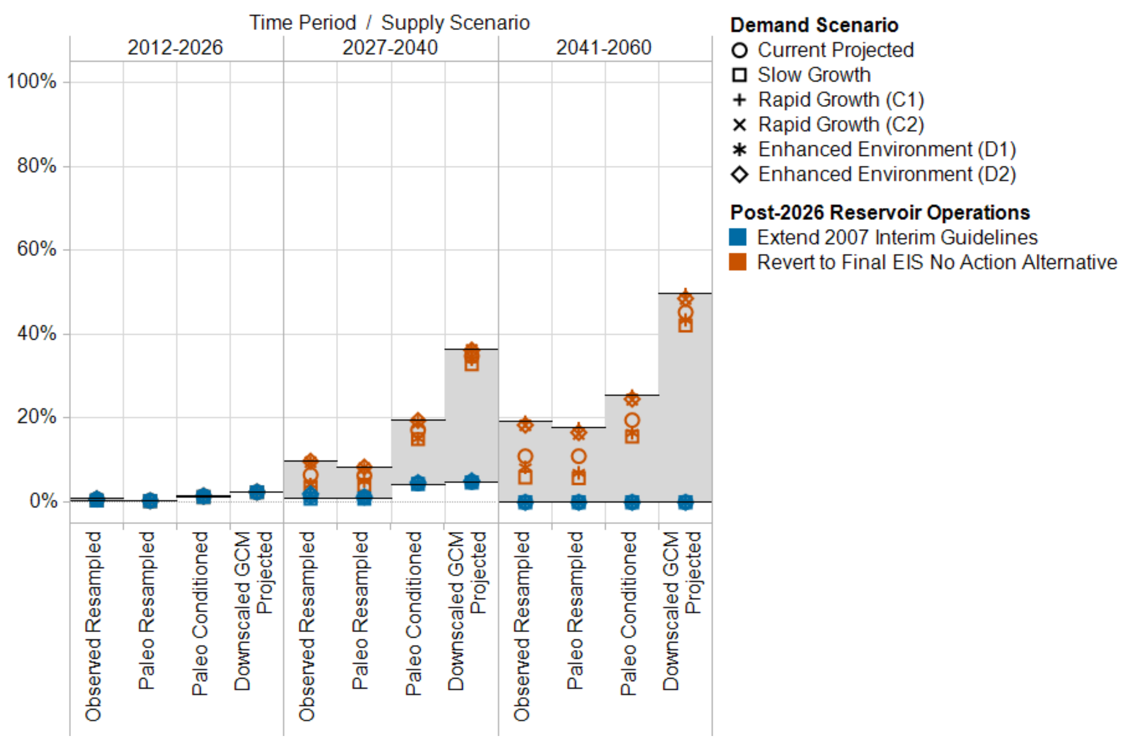


FIGURE G3-70
Percent of Years Vulnerable Without Options and Strategies by Scenario and Time Period,
Hoover Dam to Davis Dam Flow Reductions Indicator Metric (greater than 845 kaf in any 1 year)



3.2 Vulnerable Conditions

Additional detail regarding the vulnerable conditions analysis in the Study is provided below. Included are the statistical algorithm used to identify vulnerable conditions for each water delivery indicator metric as well asan example application of the algorithm. In addition, results from the vulnerable conditions analysis for each metric, including a summary table and scatter plot, and statistics summarizing the performance of the algorithm are provided.

3.2.1 Defining Vulnerable Conditions Using the Patient Rule Induction Method

The Study uses the Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) to identify vulnerable conditions. PRIM employs statistical algorithms to evaluate CRSS results and define different descriptions of vulnerable conditions. Each definition comprises a set of range restrictions for a set of variables. PRIM both (1) identifies those variables that are useful to describe vulnerabilities and (2) defines specific threshold values for each variable.

PRIM calculates possible descriptions of the vulnerabilities that differ based on the variables included and their assigned thresholds. PRIM computes three measures of merit to help determine how well a particular description explains vulnerable futures:

- **Coverage**: The fraction of all the vulnerable futures that have the vulnerable conditions. (A vulnerable future is one where the strategy does not meet its objectives.) Ideally, the vulnerable conditions would contain all the vulnerable futures and coverage would be 100 percent.
- **Density**: The fraction of all the futures in which the vulnerable conditions hold that are actually vulnerable (fail to meet their objectives). Ideally, all the futures within the vulnerable conditions would be vulnerable and density would be 100 percent.
- **Interpretability**: The ease with which users can understand the information conveyed by the vulnerable conditions. The number of conditions in the set serves as a proxy for interpretability. The smaller the number of conditions, the higher the interpretability.

These three measures are generally in tension with one another. For instance, choosing a set of conditions that explains more-vulnerable outcomes (higher coverage) will also likely explain a higher percentage of non-vulnerable outcomes (lower density).

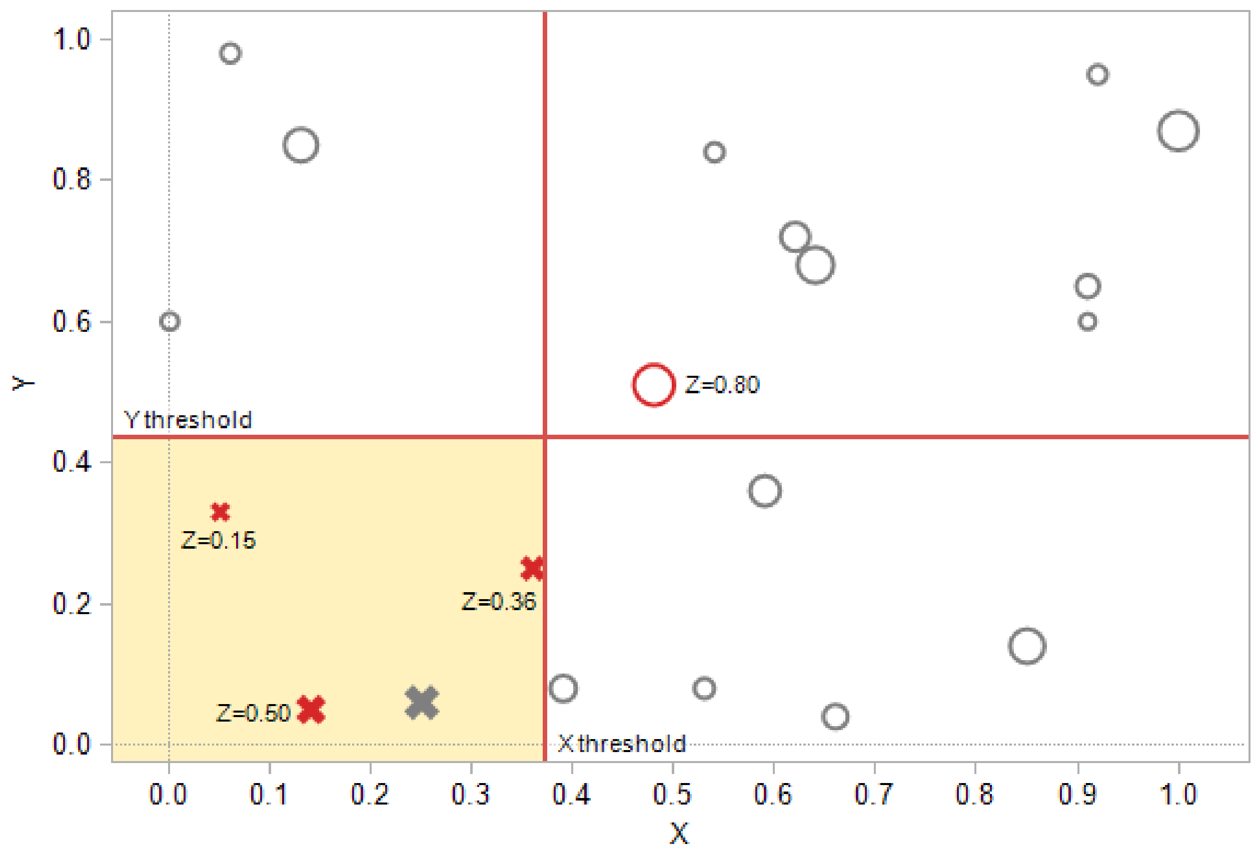
3.2.2 Patient Rule Induction Method Example

Consider a set of 20 simulations, 4 of which are considered vulnerable. Each simulation is defined by inputs (X, Y, and Z) that can take a value between 0 and 1, as shown in figure G3-71. Figure G3-72 shows each simulation result graphically with respect to inputs X (horizontal axis), Y (vertical axis), and Z (size of symbol). The red lines and yellow shading indicate the input range restrictions for one set of vulnerable conditions.

FIGURE G3-71
Example Input Values (X, Y, and Z) for 20 Simulations and Ranges Defining the Vulnerable Conditions

Red symbols indicate simulations that are vulnerable. X's indicate simulations described by the vulnerable conditions. Vertical red lines and yellow shading indicate ranges of one characterization of the vulnerable conditions.

FIGURE G3-72
Graphical Representation of 20 Simulation Outcomes with Thresholds for Vulnerable Conditions



Red symbols indicate simulations that are vulnerable. X's indicate simulations described by the vulnerable conditions. X and Y thresholds are shown by the red lines. The size of each point is defined by the Z variable. The yellow shaded region represents the region of the input space that defines the vulnerability. There is no restriction on the Z variable for this vulnerability description.

PRIM can define different vulnerable conditions for these results. Table G3-1 lists the definition, coverage, and density results for four different sets of vulnerable conditions. The conditions shown in figure G3-71, for example, restricts the X and Y variables and describe three of the four vulnerable simulations (75 percent coverage) and three out of the four simulations described by the definition are vulnerable (75 pecent density). The other vulnerability definitions shown in table G3-1 show the tradeoff between coverage, density, and number of restrictions. PRIM presents the user with a set of vulnerable conditions on the frontier of the density coverage trade-off, and the user then selects the set of conditions most appropriate for the analysis.

TABLE G3-1
Example Statistics for Several Different Example PRIM Vulnerable Conditions

Definition	Coverage	Density
X < 0.2 Y < 0.4	2/4 = 50%	2/2 = 100%
X < 3.75 **Y < 4.35**	**3/4 = 75%**	**3/4 = 75%**
X < 3.75 Y < 4.35 Z < 0.6	3/4 = 75%	3/3 = 100%
X < 0.5 Y < 0.55	4/4 = 100%	4/6 = 67%

Note: Shaded row describes results shown in figures G3-71 and G3-72.

3.2.3 Vulnerable Conditions Without Additional Options and Strategies

Results from the analysis of vulnerable conditions in a future without additional options and strategies are shown in table G3-2 for all water delivery indicator metrics. For quantitative inputs (e.g., annual mean natural flow at Lees Ferry from 2012 to 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 to 2060, for example, ranges from 10 to 18.5 million acre-feet per year (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 to 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 G3-2
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric

			System Condition				
Indicator Metric	**Description**	**Vulnerable Traces (2012–2060)**	**Annual Mean Natural Flow at Lees Ferry (2012–2060) (maf)**		**1-Year Minimum Annual Natural Flow at Lees 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%	Not Applicable	–	8.3 3 12	–	Not Applicable
			System Condition				
Indicator Metric	**Description**	**Vulnerable Traces**	**Annual Mean Natural Flow at Lees Ferry (2012–2060) (maf)**		**Driest 8-Year Period of Annual Mean Flow at Lees 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 10 18.5	AND	11.2 7 15.5	–	Not Applicable
Lake Mead Pool Elevation	*Long-term average flow below 15 maf and 8-year drought below 13 mafy*	47%	15 10 18.5	AND	13 7 15.5	AND	2007 Interim Guidelines
			14.6 10 18.5	AND	13 7 15.5	AND	Revert to 2007 Interim Guidelines Final EIS No Action Alternative

TABLE G3-2
Vulnerable Conditions Defined for Each Water Delivery Indicator Metric

Indicator Metric	Description	Vulnerable Traces (2012–2060)	System Condition				
			Annual Mean Natural Flow at Lees Ferry (2012–2060) (maf)		1-Year Minimum Annual Natural Flow at Lees Ferry (2012–2060) (maf)		Post-2026 Operation of Lakes Powell and Mead
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 (scale 10 – 18.5)	OR	11.8 (scale 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 No Action Alternative		16.1 (scale 10 – 18.5)	OR	14.2 (scale 7 – 15.5)	AND	Revert to 2007 Interim Guidelines Final EIS No Action 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%	16.0 (scale 10 – 18.5)	OR	11.6 (scale 7 – 15.5)	AND	2007 Interim Guidelines
	Long-term average flow below 16.1 mafy, with 8-year drought below 14.2 mafy and 2007 No Action Alternative		16.1 (scale 10 – 18.5)	OR	14.2 (scale 7 – 15.5)	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	Not Applicable	100%	Not Applicable				

Statistics from the PRIM analysis are summarized in table G3-3. In general, the algorithm provided usable results in all cases, with greater than 80 percent coverage and density for all but one metric and a small number of restricted dimensions to allow for better interpretation. It should be noted, however, that the large proportion of vulnerable traces for the four shortage metrics complicate the overall analysis, because it is more difficult to distinguish conditions producing vulnerability when a vulnerability occurs in a large majority of the CRSS simulations.

TABLE G3-3
Coverage and Density Results for Water Delivery Vulnerable Conditions in Baseline

Indicator Metric	Vulnerable Traces	Coverage	Density
Upper Basin Shortage	86%	98%	95%
Lee Ferry Deficit	19%	85%	87%
Lake Mead Pool Elevation	47%	86%	72%
Lower Basin Shortage (1 maf over 2 years)	86%	99%	90%
Lower Basin Shortage (1.5 maf over 5 years)	92%	100%	94%
Remaining Demand Above Lower Division States' Basic Apportionment	100%	100%	100%

In the visual summaries below, each point represents one trace in the analysis, characterized according to long-term mean annual flow (y-axis) or mean annual flow during the driest 8-year period (x-axis). Red points indicate traces with at least one vulnerability during the simulation, while 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, while each trace outside is marked with an o.

Figures G3-73 through G3-78 present scatter plots that provide a visual summary of the vulnerable condition for each water delivery indicator metric.

FIGURE G3-73
Scatter Plot of Vulnerable Conditions for the Upper Basin Shortage (exceeds 25% of requested depletion in any 1 year) Indicator Metric Without Options and Strategies

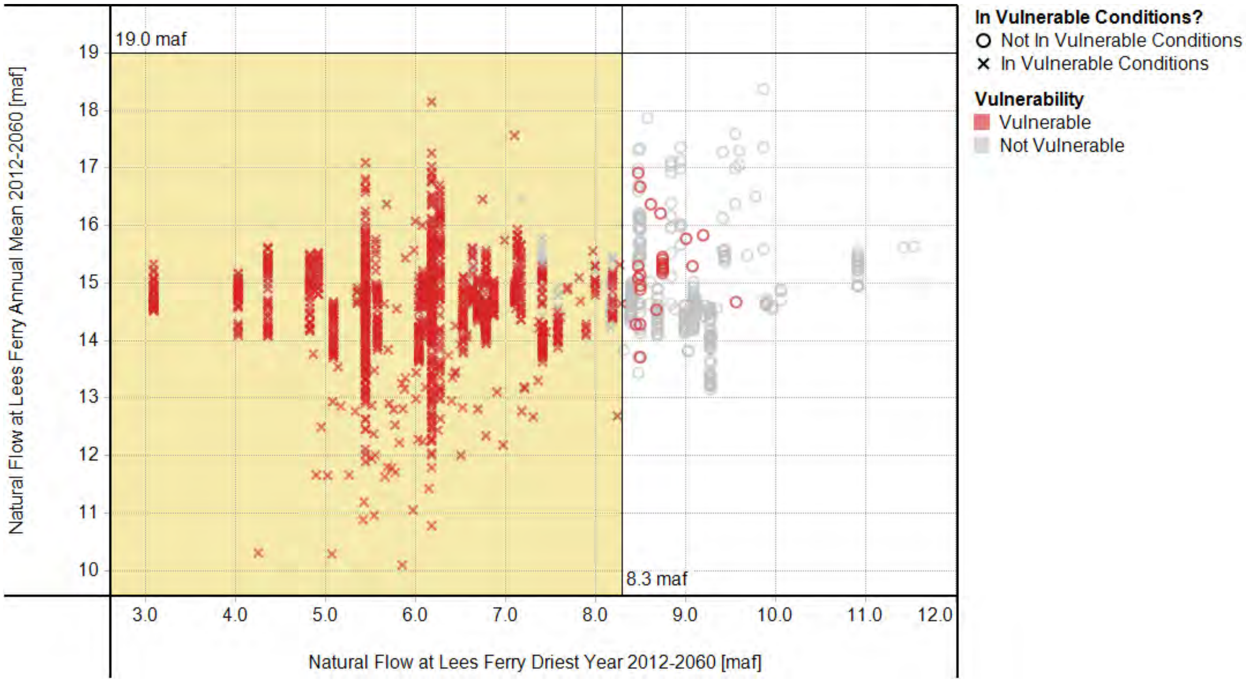


FIGURE G3-74
Scatter Plot of Vulnerable Conditions for the Lee Ferry Deficit (exceeds zero in any 1 year) Indicator Metric Without Options and Strategies

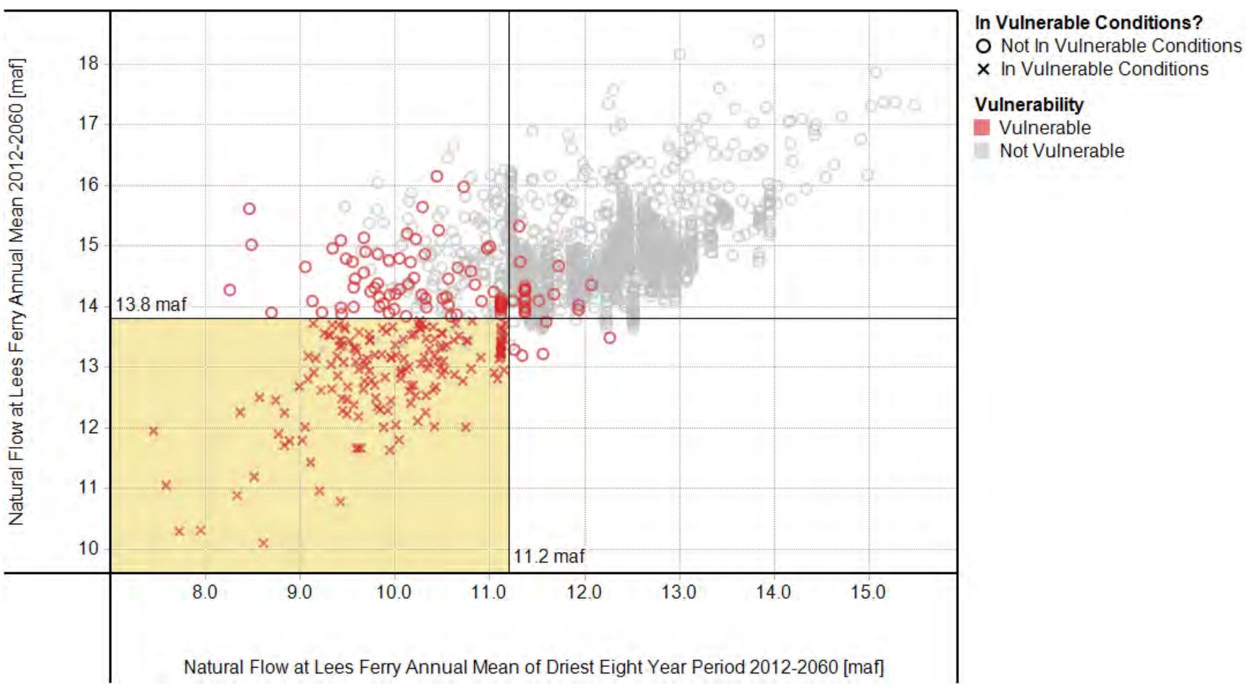


FIGURE G3-75
Scatter Plot of Vulnerable Conditions for the Lake Mead Pool Elevation <1,000 feet msl (below 1,000 feet msl in any 1 month) Indicator Metric Without Options and Strategies

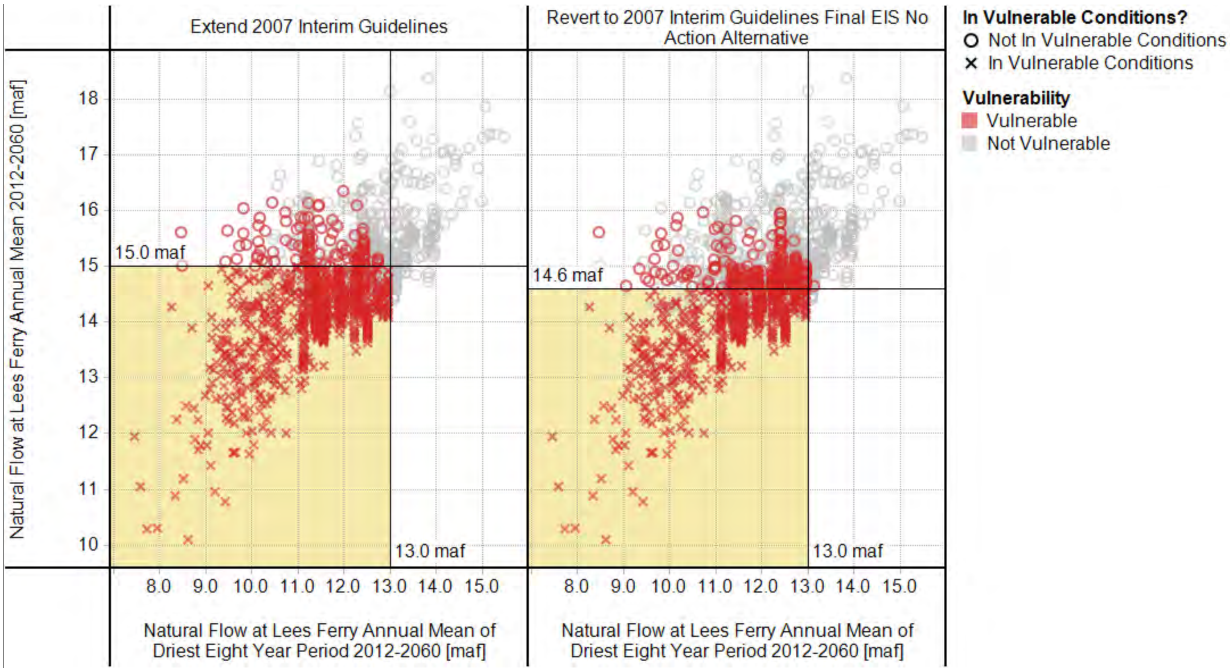


FIGURE G3-76
Scatter Plot of Vulnerable Conditions for the Lower Basin Shortage (exceeds 1 maf over any 2-year window) Indicator Metric Without Options and Strategies

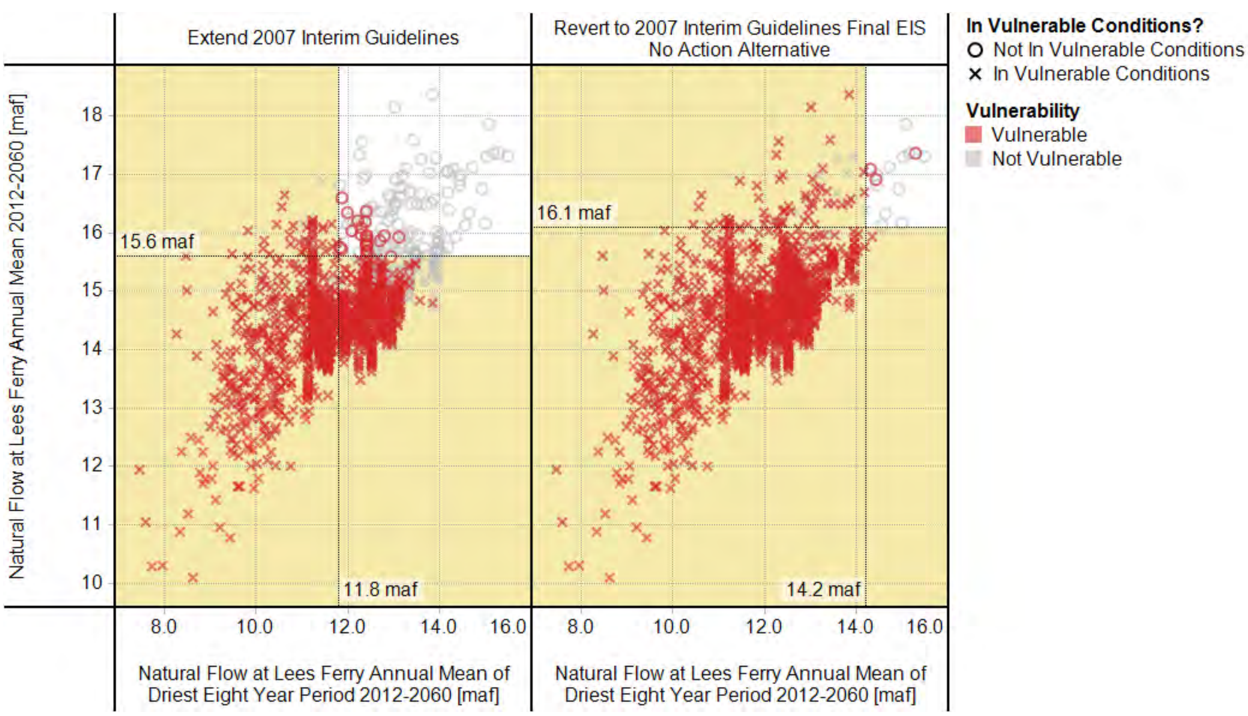


FIGURE G3-77
Scatter Plot of Vulnerable Conditions for the Lower Basin Shortage (exceeds 1.5 maf over any 5-year window) Indicator Metric Without Options and Strategies

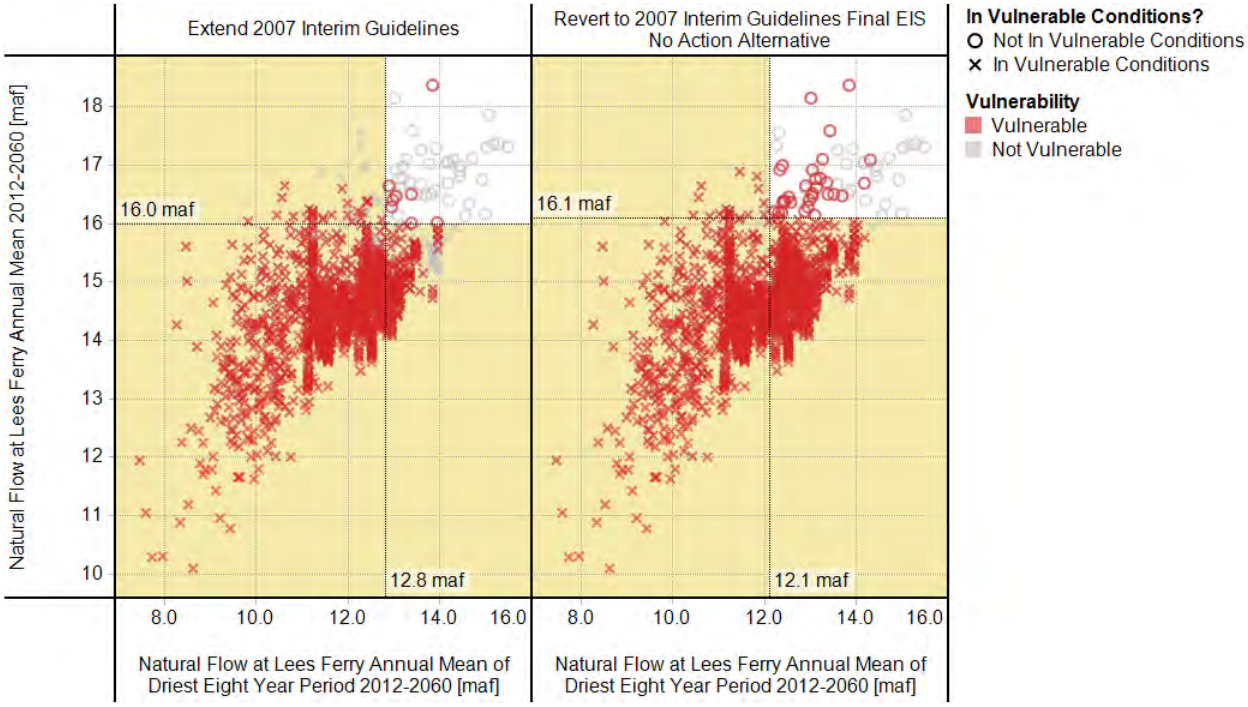
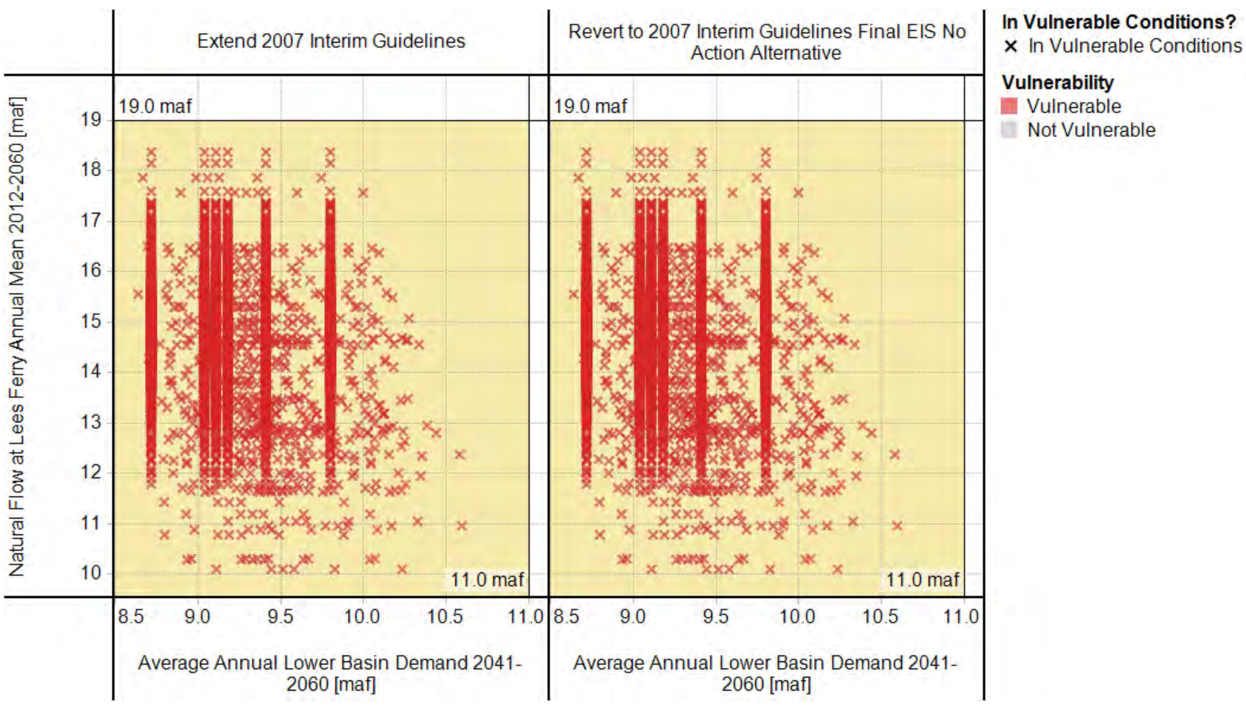


FIGURE G3-78
Scatter Plot of Vulnerable Conditions for the Remaining Demand Above Lower Division States' Basic Apportionment (exceeds moving threshold in any 1 year) Indicator Metric Without Options and Strategies



4.0 Evaluation of System Reliability with Options and Strategies

4.1 Allocating Benefits from Options to the System Versus Regions

The system reliability modeling with options and strategies first aimed to quantify the range of action that might be required to reduce/mitigate system vulnerabilities meeting demand of the Lower Division States above 7.5 maf only during Surplus Conditions. For this assessment, *Portfolio A* was evaluated to estimate the level of system improvement that could be achieved were most options implemented.

The water demand assesessment confirmed that the Lower Division States have demand above their basic apportionment of 7.5 maf. As a result, further investigation was necessary to quantify the potential range of option magnitudes needed to address demands within and beyond Lower Division States' basic apportionment. As with the system benefit assessment, the same *Portfolio A* was evaluated to estimate the amount of demand above Lower Division States' basic apportionment that could be met were most options implemented.

To implement these two approaches, CRSS used two sets of assumptions aimed at evaluating option implementation for maximum system benefit:

- Options are implemented according to the static schedule (implemented as soon as options is available)
- Demands above Lower Division States' basic apportionment are only met during Surplus Conditions or via implementation of local options such as conservation (the effect of conservation is that more demand can be met with a given delivery, and some of the new demand satisfied would otherwise be considered demand above Lower Division States' basic apportionment).

The following alternative set of assumptions were used to evaluate option implementation that maximized meeting demand above Lower Division States' basic apportionment:

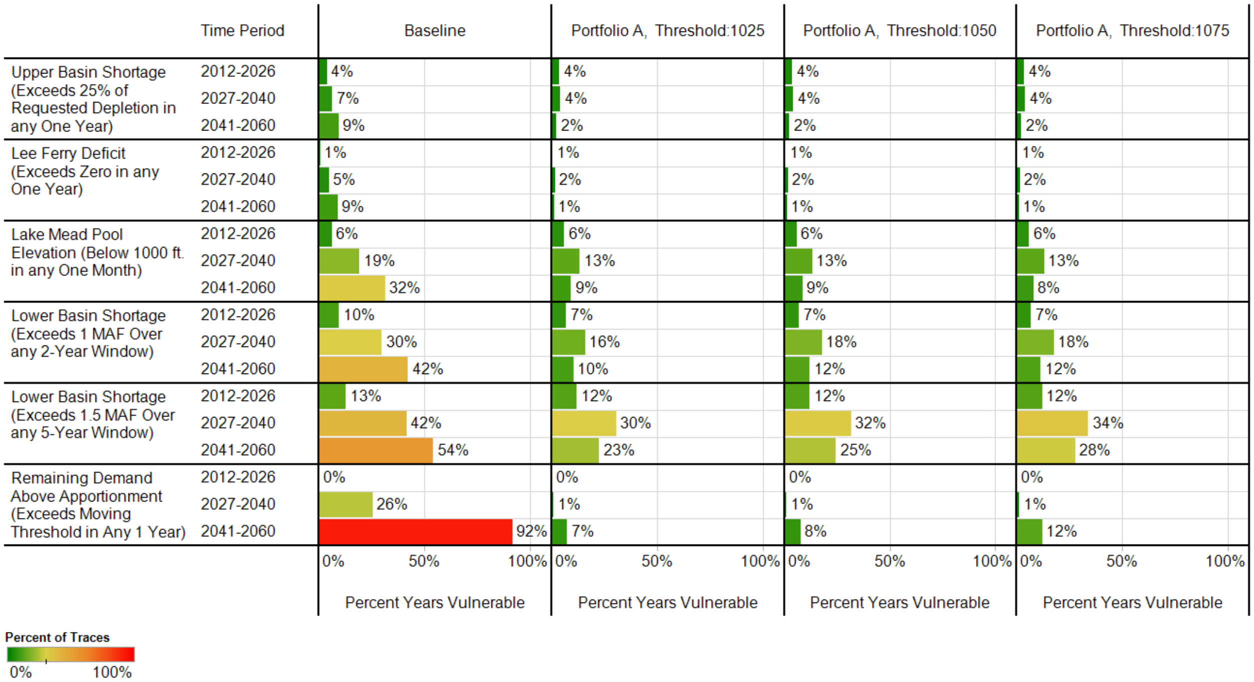
- Options are implemented according to the static schedule and whenever possible, yield is directed toward meeting demands above Lower Division States' basic apportionment.
- If demands above Lower Division States' basic apportionment are completely satisfied, any remaining option yield is put towards system benefit.

Any Basin-wide strategy must take into consideration that the Lower Division States have demand above 7.5 maf when aiming to reduce system vulnerabilities. Thus, an approach was developed in which demands above Lower Division States' basic apportionment and system resources both benefit from option yield. Such a situation could be realized by various avenues. One simple approach is to assume that option yield would first be used to replenish Lake Mead to some level. Beyond that, remaining water would be delivered to demands above Lower Division States' basic apportionment. By solidifying a storage base, future risk is mitigated while benefitting other system resources such as hydropower or water deliveries. As discussed earlier, numerous mechanism/threshold combinations could be crafted to achieve a balance between system and demand above Lower Division States' basic apportionment benefit. In reality, this would likely to be determined by a host of factors yet to be identified, such as option specifics, realized demand, and project funding. Owing to the aforementioned uncertainty and in the interest of simplicity, it was concluded that a minimum pool elevation at Lake Mead would need to be maintained before option yield could benefit demands above Lower Division States' basic apportionment. Analysis and selection of the minimum pool elevation threshold is provided in the following section. It is important to emphasize that the policy modeled here is to demonstrate a concept only.

4.1.1 System vs. Regional Benefit Threshold Sensitivity Analysis

To inform the selection of the pool elevation threshold in the above mentioned hybrid, system/regional benefit framework, a sensitivity analysis was performed. The analysis consisted of running CRSS with a range of potential thresholds for a small subset of the quantified supply, demand, and reservoir operations scenario combinations (specifically, Downscaled GCM (general circulation model) Projected and Observed Resampled hydrologies with the Current Projected demand scenario and the 2007 Interim Guidelines extended). Elevations for potential thresholds were identified matching the current shortage tier elevations (Reclamation, 2007) of (1,025 feet, 1,050 feet, and 1,075 feet msl). Overall, results showed minimal sensitivity between the three values considered. Figure G3-79 shows water supply indicator metric vulnerabilities for the Baseline and three thresholds. Portfolio capacity to reduce the Lake Mead below 1,000 feet msl vulnerability was essentially the same across all thresholds. Shortage vulnerability frequency actually increases slightly with higher thresholds. This is because changing to system benefit precludes the option water from being available to offset shortages. In contrast, the lower thresholds allow water to be available longer to offset shortages (recall that option water delivered to each state first meet any shortage volumes then demands above Lower Division States' basic apportionment). For the remaining demand above Lower Division States' basic apportionment vulnerability, all three thresholds show strong improvements. The lowest threshold does show the greatest improvement because more option water is available to meet those demands. However, threshold selection does not appear to be significantly altering portfolio performance. In light of these observations, the threshold was selected to be 1,050 feet msl. This elevation allows for some option yield to address shortage volumes (between pool elevations 1,050 and 1,075 feet msl), but does not wait until mandatory reconsultation (pool elevation 1,025 feet msl) to switch to a system benefit (Reclamation, 2007).

FIGURE G3-79
Water Delivery Indicator Metrics; Baseline and *Portfolio A* results for Downscaled GCM and Observed Resampled Scenario Hydrologies with Current Projected Demand Scenario and 2007 Interim Guidelines extended.



Note: The three thresholds considered for system versus regional benefit were Lake Mead at 1,025 feet, 1,050 feet, and 1,075 feet msl.

4.2 Signposts

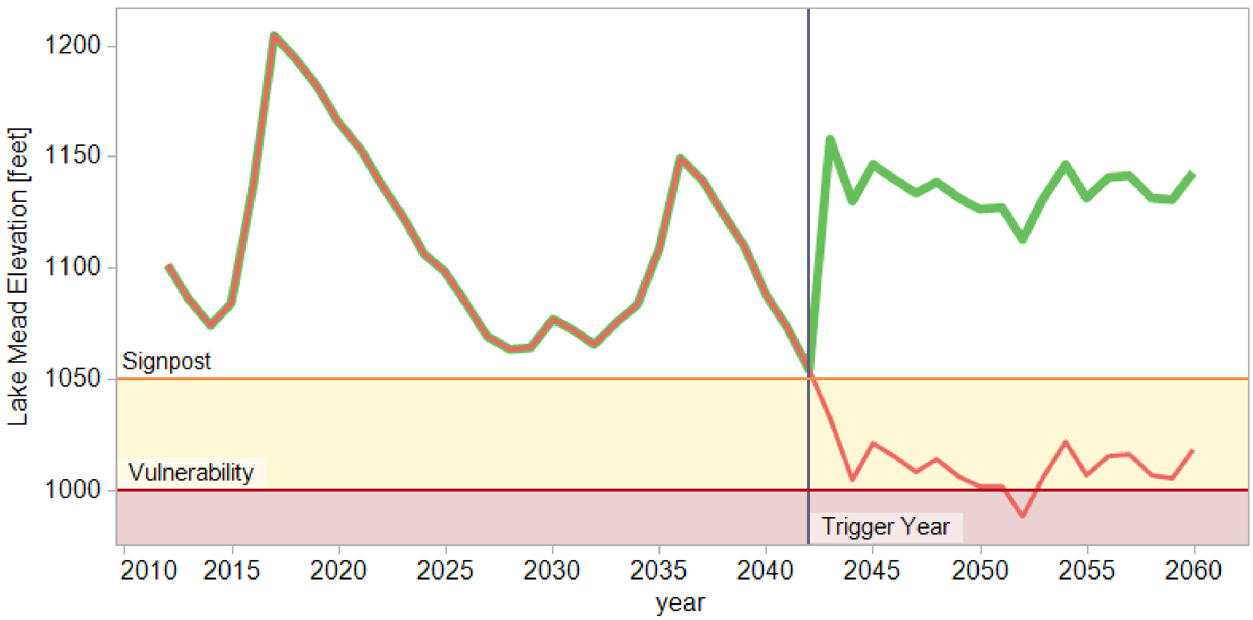
Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies describes the development of dynamic portfolios for the study. In contrast to static investments, dynamic portfolios are designed to be adaptive to changing conditions in the Basin and to invest in additional options when vulnerabilities become more likely. Key to these dynamic portfolios are signposts based on observable conditions that occur in advance of a one or more water delivery vulnerabilities. The development of these signposts is described below. The discussion includes a further description of signposts and an example of signpost implementation. The results from the analysis performed using CRSS simulations are provided to identify effective and accurate signposts occurring in advance of water delivery vulnerabilities.

4.2.1 Signpost Implementation Example

In the Study, signposts were developed only for water delivery vulnerabilities that were used to trigger option implementation. 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.

For example, the 5-year running mean natural streamflow at Lees Ferry, coupled with the current-year level of Lake Mead, could be an effective signpost to project those futures in which Lake Mead pool elevation is vulnerable. When Lake Mead is below a certain level and natural streamflow appears to be consistently low, options to address an impending vulnerability could be implemented. Figure G3-80 shows a simple example of a signpost successfully triggering a new option in 2043 to prevent a Lake Mead pool elevation vulnerability (pool elevation below 1,000 feet msl) from occurring later in the simulation.

FIGURE G3-80
Illustration of a Signpost that Triggers Augmentation to Prevent Lake Mead Levels from Dropping Below 1,000 Feet msl



The red line represents Lake Mead elevations for a single CRSS simulation under the Baseline management. The green line reflects augmentation that increases Lake Mead levels. The signpost is set at a level of 1,050 feet msl. As a simple approximation, the augmentation adds 100 feet to Lake Mead levels each year after signpost is triggered (2043).

4.2.2 Signpost Selection

To choose signposts for the dynamic portfolios, a large set of potential signposts (around 200) for the five of the six water delivery indicator metrics were first generated.[2] Each signpost is a unique combination of streamflow and reservoir elevation level thresholds, drawn from a wide range of possible values. For each metric, the signpost was evaluated in terms of how well it predicts vulnerabilities and non-vulnerabilities. A *true positive* calculation for a signpost reports the percent of years with a vulnerability in which the signpost is triggered in advance by a specified amount of lead time. A given signpost can be evaluated for different lead times, for example, between 3 and 10 years. The *true negative* rate for a signpost, conversely, reports the percent of futures with no vulnerability in which the signpost is also not measured. Lead times do not affect the true negative rates. Larger numbers for both these rates indicate more useful signposts for water planner. A low true positive rate would cause under investment in options, while a low true negative rate would likely result in over-investment.

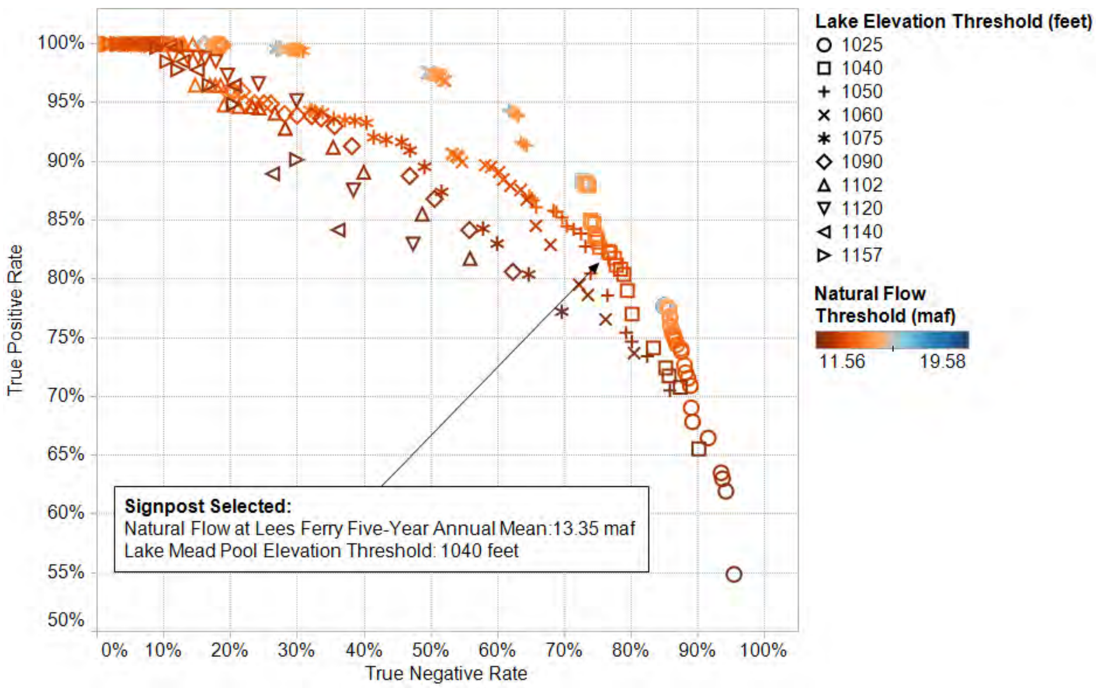
[2] No leading signpost was developed for remaining demand above apportionment, because all traces produce a vulnerability for this indicator metric at some point in the simulation in a future without additional options and strategies. Instead, the amount of remaining demand above apportionment itself serves as a signpost for future vulnerability, triggering options when demand is with 100 kaf of the vulnerability threshold.

For example, Figure G3-81 shows the signpost analysis results for the Lake Mead vulnerability for a 5-year lead time. Each point represents one possible signpost, and each signpost has two components:

- The Lake Mead pool elevation threshold (differentiated with symbols)
- The 5-year running mean natural streamflow threshold (differentiated by color)

Charts such as this one were reviewed to select signposts that struck a favorable balance between true positive and true negative rates. In general, this involved selecting a point along the upper-right edge of the results (the optimal frontier).

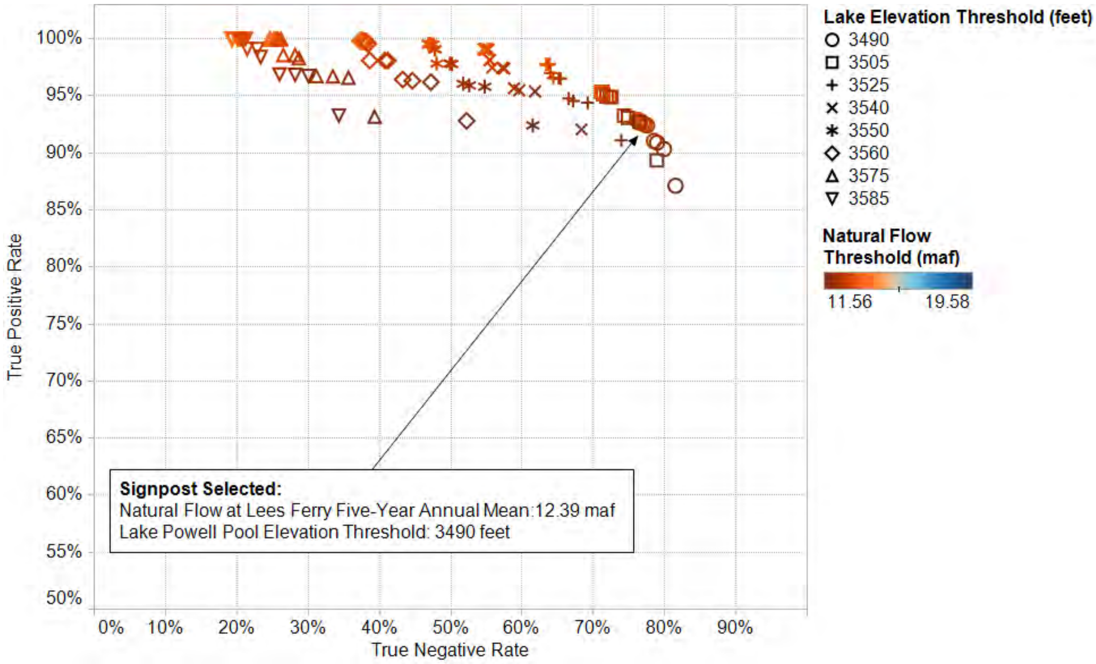
FIGURE G3-81
True Positive/True Negative Tradeoff Curve for Possible Lake Mead Pool Elevation <1,000 feet msl Signposts



Each point is one possible signpost, defined here as unique combination of a threshold for 5-year running mean natural streamflow at Lees Ferry (colors) and a threshold for Lake Mead pool elevation (symbols), measured 3 years prior to the vulnerability occurring. True positive and true negative rates are shown on the y- and x-axis, respectively.

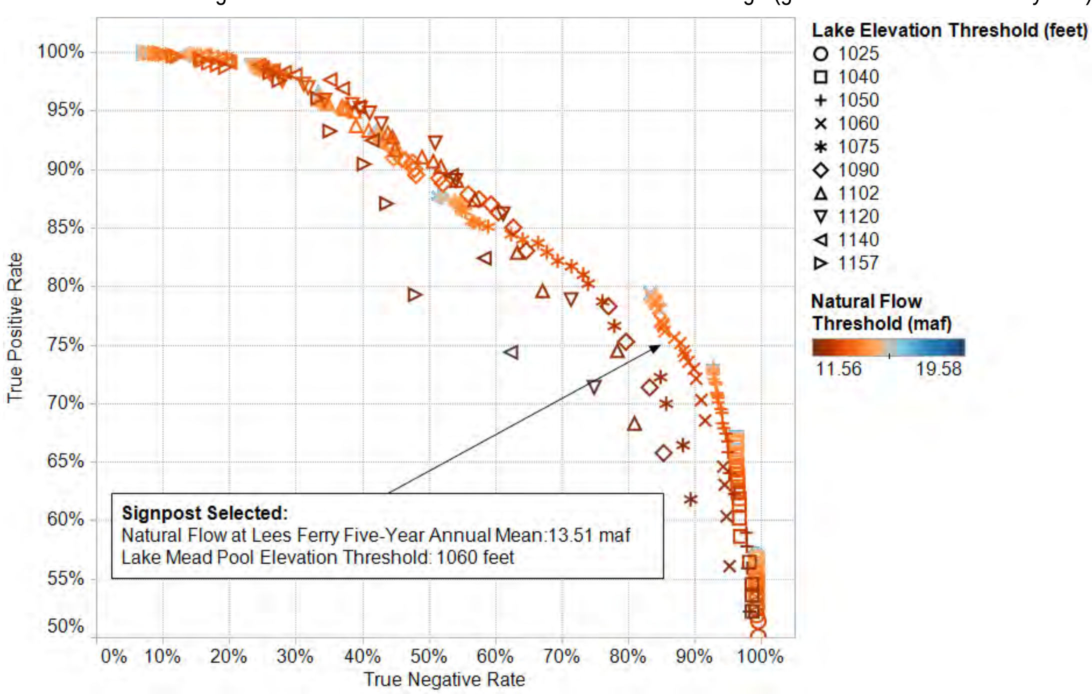
Similar scatter plots used to develop signposts for the other water delivery indicator metrics are shown in the figures G3-82 through G3-84.

FIGURE G3-82
True Positive/True Negative Tradeoff Curve for Possible Lee Ferry Deficit Signposts



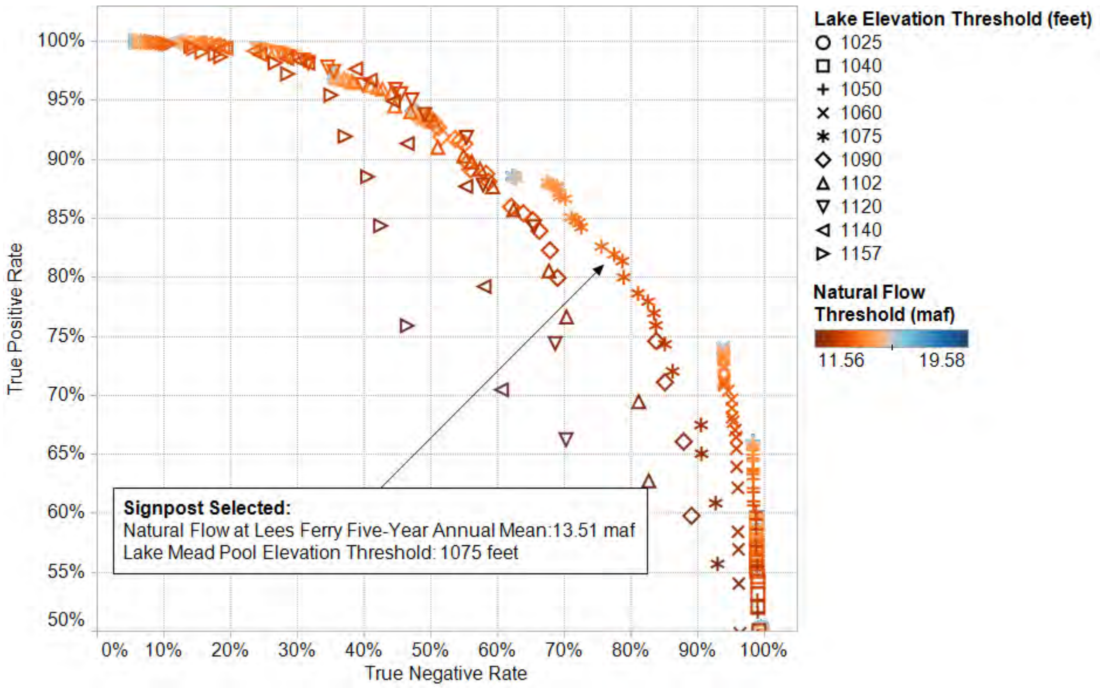
Each point is one possible signpost, defined here as unique combination of a threshold for 5-year running mean natural streamflow at Lees Ferry (colors) and a threshold for Lake Powell pool elevation (symbols), measured 5 years prior to the vulnerability occurring. True positive and true negative rates are shown on the y- and x-axis, respectively.

FIGURE G3-83
True Positive/True Negative Tradeoff Curve for Possible Lower Basin Shortage (greater than 1 maf over 2 years) Signposts



Each point is one possible signpost, defined here as unique combination of a threshold for 5-year running mean natural streamflow at Lees Ferry (colors) and a threshold for Lake Mead pool elevation (symbols), measured 3 years prior to the vulnerability occurring. True positive and true negative rates are shown on the y- and x-axis, respectively.

FIGURE G3-84
True Positive/True Negative Tradeoff Curve for Possible Lower Basin Shortage (> 1.5 maf over 5 years) Signposts



Each point is one possible signpost, defined here as unique combination of a threshold for 5-year running mean natural streamflow at Lees Ferry (colors) and a threshold for Lake Mead pool elevation (symbols), measured 3 years prior to the vulnerability occurring. True positive and true negative rates are shown on the y- and x-axis, respectively.

4.3 Study Portfolio Evaluation

This section includes selected additional results from CRSS with options and strategies not otherwise provided in Technical Report G. Included are subsections showing the potential changes in system response variables, reductions in water delivery vulnerabilities with portfolios implemented, and implemented options, respectively.

4.3.1 System Response Variables

Figures G3-85 to G3-102 show system response variable results from CRSS modeling with options and strategies. These variables include river flow, reservoir storage, reservoir release, reservoir pool elevation, shortage, surplus, and energy production. Percentile time series plots and cumulative distribution functions used to present these results show scenarios combined on a by portfolio basis.

FIGURE G3-85
10th, 50th, 90th Percentiles for Annual Flow of Green River at Green River, Utah, With Options and Strategies

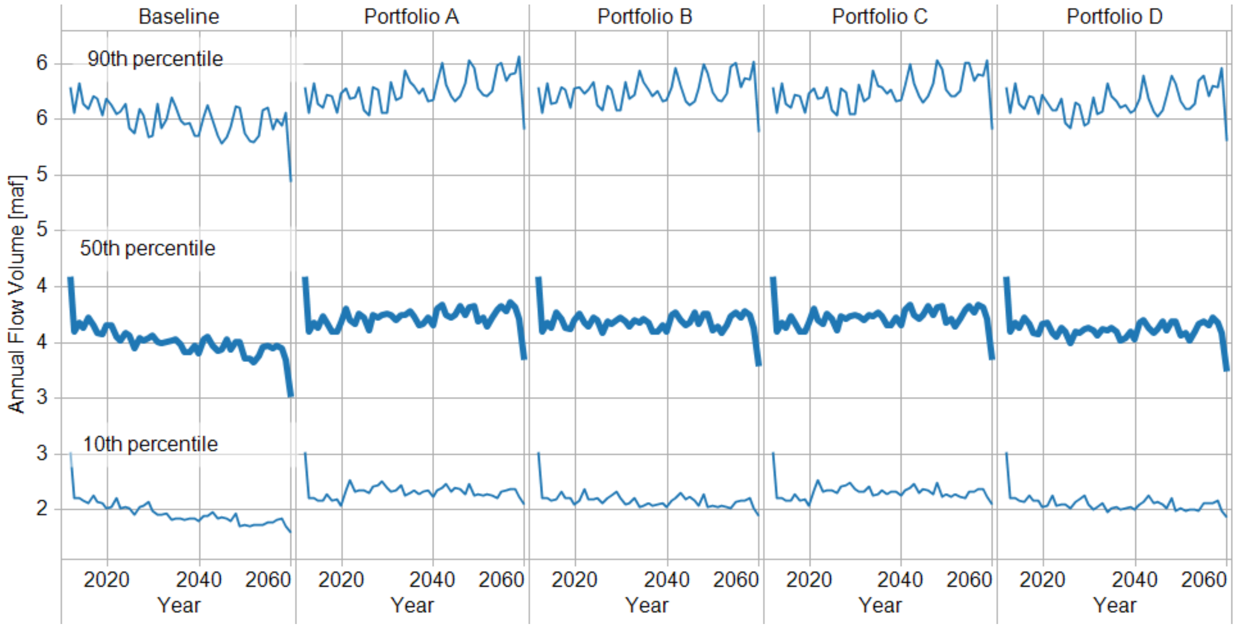


FIGURE G3-86
10th, 50th, 90th Percentiles for Annual Flow of Colorado River near Cisco, Utah, With Options and Strategies

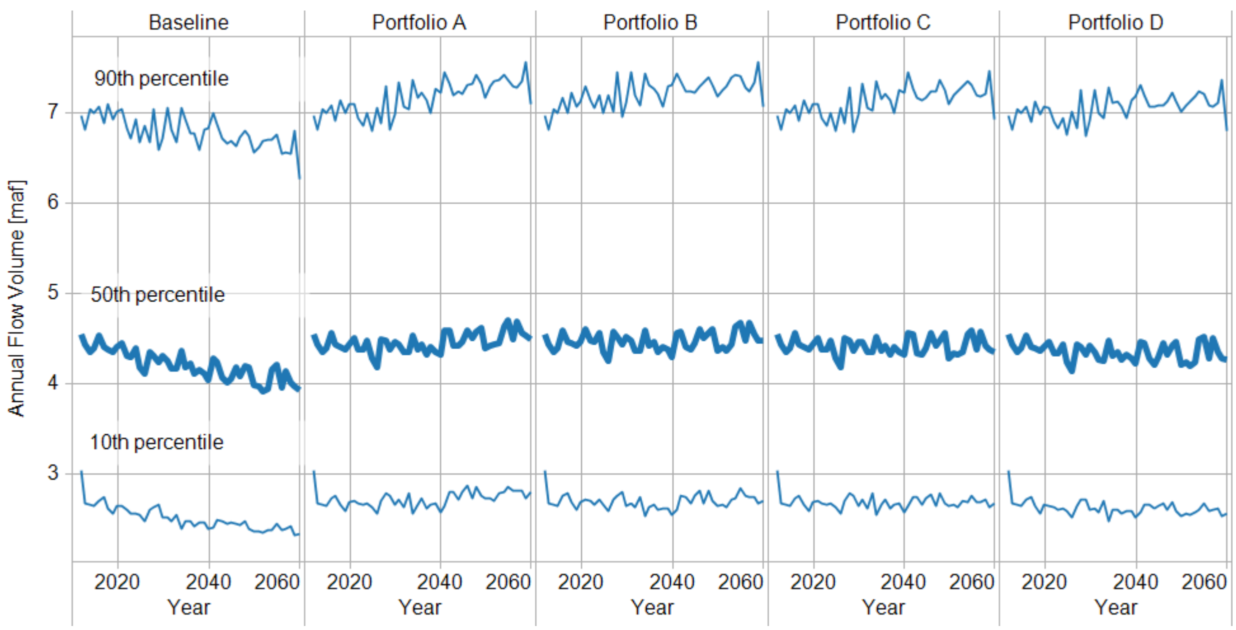


FIGURE G3-87
10th, 50th, 90th Percentiles for Annual Flow of San Juan River near Bluff, Utah, With Options and Strategies

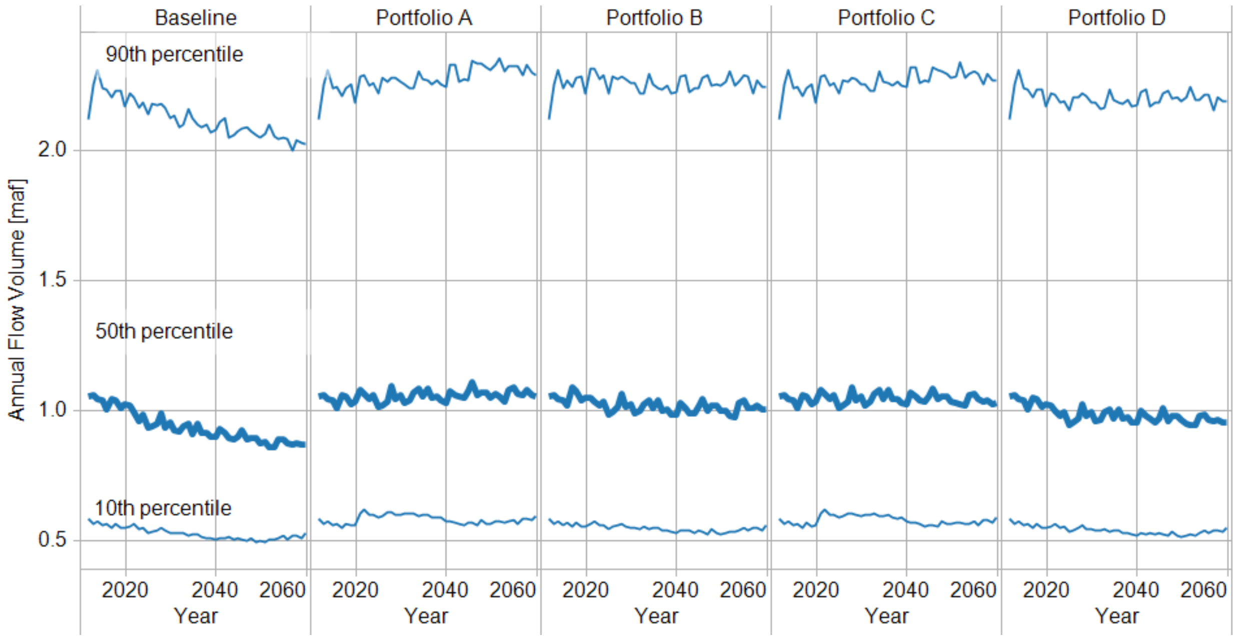


FIGURE G3-88
10th, 50th, 90th Percentiles for Total Storage Above Lake Powell With Options and Strategies

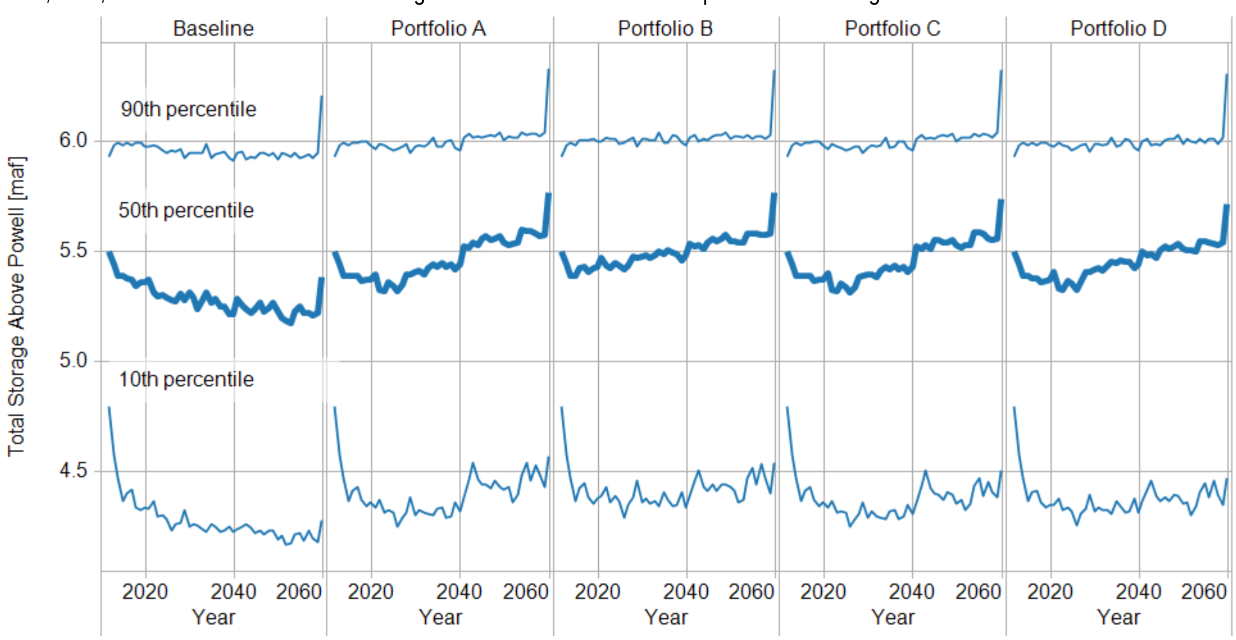


FIGURE G3-89
10th, 50th, 90th Percentiles for Upper Basin Annual Shortage with Options and Strategies

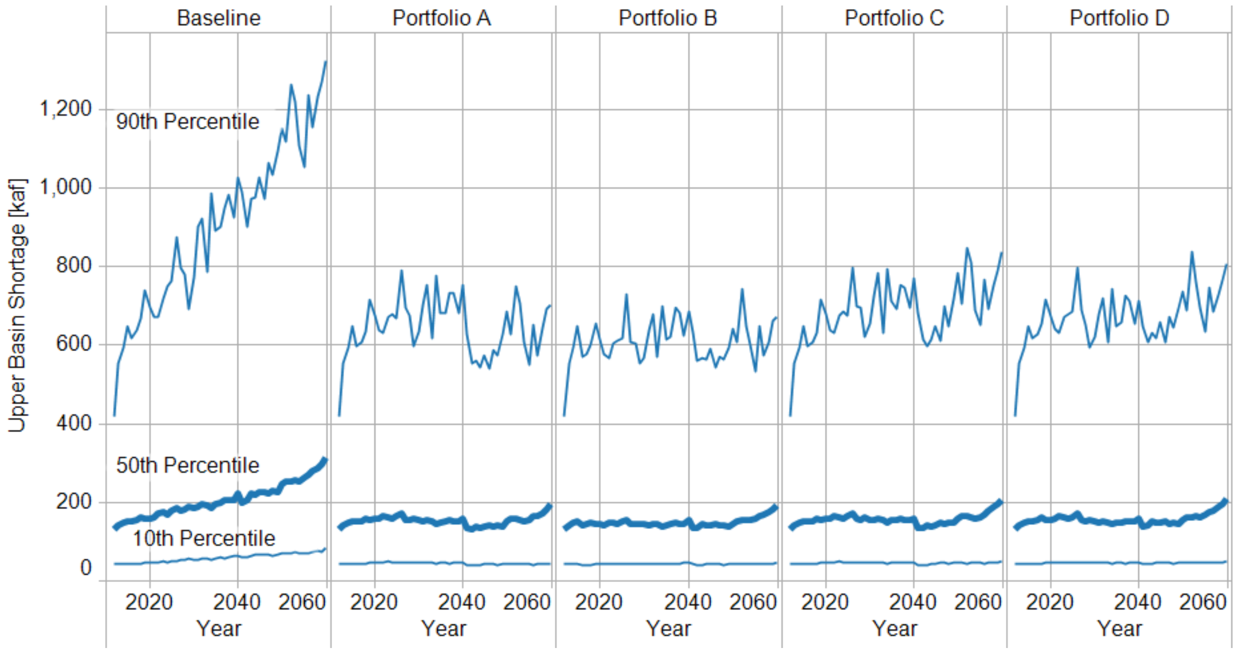


FIGURE G3-90
10th, 50th, 90th Percentiles for Lake Powell Pool Elevation With Options and Strategies

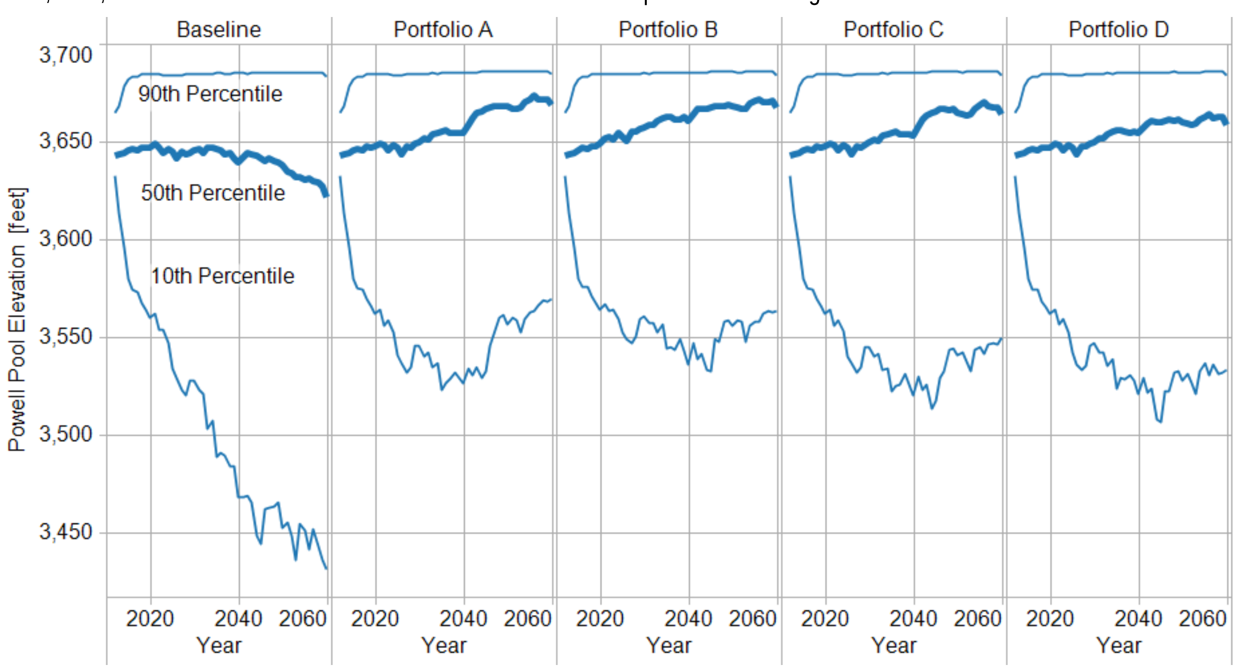


FIGURE G3-91
10th, 50th, 90th Percentiles for Total Upper Basin Energy Production with Options and Strategies

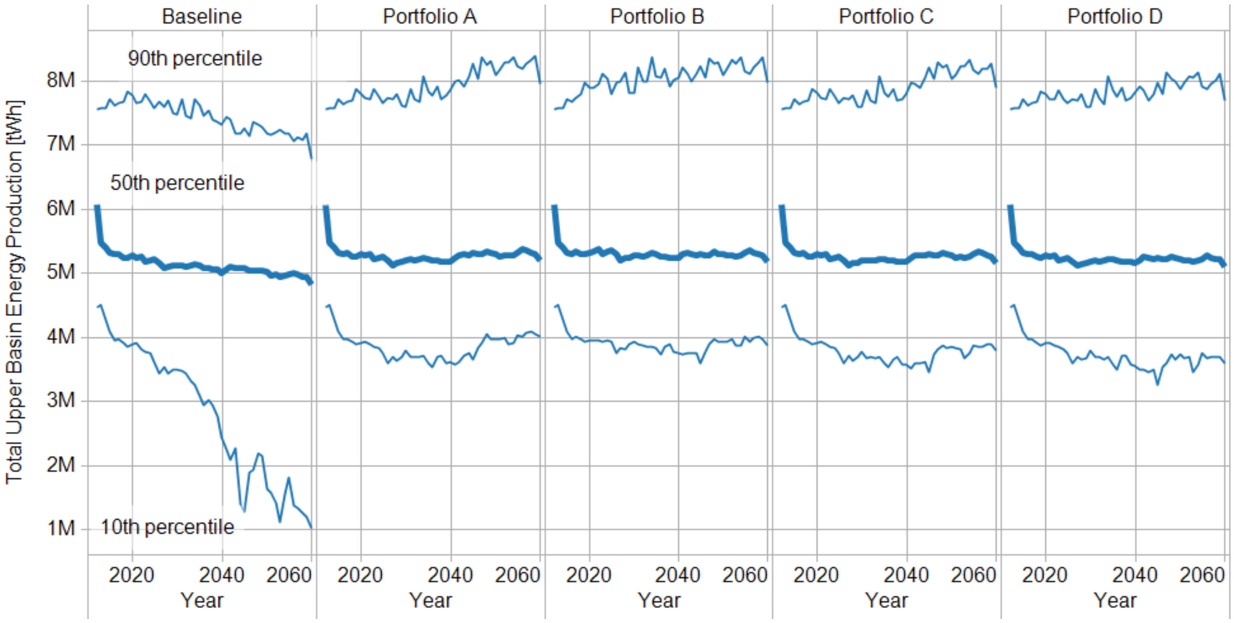


FIGURE G3-92
Cumulative Density Function for Total Upper Basin Energy Production With Options and Strategies

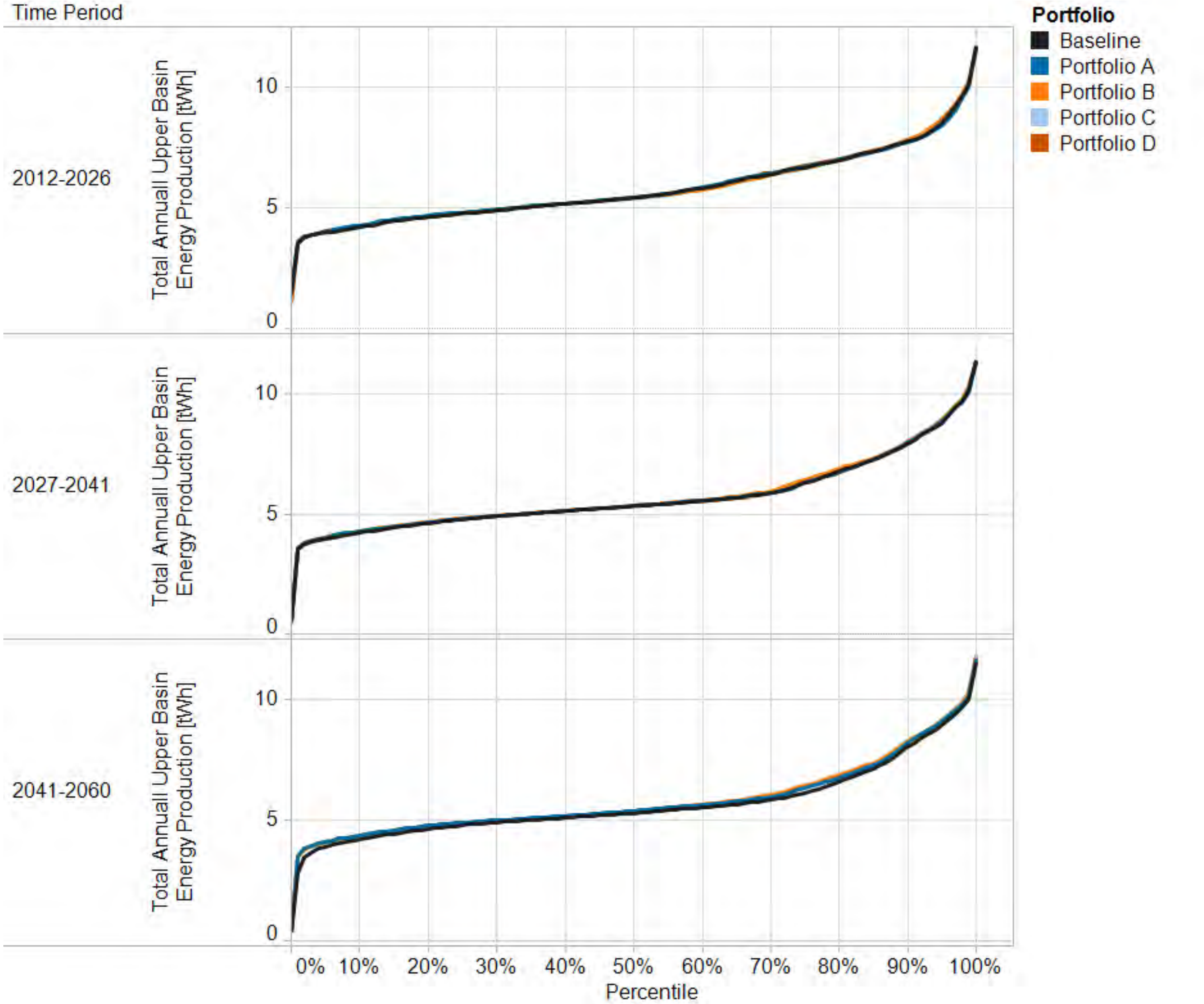


FIGURE G3-93
10th, 50th, 90th Percentiles for Powell Water Year Release With Options and Strategies

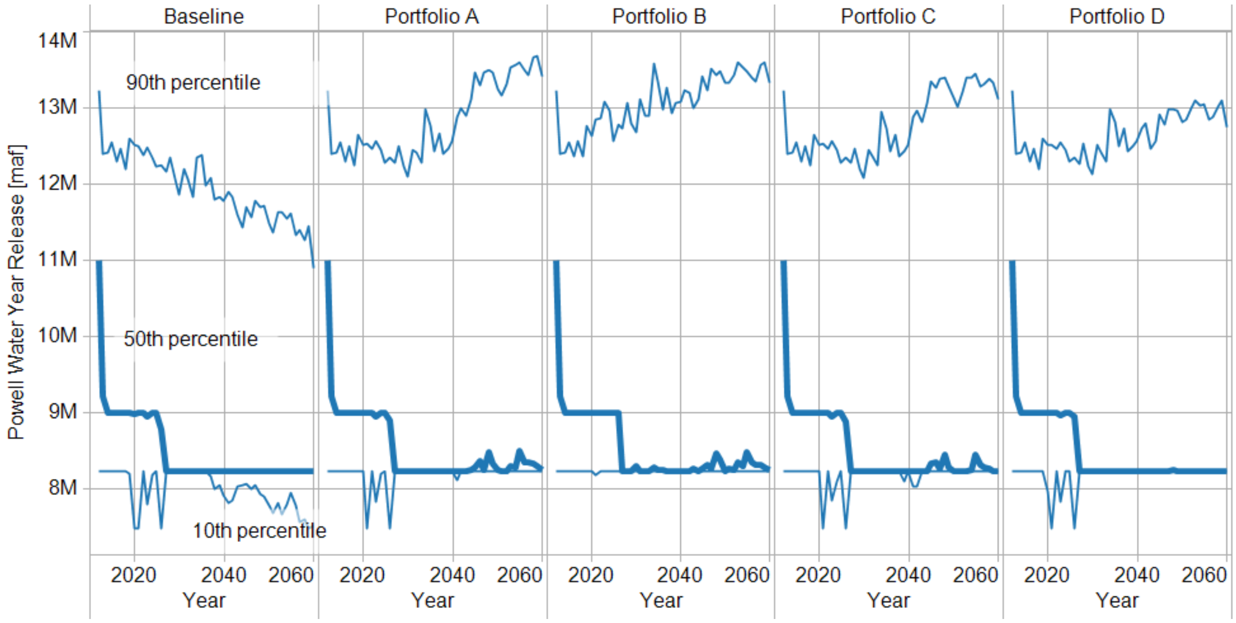


FIGURE G3-94
Percent Traces and 10th, 50th, and 90th Percentiles for Lee Ferry Deficit With Options and Strategies

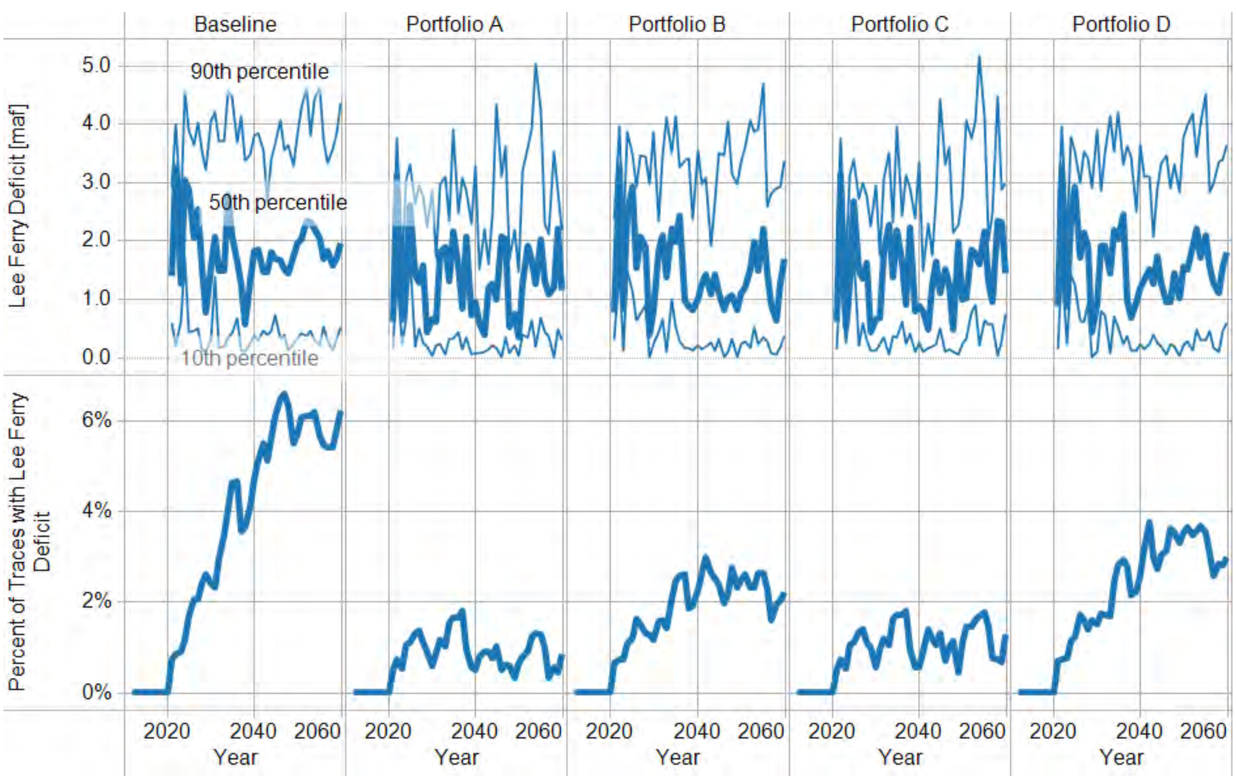


FIGURE G3-95
10th, 50th, 90th Percentiles for Lake Mead Pool Elevation With Options and Strategies

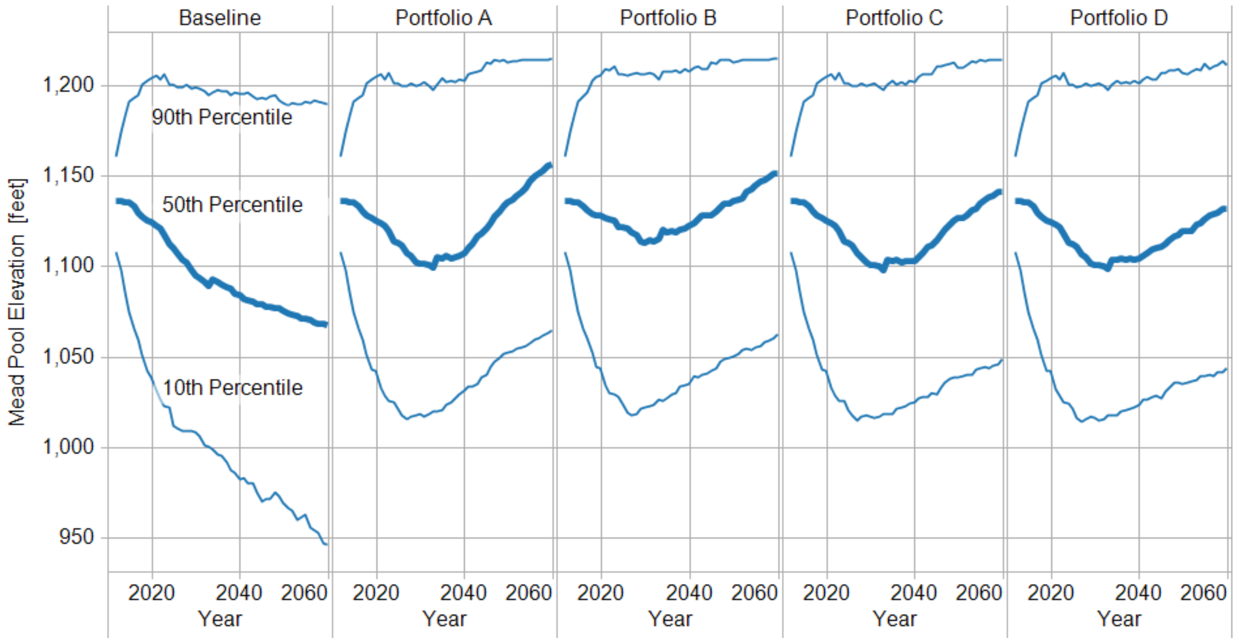


FIGURE G3-96
Percent Traces and 10th, 50th, and 90th Percentiles for Lower Basin Annual Total Shortage (including remaining demands above Lower Division States' basic apportionments) With Options and Strategies

FIGURE G3-97
Percent Traces and 10th, 50th, 90th Percentiles of Lower Basin Annual Regulatory Shortage With Options and Strategies

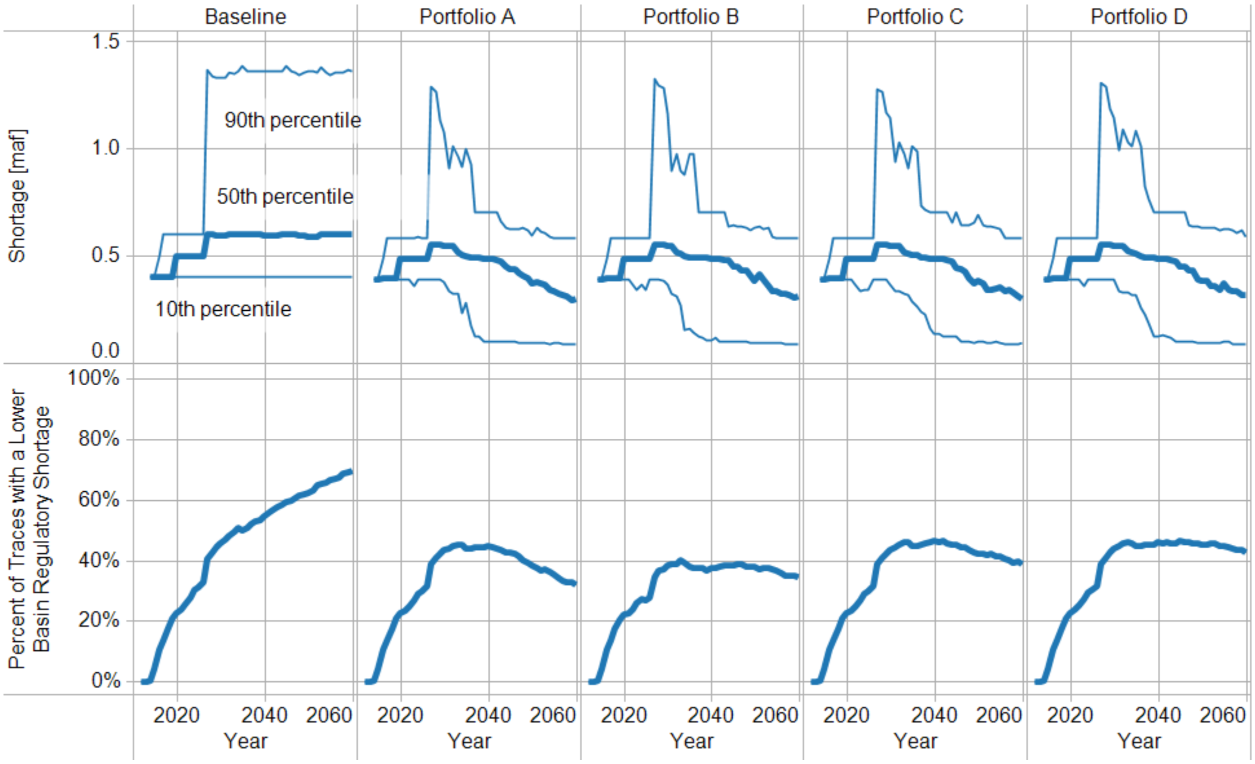


FIGURE G3-98
Percent Traces with Lower Basin Surplus With Options and Strategies

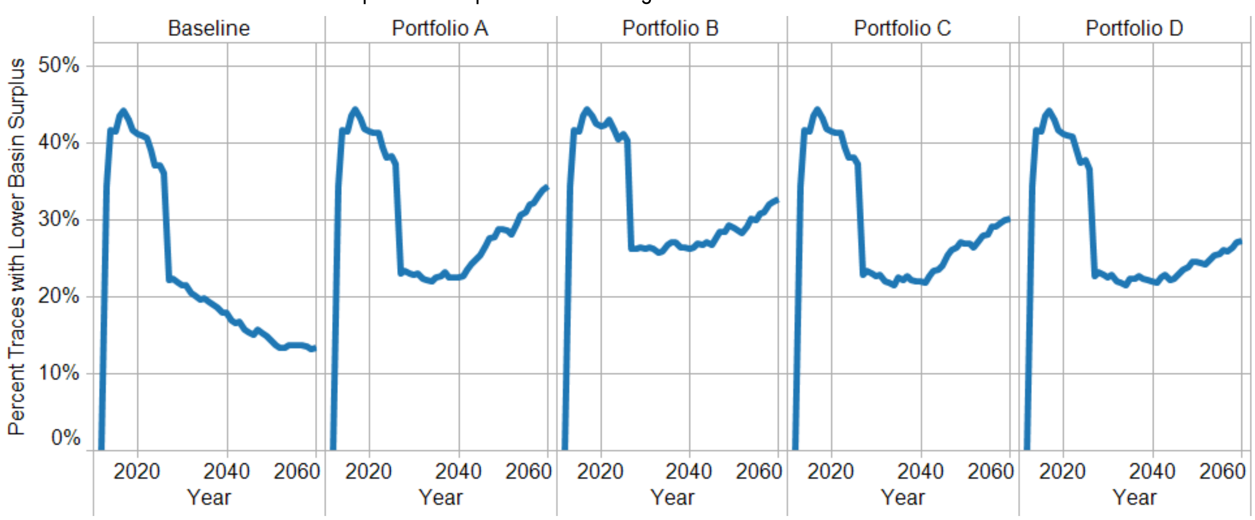


FIGURE G3-99
10th, 50th, 90th Percentiles for Hoover Energy Production With Options and Strategies

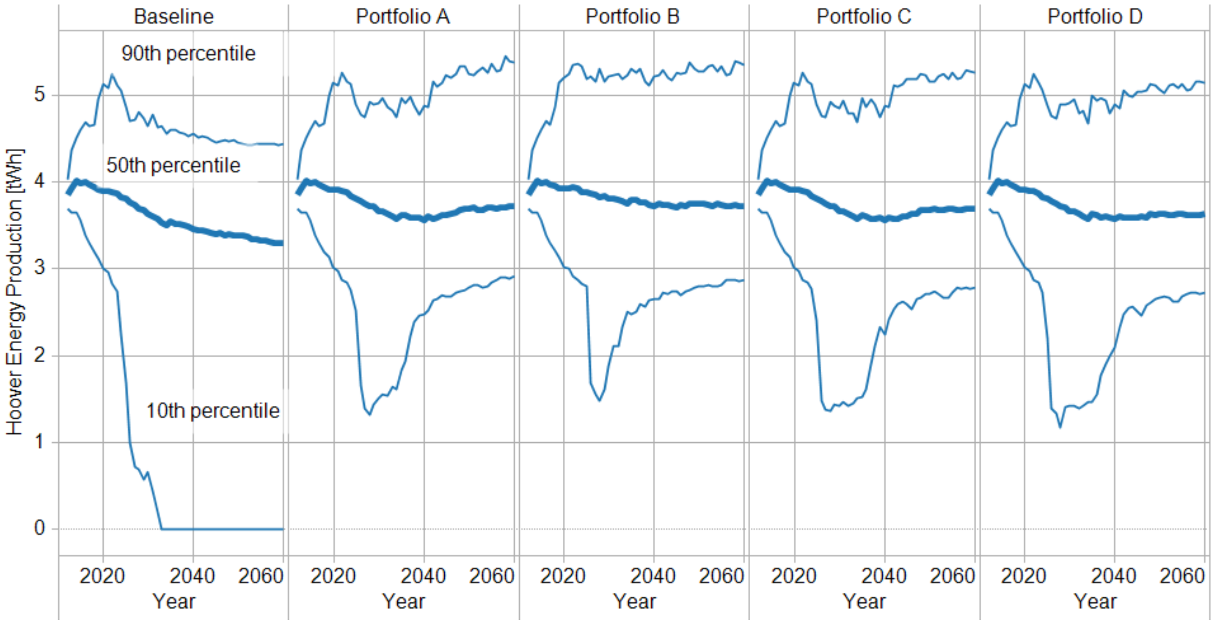


FIGURE G3-100
Cumulative Density Function for Hoover Energy Production With Options and Strategies

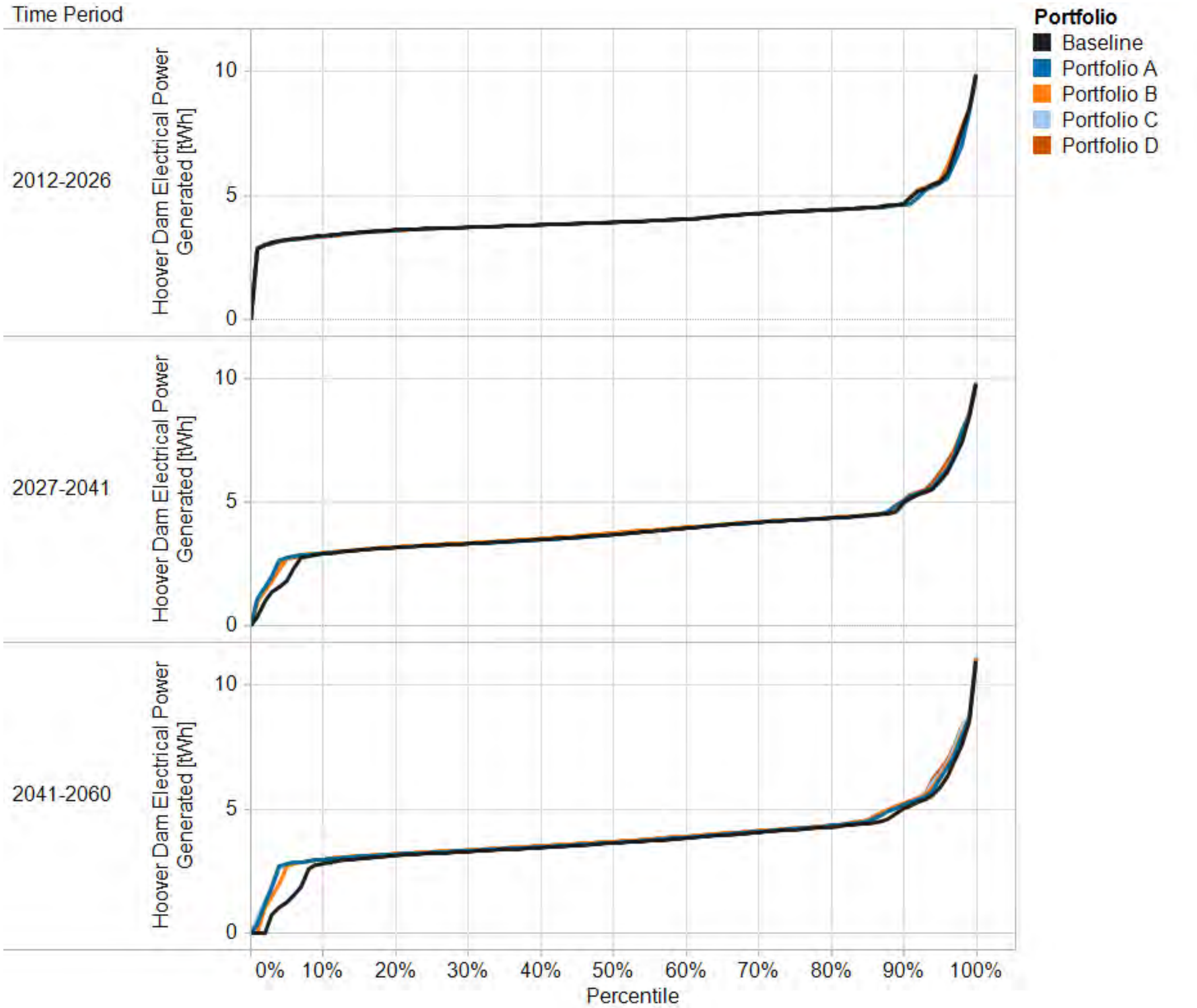


FIGURE G3-101
10th, 50th, 90th Percentiles for Parker and Davis Energy Production With Options and Strategies

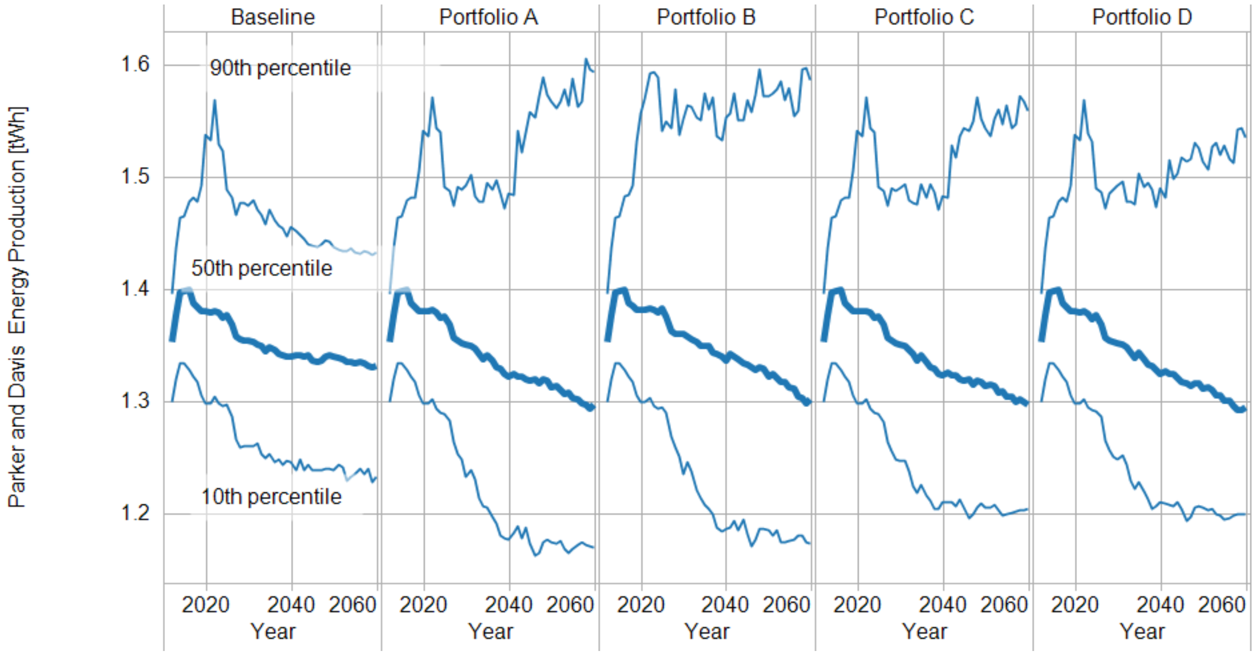
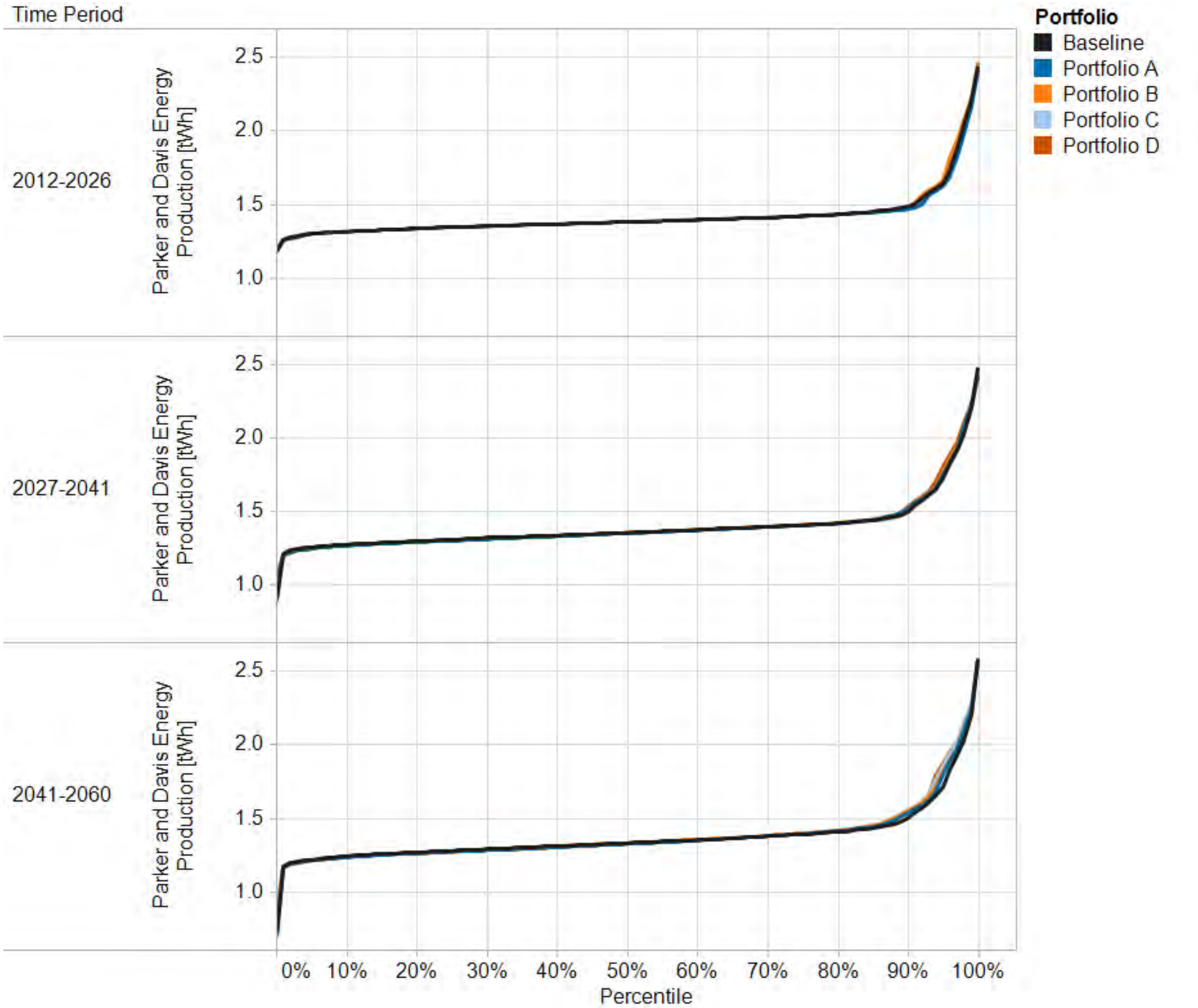


FIGURE G3-102
Cumulative Density Function for Parker and Davis Energy Production With Options and Strategies



4.3.2 Indicator Metrics

Figures G3-103 through G3-113 are histograms showing the percent of simulated traces with vulnerable years, in 5-year bins (e.g., 1 to 5 years vulnerable, 6 to 10 years vulnerable). Bins for the number of vulnerable years are shown on the y-axis, and the proportion of vulnerable traces is shown on the x-axis. Results are further subdivided to show the set of traces inside (top panel) or outside (bottom panel) the vulnerable conditions previously defined for each water delivery indicator metric.

FIGURE G3-103
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Upper Basin Shortage (exceeds 25% of requested depletion in any 1 year) Indicator Metric, Inside Vulnerable Conditions

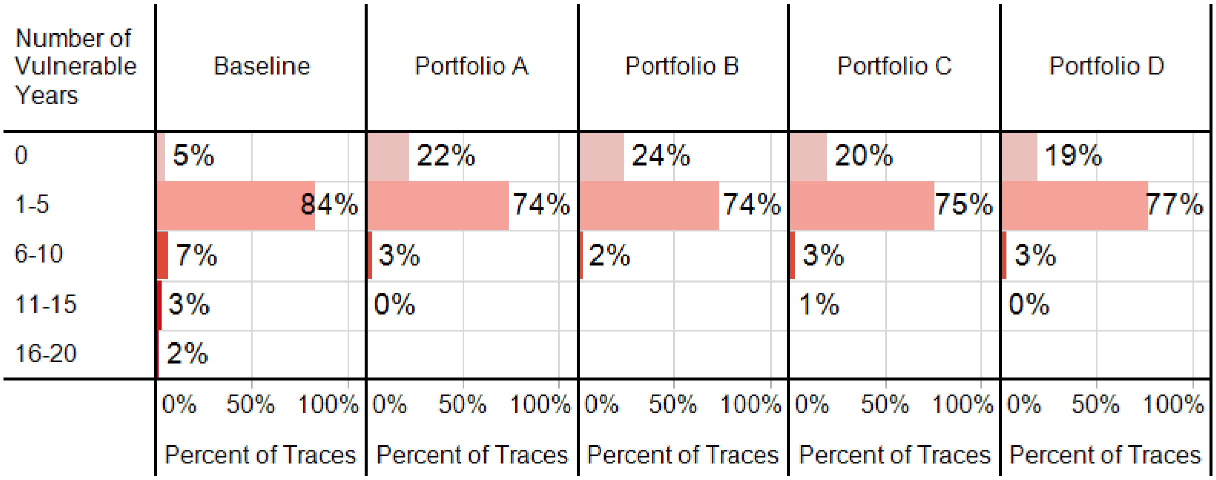


FIGURE G3-104
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Upper Basin Shortage (exceeds 25% of requested depletion in any 1 year) Indicator Metric, Outside Vulnerable Conditions

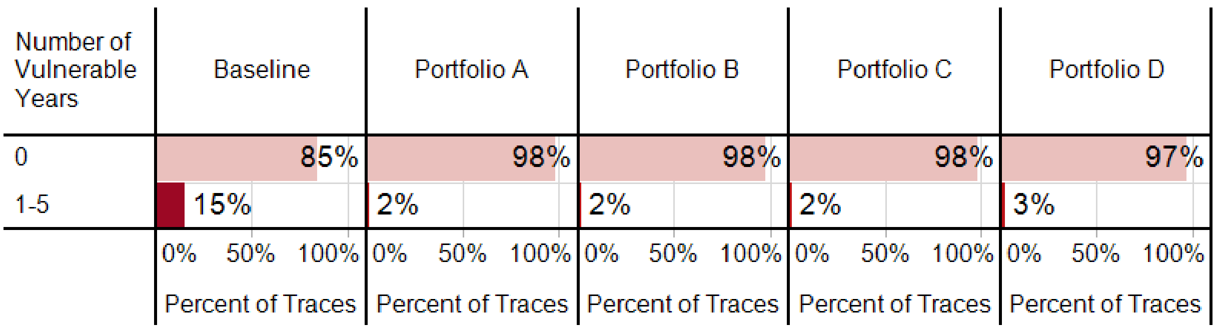


FIGURE G3-105
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lee Ferry Deficit (exceeds zero in any 1 year) Indicator Metric, Inside Vulnerable Conditions

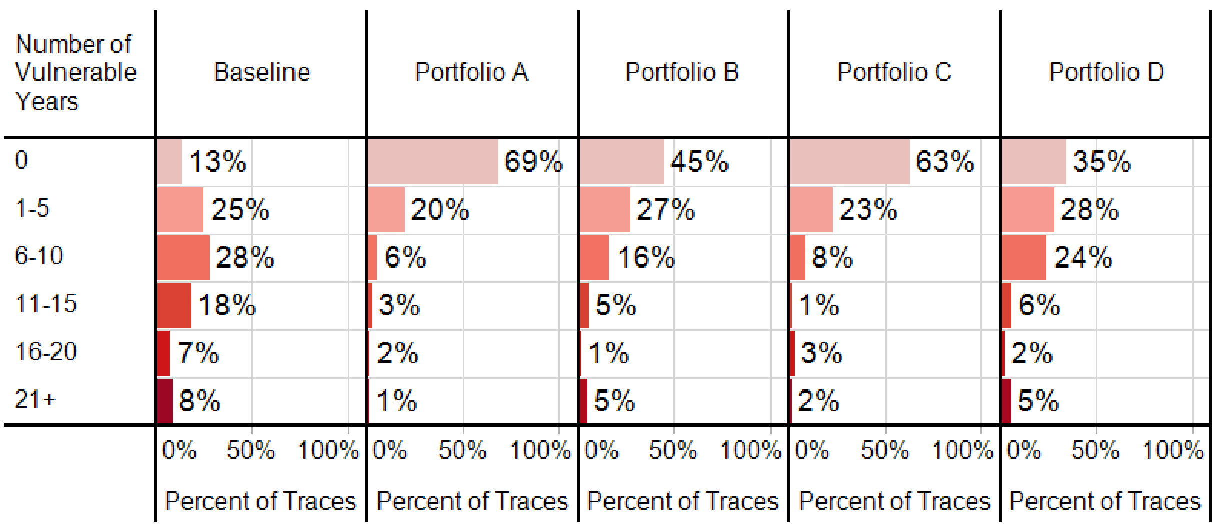


FIGURE G3-106
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lee Ferry Deficit (exceeds zero in any 1 year) Indicator Metric, Outside Vulnerable Conditions

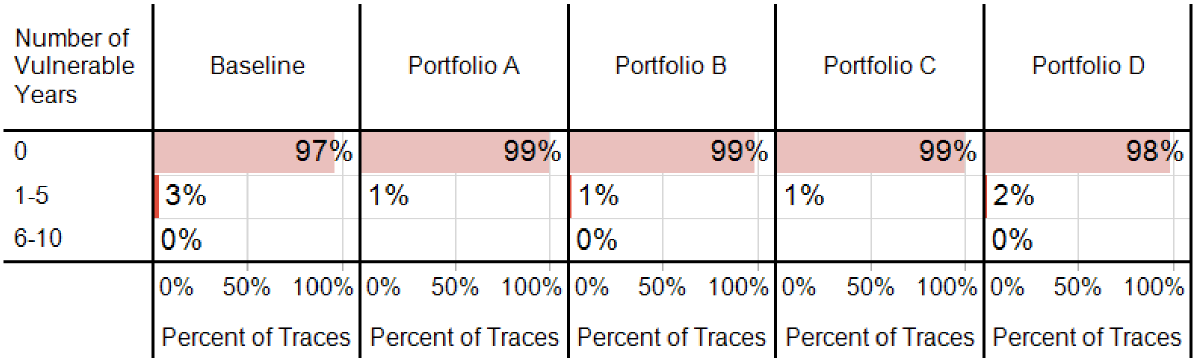


FIGURE G3-107
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lake Mead Pool Elevation <1,000 feet msl (below 1,000 feet msl in any 1 month) Indicator Metric, Inside Vulnerable Conditions

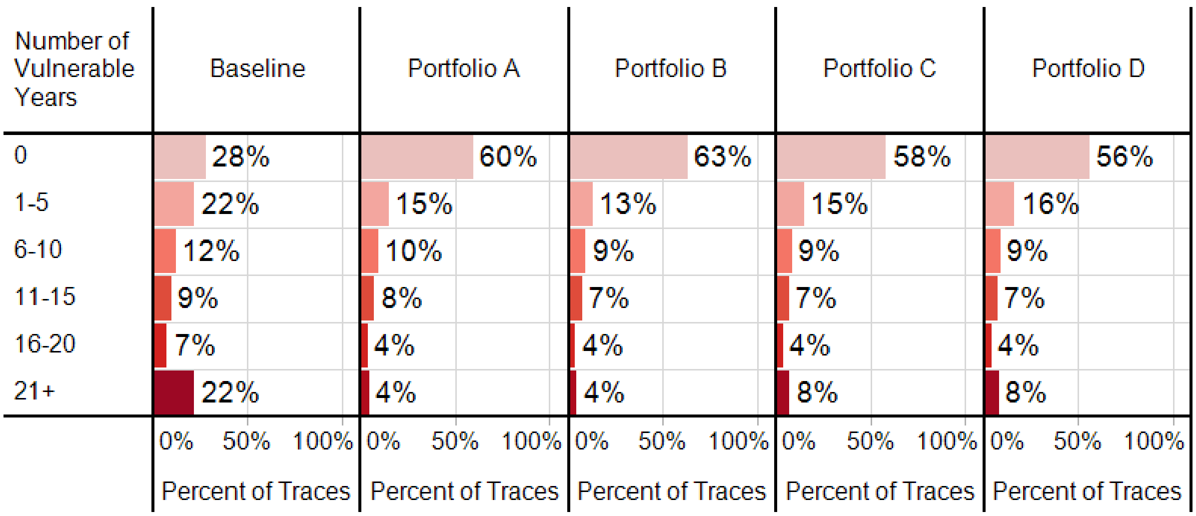


FIGURE G3-108
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lake Mead Pool Elevation <1,000 feet msl (below 1,000 feet msl in any 1 month) Indicator Metric, Outside Vulnerable Conditions

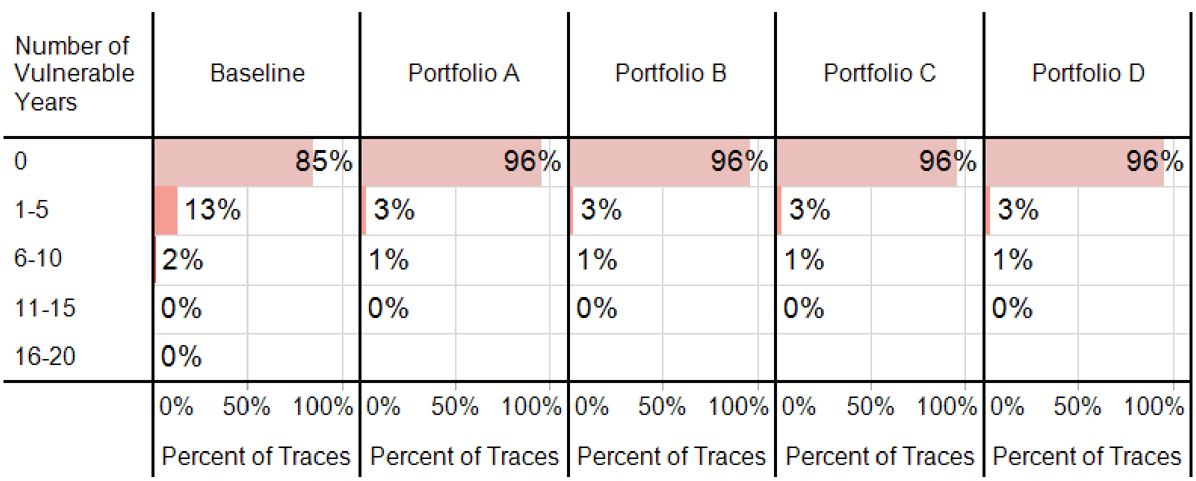


FIGURE G3-109
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lower Basin Shortage (exceeds 1 maf over any 2-year window) Indicator Metric, Inside Vulnerable Conditions

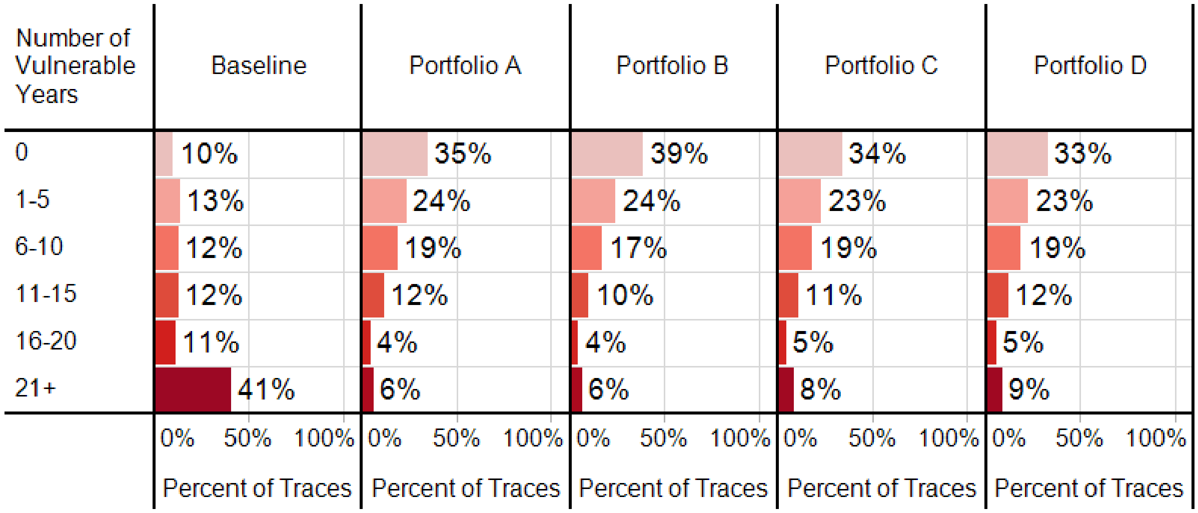


FIGURE G3-110
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lower Basin Shortage (exceeds 1 maf over any 2-year window) Indicator Metric, Outside Vulnerable Conditions

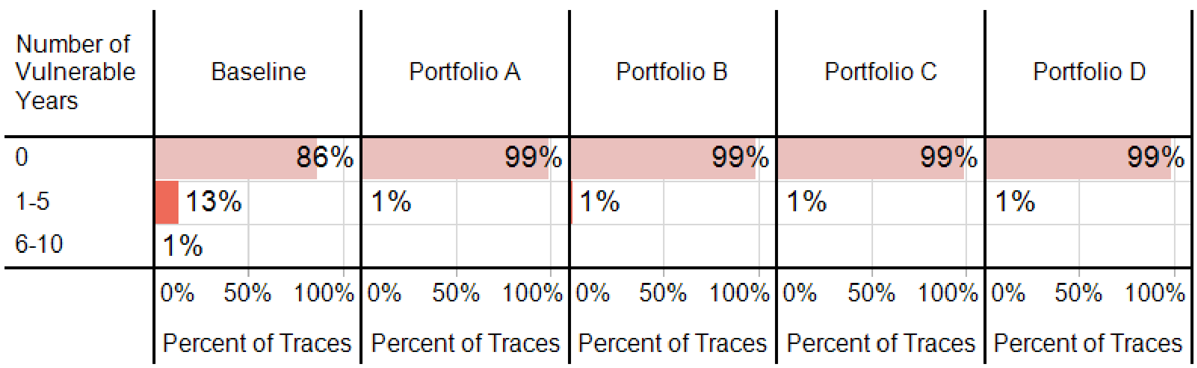


FIGURE G3-111
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lower Basin Shortage (exceeds 1.5 maf over any 5-year window) Indicator Metric, Inside Vulnerable Conditions

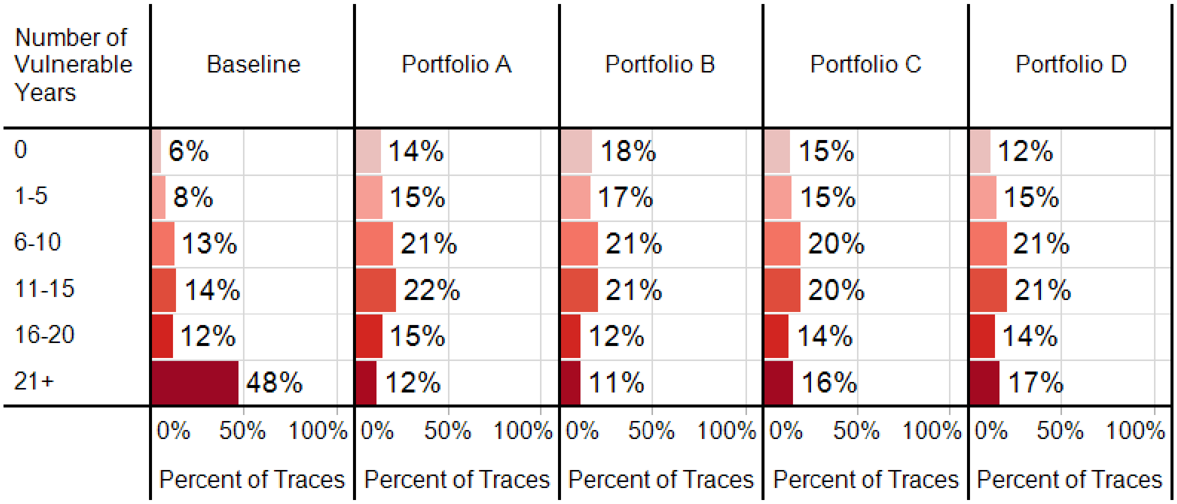


FIGURE G3-112
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Lower Basin Shortage (exceeds 1.5 maf over any 5-year window) Indicator Metric, Outside Vulnerable Conditions

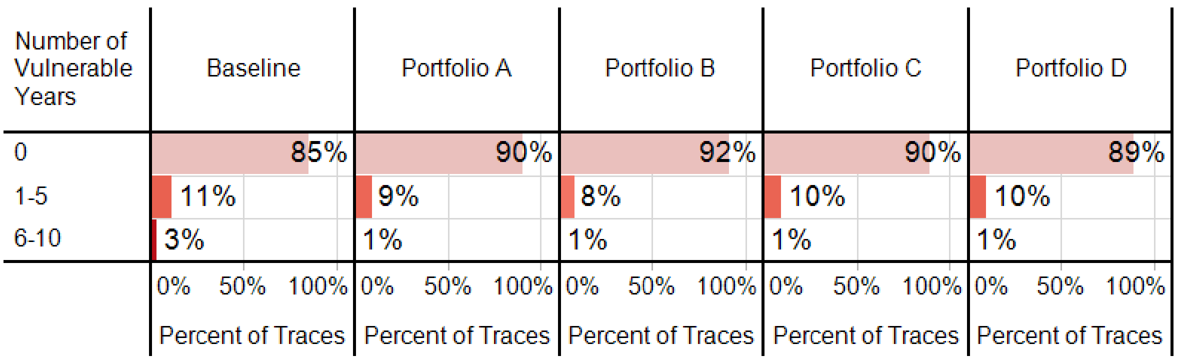
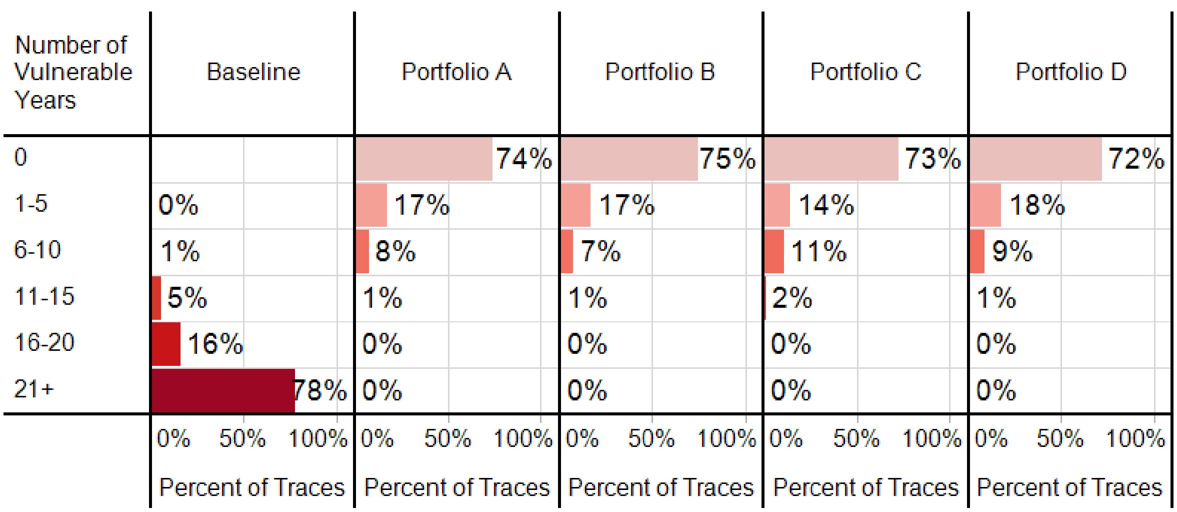


FIGURE G3-113
Number of Vulnerable Years Across Traces 2012–2060 for All Scenarios Remaining Demand Above Lower Division States' Basic Apportionment (exceeds moving threshold in any 1 year) Indicator Metric, All Traces (all traces are vulnerable)



Another way to visualize these results is by looking for patterns of vulnerable traces across the dimensions that define the vulnerable conditions for each water delivery indicator metric. Figures G3-114 through G3-119 present the same scatter plots showing vulnerable conditions as shown earlier in this appendix, but with portfolios implemented. The axes show the dimensions that define the vulnerable conditions, which vary by water delivery metric. Each point in the plot shows one trace outcome across the 2012 to 2060 time span, with vulnerable traces colored red and non-vulnerable traces colored gray. Points inside the vulnerable conditions for a given metric are marked with x's, and points outside are marked with o's.

In these figures, the vulnerable conditions definitions are constant across all portfolios for comparison with the Baseline, but the pattern of vulnerable traces varies by portfolio to show where vulnerable traces (red points) become non-vulnerable (gray points) with the portfolio.

FIGURE G3-114
Reduction in Vulnerable Traces with Portfolios in Place, Upper Basin Shortage (exceeds 25% of requested depletion in any 1 year) Indicator Metric

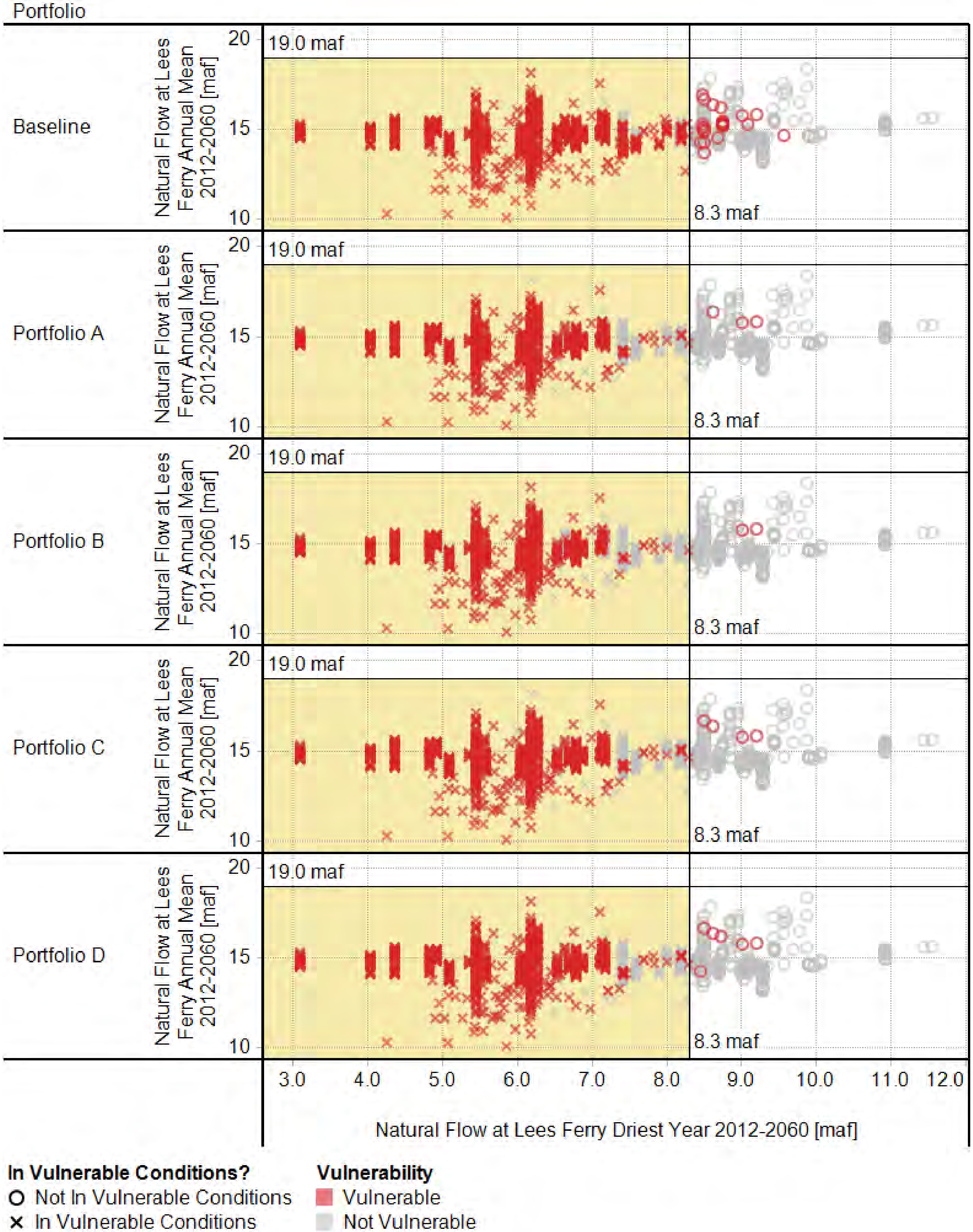


FIGURE G3-115
Reduction in Vulnerable Traces with Portfolios in Place, Lee Ferry Deficit (exceeds zero in any 1 year) Indicator Metric

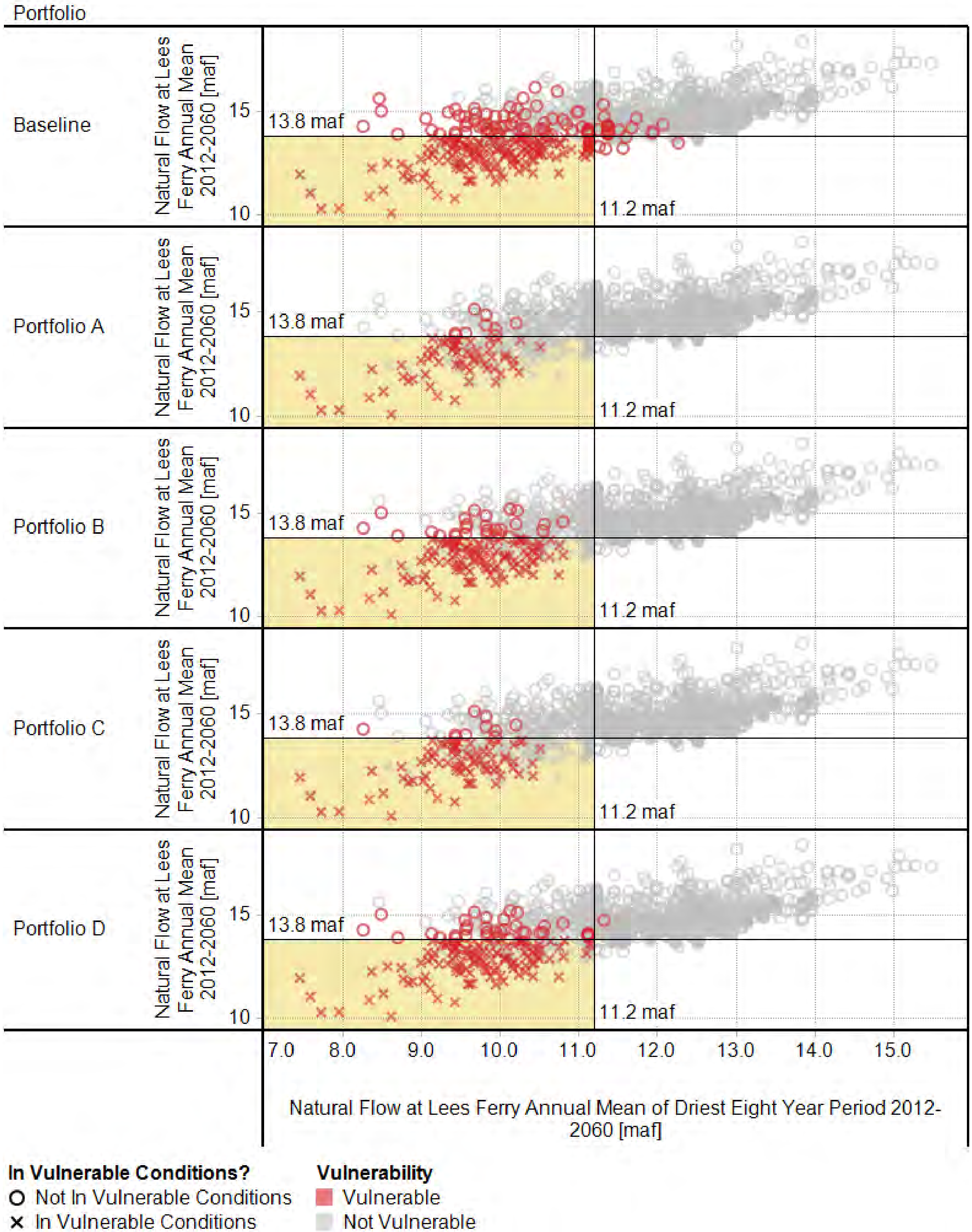


FIGURE G3-116
Reduction in Vulnerable Traces with Portfolios in Place, Lake Mead Pool Elevation <1,000 feet msl (below 1,000 feet msl in any 1 month) Indicator Metric

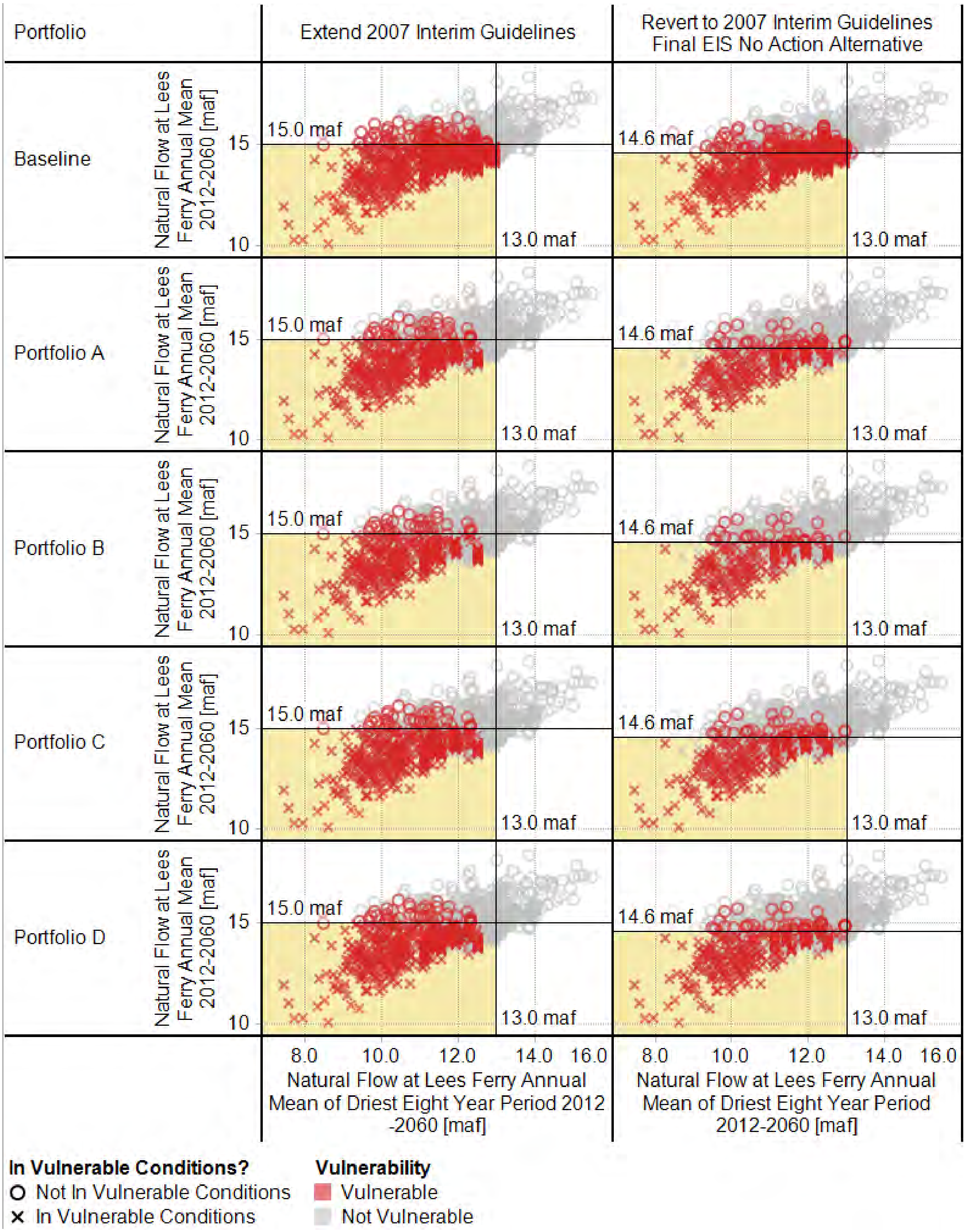


FIGURE G3-117
Reduction in Vulnerable Traces with Portfolios in Place, Lower Basin Shortage (exceeds 1 maf over any 2-year window) Indicator Metric

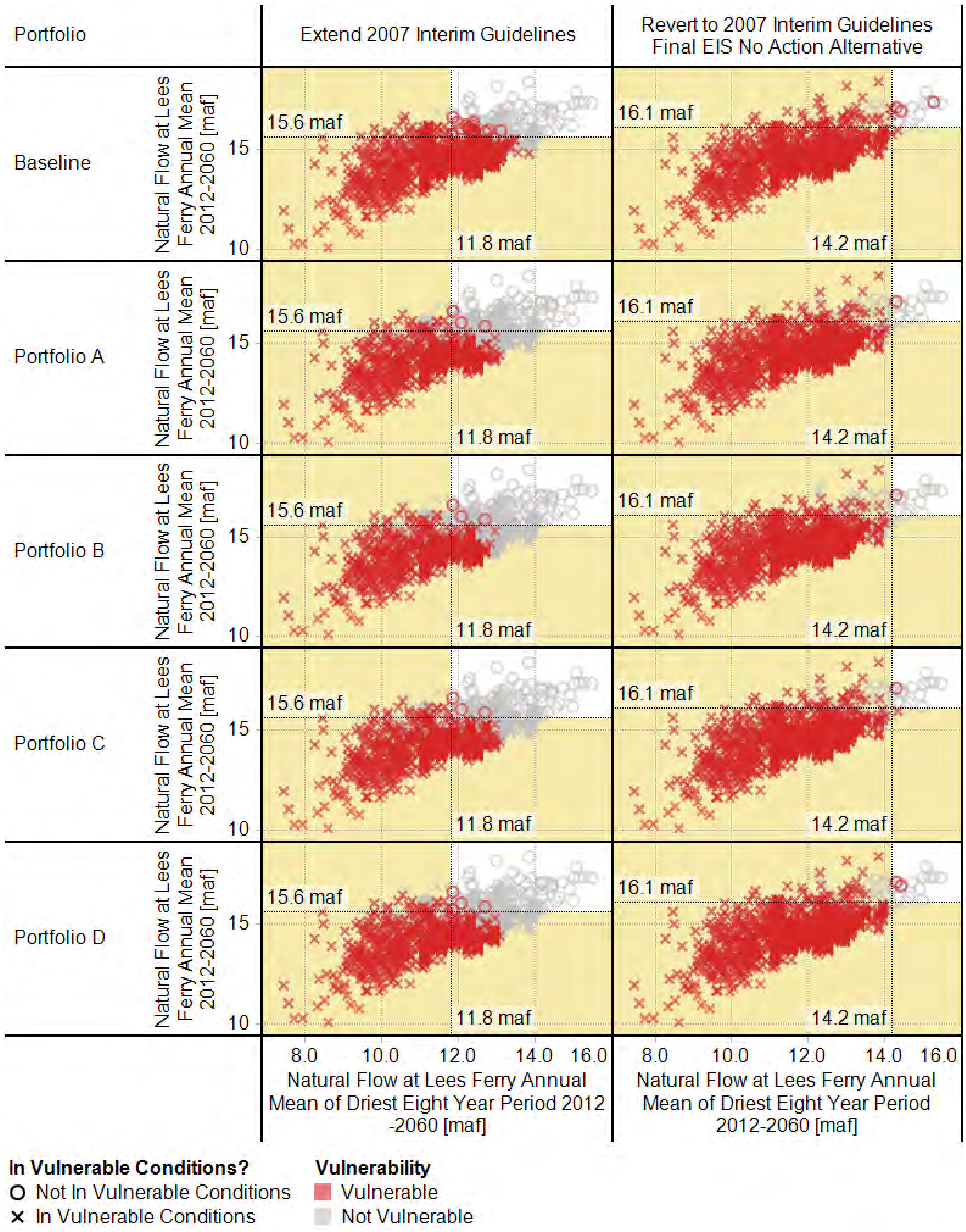


FIGURE G3-118
Reduction in Vulnerable Traces with Portfolios in Place, Lower Basin Shortage (exceeds 1.5 maf over any 5-year window) Indicator Metric

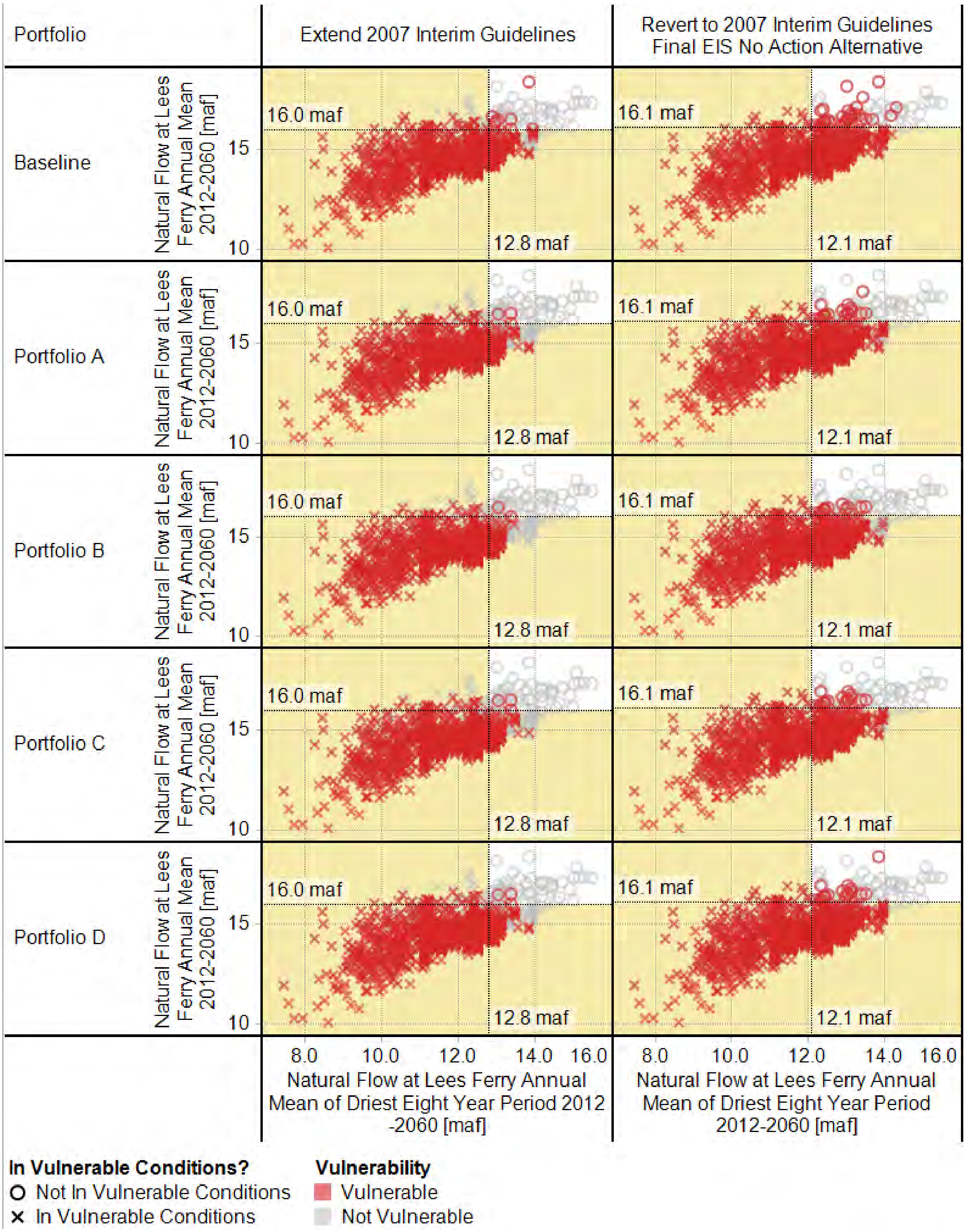
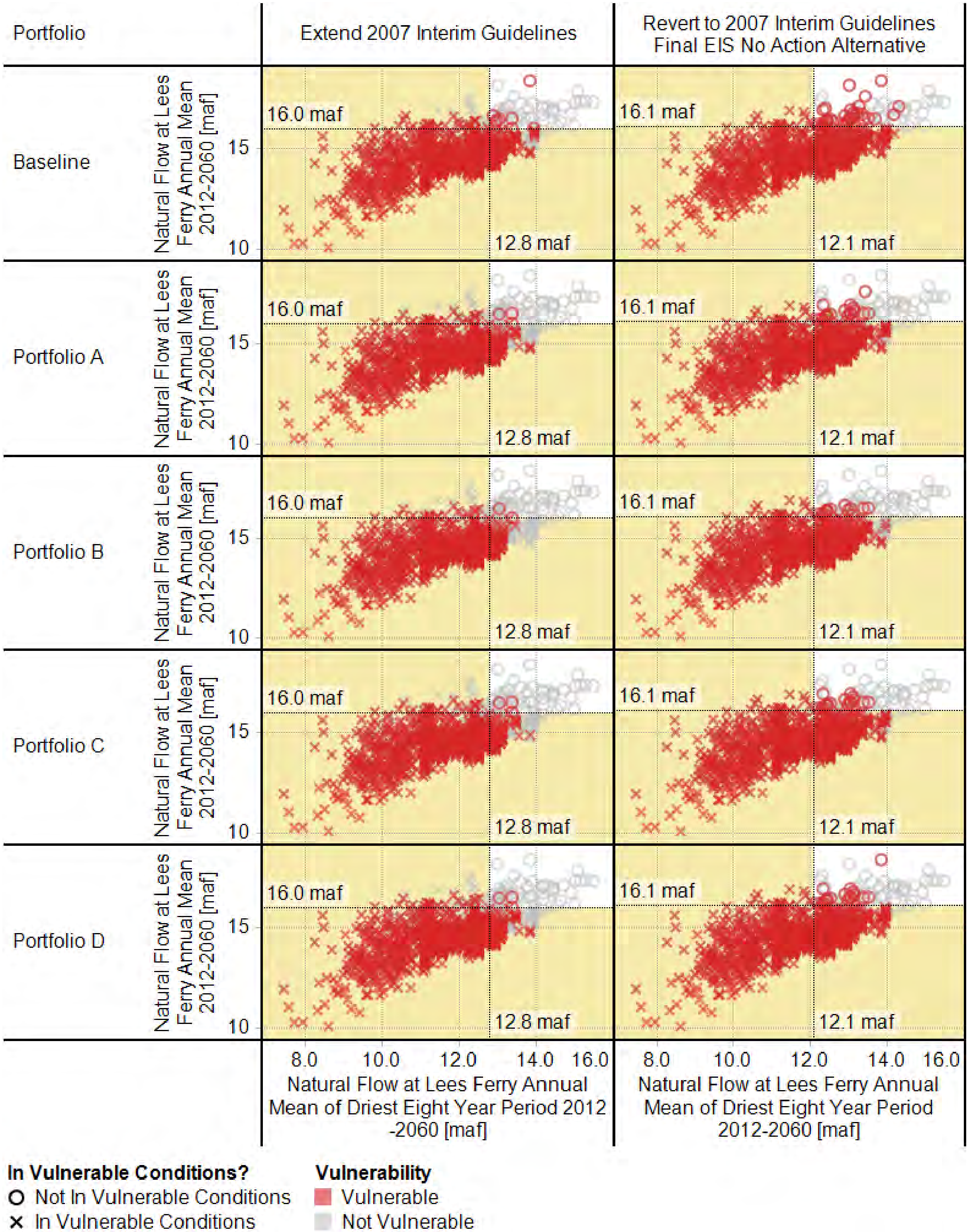


FIGURE G3-119
Reduction in Vulnerable Traces with Portfolios in Place, Remaining Demand Above Lower Division States' Basic Apportionment (exceeds moving threshold in any 1 year) Indicator Metric



Results from the analysis of vulnerable conditions in a future with *Portfolio A* implemented strategies are shown in table G3-4 for all water delivery indicator metrics. 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, and the columns to the right 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. Table G3-5 provides the density and coverage statistics for the vulnerable conditions presented in table G3-4.

TABLE G3-4
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 Lees Ferry (2012–2060) (maf)		**1-Year Minimum Annual Natural Flow at Lees Ferry (2012–2060) (maf)**		**Post-2026 Operation of Lakes Powell and Mead**
Upper Basin Shortage	86% → 69%	Not Applicable	–	7.0 8.3 3 12	–	Not Applicable
Indicator Metric	**Vulnerable Traces (Baseline → with Portfolio)**	**System Condition**				
		Annual Mean Natural Flow at Lees Ferry (2012–2060) (maf)		**Driest 8-Year Period of Annual Mean Natural Flow at Lees Ferry (maf)**		**Post-2026 Operation of Lakes Powell and Mead**
Lee Ferry Deficit	19% → 6%	13.2 13.8 10 18.5	AND	10.0 11.2 7 15.5	–	Not Applicable
Lake Mead Pool Elevation	47% → 24%	14.5 15 10 18.5	AND	12.0 13 7 15.5	AND	2007 Interim Guidelines
		14.1 14.6 10 18.5	AND	11.3 13 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 15.6 10 18.5	OR	11.8 11.8 7 15.5	AND	2007 Interim Guidelines
		15.6 16.1 10 18.5	OR	13.7 14.2 7 15.5	AND	Revert to 2007 Interim Guidelines Final EIS No Action Alternative

TABLE G3-4
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 Lees Ferry (2012–2060) (maf)		**1-Year Minimum Annual Natural Flow at Lees Ferry (2012–2060) (maf)**		**Post-2026 Operation of Lakes Powell and Mead**
Upper Basin Shortage	86% → 69%	Not Applicable	–	7.0 8.3 3 12	–	Not Applicable
Indicator Metric	**Vulnerable Traces (Baseline → with Portfolio)**	**System Condition**				
		Annual Mean Natural Flow at Lees Ferry (2012–2060) (maf)		**Driest 8-Year Period of Annual Mean Natural Flow at Lees Ferry (maf)**		**Post-2026 Operation of Lakes Powell and Mead**
Lee Ferry Deficit	19% → 6%	13.2 13.8 10 18.5	AND	10.0 11.2 7 15.5	–	Not Applicable
Lake Mead Pool Elevation	47% → 24%	14.5 15 10 18.5	AND	12.0 13 7 15.5	AND	2007 Interim Guidelines
		14.1 14.6 10 18.5	AND	11.3 13 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 15.6 10 18.5	OR	11.8 11.8 7 15.5	AND	2007 Interim Guidelines
		15.6 16.1 10 18.5	OR	13.7 14.2 7 15.5	AND	Revert to 2007 Interim Guidelines Final EIS No Action Alternative

TABLE G3-4
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 Lees Ferry (2012–2060) (maf)		1-Year Minimum Annual Natural Flow at Lees 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 (10; 16.0; 18.5)	OR	12.8 (7; 11.6; 15.5)	AND	2007 Interim Guidelines
		16.5 (10; 16.1; 18.5)	OR	12.1 (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 Lees 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 (10; NA; 18.5)	OR	9.7 (9; NA; 11)	AND	2007 Interim Guidelines
		15.4 (10; NA; 18.5)	OR	10.2 (9; NA; 11)	AND	Revert to 2007 Interim Guidelines Final EIS No Action Alternative

TABLE G3-5
Coverage and Density Results for Water Delivery Vulnerable Conditions in *Portfolio A*

Indicator Metric	Vulnerable Traces	Coverage	Density
Upper Basin Shortage	69%	96%	85%
Lee Ferry Deficit	6%	77%	57%
Lake Mead Pool Elevation	24%	53%	80%
Lower Basin Shortage (1 maf over 2 years)	62%	84%	80%
Lower Basin Shortage (1.5 maf over 5 years)	83%	77%	89%
Remaining Demand Above Lower Division States' Basic Apportionment	26%	57%	57%

5.0 Summary

This appendix offers supplementary content for *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*. The results and methods presented herein focus on system response variables, indicator metrics, vulnerability and vulnerable conditions. For individual metric results, see appendix G4.

6.0 References

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