RECLAMATION

Managing Water in the West

Colorado River Basin Water Supply and Demand Study

Study Report

U.S. Department of the Interior
Bureau of Reclamation

December 2012

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Acknowledgement

The Colorado River Basin Water Supply and Demand Study represents the most comprehensive analysis ever undertaken within the Colorado River Basin. Its successful completion could only have been accomplished through the dedication and hard work of the Bureau of Reclamation, the consuting team, the seven Colorado River Basin States, and the collaboration of stakeholders throughout the Basin, including federally recognized tribes, agricultural users, purveyors of municipal and industrial water, power users, and conservation and recreational groups. The Study is a model, not only for future basin studies, but for watershed planning across the country, and it will provide the basis for planning for future growth and climate change in the western US and its many watersheds for decades to come.

Special gratitude and appreciation is extended to Christina Robinson-Swett who created the document cover art.

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Acronyms and Abbreviations

2007 Interim Guidelines	*Record of Decision for Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*
2007 Interim Guidelines Final EIS	*Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement*
af	acre- feet
afy	acre-feet per year
Ag	agricultural
Basin	Colorado River Basin
Basin States	Colorado River Basin States
CAP	Central Arizona Project
Compact	Colorado River Compact
CRSS	Colorado River Simulation System
CU&L Reports	Consumptive Uses and Losses Reports
desal	desalination
DOI	U.S. Department of the Interior
GCM	General Circulation Model
ICS	Intentionally Created Surplus
kaf	thousand acre-feet
LB	Lower Basin
M&I	municipal and industrial
maf	million acre-feet
mafy	million acre-feet per year
Mexico	United Mexican States
mod	modification
msl	above mean sea level
Reclamation	Bureau of Reclamation
SECURE	Science and Engineering to Comprehensively Understand and Responsively Enhance
SoCal	Southern California

SSI	self-served industrial
Study	Colorado River Basin Water Supply and Demand Study
tribes	federally recognized tribes
UB	Upper Basin
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity

Study Report

1.0 Introduction

The Colorado River Basin Water Supply and Demand Study (Study), initiated in January 2010, was conducted by the Bureau of Reclamation's (Reclamation) Upper Colorado and Lower Colorado regions, and agencies representing the seven Colorado River Basin States[1] (Basin States) in collaboration with stakeholders throughout the Colorado River Basin (Basin). As defined in the *Plan of Study*, the purpose of the Study is to define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin States that receive Colorado River water over the next 50 years (through 2060), and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The Study does not result in a decision as to how future imbalances will or should be addressed. Rather, the Study provides a common technical foundation that frames the range of potential imbalances that may be faced in the future and the range of solutions that may be considered to resolve those imbalances.

Due to the inherent complexities of the Study and the many diverse interests and perspectives of the various stakeholders, interim reports and technical updates were published to reflect continual technical developments and the ongoing input of stakeholders. Throughout the course of the Study, eight of these interim products were published. These documents are listed in *Appendix 2 – Previously Published Documents.* The final documentation for the Study is organized into three major parts: an Executive Summary, this *Study Report* (including appendices), and technical reports (including appendices).

This *Study Report* provides a summary of each of the Study's seven technical reports as well as future considerations and potential next steps that could be conducted as follow-on activities to the Study. This *Study Report* includes seven appendices:

- *Appendix 1 – Plan of Study*
- *Appendix 2 – Previously Published Study Documents*
- *Appendix 3 – Summary of Past Colorado River Basin Planning Studies*
- *Appendix 4 – Study Participants*
- *Appendix 5 – Public Involvement Plan*
- *Appendix 6 – Outreach Activities*
- *Appendix 7 – Peer Review Summary Report*

The seven technical reports summarized in this *Study Report* are listed below:

- ***Technical Report A – Scenario Development.*** This report describes the scenario planning approach used to incorporate uncertainty in future water supply and water demand.
- ***Technical Report B – Water Supply Assessment.*** This report describes the water supply scenarios and presents the analysis and comparison of those scenarios.

[1] Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming.

- ***Technical Report C – Water Demand Assessment.*** This report describes the water demand scenarios, presents the analysis and comparison of those scenarios, and presents information on historical consumptive use.
- ***Technical Report D – System Reliability Metrics.*** This report describes the metrics that have been identified for use in the assessment of the reliability of the system to meet resource needs under future supply and demand scenarios.
- ***Technical Report E – Approach to Develop and Evaluate Options and Strategies to Balance Supply and Demand.*** This report provides the overall analytical approach used to analyze opportunities to resolve projected water supply and demand imbalances.
- ***Technical Report F – Development of Options and Strategies.*** This report describes the ideas (options) submitted to the Study to help resolve water supply and demand imbalances and the development of portfolios from those options.
- ***Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies.*** This report presents the reliability of the system to meet resource needs under future water supply and demand scenarios and the effectiveness of options and strategies at improving that reliability.

Project participants and stakeholders are encouraged to comment on the information provided in this *Study Report* and associated technical reports. Written comments should be submitted within 90 days following the release of this report. The comments will be summarized and posted to the Study website, and will be considered in future planning activities in the Basin. Comments may be submitted in the following ways:

1. Via the Study website at http://www.usbr.gov/lc/region/programs/crbstudy.html
2. Email to ColoradoRiverBasinStudy@usbr.gov
3. U.S. mail to U.S. Bureau of Reclamation, Attention: Ms. Pam Adams, LC-2721, P.O. Box 61470, Boulder City, NV 89006-1470
4. Facsimile transmission to 702-293-8418

2.0 Background and Need

Today, almost 40 million[2] people in the seven western states of Arizona, California, Nevada (Lower Division States) and Colorado, New Mexico, Utah and Wyoming (Upper Division States), collectively referenced as the Basin States, rely on the Colorado River and its tributaries to provide some, if not all, of their municipal water needs. That same water source irrigates nearly 5.5 million acres of land[3] in the Basin – producing some 15 percent of the nation's crops and about 13 percent of its livestock, which combined generate many billions of dollars a year in agricultural benefits. The Colorado River is also the lifeblood for at least 22 federally recognized

[2] About 40 million people are estimated to be in the Study Area, which encompasses the hydrologic boundaries of the Basin in the United States plus the adjacent areas of the Basin States that receive Colorado River water, by 2015. See *Technical Report C – Water Demand Assessment* for additional detail.

[3] It is estimated that there will be about 5.5 million irrigated acres in the Study Area by 2015. See *Technical Report C – Water Demand Assessment* for additional detail.

tribes (tribes), 7 National Wildlife Refuges, 4 National Recreation Areas, and 11 National Parks. Hydropower facilities along the Colorado River supply more than 4,200 megawatts of vitally important electrical capacity to helping to meet the power needs of the West and reduce the use of fossil fuels. In addition, the Colorado River is vital to the United Mexican States (Mexico). The river supports a thriving agricultural industry in the Mexicali Valley and provides municipal water supplies for communities as far away as Tijuana.

The Colorado River system is operated in accordance with the Law of the River[4]. Apportioned water in the Basin exceeds the approximate 100-year record (1906 through 2011) Basin-wide average long-term historical natural flow[5] of about 16.4 million acre-feet (maf). However, the Upper Basin States have not fully developed use of their 7.5-maf apportionment, and total consumptive use and losses in the Basin has averaged approximately 15.3[6] maf over the last 10 years. Figure 1 shows the historical annual Basin water supply (estimated using the natural flow record) and water use[7]. This figure shows that there have been multiple years when use was greater than the supply. Because of the Colorado River system's ability to store approximately 60 maf, or nearly 4 years of average natural flow of the river, all requested deliveries were met in the Lower Basin during those times. However, there have been periodic shortages throughout the Upper Basin and the adjacent areas of the Basin States that receive Colorado River water.

2.1 Ongoing Efforts to Resolve Water Supply and Demand Imbalances

Throughout the 20th century, the challenges and complexities of ensuring a sustainable water supply and meeting future demand have been recognized. These challenges are documented in several studies conducted by Reclamation and the Basin States over the past six decades (see *Appendix 3 – Summary of Past Colorado River Basin Planning Studies*). Appendix 3 provides a summary of studies which discussed future water supply and demand imbalances and in some cases proposed solutions to dealing with these imbalances.

These studies include:

- *Colorado River Storage Project and Participating Projects; Upper Colorado River Basin* (Reclamation, 1950). This report combined various individual Upper Basin reservoir proposals into a comprehensive plan to increase long-term carryover water storage.
- *Pacific Southwest Water Plan* (Reclamation, 1964). This report projected a Lower Basin water supply and demand imbalance and proposed a comprehensive plan to improve water supply and distribution, including the importation of water from the northern California coastal area.

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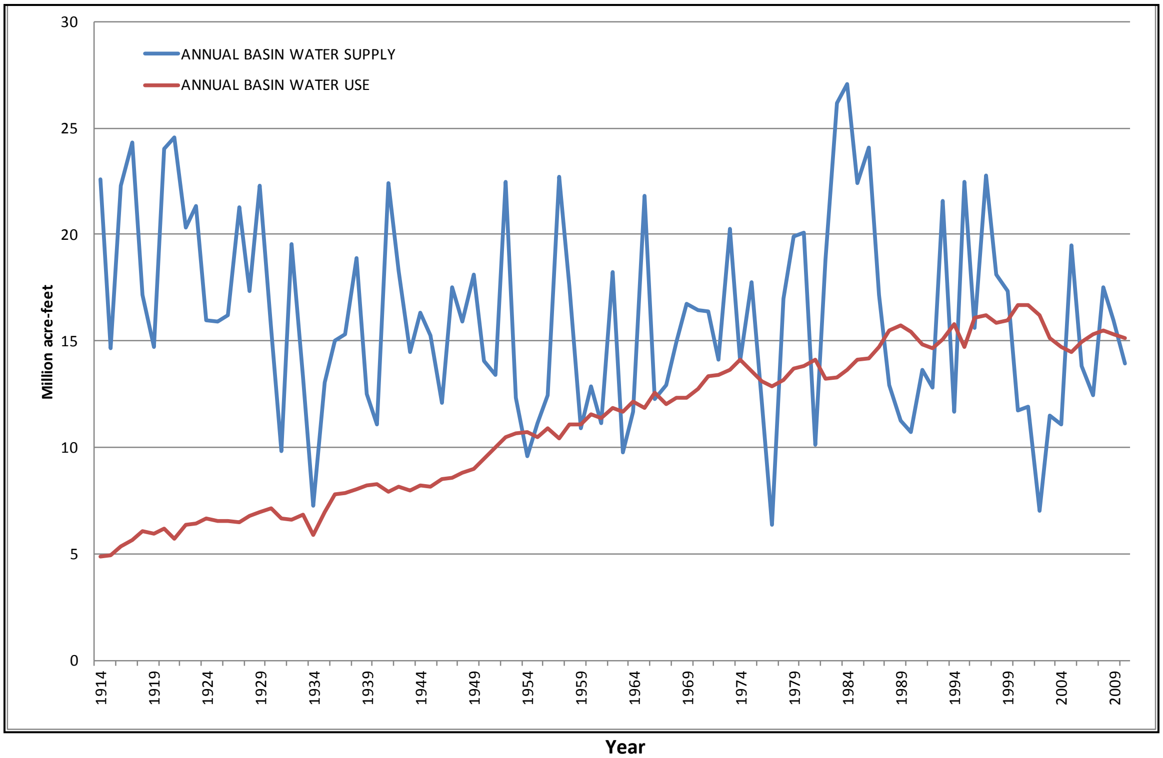
4 The treaties, compacts, decrees, statutes, regulations, contracts and other legal documents and agreements applicable to the allocation, appropriation, development, exportation and management of the waters of the Colorado River Basin are often collectively referred to as the Law of the River. There is no single, universally agreed upon definition of the Law of the River, but it is useful as a shorthand reference to describe this longstanding and complex body of legal agreements governing the Colorado River.

5 Natural flow represents the flow that would have occurred at the location had depletions and reservoir regulation not been present upstream of that location.

6 Basin-wide consumptive use and losses estimated over the period 2002-2011, including the 1944 Treaty delivery to Mexico, reservoir evaporation, and other losses due to native vegetation and operational inefficiencies.

7 Historical use (as shown in Figure 1) does not necessarily reflect historical water demand, particularly for periods of drought. A decrease in reported use during a drought period may reflect the lack of available supply at the point of use rather than a decrease in the need for water.

FIGURE 1
Historical Annual Colorado River Basin Water Supply and Use



Historical water use is the total use of water throughout the Basin for agricultural, municipal and industrial (M&I), and other consumptive uses including Mexico, plus losses through evaporation at mainstream reservoirs and use by native and non-native vegetation. Natural flow is used as an estimate of water supply in the Basin. In the current natural flow record, historical inflows based on U.S. Geological Survey (USGS gaged records are used as estimates of natural flow for the Paria River, Little Colorado River, Virgin River, and Bill Williams River without adjustment for upstream water uses. However, the Gila River is not included in the natural flow record. Therefore, the use reported here excludes consumptive uses on these tributaries. See Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System for additional detail regarding the treatment of these tributaries in the Study.

- *Comprehensive Framework Study, Lower Colorado Region* (Pacific Southwest Inter-agency Committee, 1971a). This federal-state study projected a Lower Basin water supply and demand imbalance and concluded that a future water import program would be needed as part of a proposed framework program for the development and management of Lower Basin water resources to 2020.
- *Comprehensive Framework Study, Upper Colorado Region* (Pacific Southwest Inter-agency Committee, 1971b). This federal-state study presented a framework program for the development and management of the water and related land resources of the Upper Basin to 2020, including alternative plans with emphases on differing water uses, some of which were dependent on water importation.
- *Westwide Study Report on Critical Water Problems Facing the Eleven Western United States* (Reclamation, 1975). This federal-state study described key factors affecting future water needs, formulated alternative future demand scenarios, and identified options for dealing with anticipated shortages. The study concluded that in spite of conservation, the Basin faces

future water shortages unless its natural flows are augmented or water-dependent Basin development is curtailed.

These studies clearly recognized the challenges facing the Basin. The Colorado River Basin Project Act of 1968, which authorized the construction of the Central Arizona Project (CAP), the Southern Nevada Water Project, and other projects in the Lower Basin, further discussed the need for augmentation.[8]

Historically, water planning efforts resulted in the construction of significant infrastructure. Notable examples include Hoover and Glen Canyon Dams, the Central Arizona and Central Utah projects, Colorado's many headwaters trans-basin diversions, California's Colorado River Aqueduct, the All-American Canal, and a wide range of other local and regional water infrastructure projects. In the latter part of the 20th century and in the early portion of the 21st century, focus has shifted from developing available water resources to an emphasis on improving the efficiency of the operation of Colorado River reservoirs and increasing the level of predictability afforded to entities who receive Colorado River water through better planning and managing of available water supplies. Two notable examples from this period are the *Operation of Glen Canyon Dam Final Environmental Impact Statement* (Reclamation, 1996) and 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]). Both of these resulted in the adoption of new reservoir operating policies.

Colorado River stakeholders have made significant investments in developing other water resources and implementing programs and policies to balance current and future supplies with existing and future demands. Many of these efforts have resulted in solutions to past water management challenges and will continue to provide benefit to the system in meeting the challenges that lie ahead.

2.2 The Need for the Study

Concerns regarding the reliability of the Colorado River system to meet future needs are even more apparent today. The Basin States include some of the fastest-growing urban and industrial areas in the United States. California is ranked among the five fastest-growing states in the country. Arizona and Colorado are in the top 10 fastest-growing states in the country. The continued growth and sustainability of the communities and economies of metropolitan areas such as Albuquerque, Denver, Las Vegas, Los Angeles, Phoenix, Salt Lake City, and San Diego are tied to future water availability from the Colorado River. Water demand for other uses, including the environment, recreation, and tribal water rights settlements, also continues to increase. Potential future increases in temperatures in the Basin, continuing and accelerating a trend observed over most of the Basin during the past 30 to 40 years (National Research Council, 2007), would increase evapotranspiration from vegetation, as well as water loss due to evaporation from reservoirs.

[8] Section 202 of the Colorado River Basin Project Act provides in part that "The satisfaction of the requirements of the Mexican Water Treaty, shall be from the waters of the Colorado River pursuant to the treaties, laws, and compacts presently relating thereto, until such time as a feasible plan showing the most economical means of augmenting the water supply available in the Colorado River below Lee Ferry by two and one-half million acre-feet shall be authorized by the Congress and is in operation as provided in this Act."

How climate change and variability affect the Basin water supply has been the focus of many scientific studies. Climate experts expect the southwestern United States to be drier in the future and to experience droughts that are of greater severity than those seen in the past. Recent studies have postulated that the average yield of the Colorado River could be reduced by as much as 20 percent due to climate change (Hoerling et al., 2009). Increasing demands, coupled with decreasing supplies, will certainly exacerbate imbalances throughout the Basin.

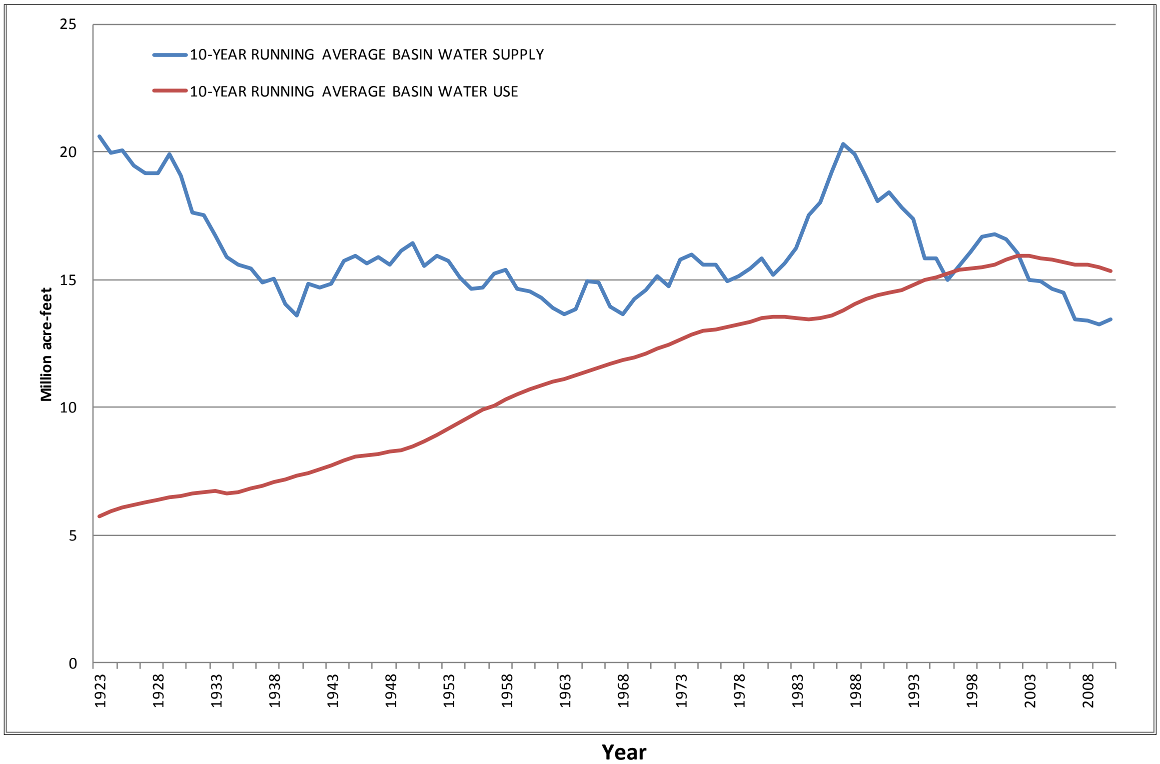
Although a shortage to the Lower Division States (i.e., insufficient water available to satisfy annual consumptive use of 7.5 maf) has not been experienced to date, some water agencies have experienced shortages in water deliveries to their customers in recent years. In California, drought conditions, along with increased regulatory restrictions, caused the Metropolitan Water District of Southern California to reduce firm water deliveries to its customers in 2009 for the first time in nearly 20 years. The water supply allocation plan offered local water providers the flexibility to choose among various conservation strategies, from tiered pricing to limits on outdoor water use, to help ensure that demands stayed in balance with limited supplies. In addition, to help meet critical water supply needs in urban areas, programs have been implemented to fallow land in agricultural areas and transfer the conserved water to urban areas. Although this has helped to meet the water needs of the urban areas, it has also reduced the food and fiber production from the region.

The Upper Basin will need to develop additional water supplies in order to realize full use of its Colorado River Compact apportionment, but such development reduces certainty. Shortages in the Upper Basin are a reality today. Unlike the Lower Basin, which draws its supply from storage in Lake Mead, the Upper Basin is more dependent on annual streamflow to meet its needs.

As of December 10, 2012, Lake Mead is at approximately 51 percent capacity, with a water surface elevation of approximately 1,118 feet above mean sea level (msl). If the current drought continued and water levels in Lake Mead fell to 1,075 feet msl, the amount of water apportioned for use in Arizona and Nevada would be reduced, pursuant to 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 the Interior [DOI], 2007). If water levels in Lake Mead fell below 1,025 feet msl, the CAP, which delivers Colorado River water to the Phoenix and Tucson metropolitan areas, would have its supply cut by nearly a third. Under the same circumstance, the Southern Nevada Water Authority’s supplies, of which 90 percent come from the Colorado River and serve more than 2 million people in the Las Vegas area, would be curtailed by 20,000 acre-feet (af) annually, nearly 7 percent of Nevada’s basic annual apportionment.

Figure 2 presents the data from figure 1 as a 10-year running average to smooth out the annual variability so that trends are more visible. This figure clearly illustrates the existing supply and demand imbalance in the Basin. This imbalance will grow in the future if the potential effects of climate change are realized and demands continue to increase. A combination of options, including conservation and reuse, development of local groundwater supplies, desalination, augmentation, and the transfer of water from agricultural to urban uses, will likely be needed. The Study has assessed these and other options for resolving the projected imbalances in both the Upper and Lower Basins and has laid the foundation from which future discussions can occur to develop recommendations to sustain the environment, people, and economy of this region.

FIGURE 2
Historical 10-Year Running Average Colorado River Basin Water Supply and Use



Historical water use is the total use of water throughout the Basin for agricultural, M&I, and other consumptive uses including Mexico, plus losses due to evaporation at mainstream reservoirs and use by native and non-native vegetation. Natural flow is used as an estimate of water supply in the Basin. In the current natural flow record, historical inflows based on USGS gaged records are used as estimates of natural flow for the Paria River, Little Colorado River, Virgin River, and Bill Williams River. Additionally, the Gila River is not included in the natural flow record. As such, the use reported here excludes consumptive uses on these tributaries. See Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System for additional detail regarding the treatment of these tributaries in the Study.

3.0 Basin Study Program

The Basin Study Program is part of DOI's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program[9], which addresses 21st-century water supply challenges such as population growth, increased competition for finite water supplies, and climate change. The establishment of the WaterSMART Program addresses the authorities within the SECURE (Science and Engineering to Comprehensively Understand and Responsively Enhance) Water Act (Subtitle F of the Omnibus Public Land Management Act of 2009, Public Law 111-11), enacted into law on March 30, 2009. The SECURE Water Act provides authority for federal water and science agencies to work with state and local water managers to plan for climate change and other threats to water supplies, and take action to secure water resources for the communities, economies, and the ecosystems they support.

9 Additional information regarding this program can be found at http://www.usbr.gov/WaterSMART/.

In 2009, Reclamation initiated the Basin Study Program to fund comprehensive studies to define options for meeting future water demands in river basins in the West where imbalances in supply and demand exist or are projected. At that time, it was envisioned that a Basin Study would quantify current and future water supply and demand imbalances, assess the resulting risks to the basin resources, and assess options to resolve those imbalances. Since that time, the Basin Study Program has evolved to focus on the development and analysis of options to address water supply and demand imbalances. The quantification of climate impacts to supply and demand and the subsequent risk assessment are now conducted through an activity known as the West-wide Climate Risk Assessments (another activity under the WaterSMART Program) and are used to inform subsequent Basin studies.

In March 2011, a report to Congress was released to respond to requirements of the SECURE Water Act (Reclamation, 2011a). The SECURE Report provides information on the future risks to water supply in the eight major Reclamation river basins, whereas the Study was a more-detailed, Basin-wide risk assessment that focused on the development and evaluation of opportunities to mitigate and adapt to those risks. There are minor differences in the streamflow projections based on general circulation models presented in the SECURE Report compared to the projections presented in this report. These differences are attributable to methodological and reporting differences between the two efforts and are summarized in a later section of this report and in *Technical Report B – Water Supply Assessment*.

4.0 Study Objectives and Approach

Representatives of the seven Basin States submitted a letter of intent in February 2009, under the Basin Study Program, to help fund and participate in a study of the Basin. Based on that letter of intent, Reclamation's Upper Colorado and Lower Colorado regions, in collaboration with the Basin States, developed and submitted a proposal in June 2009 to fund the Study. The proposal was selected for funding in September 2009, and a financial agreement between the Basin States and Reclamation for the Study was signed in February 2010. Reclamation entered into contracts with CH2M HILL (including Black & Veatch and Cardno-ENTRIX) and the RAND Corporation to provide technical and administrative support for the Study.

The *Plan of Study*, provided in appendix 1, states that the purpose of the Study is to define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin States that receive Colorado River water over the next 50 years (through 2060), and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The *Plan of Study* lays out specific objectives to be addressed through the Study, including:

- Characterization of the current water supply and demand imbalances in the Basin and the assessment of the risks to Basin resources from historical climate variability
- Characterization of future water supply and demand imbalances under varying water supply and demand conditions in the Basin and the assessment of the risks to Basin resources from potential future impacts of climate change

- Identification of potential strategies and options to resolve Basin-wide water supply and demand imbalances, including:
  - Modifications to the operating guidelines or procedures of water supply systems
  - Modifications to existing facilities and development of new facilities
  - Modifications to existing water conservation and management programs and development of new programs
  - Modifications to existing water supply enhancement programs and development of new programs
  - Other structural and non-structural solutions
- Identification of potential legal and regulatory constraints and analysis of potential impacts to water users and Basin resources for the strategies and options considered
- Prioritization of identified strategies and options and recommendations for potential future actions, including feasibility studies, environmental compliance activities, demonstration programs, and/or implementation as appropriate

The Study Area is defined by the hydrologic boundaries of the Basin within the United States, plus the adjacent areas of the Basin States that receive Colorado River water, as depicted in figure 3.

The Study was conducted in four major phases: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Options and Strategies for balancing supply and demand. Figure 4 illustrates these phases and some of their inter-relationships.

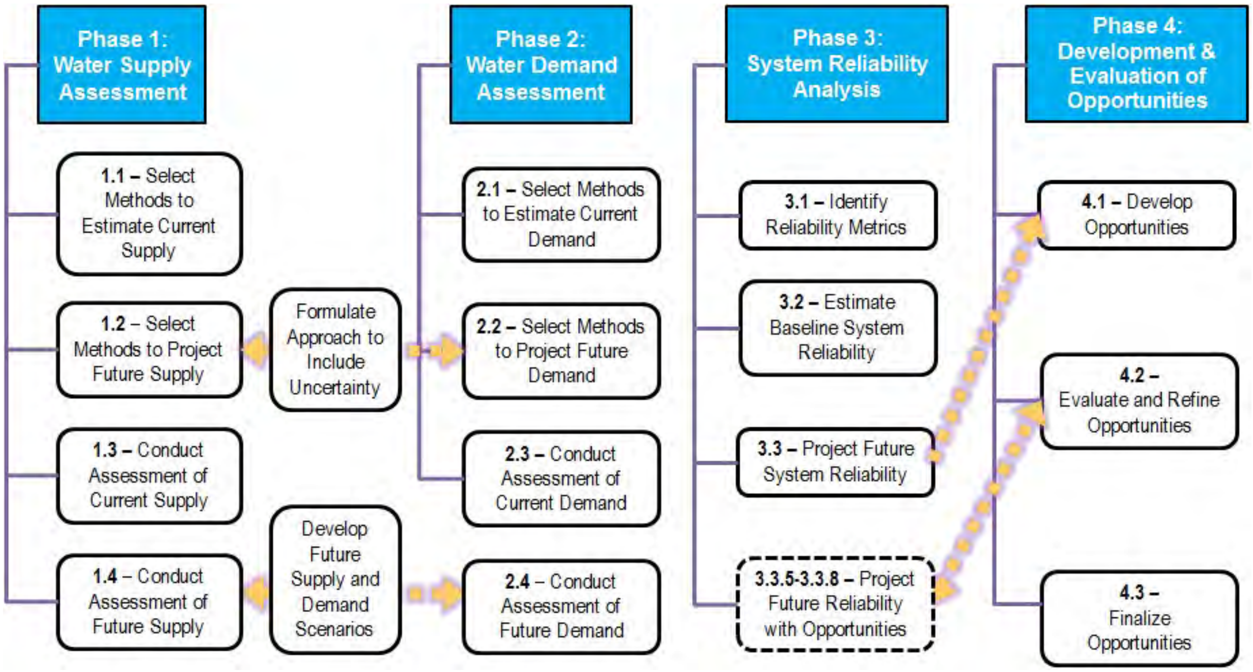
4.1 Study Organization

As envisioned by the *Plan of Study*, two co-Study managers (one from Reclamation and the other representing the Basin States) led and were responsible for the overall direction and management of the Study. In addition, the following teams were established to facilitate the completion of the Study. Members of the Steering, Project, and Study Teams, as well as members of the Study's various technical sub-teams, are listed in *Appendix 4 – Study Participants*:

- The Steering Team (one member from each of Reclamation's Upper Colorado and Lower Colorado regions, one member from each of the seven Basin States, and one member from the Upper Colorado River Commission) steered and guided the efforts of the Project Team such that the objectives of the Study were met in an effective, efficient manner, and within the Study's financial and time constraints. Based on requests from the Ten Tribes Partnership, tribal representatives were invited to participate in Steering Team meetings.
- The Project Team (composed of personnel from the Basin States, water agencies in the Basin States, Reclamation's Upper Colorado and Lower Colorado regions, and from the consulting entities) ensured that the tasks that relate to the Study were completed in a cost-effective, timely manner and were technically sound.

FIGURE 3
The Study Area

FIGURE 4
Study Phases and Tasks



- The Study Team (composed of key personnel from the Upper Colorado and Lower Colorado regions and the consulting entities) completed the Study tasks.
- Sub-teams (composed of Project Team members and representatives from other interested parties with expertise sought by the sub-team) were formed as needed to perform specific technical tasks. Sub-teams consisted of personnel from tribes, conservation organizations, federal agencies, and other interested stakeholder groups.

4.2 Study Outreach

The Study was conducted in collaboration with stakeholders throughout the Basin. Interest was broad and included tribes, agricultural users, purveyors of M&I water, power users, and conservation and recreation groups. Through outreach efforts, interested parties were informed about the Study and asked to provide input reflecting their concerns and thoughts about the future reliability of the Colorado River. This broad participation and input was critical to the Study's success. Interested parties were encouraged to become involved in the Study and were provided a variety of options to do so. These options, which were not mutually exclusive, ranged from attending public meetings and informational webinars to participating directly in the development of work products through the Study's technical sub-teams. The tools and the processes employed in outreach activities are detailed in *Appendix 5 – Public Involvement Plan.* In accordance with the Public Involvement Plan, outreach activities included:

- Establishing a Study website to provide on-line information. The Study web page is http://www.usbr.gov/lc/region/programs/crbstudy.html.
- Establishing an e-mail address to distribute information and receive input. The Study email address is ColoradoRiverBasinStudy@usbr.gov.

- Establishing a facsimile number (702–293–8418) to allow input by fax.
- Establishing a mailing list to ensure that all interested parties receive information, particularly concerning the scheduling and access to public meetings.
- Scheduling public meetings for strategic times during the Study. Six public meetings were conducted during the Study.
- Holding additional meetings with interested parties during the Study period.

More than 170 outreach events occurred during the Study, and these activities are listed in *Appendix 6 – Outreach Activities*.

4.3 Peer Review

A peer review of the Study was conducted to ensure that assumptions, findings, and conclusions of the Study were clearly stated and supported; oversights, omissions, and inconsistencies were identified; and limitations and uncertainties were disclosed. The reviewers were provided with focused technical questions while also being directed to offer a broad evaluation of the overall product.

Peer review comments were considered and incorporated into this and the Study's Technical Reports where relevant and appropriate. *Appendix 7 – Peer Review Summary Report* lists the reviewers, summarizes the comments received and what actions were undertaken to address the reviewers' comments.

In general, the peer review comments indicated that the assessments had been performed adequately and the analyses met the intent of the Study. Many comments dealt with the clarity of the discussion. To address issues of clarity, discussion was added to the reports and description was added to figures and tables as necessary. Study limitations (both in terms of scope and length) prevented the more in-depth supplemental analyses some of the peer reviewers suggestions. Several suggestions for additional analysis are incorporated in the next steps described in section 10.

5.0 Projected Future Supply and Demand Scenarios

The amount of water available and changes in the demand for water throughout the Basin over the next 50 years are highly uncertain and dependent upon a number of factors. The potential impacts of future climate variability and climate change further contribute to these uncertainties. Nevertheless, projections of future supply and demand were needed to assess the future reliability of the Colorado River system to meet Basin resource needs and to identify options and strategies to mitigate future risks to those resources. These projections had to be sufficiently broad to capture the plausible ranges of uncertainty in future water supply and demand.

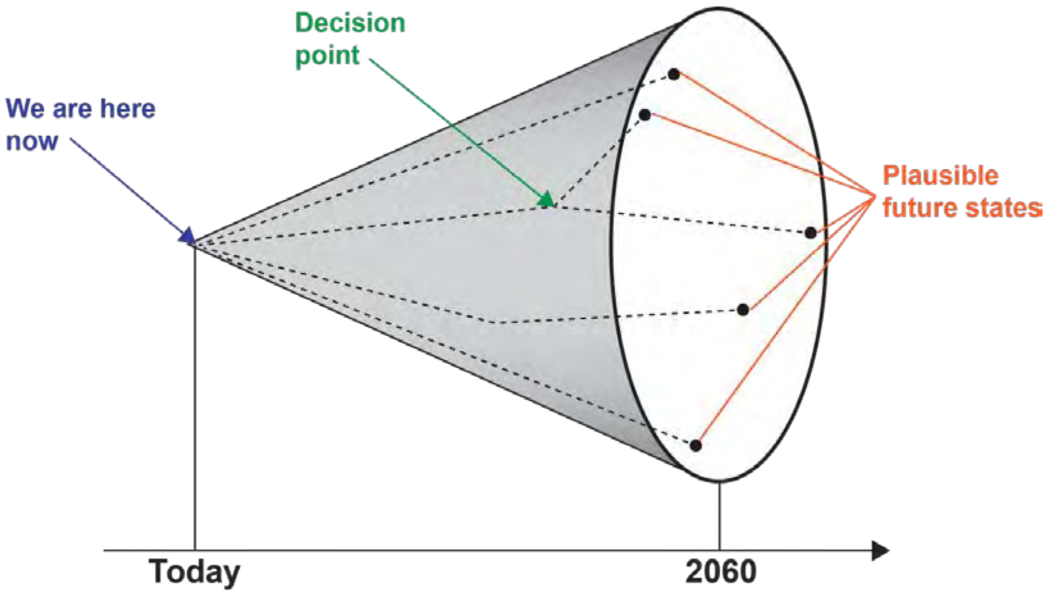
5.1 Summary of *Technical Report A – Scenario Development*

A scenario planning process was used to guide the development of scenarios for providing a broad range of projections of future water supply and demand, resulting in four scenarios related to future water supply and six scenarios related to future water demand. The following section summarizes the approach to scenario development. applied to the Study.

5.1.1 Objective and Approach

Scenarios are not predictions or forecasts of the future. Rather, they are alternative views of how the future might unfold. Figure 5 illustrates this concept. At present, an understanding of the state of the Colorado River system exists as indicated by the single point labeled "Today" on the x-axis of the figure. A range of plausible futures, represented by the funnel, can be identified. The suite of scenarios used in the planning effort should be sufficiently broad to span this plausible range of the funnel.

FIGURE 5
Conceptual Representation of the Uncertain Future of a System, Also Known as "The Scenario Funnel"
Adapted from Timpe and Scheepers, 2003.



The scenario planning process involved:

- Identifying the key forces that would likely drive future water supply and water demand
- Ranking the driving forces (the factors that would likely have the greatest influence on the future state of the system and thereby the performance of the system over time) by their relative importance and uncertainty
- Using the most highly uncertain and highly important driving forces ("critical uncertainties") to identify various themes and "storylines" (narrative descriptions of scenarios) to describe how water supply and water demand may evolve in the future

Quantification of the storylines resulted in water supply and water demand scenarios used to assess future system reliability and thus inform the development of options and strategies to resolve imbalances between water supply and demands.

The general steps involved in the scenario planning process as applied to a water resource planning study were customized to meet the needs of the Study as described in *Technical Report A – Scenario Development.* The approach included input from a broad sampling of stakeholders, experts, and others interested in the management of the system. This input was crucial throughout the development of scenarios to ensure that the resulting scenarios represent the plausible range of futures in the view of those who best know the system.

5.1.2 Summary of Results

A list of 18 specific driving forces relevant to understanding potential future conditions was developed with stakeholder involvement using the general categories listed below and based on experience managing the Colorado River system.

- Natural Systems
- Demographic
- Economic
- Technological
- Social
- Governance

Table 1 lists the driving forces and numbers that were assigned to them. The numbers were assigned for identification purposes only and do not imply a relative priority.

TABLE 1
List of Driving Forces Influencing Future Colorado River System Reliability

No.	Driving Force
1	Changes in streamflow variability and trends
2	Changes in climate variability and trends (e.g., temperature, precipitation)
3	Changes in watershed conditions (e.g., diseases, species transitions)
4	Changes in population and distribution
5	Changes in agricultural land use (e.g., irrigated agricultural areas, crop mixes)
6	Changes in urban land use (e.g., conversion, density, urbanization)
7	Changes in public land use (e.g., forest practices, grazing, wilderness areas)
8	Changes in agricultural water use efficiency
9	Changes in M&I water use efficiency
10	Changes in institutional and regulatory conditions (e.g., laws, regulations)
11	Changes to organization or management structures (e.g., state, federal, bi-national institutions)
12	Changes in water needs for energy generation (e.g., solar, oil shale, thermal, nuclear)
13	Changes in flow-dependent ecosystem needs for Endangered Species Act-listed species
14	Changes in other flow-dependent ecosystem needs
15	Changes in social values affecting water use
16	Changes in cost of energy affecting water availability and use
17	Changes in water availability due to tribal water use and settlement of tribal water rights claims
18	Changes in water quality, including physical, biological, and chemical processes

Based on these driving forces, 12 critical uncertainties were identified. Two critical uncertainties primarily affect the future of water supply and 10 critical uncertainties affect the future of water demand.

The two critical uncertainties primarily affecting the future of water supply are (1) Changes in Streamflow Variability and Trends and (2) Changes in Climate Variability and Trends. A set of four scenarios focused around these critical uncertainties was constructed to represent a broad range of plausible future water supply conditionsin the Basin through the next 50 years. The scenarios were informed by the past, present, and projections of possible futures through incorporation of the paleo-reconstructed streamflow record, the observed historical streamflow record, and projections of streamflow using climate projections from general circulation models (GCMs). The four water supply scenarios and associated themes are presented below.

The scenario development approach identified 10 critical uncertainties primarily affecting the future of water demand. These critical uncertainties are displayed in table 2.

TABLE 2
Critical Uncertainties Affecting Water Demand Scenarios

Critical Uncertainty Identified in Survey	General Driving Force Category
Changes in Population and Distribution Changes in Agricultural Land Use (e.g., irrigated agricultural areas, crop mixes)	Demographics and Land Use
Changes in Agricultural Water Use Efficiency Changes in M&I Water Use Efficiency Changes in Water Needs for Energy Generation (e.g., solar, oil shale, thermal, nuclear)	Technology and Economics
Changes in Institutional and Regulatory Conditions (e.g., laws, regulations) Changes in Flow-dependent Ecosystem Needs for Endangered Species Act-listed Species Changes in Other Flow-dependent Ecosystem Needs Changes in Social Values Affecting Water Use Changes in Water Availability due to Tribal Water Use and Settlement of Tribal Water Rights Claims	Social and Governance

After aligning the associations of the critical uncertainties with the key factors of either water supply and demand, the scenario development process was completed based on the process previously described. These critical uncertainties were combined to generate four water supply scenarios and four water demand storylines. These storylines and their associated themes are described below.

Each of the water supply scenarios was quantified and analyzed. That work, including the approach and key results, is documented in *Technical Report B – Water Supply Assessment* and summarized in the next section of this report. The methodology used to quantify the demand scenarios, as well as an assessment of historical consumptive uses and losses, are described in *Technical Report C – Water Demand Assessment* and summarized in subsequent sections of this report.

5.2 Summary of *Technical Report B – Water Supply Assessment*

Four water supply scenarios were developed using the scenario planning approach previously described. This section summarizes the quantification of those scenarios and the resulting range of potential future streamflow in the Basin.

5.2.1 Objective and Approach

The objective of the Water Supply Assessment was to characterize and quantify the probable magnitude and variability of historical and future natural flows in the Basin. Natural flow represents the flow that would have occurred at a location had depletions and reservoir regulation not been present upstream of that location. The assessment included the potential effects of future climate variability and climate change and provides quantified projections of future hydrology.

Using the scenario planning process described above and in *Technical Report A – Scenario Development*, four water supply scenarios were identified and quantified, each representing plausible future water supply conditions. These water supply scenarios and their associated themes are presented in detail in *Technical Report B – Water Supply Assessment.* The following scenarios and associated themes were considered in the Study:

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

Before 2004, Reclamation used the historical record of natural flow in planning studies. The implicit assumption was observed natural flow would be representative of future streamflow variability and trends. In 2004, Reclamation initiated a multi-faceted research and development program to develop methods beyond those using the observed record for projecting possible future inflow sequences for Basin planning studies. Through this effort, two additional water supply scenarios were developed; they have been used in previous Basin planning studies that assume the observed and paleo-reconstructed streamflow records are representative of future streamflow variability and trends. These scenarios were most recently detailed in appendix N of the 2007 Interim Guidelines Final EIS. The three scenarios previously used are the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios.

A resampling technique known as the Indexed Sequential Method (Ouarda et al., 1997) was applied to the observed and paleo-streamflow records to generate multiple sequences of future streamflow in the Observed Resampled (102 sequences) and Paleo Resampled (1,244 sequences) scenarios. Sequences for the Paleo Conditioned scenario were generated by applying a non-parametric technique to “blend” the observed and paleo streamflow records (1,000 sequences).

To ensure that the water supply scenarios encompassed a sufficiently broad range of future water supply conditions, a fourth scenario was developed that used downscaled GCM projections, titled the Downscaled GCM Projected scenario.

The Downscaled GCM Projected scenario entailed a method in which climate forcings (primarily temperature and precipitation) from 112 climate projections used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (Intergovernmental Panel on Climate Change, 2007), subsequently bias corrected and statistically downscaled (Maurer et al., 2007), were input to the Variable Infiltration Capacity (VIC) hydrologic model (Christensen and Lettenmaier, 2009) to simulate streamflow. The VIC model (Liang et al., 1994, 1996; Nijssen et al., 1997) is a spatially distributed macro-scale hydrologic model that solves the water balance at each model grid cell. The VIC model was populated with the historical temperature and precipitation data to simulate historical hydrologic parameters (Maurer et al., 2002). *Technical Report B – Water Supply Assessment*, *Appendix B4 – Variable Infiltration Capacity (VIC) Hydrologic Modeling Methods and Simulations* provides details on the VIC model and its application in the Study. A streamflow bias correction method was developed and applied to the “raw” VIC-simulated flows to account for any systematic bias in the hydrology model and/or climate data sets. The Downscaled GCM Projected scenario consisted of 112 sequences of future streamflow. The 112 climate projections comprised projections assuming three independent greenhouse gas emission scenarios (high, medium, and low), 16 distinct GCMs, and multiple simulations due to differences in starting climate system state (initial oceanic and atmospheric conditions).

These four methods were used to develop hydrologic inputs into the Colorado River Simulation System (CRSS)[10]. CRSS is Reclamation’s primary Basin-wide simulation model used for long-term planning studies and, in its current configuration, requires natural flow inputs at 29 locations on a monthly time step over the Study’s planning horizon.

5.2.2 Summary of Results

Historical Supply

The Study assessed historical water supply in the Basin. The assessment was composed of a discussion of methods followed by the results for four groups of water supply indicators: climate, hydrologic processes, climate teleconnections, and streamflow. Two historical streamflow data sets, the observed record spanning the period 1906 through 2007 and the paleo-reconstructed record spanning the period 762 through 2005 (Meko et al., 2007), were used to characterize historical streamflow patterns and variability. The following observations and conclusions were made:

- There has been a warming trend in both the Upper and Lower Basins since the 1970s, which is consistent with observed North American and global trends.

[10] CRSS was the primary modeling tool used in the Study. It simulates the operation of the major Colorado River system reservoirs on a monthly time step and provides information regarding the projected state of the system in terms of output variables. Outputs include the amount of water in storage, reservoir elevations, releases from the dams, hydropower generation, the amount of water flowing at various points in the system, the total dissolved solids content, and diversions to and return flows from the water users in the system.

- Widespread decreases in springtime snowpack were observed, with consistent results across the lower elevation northern latitudes of the western United States. Losses of snow water equivalent tended to be largest at low elevations and strongly suggested a temperature-related effect.
- Natural inter-annual variability in streamflow tended to be more dominant than the relationships to either the El Niño–Southern Oscillation or the Pacific Decadal Oscillation. However, in 2011 and 2012, the climate was entering a strong combined cool phase of both El Niño–Southern Oscillation Pacific Decadal Oscillation. The alignment of both signals in the cool phase suggests a propensity for continued drying trends in the coming years.
- The recent deficit (defined as the difference between the 2-year running average flow and the long-term mean annual flow) that started in 2000 is more severe than any other deficit in the observed period, at 9 years and 28 maf.
- The period from 762 through 2005 contained deficits that were longer in duration (16 years) and larger (as much as 35 maf) than those in the period from 1906 through 2005. Thus, the wet–dry sequences from the much longer paleo record suggest that deficits of greater severity than the recent deficit are possible.

In summary, the trends over the observed period and over the recent climatological regime suggest declining streamflows, increases in variability, and seasonal shifts in streamflow that may be related to warming. The paleo reconstruction indicates a slightly lower mean inflow than the observed record. The paleo reconstruction also suggests that annual and inter-annual flows have been more variable in terms of both wet and dry sequences than the observed record period. Deficits of longer duration and greater magnitude can be expected based on the paleo record, although the paleo record shows that past deficits were not significantly more intense than the observed record.

Future Projected Supply

The Observed Resampled, Paleo Resampled, and Paleo Conditioned methods did not consider the impacts of a changing climate beyond what has occurred historically. Therefore, the key findings related to projected changes in temperature, precipitation, snowpack, and runoff over the next 50 years that may be expected under the Downscaled GCM Projected scenario in particular are presented below. These findings are based on the assessment described in *Technical Report B – Water Supply Assessment.*

- Warming is projected to increase across the Basin, with the largest changes in spring and summer and with larger changes in the Upper Basin than in the Lower Basin. Annual Basin-wide average temperature increases are projected to be approximately 1.3 and 2.4 degrees Celsius over the periods 2011 through 2040 and 2041 through 2070, respectively. Increases are measured relative to the 30-year historical period of 1971 through 2000.
- Precipitation patterns continue to be spatially and temporally complex, but projected seasonal trends toward drying are significant in certain regions. A general trend towards drying is present in the Basin, although increases in precipitation are projected for some higher elevation and hydrologically productive regions. Consistent and expansive drying conditions are projected for the spring throughout the Basin. For much of the Basin, drying conditions are also projected in the summer, although some areas of the Lower Basin are projected to experience slight increases in precipitation, which may be attributed to the monsoonal

influence in this region. Upper Basin precipitation is projected to increase in the fall and winter and the Lower Basin is projected to experience decreases.

- Snowpack is projected to decrease as more precipitation falls as rain rather than snow and warmer temperatures cause an earlier melt. Decreased snowpack in the fall and early winter is projected in areas where precipitation does not change or increases, and is caused by more rain and less snow due to warming. Substantial decreases in spring snowpack are projected to be widespread, due to earlier melt or sublimation of snowpack.
- Runoff (both direct and baseflow) is spatially diverse, but is generally projected to decrease, except in the northern Rockies. As with precipitation, runoff is projected to increase significantly in the higher elevation Upper Basin during winter, but is projected to decrease during spring and summer.

Future Colorado River flows were developed for all water supply scenarios. Figure 6 shows the range of annual flows for the Colorado River at Lees Ferry for each of the scenarios over the Study period.

The long term (2011–2060) mean natural flow for the Colorado River at Lees Ferry over the next 50 years ranged from 14.7 to 15.0 maf for the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios. The Downscaled GCM Projected scenario resulted in mean annual flows of approximately 13.7 maf, an 8.7 percent reduction from the observed mean. The range of mean flows was greatest under the Downscaled GCM Projected scenario, with the inter-quartile range spanning roughly 12.6 to 14.9 maf and the minimum/maximum range covering 10 to 17 maf.

A skew of zero implies a normal distribution, in which wetter years and magnitudes are evenly balanced with drier years. Most scenarios had a positive skew, suggesting a bias to the drier side of the distribution. This was particularly noticeable in the Downscaled GCM Projected scenario.

The minimum annual flows were fairly consistent across the scenarios, with the Paleo Resampled scenario exhibiting the most extreme low-flow condition. The Downscaled GCM Projected scenario exhibited a range of maximum annual flows not seen in any of the other scenarios.

Table 3 presents a comparison of several key streamflow statistics for each scenario. The statistics are grouped by annual, monthly, deficit, and surplus period statistics. For the purpose of the Study, deficit and surplus periods occur whenever the running 2-year average flow falls below (deficit) or above (surplus) 15.0 maf, the observed mean. Deficit and surplus period statistics indicate the range of inter-annual variability of streamflow across the scenarios.

In comparison to the Observed Resampled scenario, the other scenarios exhibited a substantial increase in inter-annual variability, both in sustained deficits and surpluses. The maximum length of sustained deficit in the Observed Resampled scenario was 8 years, whereas the maximum sustained surplus was 7 years. The Paleo Resampled, Paleo Conditioned, and Downscaled GCM Projected scenarios all produced deficit and surplus periods that were much longer. The frequency of deficit spells that were 5 years or longer was also higher under these scenarios, with the Downscaled GCM Projected scenarios exhibiting a likelihood of almost 50 percent over the next 50 years. However, the frequency of surplus spells that were 5 years or longer was highest under the Observed Resampled scenario.

FIGURE 6
Summary Statistics for Annual Colorado River at Lees Ferry Natural Flows for Supply Scenarios
Figure shows the median (dash), 25th–75th percentile band (box), and maximum/minimum (line).

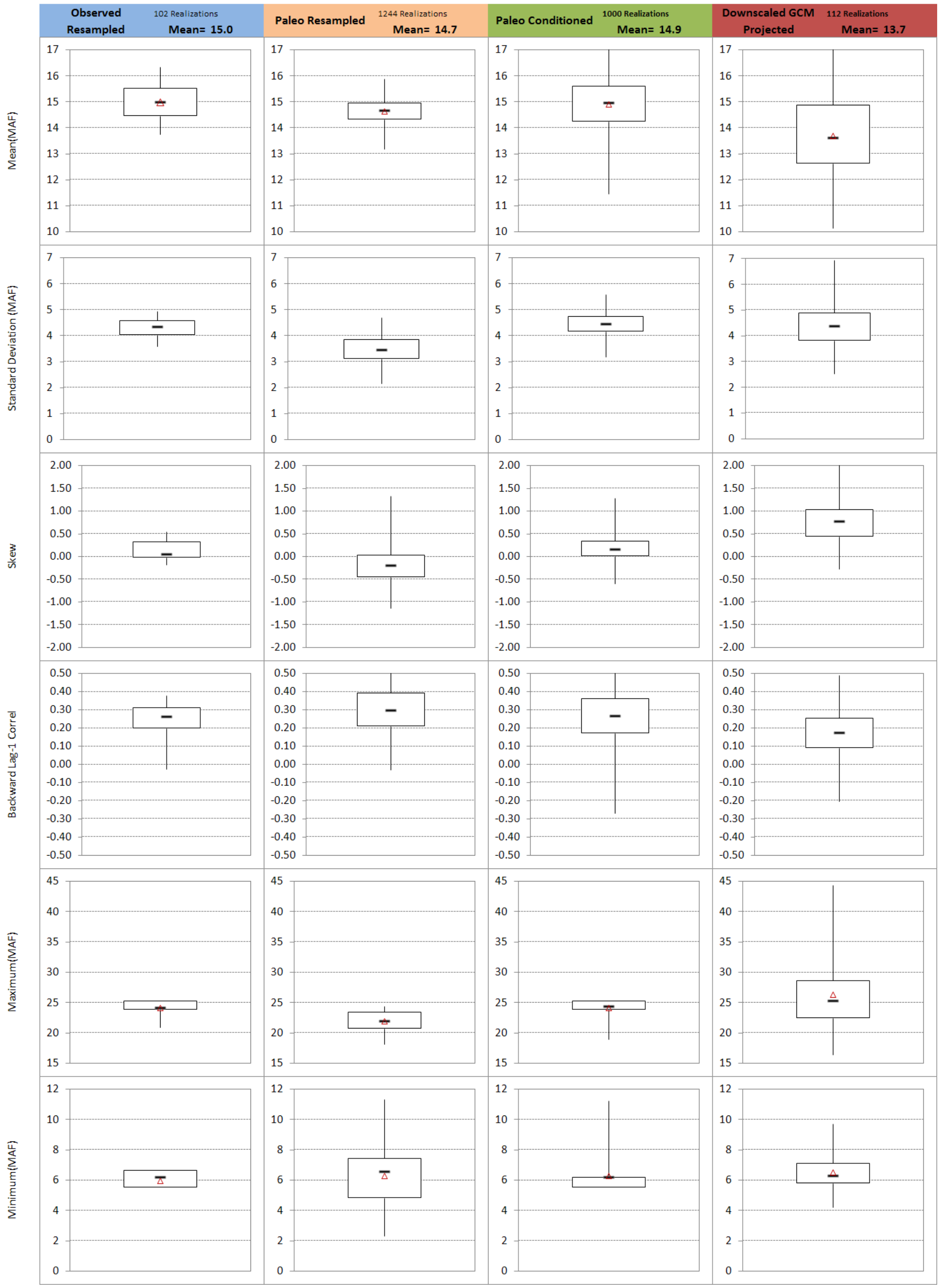


TABLE 3
Summary of Key Streamflow Statistics for Each Water Supply Scenario

	Statistic[1]	Scenario			
		Observed Resampled	Paleo Resampled	Paleo Conditioned	Downscaled GCM Projected
Annual (Water Year)	Average Annual Flow (maf)	15.0	14.7	14.9	13.7
	Percent Change from Long-term Mean (1906–2007)	0%	-2%	-1%	-8.7%
	Median (maf)	15.0	14.7	15.0	13.6
	25th Percentile (maf)	14.5	14.3	14.2	12.6
	75th Percentile (maf)	15.5	15.0	15.6	14.9
	Minimum Year Flow (maf)	5.6	2.3	5.6	4.2
	Maximum Year Flow (maf)	25.2	24.3	25.2	44.3
Monthly	Peak Month	June	June	June	June
	Peak Month Mean Flow (thousand acre-feet [kaf])	4,007	3,914	4,000	3,393
	Peak Month Maximum Flow (kaf)	8,467	8,531	8,678	14,693
	Month at Which Half of Annual Flow (Water Year) was Exceeded	June	June	June	June
Deficit Periods[2]	Maximum Deficit (maf)	28.2	38.4	98.5	246.1
	Maximum Spell Length (years)	8	17	24	50
	Intensity (Deficit/Length) (mafy)	3.5	2.3	4.1	7.4
	Frequency of 5+ Year Spell Length (percent)	22%	30%	25%	48%
	Maximum 8-year Deficit (longest in 1906–2007 observed record, maf)	28.2	29.8	50	48.6
Surplus Periods[3]	Maximum Surplus (maf)	22.2	36.2	88	74.7
	Maximum Spell Length (years)	7	15	25	19
	Intensity (Surplus/Length) (mafy)	3.2	2.4	3.5	13.2
	Frequency of 5+ Year Spell Length (percent)	28%	15%	18%	<1%
	Maximum 7-year Surplus (longest in 1906–2007 observed record, maf)	22.2	29.2	44	39.2

[1] Statistics are computed over the Study period, 2011–2060.
[2] A deficit period occurs whenever the running 2-year average flow is below the observed mean from 1906–2007 of 15.0 maf.
[3] A surplus period occurs whenever the running 2-year average flow is above the observed mean from 1906–2007 of 15.0 maf.

The results suggest that under sequences in the Downscaled GCM Projected scenario, sustained periods of dryness may occur (deficit lengths of up to 50 years). Most projections resulted in long-term mean annual flows that were less than the 15 maf observed mean, while other projections resulted in long-term mean annual flows that were greater than the 15 maf observed mean. The future projected climate essentially arrived at a new mean state.

The processes in which GCM projections were used to generate projections of future streamflow contained a number of areas of uncertainty and reflected methodological choices made in the Study. For example, different methodological choices with respect to downscaling techniques, as well as selection of a different hydrologic model used to translate GCM output into streamflow, yielded different results.

There are some minor methodological differences in the technical approach to develop streamflow projections informed by GCMs and the analysis of those projections between the results presented here and those presented in the SECURE Report. The methodological differences consist primarily of the application of a secondary bias correction to the results presented here. Reporting differences are due to the selection of baseline conditions for comparison and the future analysis period. Specifically, the SECURE Report computed future decadal changes from a 1991 through 2000 baseline condition, whereas the change statistics reported here were computed between the observed record and the Study period of 2011 through 2060. Therefore, results of the Study and those in the SECURE Report are not identical.

5.3 Summary of *Technical Report C – Water Demand Assessment*

Four water demand storylines were developed using the scenario planning approach previously described. This section summarizes the quantification of the six scenarios resulting from those storylines and the resulting range of potential future demand in the Basin.

5.3.1 Objective and Approach

The Water Demand Assessment examined the quantity and location of current and future water demands in the Study Area. These water demands were derived from Basin resource needs, including M&I use, hydropower generation, recreation, and fish and wildlife habitat. In addition, losses in the Study Area from evaporation and other factors were assessed. Because future water supply and demand throughout the Basin are uncertain, scenarios were developed that are sufficiently broad to span that uncertainty, including the potential effects of future climate change.

Future demands are a function of socioeconomic parameters such as future population, irrigated land area, M&I and agricultural water use efficiency, tribal water use, energy production growth and associated water use, and others. Through the scenario planning process applied in the Study, the most critical uncertainties affecting future demand were identified, and a range of future demand scenarios was envisioned. Narrative descriptions of these scenarios (storylines) were developed and provide a rational basis for consideration of a wide array of future conditions. These storylines and their associated themes are:

- Current Projected (A): Growth, development patterns, and institutions continue along recent trends
- Slow Growth (B): Slow growth with emphasis on economic efficiency

- Rapid Growth (C1 and C2): Economic resurgence (population and energy) and current preferences toward human and environmental values
- Enhanced Environment (D1 and D2): Expanded environmental awareness and stewardship with growing economy

Under the storylines, two logical branches or directions were considered for the Rapid Growth (slower technology adoption—C1 and rapid technology adoption and increase in social values—C2) and Enhanced Environment (current growth trend—D1 and higher growth and technology—D2) scenarios. For example, population growth or increasing energy needs and subsequent water demand could be offset by associated technological innovations influencing water use. The four storylines, two with branches, resulted in six water demand scenarios. Complete narrative descriptions of the scenarios (storylines) are presented in *Technical Report C – Water Demand Assessment, Appendix C14 – Water Demand Scenario Storylines.*

The process to develop the critical uncertainties and demand storylines, and quantify scenarios, engaged a wide array of stakeholders and reflects a broad range of plausible conditions considering differing views of the future. In order to establish a solid foundation relating to methods and assumptions for quantifying future demands, the Study focused initial efforts on quantifying the Current Projected (A) scenario. The Current Projected (A) scenario provided the basis for consideration of departures from these assumptions, leading to the quantification of the Slow Growth, Rapid Growth, and Enhanced Environment demand scenarios. Each of the scenarios was quantified through significant input from the Basin States, with additional input provided by tribes, U.S. Fish and Wildlife Service personnel, and conservation organizations. Demand for each scenario was quantified by estimating values for individual parameters (such as population, irrigated acreage, water use efficiencies) associated with storylines and specific scenario assumptions.

Table 4 presents the demand categories, their definitions, and associated parameters collected or developed for the Study. As part of the scenario quantification process, general relationships were used to relate the expected changes in parameters for each scenario in comparison to the Current Projected (A) scenario consistent with each storyline.

Future demands may be affected by climate change, primarily changes in ambient temperature and the amount and distribution of precipitation. As such, the possible effects of changing temperature and precipitation on evapotranspiration, which may affect agriculture and outdoor M&I demand, and effects on phreatophyte and reservoir evaporation losses were also assessed in the Study. The potential impacts to evapotranspiration rates affecting agricultural demand were assessed using the Penman-Moteith method to estimate potential evapotranspiration (PET) under varying climatic conditions.

TABLE 4
Definition of Demand Categories and Their Associated Parameters

Demand Category	Definition	Parameters
Agriculture	Water used to meet irrigation requirements of agricultural crops, maintain stock ponds, and sustain livestock	Irrigated acreage, irrigation efficiency
M&I	Water used to meet urban and rural population needs, and industrial needs within urban areas	Population, population distribution, M&I water use efficiency, consumptive use factor
Energy	Water used for energy services and development	Water needs for energy generation
Minerals	Water used for mineral extraction not related to energy services	Water needs for mineral extraction
Fish, Wildlife, Recreation[1]	Water used to meet National Wildlife Refuge, National Recreation Area, state park, and off-stream wetland habitat needs	Institutional and regulatory conditions, social values affecting water use, Endangered Species Act-listed species needs, and ecosystem needs
Tribal	Water used to meet tribal needs and settlement of tribal water rights claims	Tribal use, settlements, and claims

[1] This demand category represents the consumptive use portion of demand. Non-consumptive demands are considered in metrics, see *Technical Report D – System Reliability Metrics*.

5.3.2 Summary of Results

Historical Consumptive Use

Figures 7 and 8 present the range of historical Colorado River water consumptive use and loss compiled by basin and category. This information was compiled from Reclamation's Colorado River System Consumptive Uses and Losses Reports (CU&L Reports[11]), Reclamation's Colorado River Accounting and Water Use Reports[12], and additional input from the Basin States. The categories of consumptive uses and losses presented consist of the following: agriculture; M&I; energy; minerals; fish, wildlife, and recreation; exports; reservoir evaporation; and other losses.

There are data and methodological inconsistencies in the CU&L Reports with respect to the Lower Basin tributaries (the Little Colorado, Virgin, Bill Williams and Gila rivers). These inconsistencies are primarily the result of changing methodologies between the 5-year reporting periods. Similar inconsistencies were found in these reports with respect to the Upper Basin until Reclamation undertook a multi-year effort to resolve them. This effort has not occurred for the Lower Basin tributaries, and the quality of information has suffered. Independent of the Study, Reclamation will engage in efforts to resolve and correct, in collaboration with the Basin States, the methodological and data inconsistencies in the CU&L Reports pertaining to all of the Lower Basin tributaries. Refer to *Technical Report C – Water Demand Assessment, Appendix C11 –*

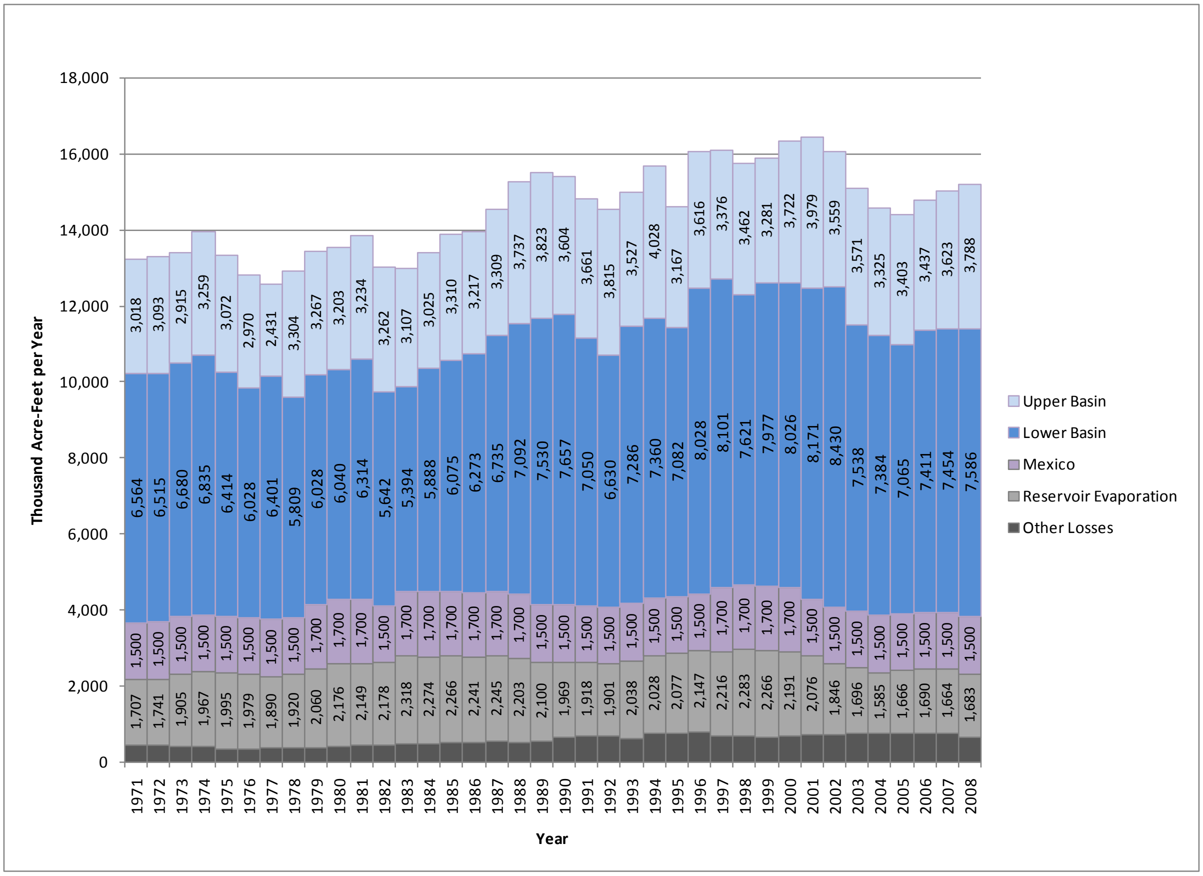
[11] Some states produce independent estimates of consumptive uses and losses. For consistency, the analysis of historical consumptive uses and losses in the Study was based on Reclamation's CU&L Reports, available at http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html.

[12] http://www.usbr.gov/lc/region/g4000/wtracct.html.

Modeling of Lower Basin Tributaries in the Colorado River Simulation System, for a description of these issues and commitments.

Consumptive uses and losses in the Basin increased from 1971 to the start of the drought that began in 2000. The information presented in figure 7 indicates that from 1971 through 1999, Basin-wide consumptive uses and losses (including deliveries to Mexico pursuant to the 1944 Treaty[13]) have grown from approximately 13 maf in 1971 to 16 maf in 1999, an increase of about 23 percent. Over the same period, Upper Basin uses have grown from approximately 3.0 maf in 1971 to 3.3 maf in 1999, an increase of about 10 percent. Lower Basin uses have grown from approximately 6.6 maf in 1971 to 8.0 maf[14] in 1999, an increase of about 21 percent.

FIGURE 7
Historical Colorado River Water Consumptive Use[1] by Basin,[2] Delivery to Mexico, Reservoir Evaporation, and Other Losses,[3] 1971–2008



[1] Excluding consumptive use in Lower Basin tributaries.
[2] Uses in the Lower Division States greater than 7.5 maf occur during Surplus Conditions.
[3] Phreatophyte and operational inefficiency losses.

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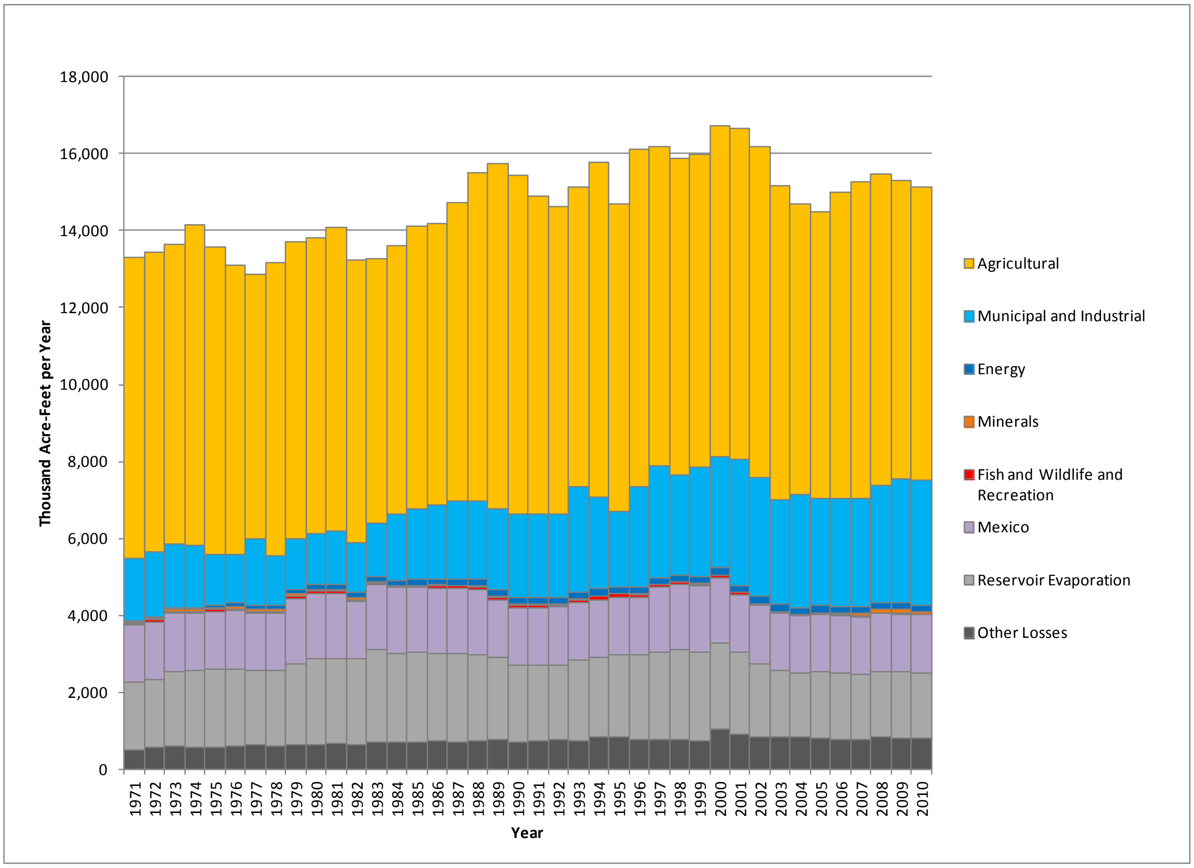
[13] Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande, Treaty between the United States and Mexico, 1944.

[14] Uses in the Lower Division States greater than 7.5 maf occur during Surplus Conditions.

FIGURE 8
Historical Colorado River Water Consumptive Use[1] by Use Category,[2] Delivery to Mexico, Reservoir Evaporation, and Other Losses,[3] 1971–2010



[1] Excluding consumptive use in Lower Basin tributaries.

[2] Reservoir evaporation losses are accounted differently in the Upper and Lower Basin. In the Upper Basin, reservoir evaporation losses are accounted as part of each state's total uses. In the Lower Basin, reservoir evaporation losses are accounted separately from each state's uses. Reservoir evaporation losses from Upper and Lower Basin reservoirs have been aggregated for this presentation.

[3] Phreatophyte and operational inefficiency losses.

Agricultural and M&I uses have grown over this period, as have reservoir evaporation losses. As shown in figure 8, agricultural uses have grown from approximately 7.7 maf in 1971 to 8 maf in 1999, an increase of about 4 percent. M&I uses have grown from approximately 1.4 maf in 1971 to 2.2 maf in 1999, an increase of about 57 percent. Reservoir evaporation losses have grown from 1.7 maf in 1971 to 2.3 maf in 1999, an increase of 35 percent.

In the assessment of the possible impacts to agricultural demands due to changes in precipitation and temperature, agricultural water demands are assumed to increase by approximately 5 percent for each Celsius degree increase in temperature, and by approximately 1 percent for each 5 percent reduction in precipitation.

Future Projected Demand

The quantification of the Current Projected (A) scenario was used as a starting point for the quantification of the remaining scenarios. Historical consumptive use and loss information was used in conjunction with future planning data (e.g., land use, policy, population growth, economic conditions) to inform the development of future projected demand. Although current projections are not direct mathematical projections of historical data, the Current Projected (A) scenario in particular relies on knowledge of the historical consumptive uses and losses, as described above, as well as planning data and expertise to estimate future trends in water demands. General relationships were used to relate the expected changes in parameters for each scenario in comparison to the Current Projected (A) scenario consistent with each storyline. These are shown conceptually in table 5.

Table 6 presents summary results for the demand scenarios considered in the Study. The table presents agricultural and M&I demand parameters for the Study Area, which distinguishes the scenarios, the resulting Study Area demand, and finally the Colorado River demand by category. Colorado River demand is defined as Study Area demand less the demand projected to be supplied by other sources. The Study and the results presented in this report focus on the resulting Colorado River demand.

The Study Area demand ranges between 28.7 and 32.5 maf by 2060, with Colorado River demand[15] ranging between 13.8 and 16.2 maf. Some of the increase in Study Area demand is projected to be met through increases in other supplies, primarily in Colorado and California. The increase in Colorado River demand from 2015 through 2060 is estimated to be between 1.1 and 3.4 maf, with the Lower Basin making up about 60 percent of the increase. Of the total increase in Colorado River demand, for the growing categories, between 64 and 76 percent of the growth is contributed by the M&I demand category. The growth in energy, tribal, and mineral categories constitutes the remaining increase in demand.

Relative to water use across sectors, Study Area comparisons reflect differing levels of and interplay among changing societal values, economic drivers, and various types of resource constraints. An exception to this comparison is with respect to tribal demands. It was determined during the quantification process that the factors affecting tribal demands are not particularly well-represented by the driving force categories established by the Study. For the most part, tribal demands are based on quantified rights in Current Projected (A), Slow Growth (B), and Enhanced Environment (D1) scenarios, but consider additional demands beyond current settlements in the Rapid Growth (C1 and C2) and Enhanced Environment (D2) scenarios. Additionally, it is important to recognize that the quantification of water supply and demand scenarios may compare differently at state and individual planning area levels. State level demands generally follow broad identifiable trends, whereas individual planning areas consider locally relevant information, plans, timelines, and constraints.

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[15] Mexico's allotment and losses such as reservoir evaporation, phreatophyte losses, and operational inefficiencies are not part of this total. These factors were included in the modeling supporting the system reliability analysis.

TABLE 5
Scenario Matrix of Typical Changes in Parameters Defined by the Water Demand Storylines
(In general, these represent parameter change from 2015, with growth as a blue "up" arrow, no change as a yellow bar, or reduction as a green "down" arrow. The size of the arrow represents larger or smaller change for a given parameter.)

	Population	M&I Per Capita Use	Self Served Industrial Demand[1]	Agricultural Irrigated Acreage	Agricultural Per Acre Delivery	Energy Water Demand	Minerals Demand	Fish, Wildlife, Recreation Demand	Tribal Demand
Current Projected (A)	↑	↓	↑	↓	▬	↑	▬	▬	↑
Slow Growth (B)	↑	↓	↑	↓	↑	↑	▬	▬	↑
Rapid Growth (C1)	↑	↓	↑	↓	↑	↑	↑	▬	↑
Rapid Growth (C2)	↑	↓	↑	↓	↓	↓	↓	↑	↑
Enhanced Environment (D1)	↑	↓	↑	↑	▬	↓	↓	↑	↑
Enhanced Environment (D2)	↑	↓	↑	↑	↓	↓	↓	↑	↑

[1] Self-served industrial (SSI) demand represents the demand of industries in a given area that have water supply systems independent of municipal systems.

TABLE 6
Summary Results of Water Demand Scenario Quantification by 2060

Parameter	2015	2060 Scenario Parameters					
		A	B	C1	C2	D1	D2
Key Study Area Demand Scenario Parameters							
Population (millions)	38.9–41.1	62.4	49.3	76.5	76.5	62.4	76.5
Change in per capita water usage (%), from 2015	–	-9%	-7%	-9%	-16%	-19%	-17%
Irrigated acreage (millions of acres)	5.4–5.5	5.1	5.2	4.6	4.6	5.0	5.0
Change in per-acre water delivery (%), from 2015[1]	–	+1%	+2%	+1%	+3%	0%	+3%
Study Area Demand (maf)							
Agricultural Demand	16.4–16.7	15.2	15.7	13.7	13.8	14.9	14.9
M&I Demand	8.4–8.8	12.5	10.2	15.1	13.9	11.0	13.7
Energy Demand	0.34–0.63	0.66	0.57	1.01	0.58	0.51	0.56
Minerals Demand	0.1–0.11	0.18	0.18	0.22	0.15	0.15	0.15
Fish, Wildlife, and Recreation Demand	0.16–0.23	0.08	0.08	0.08	0.10	0.16	0.16
Tribal Demand[2]	1.6–1.8	2.0	2.0	2.4	2.4	2.0	2.4
Total Study Area Demand[3]	**27.3–27.8**	**30.6**	**28.7**	**32.5**	**30.9**	**28.7**	**31.9**
Colorado River Demand (maf)							
Agricultural Demand	7.1–7.2	6.7	6.8	6.6	6.7	6.6	6.8
M&I Demand	3.4–3.5	5.1	4.5	6.2	5.2	4.8	5.4
Energy Demand	0.21–0.23	0.44	0.38	0.74	0.37	0.34	0.35
Minerals Demand	0.09–0.11	0.17	0.18	0.21	0.14	0.14	0.14
Fish, Wildlife, and Recreation Demand	0.15–0.21	0.06	0.07	0.06	0.08	0.15	0.15
Tribal Demand[2]	1.5–1.7	2.0	1.9	2.4	2.4	2.0	2.4
Total Colorado River Demand[3]	**12.6–12.8**	**14.5**	**13.8**	**16.2**	**15.0**	**14.0**	**15.2**

[1] Does not include reductions associated with conservation and efficiency programs such as those in Imperial Irrigation District that are part of transfer and acquisition agreements.

[2] Tribal demand within the state of Colorado was included in other demand categories.

[3] Excludes Mexico's allotment and losses (reservoir evaporation, phreatophytes, and operational inefficiencies). These factors were included in the modeling supporting the system reliability analysis.

The Colorado River demand at three geographic levels is presented in figures 9 and 10. These figures show Study Area, Upper and Lower Basin, and individual state demand across all scenarios. The bars at the right in these figures show the relative contribution of each demand category to the total Colorado River demand at a point in time (2015, 2035, or 2060) in the Current Projected (A) scenario. In general, the category proportions remain relatively consistent across the scenarios. For the purposes of the Study, demand was not limited by the Law of the River apportionments. In this way, the demand for Colorado River and tributary water can be assessed in the context of overall Study Area demand and supplies available from other sources.

As shown in figure 9, the change in both magnitude and percentage of Colorado River demand varies considerably across the states. Colorado and Arizona show the greatest magnitude of overall growth in Colorado River demand from 2015 through 2060 across the scenarios, ranging between about 0.2 and 1.2 maf of increased demand by 2060 in Arizona and 0.04 and 0.64 maf in Colorado.

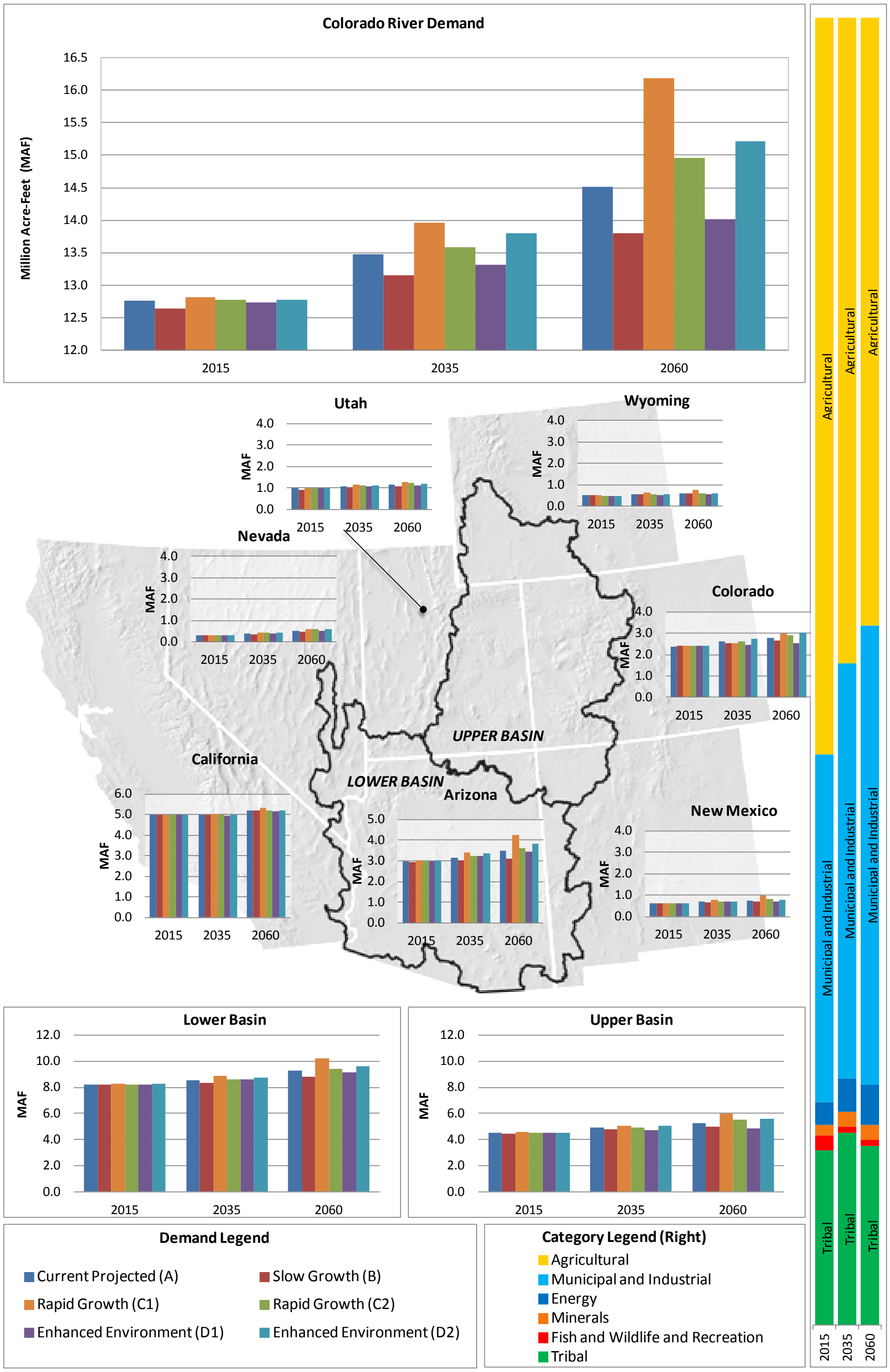
The broad demand range across scenarios in these states is due to substantial growth in M&I demand, particularly in central Arizona and the Front Range of Colorado. Increase in tribal demand is also a significant contributor to the increases in Arizona. Demand in Nevada and California is projected to increase by about 0.2 to 0.35 maf, due to population growth in Nevada and California (with supply currently limited by Colorado River Aqueduct capacity). Demand in New Mexico, Utah, and Wyoming grows by about 0.1 to 0.2 maf under most scenarios. Under the Rapid Growth (C1 and C2) scenarios, however, the growth is about 0.3 maf in Utah, where population is projected to increase by nearly 4 million and per capita water use reductions do not fully offset the rapid growth.

When demand by category is examined in figure 10, the contribution of demand by category across the Upper and Lower Basins vary, with nearly equal agricultural and M&I demand in the Lower Basin and nearly two-thirds of the demand in the Upper Basin from agriculture. The category contribution to the total demand varies considerably across states as well, with no two states having comparable proportions of categories.

Tribes hold quantified rights to a significant amount of water from the Colorado River and its tributaries (approximately 2.9 maf of annual diversion rights). In many cases, these rights are senior to other uses. Therefore, representing these rights and the associated demand is a critical component of assessing future water demand in the Basin. An additional component of future demand is an assessment of demands by tribes that have unquantified rights or claims. Where this information was provided by tribes, it was incorporated into the Study as appropriate.

Throughout the Study, Reclamation met with tribes in the Upper Basin, Lower Colorado River mainstem, and tribes served by water provided (directly or pursuant to exchanges) through the CAP facilities under contracts between tribes and the United States. In addition, Reclamation worked with the Ten Tribes Partnership, whose members have landholdings in the Upper and Lower Basins through which the Colorado River and various tributaries flow, as well as the Inter Tribal Council of Arizona, whose members are the governments of 20 tribes with land in Arizona. Based on this input, tribal demand, under all scenarios for all states (with the exception of Colorado, where tribal demand was not separated from other demands within the state, as requested by the tribes) met or surpassed the quantified tribal right by 2060. Refer to *Technical Report C – Water Demand Assessment, Appendix C9 – Tribal Water Demand Scenario Quantification* for details of quantified rights and future projected demands by tribe.

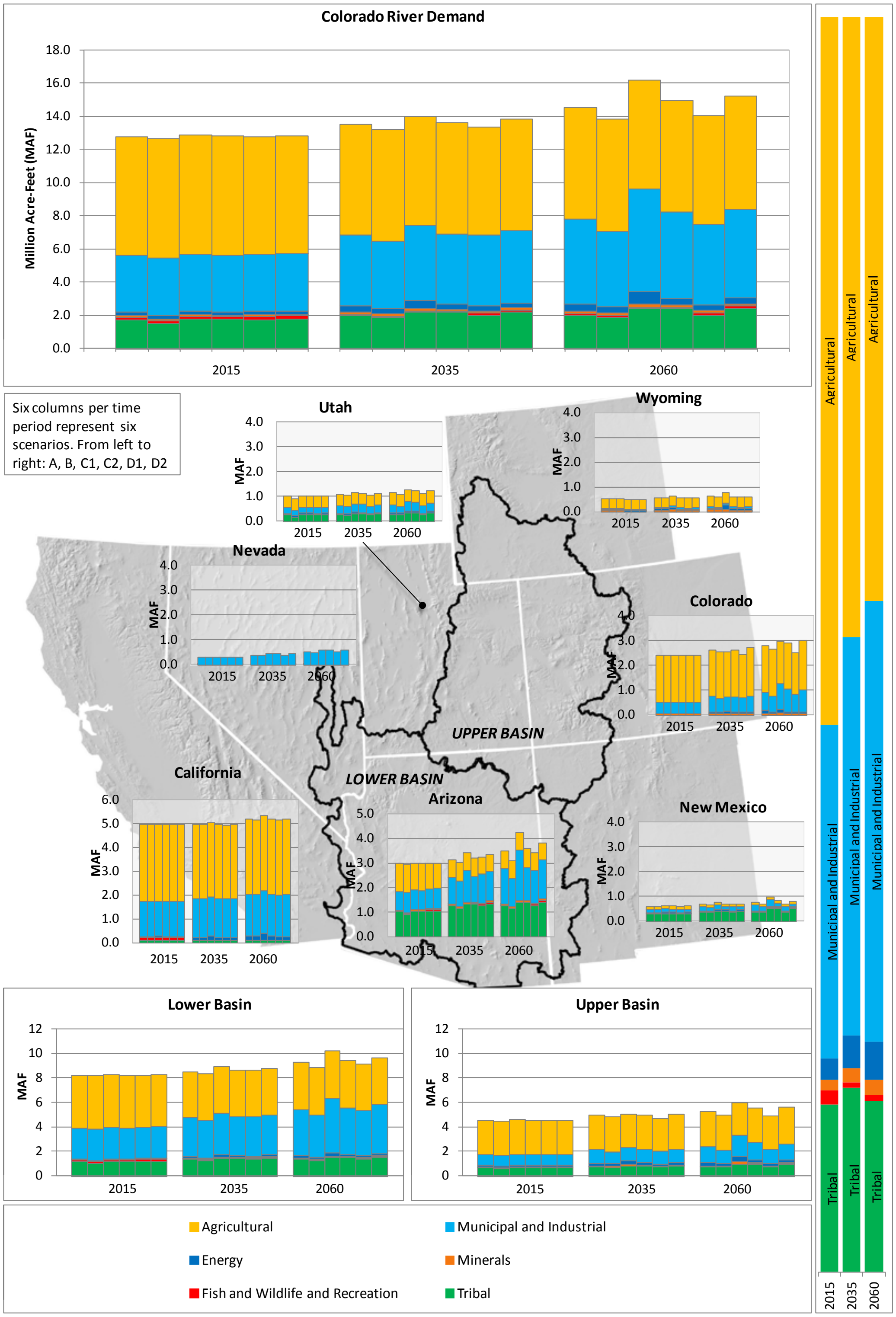
FIGURE 9
Colorado River Water Demand[1,2]



[1] Demands do not include Mexico's allotment and losses such as reservoir evaporation. These factors were included in the modeling supporting the system reliability analysis.

[2] Tribal demand in Colorado, at the request of the Southern Ute Indian and Ute Mountain Ute tribes, was not separated from other categories in the state.

FIGURE 10
Colorado River Water Demand by Category[1,2]



[1] Demands do not include Mexico's allotment and losses such as reservoir evaporation. These factors were included in the modeling supporting the system reliability analysis.

[2] Tribal demand in Colorado, at the request of the Southern Ute Indian and Ute Mountain Ute tribes, was not separated from other categories in the state.

Projected Effect of a Changing Climate on Future Demands

Future demands may be affected by a changing climate, primarily due to changes in ambient temperature and the amount and distribution of precipitation. The Study addressed possible effects of changing temperature and precipitation on evapotranspiration, which affects agriculture and outdoor M&I demand, and phreatophyte and reservoir evaporation losses. Possible changes in demand related to climate change not evaluated in the Study are changes in water demand for energy production, changes to environmental flow requirements associated with increasing ambient temperature, and changes in crop type.

As part of the hydrologic modeling for the Study, and to be consistent between the calculations used to generate water supply scenarios, a physically based method, Penman-Monteith, as implemented in the VIC model, was proposed to adjust agricultural, outdoor M&I demands, phreatophyte losses, and reservoir evaporation rates due to climate change. Details on the methods used to construct the climate index factors for adjusting demands and losses under climate change are provided in *Technical Report C – Water Demand Assessment, Appendix C15 – Climate Change Effects on Water Demand and Losses*. The mean change in evapotranspirative demand is on the order of 4 percent by 2060, compared to demands without changes in climate. A total demand increase of more than 500 kaf per year by 2060 is estimated considering potential effects of climate change. These changes will evolve over time with a warming climate, and could be higher or lower depending on the climate projection, but the magnitude of the climate impact to demands is expected to be substantial.

FIGURE 11
Current Projected (A) Scenario Demands Adjusted for Possible Future Climate Change

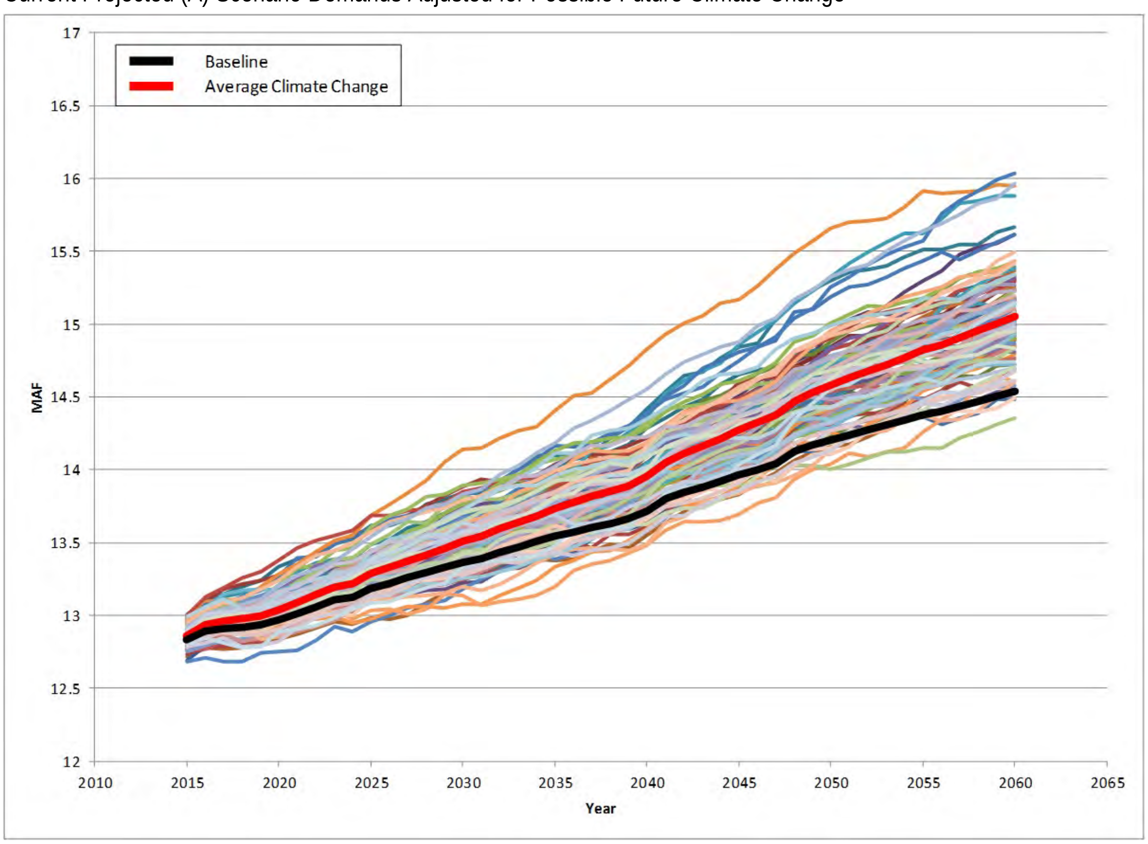
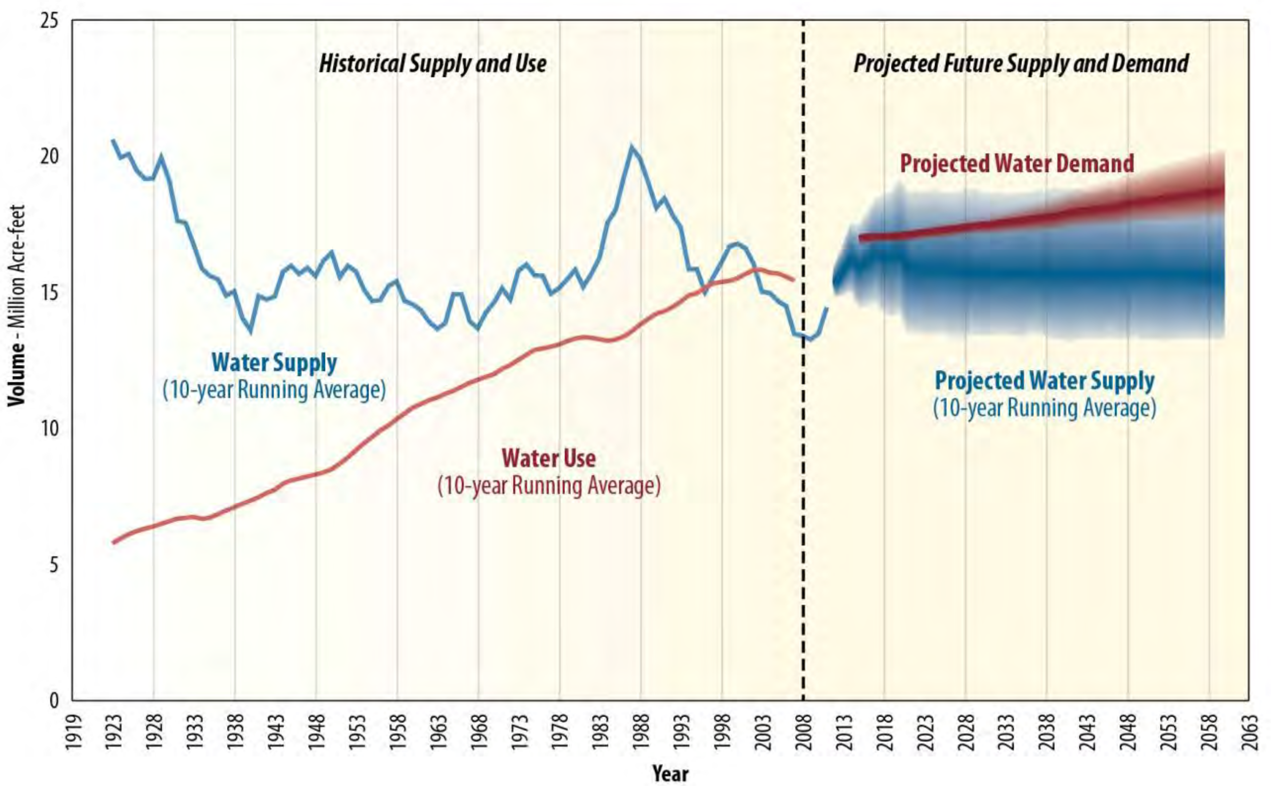


Figure 11 presents the factors as applied to the Current Projected (A) scenario demands excluding Mexico's allotment, reservoir evaporation,[16] and other losses.[17] The thick black line represents projected demand under current climate; the thick red line represents the average annual demand as adjusted for the climate change scenarios and the other lines represent individual projections of future climate.

6.0 Projected Future Supply and Demand Imbalances and System Reliability Metrics

Using the projections of future water supply and demand identified through the scenario development and quantification process, the range of the projected total future supply and demand in the Basin is shown conceptually in figure 12. Although a range of future imbalances is plausible, when comparing the median of water supply projections to the median of the water demand projections, the long-term imbalance in future supply and demand is projected to be about 3.2 maf by 2060.

FIGURE 12
Historical Supply and Use[1] and Projected Future Colorado River Basin Water Supply and Demand[1]



[1] Water use and demand include Mexico's allotment and losses such as those due to reservoir evaporation, native vegetation, and operational inefficiencies.

[16] Climate change effects on reservoir evaporation are adjusted dynamically through CRSS simulations.

[17] Phreatophytes are included in the "other losses" category. Losses due to phreatophytes are adjusted for climate change using similar methods as those proposed for agricultural irrigation.

It is important to recognize two points concerning this result. First, the 3.2 maf imbalance is based on the median imbalance for a particular year and can either be more or less from year to year under any one of the projections. Second, single-year imbalances of this magnitude have occurred several times in the past. Although there have been shortages in supply in Upper Basin tributaries, Colorado River deliveries of basic apportionments in the Lower Basin have been made with 100 percent reliability, primarily as a result of the ability to capture water in system reservoirs during high-flow years and to deliver that water during low-flow years. The system reliability analysis entailed simulating the operation of the system, including the effects to reservoir storage, and provides detailed information regarding the specific timing and magnitude of potential imbalances and how the Basin resources may be affected. System reliability metrics, summarized in the following section, are measures that indicate these impacts.

6.1 Summary of *Technical Report D – System Reliability Metrics*

System reliability metrics are measures that indicate the ability of the Colorado River system to meet Basin resource needs under multiple future conditions. These metrics were used to measure the potential impacts to Basin resources from future supply and demand imbalances and to measure the effectiveness of options and strategies to address those imbalances.

6.1.1 Objective and Approach

A seven-step process was adopted to develop the metrics used in the system reliability analysis. This process is detailed in *Technical Report D – System Reliability Metrics*, particularly figure D-1. The process for developing system reliability metrics began with the identification of resource categories. Based on the *Plan of Study* (see appendix 1) and working closely with stakeholders through the Metrics Sub-Team, six resource categories were identified. Following the identification of the resource categories, several attributes of interest associated with each resource category were identified.

6.1.2 Summary of Results

Table 7 presents the six resource categories and corresponding attributes of interest. To further define system reliability metrics associated with attributes of interest, locations in the Basin were selected where metrics could offer information about the performance of the system. Metrics were evaluated in either a quantitative or qualitative fashion. A metric was evaluated quantitatively if: (a) direct evaluation was possible using output from CRSS or results from post-processing of CRSS output data, or (b) an indirect indicator of the attribute of interest at the specified location could be developed, based on output from CRSS or post-processing of CRSS output data.

The ability to assess impacts to Basin resources was limited by the spatial and temporal detail of CRSS. In these cases, system reliability metrics were either assessed in a qualitative manner or, where time and resources permitted, additional analysis was conducted to result in a quantitative assessment. The map in figure 13 displays the Study Area and denotes the locations of the metrics that were defined. The locations of the water deliveries metrics were not included because there were more than 200 locations throughout the Study Area, though the primary locations used in the system reliability analysis were deliveries to the Upper and Lower Basins.

TABLE 7
Resource Categories and Attributes of Interest

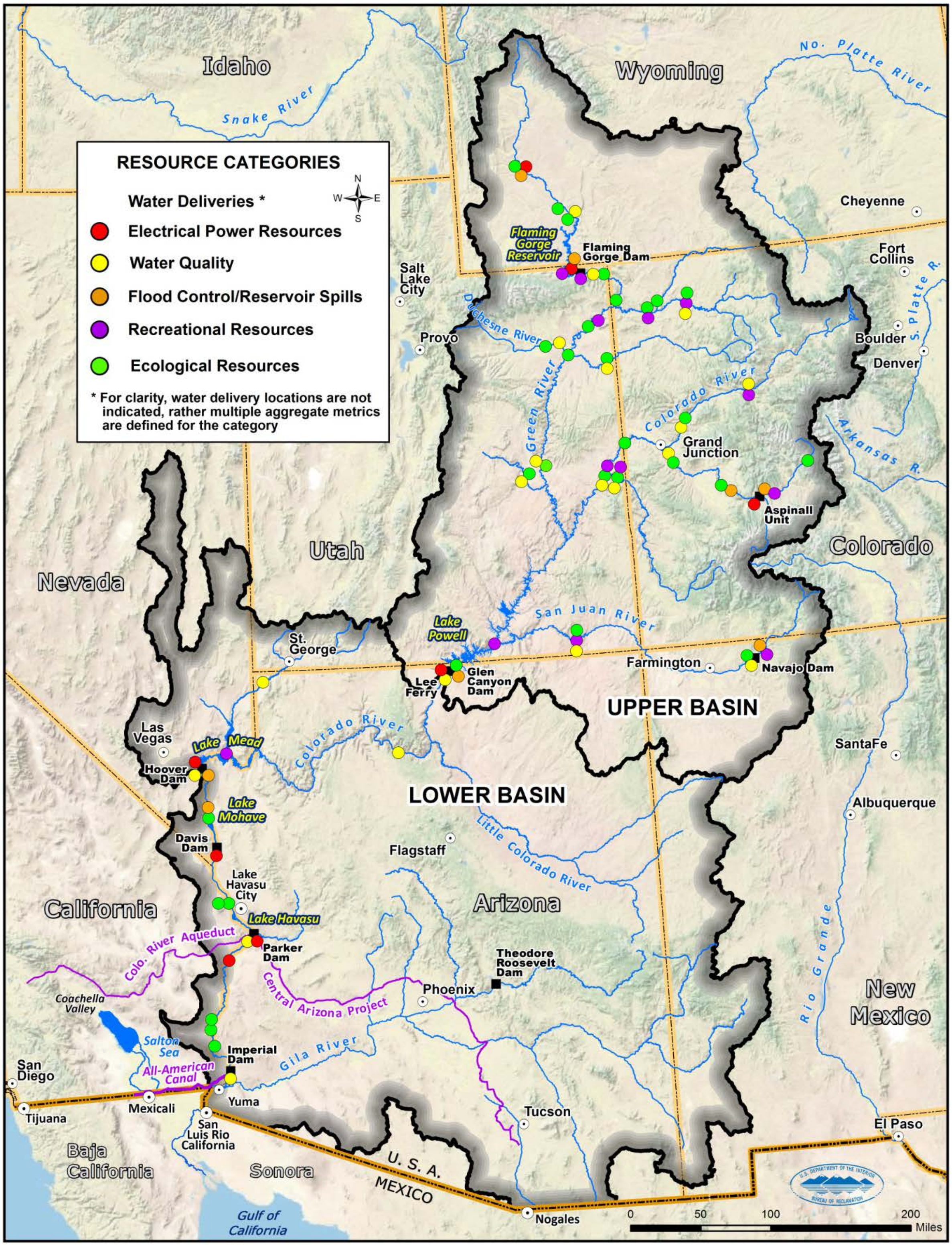
Resource Category	Attribute of Interest
Water Deliveries	• Consumptive Uses and Shortages • Water Levels Related to Intake Facilities • Socioeconomic Impacts Related to Shortages
Electrical Power Resources	• Electrical Power Generated • Economic Value of Electrical Power Generated • Available Generation Capacity • Impact on Power Rates
Water Quality	• Salinity • Sediment Transport • Temperature • Other Water Quality Attributes • Socioeconomic Impacts Related to Salinity
Flood Control	• Flood Control Releases and Reservoir Spills • Critical River Stages with Flooding Risk
Recreational Resources	• Shoreline Public Use Facilities • River and Whitewater Boating • Other Recreational Attributes • Socioeconomic Impacts Related to Recreation
Ecological Resources	• Threatened and Endangered Species • Aquatic and Riparian Habitats • Wildlife Refuges and Fish Hatcheries

7.0 Options and Strategies to Resolve Supply and Demand Imbalances

In November 2011, the Study began its fourth and final phase: Development of Options and Strategies to balance supply and demand. From November 2011 through February 2012, input was solicited from Study participants, interested stakeholders, and the general public on options and strategies for helping to resolve future water supply and demand imbalances in the Basin. Over this period over 150 options were submitted to the Study.

This section describes the options that were received, the evaluation of those options, and the development of portfolios or packages of options that reflect different strategies for resolving future imbalances.

FIGURE 13
Study Area with Locations of Defined Metrics



7.1 Summary of *Technical Report E – Approach to Develop and Evaluate Options and Strategies*

The approach toward developing and evaluating options and strategies to balance future supply and demand is described in *Technical Report E – Approach to Develop and Evaluate Options and Strategies*. The overall approach follows the assessment of plausible future water supply and demand scenarios described in Technical Reports A, B, and C, and the identification of system reliability metrics described in Technical Report D. The following steps were undertaken in this approach:

- Evaluation of system reliability without options and strategies
- Characterization of system vulnerabilities
- Identification and characterization of options
- Development of portfolios of options
- Evaluation of system reliability with options and strategies

This approach consisted of a structured process for evaluating system reliability across the range of resources metrics, identifying options that could improve the reliability, development of combinations of options based on particular response strategies (portfolios), and evaluation of the improved system reliability with the application of these portfolios. The steps involving the evaluation of system reliability and vulnerability analysis are further outlined in *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*. The steps involving the identification and characterization of options and the development of portfolios are described in *Technical Report F – Development of Options and Strategies.*

7.2 Summary of *Technical Report F – Development of Options and Strategies*

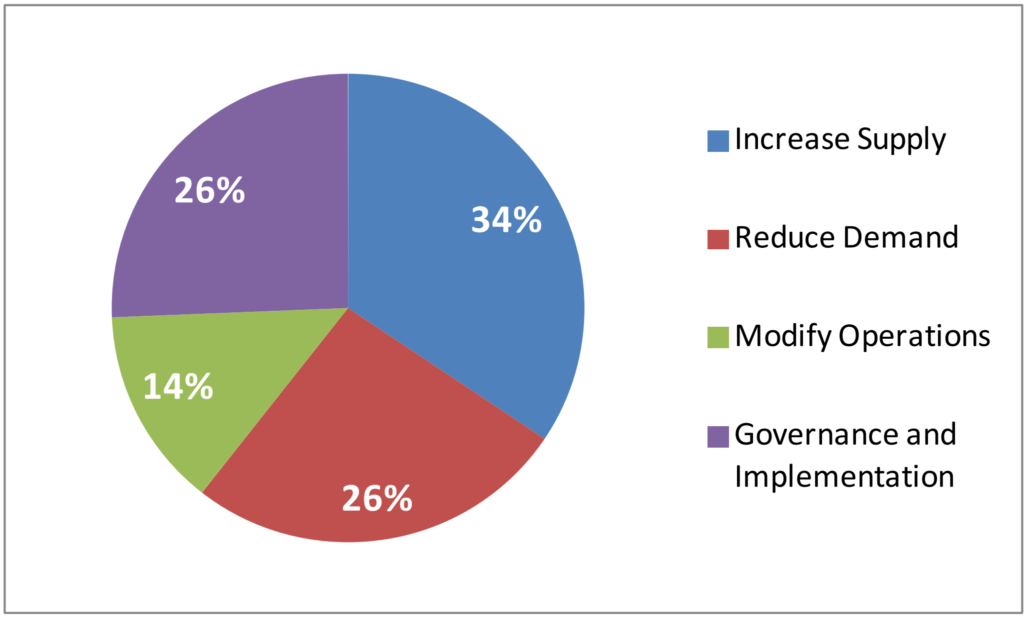
The general approach for the development of options and strategies involved the following steps: (1) soliciting input on options for consideration in order to examine a broad range of potential options, (2) organizing options into common types, (3) developing representative options from the pool of submitted options, (4) characterizing options using a set of 17 criteria that reflected a broad set of attributes of interest, and (5) developing portfolios that represent potential strategies to address future supply and demand imbalances. Details of the process and results for each of the steps are described in *Technical Report F – Development of Options and Strategies* and summarized below.

7.2.1 Summary of Options Received

Options received were organized into four types: (1) those increasing Basin water supply, (2) those reducing Basin water demand, (3) those modifying operations, and (4) those focusing on Basin governance and implementation.

A total of 55 options were submitted related to increasing supply, 42 options related to reducing demand, 22 options related to modifying operations, and 41 options related to governance and implementation. The percentage of options in each type is shown in the chart in figure 14.

FIGURE 14
Distribution of Options Received



Within each of the four option types, categories of options, such as importation, desalination, and M&I conservation, etc. were developed. Each submitted option was assigned to one category based on its primary function. From these option categories, about 40 unique representative options were described to capture the range of options submitted to and considered in the Study. Subsequent sections summarize the option categories and describe representative options that were received and considered in the Study.

7.2.2 Approach to Characterize Options

The *Plan of Study* identified specific objectives related to the development and evaluation of options. As the Study progressed, a definitive process for the characterization of options was developed. This process included the quantitative characterization of options through the assignment of ratings to a number of evaluation criteria. The process also included the qualitative characterization of options that did not directly increase supply or reduce demand. The qualitative characterization consisted of the identification of opportunities and constraints, including potential legal and regulatory issues.

Option characterization was performed to describe each of the submitted options, provide a relative comparison of the option attributes, and support the eventual development of option and portfolio evaluations. Characterization of proposed options was based primarily on information provided by the option submitter; however, existing literature and/or relevant studies also were reviewed to support the characterization process.

Characterization of the options was based on 17 evaluation criteria that are consistent with the criteria outlined in the *Plan of Study*, as summarized in table 8. These criteria are described more fully in *Technical Report F – Development of Options and Strategies*.

TABLE 8
Criteria Used to Characterize Representative Options

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

In general, each option was provided with a five-point rating (“A” through “E”) for each of the criteria. “A” generally represented the most favorable rating and “E” represented the least favorable.

The cost criterion includes capital and annual costs expressed in terms of unit costs in present value dollars per acre-foot. All costs presented were developed based on annualized capital costs added to annual operation and maintenance (O&M) costs divided by the annual yield of the option.

7.2.3 Summary of Option Characterization

Importation

River and other out-of-Basin freshwater imports have been proposed to increase the overall water supply of the Basin. Fifteen options related to river or other freshwater imports were received. The submitted options were reviewed and organized into three groups according to the location at which the imported water would provide water to the Colorado River or would provide exchange water for regions reliant upon Colorado River supplies.

One group consists of options for importing water from the Missouri River or Mississippi River to areas adjacent to the Basin that could use this water to meet projected shortfalls and/or reduce the amount of water these areas divert from the Basin. Water would be conveyed to the Front Range of Colorado and specific areas of New Mexico and integrated into existing water supply systems. Although these options are termed "imports," water would not actually be imported into the Basin. Rather, water would be delivered to these adjacent areas to reduce the amount of water that could be exported from the upper Colorado and San Juan rivers.

The second group of options includes diverting water from the upper headwaters of rivers adjacent to the Green River to the headwaters of the Green River. Potential sources of supply are diversions from the Bear River, upper Snake River, or Yellowstone River.

The third group consists of options that focus on importing high-quality water from other regions using ocean routes to Southern California coastal areas. Potential sources of water include the Columbia River[18], rivers in Alaska, or icebergs. Delivery mechanisms include sub-ocean pipelines for Columbia River supplies, tanker ships for Alaskan river supplies, or tug boats for icebergs. All of the options in this group require extensive transport or conveyance of water from the source regions to Southern California and require relatively complex facilities and operations to integrate the supply within the current water supply system in Southern California.

Desalination

Ocean and brackish water desalination has been proposed to increase the overall water supply of the Basin. Fifteen options related to desalination were received. The submitted options were reviewed and organized into three groups according to the source of water to be desalinated.

The first group consists of constructing new or expanding existing (or currently proposed) ocean desalination plants in strategic locations along the southern California coast or near the international boundary with Mexico. This concept also includes constructing new ocean desalination plants along the Gulf of California, Mexico. For both the Pacific Ocean and Gulf of California desalination plants, water users downstream would use desalted water in lieu of Colorado River water. Thus there would be less water diverted and/or released from Lake Havasu, the benefits of which would be seen up the river system to Lake Mead and possibly beyond to Lake Powell.

The second group of options includes constructing new diversions upstream of the Salton Sea on the New and Alamo rivers that would capture agricultural drainage water and deliver it to a regional brackish water desalination facility. The desalinated water would be delivered back to

[18] Among the more than 150 options submitted to Reclamation as responsive to the *Plan of Study*, additional importation of water supplies from various sources, including importation of water from the Snake and Columbia River systems, were submitted to the Study. Such options were appropriately reflected in the Study but did not undergo additional analysis as part of a regional or river basin plan or any plan for a specific Federal water resource project. This Study is not a regional or river basin plan or proposal or plan for any Federal water resource project.

the All American Canal and exchanged for an in-kind amount of reduction in diversions from the Colorado River at Imperial Dam.

The third group consists of options for desalination of brackish water in Southern California and Arizona consistent with past similar projects, and also refurbishing the Yuma Desalting Plant to allow full-scale production.

Reuse

Reuse of existing water supplies was proposed as a method of increasing overall water supply in the Basin. Eleven options were submitted related to wastewater reuse. The submitted options were reviewed and organized into three groups. Representative options were developed for each option group to represent the distinct nature of the options within each group.

The first group of options related to various methods of reuse of municipal wastewater in major urban areas. Municipal wastewater reuse considers new and expanded programs for non-potable purposes such as irrigation and also for potential potable purposes through indirect or direct methods.

The second group consisted of the reuse of industrial wastewater that is not traditionally discharged through municipal wastewater systems.

The third group consisted of reuse of grey water at individual homes or communities for non-potable purposes. Grey water is typically defined as untreated wastewater that has not been contaminated by any toilet discharge, has not been affected by unhealthy bodily wastes, and does not present a threat from contamination by unhealthful processing, manufacturing, or operating wastes (California Building Standards Commission, 2010).

Local Supply

Developing new local supply was proposed to increase the overall water supply of the Basin. Four options related to local supply were received. The submitted options were reviewed and organized into two groups according to the source of local supply.

In the process of developing natural gas resources, poor-quality groundwater is typically "produced" from natural gas wells. The coal bed methane industry has generally disposed of produced water at the least possible cost rather than treat and use this potential resource. In most cases, coal bed methane-produced waters are disposed by injection into Class II underground injection wells. This group of options considers treating the relatively high-salinity water and using it to augment supply in the Basin.

Rainwater harvesting is the capture, diversion, and storage of rainwater for landscape irrigation and other uses. This option group considers how individual household rainwater harvesting can increase local supply throughout the Basin, with particular emphasis on those areas that do not return flows to other users downstream. Rainwater harvesting is not legally permitted in Colorado, and this state-specific issue was recognized within the Study.

Watershed Management

Changes to watershed management were proposed to increase the overall water supply of the Basin. Ten options related to watershed management were received. The submitted options were reviewed and organized into five groups according to the specific type of watershed management recommendations.

Control of invasive tamarisk has been proposed for riparian areas to reduce the overall consumptive use and increase streamflow in the Colorado River. Removal of tamarisk is proposed on riparian benches where water that would have otherwise contributed to streamflow is being consumptively used by tamarisk.

A large percentage of the runoff from the Basin is derived from forests, particularly in Colorado. Previous studies and information have demonstrated that areas in which forest cover is reduced by clear-cutting or fires have shown dramatically increased amounts of runoff. The forest management group of options would entail the replacement of mature forests that have been cleared by harvesting, fires, or insect infestations with stands of replacement growth more likely to be favorable for generating runoff.

Brush control involves reducing brush and therefore reducing consumptive use by vegetation communities. The brush control group of options recommends various techniques available for brush removal, including chemical spraying, chaining, roller chopping, root plowing, grubbing, and controlled fires.

Dust control options propose to control land-based dust sources that contribute to dust accumulation on snow, which changes the albedo, or reflectivity, of the snow resulting in earlier snowmelt (Painter et al., 2007, 2010, and 2012; Skiles et al., 2012) and more evaporative moisture losses. By implementing measures to reduce the accumulation of dust on snow, lower evaporative losses are anticipated.

Weather modification was proposed for increasing precipitation in Basin. Cloud seeding is the most prominent method considered for weather modification. In particular, the seeding of clouds with silver iodide to serve as condensation nuclei can increase snowfall over mountainous regions. Winter cloud seeding operations have been in operation throughout the West since the late 1940s. In recent years, ongoing cloud seeding operations have been documented in at least five of the seven Basin States.

Municipal and Industrial Water Conservation

Development of additional M&I water conservation was proposed to further reduce the overall M&I water demand in areas currently relying upon water supply from the Colorado River. Twenty-nine M&I conservation options were submitted for consideration in the Study, with several of the submitted options suggesting specific conservation measures.

Because levels of current and future conservation vary throughout the Study Area, different levels of potential savings are possible for a given conservation measure. These savings range from essentially no savings where measures have been fully enacted to significant savings where measures have not been enacted or where adoption rates are relatively low. Disaggregating the savings potential by conservation measure and individual location was beyond the scope of the Study. Instead, M&I conservation measures were considered for the entire Study Area with the acknowledgement that, despite state and regional differences in current levels of conservation and potential for future conservation, some additional conservation is achievable on a Study Area-wide basis.

In order to examine the potential for additional M&I conservation and to explore the range of costs and other factors, three levels of conservation were considered based on assumed levels of reductions and adoption rates for residential indoor, commercial-institutional-industrial, landscape, and water loss. Conservation considered in the demand scenarios ranged from about

300 kaf per year to more than 1.1 million acre-feet per year (mafy) in 2060, depending on the assumptions within each scenario regarding the degree of per capita water demand reductions[19]. Additional conservation beyond that included in the demand scenarios was considered in three additional conservation levels (Level 1, 2, and 3) that generate up to a range of 0.7 to 1.3 maf of additional water savings in 2060, depending on the demand scenario. The potential savings of the options would be small in the early years of implementation and grow over time.

Agricultural Water Conservation

Options were submitted proposing agricultural water conservation to reduce the overall water demand in areas currently relying upon water supply from the Colorado River. These options ranged in type from specific conservation mechanisms or best management practices (e.g., improved irrigation efficiencies, modernization, conveyance system efficiencies, changes in types of crops under irrigation) to general implementation approaches to achieve further water conservation (e.g., water pricing or water transfers).

The concepts received were first organized into six Basin-wide agricultural water conservation mechanisms that reflect different types of activities that could generate water savings in the agricultural sector. These agricultural water conservation measures consist of advanced irrigation scheduling, deficit irrigation, on-farm irrigation system improvements, controlled environment agriculture, conveyance system efficiency improvements, and fallowing of irrigated lands. Because the method of implementation is important for realization of water savings, two implementation approaches that could be used to encourage or incentivize adoption of these water conservation mechanisms were considered:

(1) ***Basin-wide agricultural conservation*** through a federal or state incentivized program to encourage agricultural water use efficiency and,

(2) ***Basin-wide agricultural conservation with water transfers*** on a willing transferor-willing transferee basis that promotes water conservation and/or short-term or permanent fallowing of irrigated lands to transfer conserved water for a similar or different use.

For purposes of the Study, each of the various conservation measures was examined as a Basin-wide potential, but in reality the measures will have important regional limitations and in some cases may be mutually exclusive. The various measures should not be considered as additive. Because the conservation measures could produce different amounts of savings depending on the location in the Basin, implementation approach, and combination of measures, the total quantities were estimated as an aggregate for each implementation approach. Up to 1 mafy of potential savings by 2060 was considered for each approach (conservation and conservation with transfers) although the approaches are not considered additive. The 1 mafy of potential savings recognizes an amount of additional water conservation above and beyond the significant existing and future water conservation programs that are already included in the Study’s demand scenarios.

Energy Water Use Efficiency

Options to improve the water use efficiency of the energy sector have been proposed to reduce the water demand of the Basin. Four options related to energy water use efficiency were

[19] The level of M&I conservation included in the water demand scenarios was estimated by first re-computing the M&I demands under each scenario assuming the 2015 gallons per capita per day value from that scenario. The difference in the M&I demand in 2060 with gallons per capita per day held at 2015 levels from the M&I demand in 2060 under the actual demand scenario is the amount of M&I conservation achieved under that demand scenario.

received. The submitted options were reviewed and organized into two groups according to the different concepts proposed for reducing water demand.

The first group of options includes removing the evaporative cooling systems at the 15 largest power plants in the Basin and installing air-cooling systems. The second group of options addresses the need for a reliable water source for oil and gas development, and suggests options for ensuring sufficient supplies through a number of improved efficiency measures.

System Operations

Options dealing with modified system operations have been proposed to increase the overall water supply, decrease demand, reduce evaporation losses, and improve efficiency within the Basin. The submitted options were reviewed and organized into three option groups according to the overarching concept driving the new or modified operation.

The first group includes physical and chemical methods to reduce evaporation from the major canals and reservoirs. Physical covers would incorporate solar photovoltaic panels to simultaneously reduce evaporation and generate electricity, and concepts involving chemical covers include the introduction of a chemical to the water surface of large reservoirs to reduce the evaporation rates of the reservoirs.

The second group proposed new water storage to increase the amount of system storage available for either hydropower optimization or capture of water released but not diverted. It also included improved groundwater management.

The third group of options consists of recommendations for changing current reservoir operations in the Basin to improve water management. These options consist of reoperation to reduce reservoir evaporation, maximize hydropower generation, or improve environmental conditions.

Water Transfers, Exchanges, and Banking

Water transfers, exchanges, and banking have been proposed to increase the efficient use of existing supplies in the Basin. This group consists of options that are reflected in the following representative options: water transfers and exchanges, guided water markets, Upper Basin water banking, Lower Basin water banking, and groundwater banking.

Because of their complexity and the inability to develop representative options indicative of all water banking or transfer-type options, these options have not been assigned ratings for the 17 criteria. Water transfers and banking options generally require working in conjunction with conservation options (agricultural or M&I) in order to generate the water to be transferred or banked.

The guided water markets option would attempt a strategic, guided approach to transactions that could be used proactively to meet demand reduction goals to reduce the risk for Lee Ferry deficit. Another option proposes that a similar concept to the Intentionally Created Surplus (ICS) program in the Lower Basin be applied in the Upper Basin. This option creates an Upper Basin water bank in either Lake Powell or in an off-stream groundwater bank to increase protection against a Lee Ferry deficit in extremely dry conditions.

The 2007 Interim Guidelines (DOI, 2007) implemented an ICS mechanism to provide for the creation, accounting, and delivery of conserved system and non-system water, thereby promoting water conservation in the Lower Basin. The ICS mechanism allows for conserved water in the Lower Basin to be stored in Lake Mead for subsequent delivery in future years. Several options suggested continuing this program beyond the expiration of the 2007 Interim Guidelines in 2026 and expanding or modifying it to include participants beyond entitlement holders to Colorado River mainstem water in the Lower Basin, including Mexico[20].

Finally, some options focused on using groundwater recharge and recovery as an underground water bank. An entity could divert water to groundwater storage when there is a surplus or reduced need for surface supplies. When there is a critical or increased need for additional supply, the entity could then withdraw an equivalent amount of water that it previously banked subject to withdrawal limits. This concept is already used in several areas of the Lower Basin.

Water Management and Allocation

Options were submitted that suggested modifications to Basin water management processes and changes in the distribution of water supply available in the Basin under the Law of the River. There are four representative options in this group: changes to apportionment of water supply, processes for expanded stakeholder involvement, population control, and conservation and trust funds. These options suggested modified methods for governing or managing water supply and demand in the Basin. Although these have been included in the Study for completeness and continued dialogue, mechanisms currently exist for flexible operations without destabilizing the Law of the River or triggering lengthy legal battles that would inevitably occur with any attempt to re-allocate the river.

Tribal Water

Tribes hold quantified rights to a significant amount of water from the Colorado River and its tributaries (approximately 2.9 maf of annual diversion rights). In many cases, these rights are senior to other users. Options pertaining to water development and use were submitted by tribes for consideration in the Study and include concepts such as voluntary tribal water transfers, tribal water storage and ICS, convening of an inter-governmental forum, resolution of tribal claims, affordability of tribal water and removing barriers to tribal participation in federal programs, recognition limits to reduce demand, stabilization of soil, and development of non-tributary groundwater. Recalmation will work with tribes in future efforts regarding tribal water issues reflected in this report.

Data and Information

Options were submitted that suggested improvements to the data and information used by Reclamation for analysis and modeling. These options involved improved water use accounting in the Upper Basin and additional improvements to CRSS. Reclamation is committed to working with the Basin States, interested stakeholders, and the USGS to improve water use accounting and to refine CRSS and other supporting models where it is feasible and useful in order to provide the most realistic representation of how the system is currently operated or may be operated in the future.

Summary of Characterization Ratings

For each of the quantified options developed for the Study, characterization ratings were assigned based on the 17 evaluation criteria. The characterization provided a relative comparison of the option attributes and supported the analysis of options and development of portfolios.

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[20] On November 20, 2012, Minute 319 was signed, which created a mechanism for Mexico to store water in Lake Mead, called Intentionally Created Mexico Allotment. This is a temporary agreement, however, and the long-term implementation of such a mechanism is subject to future Minutes.

Three of the evaluation criteria were developed with both numeric values as well as letter rating: cost, quantity of yield, and timing.

Table 9 summarizes the potential yield for each of the main option groups in 2035 and 2060. A total of 7.6 mafy of potential yield was identified for options that increase supply. The options with greatest yield of this type are related to watershed management methods, desalination of ocean and brackish water, importation, and reuse. A total of 2.2 mafy of potential savings was identified through options that reduce demand. The principal options that comprise this type are agricultural water conservation, M&I water conservation, and energy water use efficiency. Potential savings totaling 1.2 maf y were identified under the options that modify system operations and primarily reflect reducing reservoir or canal evaporation through physical or chemical covers, or through preferential reservoir storage. When considering all options and all categories by 2060, a total of over 11 mafy in potential yield was identified. The potential yield is approximately 5.7 maf y by 2035; however, not all options are equally feasible or reliable in the long term. Many options such as imports to southern California or some watershed management options are uncertain from both a technical feasibility and reliability standpoint. By excluding options that were rated low for these factors (“D” and “E”), the total potential yield was reduced to approximately 3.7 mafy by 2035 and to approximately 7 mafy by 2060.

The cost, yield, and timing of the representative options are shown in figure 15 (sorted based on cost). Some of the least-cost options are related to weather modification and chemical covers, but these have considerable uncertainty related to their long-term viability and implementation risk. Agricultural water conservation, M&I water conservation, watershed management methods, smaller import options, and brackish water desalination projects represent the next-least-expensive set of options. Larger desalination, reuse, and importation projects are estimated to have higher costs, but still be substantially less than distributed rainwater harvesting and grey water reuse options, and canal and reservoir covers.

In addition to cost, yield, and timing, each option was provided with a five-point rating (“A” through “E”) for the remaining 14 criteria. A rating of “A” generally represents the most favorable rating and “E” the least favorable. Figure 15 summarizes the resulting ratings for each of the option categories and groups. In some cases, multiple ratings are shown in this figure due to the assessment of large-scale options into smaller increments to capture the varying degree of difficulty of implementing larger options or degree of potential impacts. In general, options that improved the water use efficiency (conservation and reuse) were rated higher than other options for most of the criteria. Options such as importation, desalination, and reuse were rated favorably for technical feasibility and long-term viability risks, but less favorably for environmental criteria because of their greater energy needs and potential impacts to source or discharge areas. Most watershed management options, although potentially yielding significant new supply, were rated poorly for technical feasibility and long-term viability because of the unproven reliability of application of many of these techniques on the scale envisioned for the Basin.

TABLE 9
Summary of Option Cost and Potential Yields by 2035 and 2060

Option Category	Option Group	Estimated Cost ($/afy)	Years Before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)
Desalination	Gulf of California	2,100	20–30	200,000	1,200,000
	Pacific Ocean in California	1,850–2,100	20–25	200,000	600,000
	Pacific Ocean in Mexico	1,500	15	56,000	56,000
	Salton Sea Drainwater	1,000	15–25	200,000	500,000
	Groundwater in Southern California	750	10	20,000	20,000
	Groundwater in the Area near Yuma, Arizona	600	10	100,000	100,000
	Subtotal			**776,000**	**2,476,000**
Reuse	Municipal Wastewater	1,500–1,800	10–35	200,000	932,000
	Grey Water	4,200	10	178,000	178,000
	Industrial Wastewater	2,000	10	40,000	40,000
	Subtotal			**418,000**	**1,150,000**
Local Supply	Treatment of Coal Bed Methane-Produced Water	2,000	10	100,000	100,000
	Rainwater Harvesting	3,150	5	75,000	75,000
	Subtotal			**175,000**	**175,000**
Watershed Management	Brush Control	7,500	15	50,000	50,000
	Dust Control	220–520	15–25	280,000	400,000
	Forest Management	500	20–30	200,000	300,000
	Tamarisk Control	400	15	30,000	30,000
	Weather Modification	30–60	5–45	700,000	1,700,000
	Subtotal			**1,260,000**	**2,480,000**
Importation	Imports to the Colorado Front Range from the Missouri or Mississippi Rivers	1,700–2,300	30	0	600,000
	Imports to the Green River from the Bear, Snake[1], or Yellowstone Rivers	700–1,900	15	158,000	158,000
	Imports to Southern California via Icebergs, Waterbags, Tankers, or from the Columbia River[1]	2,700–3,400	15	600,000	600,000
	Subtotal			**758,000**	**1,358,000**
M&I Water Conservation	M&I Water Conservation	500–900	5–40	600,000	1,000,000
	Subtotal			**600,000**	**1,000,000**

TABLE 9
Summary of Option Cost and Potential Yields by 2035 and 2060

Option Category	Option Group	Estimated Cost ($/afy)	Years Before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)
Agricultural Water Conservation	Agricultural Water Conservation	150–750	10–15	1,000,000	1,000,000
	Agricultural Water Conservation with Transfers	250–750	5–15	1,000,000	1,000,000
	Subtotal			**1,000,000**[2]	**1,000,000**[2]
Energy Water Use Efficiency	Power Plant Conversion to Air Cooling	2,000	10	160,000	160,000
	Subtotal			**160,000**	**160,000**
System Operations	Evaporation Control via Canal Covers	15,000	10	18,000	18,000
	Evaporation Control via Reservoir Covers	15,000	18	200,000	200,000
	Evaporation Control via Chemical Covers on Canals and Reservoirs	100	15–25	200,000	850,000
	Modified Reservoir Operations	Unknown	15	0 – 300,000	0 - 300,000
	Construction of New Storage	2,250	15	20,000	20,000
	Subtotal			**588,000**[3]	**1,238,000**[3]
	Total of All Options			**5,735,000**[4]	**11,037,000**[4]

[1]Among the more than 150 options submitted to Reclamation as responsive to the *Plan of Study*, additional importation of water supplies from various sources, including importation of water from the Snake and Columbia River systems, were submitted to the Study. Such options were appropriately reflected in the Study but did not undergo additional analysis as part of a regional or river basin plan or any plan for a specific Federal water resource project. This Study is not a regional or river basin plan or proposal or plan for any Federal water resource project

[2] The two agricultural water conservation representative options derive potential yield from similar measures and are thus not additive

[3] Subtotal assumes 150,000 afy for the Modified Reservoir Operations representative option.

[4] Total does not account for several options that may be mutually exclusive due to regional integration limitations or are dependent on the same supply.

7.2.4 Development of Portfolios

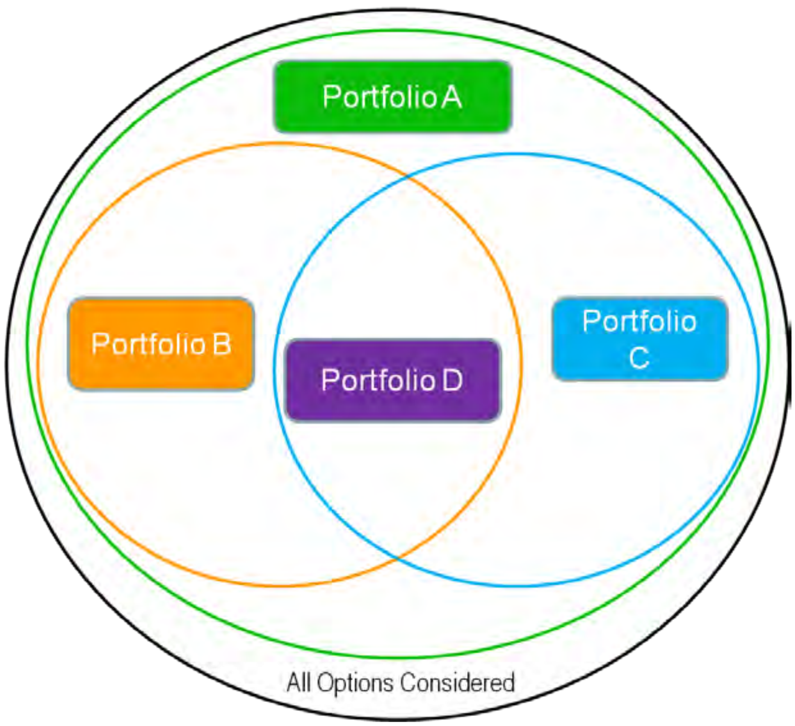
Based on the results of the characterization and development of representative options, various representative options were combined into portfolios representing different potential adaptation strategies. The Study developed four exploratory portfolios to reflect different strategies for selecting and combining options to address imbalances between water supply and water demand. Each portfolio consists of a unique selection of options to address vulnerabilities (e.g., declining Lake Mead pool elevation) that may exist under future combinations of supply and demand.

FIGURE 15
Summary of Options Characterization Ratings (aggregated by option groups)

Agricultural (Ag), Upper Basin (UB), Lower Basin (LB), Municipal and Industrial (M&I), Modification (Mod), Desalination (Desal), Southern California (SoCal)

Using the ratings associated with the criteria, preferences were expressed that resulted in two portfolios, *Portfolio B* and *Portfolio C*. Two other portfolios were then added, *Portfolio A* which represents a highly inclusive strategy (includes all options in either *Portfolio B* or *Portfolio C*) and *Portfolio D*, which represents a highly selective strategy (includes only options in both *Portfolio B* and *Portfolio C*). *Portfolio B* includes options with high technical feasibility and long-term reliability, but excludes options with the highest permitting, legal, policy, or long-term viability risks. *Portfolio B* also excludes any options that cost more than $2,500 per af. *Portfolio C* focuses on options that are also highly feasible, but excludes options that could have greater environmental impacts. This portfolio excludes options that cost more than $4,200 per af. The schematic in figure 16 shows the relationships of the options included in the Study portfolios.

FIGURE 16
Schematic Representing Options Included in the Study Portfolios



Portfolio A
Portfolio A includes options with high technical feasibility, excludes options with highest permitting, legal, policy, and long-term viability risks. This portfolio includes options that are included in both *Portfolio B* and *Portfolio C*. This portfolio also includes the Upper Basin water bank concept that is described in *Portfolio C*. *Portfolio A* includes the largest number of options and option types of the four portfolios. This portfolio is the least restrictive in terms of options.

Portfolio B
Portfolio B is based on a strategy that seeks long-term water supply reliability through implementation of options with high technical feasibility and long-term reliability. The strategy can be defined as one that seeks options with proven technology and that, once in place, will produce reliable long-term yield. The strategy represents a low-risk strategy in the long-term,

but may consider greater risk with respect to permitting and implementation. However, this portfolio excludes options with the highest permitting, legal, and policy risks. The portfolio includes a blend of options that increase supply and those that decrease demand. Water conservation and a variety of desalination options are included in the near-term (first 25 years) and imports and expansion of reuse programs dominate the longer-term options.

Portfolio C
Portfolio C focuses on options that are technically feasible but also have low environmental impacts—low energy needs, lower carbon energy sources, low permitting risk, and low impacts to other environmental factors. This portfolio also avoids options that are potentially unfavorable to recreational interests. In addition, this portfolio excludes options with the highest permitting, legal, and policy risks. The portfolio includes significant conservation in the near term and relies on reuse and watershed management rather than desalination and imports to augment supplies in the longer-term. In addition to options that either reduce demand or increase supply, the portfolio also includes a mechanism to transfer water conserved in Upper Basin through M&I, agricultural water conservation, and energy water use efficiency, to a conceptual Upper Basin water bank. Water is stored in the water bank until needed to be released in order to avoid Lee Ferry deficit[21] conditions.

Portfolio D
Portfolio D includes only those options included in both *Portfolio B* and *Portfolio C*. Significant options not included in this portfolio are several desalination options and imports from the Missouri River. In addition to containing less potential yield than other portfolios, *Portfolio D* also includes the fewest number of options.

In developing each of the unique portfolios, a set of preferences regarding the characteristics of options, as defined by the criteria ratings, was defined. These preferences defined the particular strategy of the portfolio. The Options and Strategies Sub-Team assisted in the development of the four portfolios by identifying general strategies, option criteria preference sets, and reviewing draft portfolios. Adjustments to portfolios were made to either include or exclude specific options or to specify that an option is to be implemented as soon as available based on input from the Options and Strategies Sub-Team members. The option criteria preferences included in each portfolio are shown in table 10.

7.2.5 Portfolio Comparison

The four portfolios represent different exploratory approaches for addressing the projected imbalances between water supply and demand. These portfolios were developed in conjunction with the Options and Strategies Sub-Team, but should not be considered as individual suggestive pathways. Rather, they were developed to explore the range of options, different preferences for option characteristics, and different levels of option inclusion. Table 11 provides a high-level comparison of the options that were either included in all portfolios, included in some but not all portfolios, and those options that were not included in any portfolio. As the table shows, high levels (above 400 kaf) of Gulf of California and Pacific Ocean desalination options, the most complex import options, reservoir and canal covers, and many of the watershed management

[21] Article III(d) of the Colorado River Compact stipulates that the Upper Division States will not cause the flow of the river at the Lee Ferry Compact Point to be depleted below an aggregate of 75 maf for any period of 10 consecutive years. For the purpose of the Study, a Lee Ferry deficit is defined as the difference between 75 maf and the 10-year total flow arriving at Lee Ferry.

options were not selected for inclusion in any of the portfolios. Only 12 options are included in some but not all portfolios. These included ocean desalination options, imports from the Missouri River, expensive options related to local distributed supply or reuse development such as rainwater harvesting and grey water reuse, and watershed management options such as tamarisk control and dust management.

TABLE 10
Option Criteria Preferences for the Study Portfolios

Criteria Category	Option Criteria	Portfolio			
		Portfolio A	**Portfolio B**	**Portfolio C**	**Portfolio D**
Technical	Technical Feasibility	Excludes D & E	Excludes D & E	Excludes D & E	Excludes D & E
	Implementation Risk	All	All	All	All
	Long-term Viability	Excludes E	Excludes D & E	Excludes E	Excludes D & E
	Operational Flexibility	All	All	All	All
Environmental	Permitting	Excludes E	Excludes E	Excludes D & E	Excludes D & E
	Energy Needs	All	All	Excludes D & E	Excludes D & E
	Energy Source	All	All	Excludes E	Excludes E
	Other Environmental Impacts	All	All	Excludes D & E	Excludes D & E
Social	Recreation	All	All	Excludes D & E	Excludes D & E
	Legal	Excludes E	Excludes E	Excludes E	Excludes E
	Policy	Excludes E	Excludes E	Excludes E	Excludes E
	Socioeconomics	All	All	All	All
Other	Hydropower	All	All	All	All
	Water Quality	All	All	All	All
	Cost	< $4,200/af	< $2,500/af	< $4,200/af	< $2,500/af

A rating of "A" generally represents the most favorable rating and "E" the least favorable. For example, a rating of "E" for technical feasibility indicates those options with the lowest scoring in terms of feasibility. A rating of "E" for permitting indicates those options with extremely challenging permitting requirements.

TABLE 11
Summary of Option Inclusion Across the Study Portfolios

Option Category	Option Group	Portfolios			
		Portfolio A	**Portfolio B**	**Portfolio C**	**Portfolio D**
Importation	Imports to the Colorado Front Range from the Missouri or Mississippi Rivers	X	X		
	Imports to the Green River from the Bear, Snake, or Yellowstone Rivers				
	Imports to Southern California via Icebergs, Waterbags, Tankers, or from the Columbia River				
Desalination	Gulf of California	Up to 400 kaf	Up to 400 kaf		
	Pacific Ocean in California	Up to 400 kaf	Up to 400 kaf		
	Pacific Ocean in Mexico	X	X		
	Salton Sea Drainwater	X	X	X	X
	Groundwater in Southern California	X	X	X	X
	Groundwater in the Area near Yuma, Arizona	X	X	X	X
Reuse	Municipal Wastewater	X	X	X	X
	Grey Water	X		X	
	Industrial Wastewater	X	X	X	X
Local Supply	Treatment of Coal Bed Methane-Produced Water	X	X		
	Rainwater Harvesting	X		X	
Watershed Management	Brush Control				
	Dust Control	X		X	
	Forest Management				
	Tamarisk Control	X		X	
	Weather Modification	Up to 300 kaf	Up to 300 kaf	Up to 300 kaf	Up to 300 kaf
M&I Water Conservation	M&I Conservation	X	X	X	X
Agricultural Water Conservation	Agricultural Water Conservation				
	Agricultural Water Conservation with Transfers	X	X	X	X

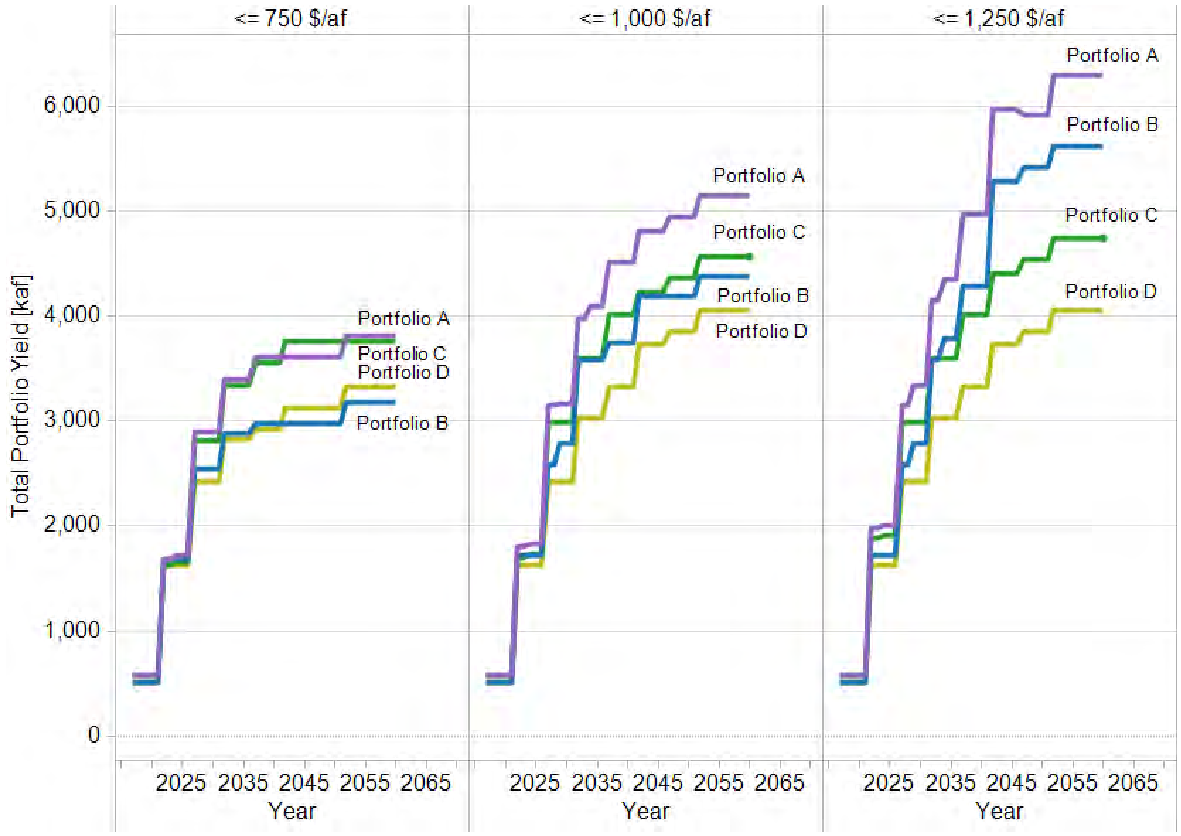
TABLE 11
Summary of Option Inclusion Across the Study Portfolios

Option Category	Option Group	Portfolios			
		Portfolio A	Portfolio B	Portfolio C	Portfolio D
Energy Water Use Efficiency	Power Plant Conversion to Air Cooling	X	X	X	X
System Operations	Evaporation Control via Canal Covers				
	Evaporation Control via Reservoir Covers				
	Evaporation Control via Chemical Covers on Canals and Reservoirs				
	Modified Reservoir Operations				
	Construction of New Storage				
Water Banking	Upper Basin Water Bank	X		X	

The differences in the selection or inclusion of options in the portfolios also influenced the total potential yield and implementation cost. Figure 17 shows the potential yield of the four portfolios over time for three different limits on the portfolio average cost. On the right, the portfolios are essentially unconstrained by cost (average costs less than $1,250 per af). Not surprisingly, *Portfolio A* has the highest potential yield (~6.3 maf) and *Portfolio D* has the lowest potential yield (~4.0 maf). *Portfolio B* and *Portfolio C* yields are similar through 2042. At that point, *Portfolio B* yield increases significantly more than *Portfolio C*. For lower average costs, the differences between the four portfolios are less significant (figure 17, left and middle), particularly between *Portfolio B* and *Portfolio C*.

The four portfolios considered in the Study represent different potential strategies for dynamically addressing system vulnerabilities that may develop in the future. Because there are many more strategies than could be evaluated in the Study, the portfolios should be considered exploratory. The primary focus of the portfolio development and subsequent evaluation in the Study was to establish the range of responses, types of options that may be considered for implementation, their effectiveness at addressing vulnerabilities, and the range of cost and other attributes resulting from different portfolio implementations.

FIGURE 17
Total Yields over Time for Average Costs less than $750/af (left), less than $1,000/af (middle), and less than $1,250/af (right) for Portfolios



8.0 Evaluation of Options and Strategies to Resolve Supply and Demand Imbalances

Potential future Basin supply and demand imbalances suggest that some course of action will be required to improve the reliability of the system to meet the stresses on the Basin resources. From solicitation of public input, over 150 options to help improve or maintain Basin resource reliability were received, many aimed at closing the supply and demand imbalance. The purpose of *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies* was to assess the effectiveness of those options at improving the reliability of the system to meet Basin resource needs.

8.1 Summary of *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*

8.1.1 System Reliability Analysis without Options and Strategies

The system reliability analysis without future actions or "Baseline" conditions, were modeled using CRSS, Reclamation's long-term planning model, implemented in the RiverWare™ generalized river-reservoir modeling software. All combinations of the supply and demand scenarios were including the Baseline analysis. Additionally, two operational assumptions regarding Lake Powell and Lake Mead operations past the effective period of the 2007 Interim

Guidelines in 2026 were considered. Since each supply scenario has over 100 individual sequences, the Baseline system reliability is comprised of over 20,000 simulations or “traces”.

The Baseline simulations showed reduced streamflow at key locations and declining reservoir water elevations (pool elevation), as well as increasing risk of shortfalls in water availability to meet consumptive use demands. These conditions are further exacerbated when only considering the Downscaled GCM Projected water supply scenario. Although some of these findings translate directly to resource performance, many do not.

From the system reliability metrics (metrics) described in *Technical Report D – System Reliability Metrics*, a set of indicator metrics were developed to inform the assessment of vulnerability. Defining vulnerability required the definition of thesholds beyond which the resource was deemed vulnerable. This offered perspective on resource performance and also a quantifiable measure of outcomes. Consistent with the reductions in system reliability, resource-specific vulnerabilities were also found to increase as the supply and demand imbalance grows. Specific resource vulnerabilities resulting without options in place are discussed in the subsequent section, alongside the resulting vulnerability with options in place. The Baseline and each portfolio were evaluated for each combination of water supply and water demand scenarios and for operational assumptions.

8.1.2 System Reliability Analysis with Options and Strategies

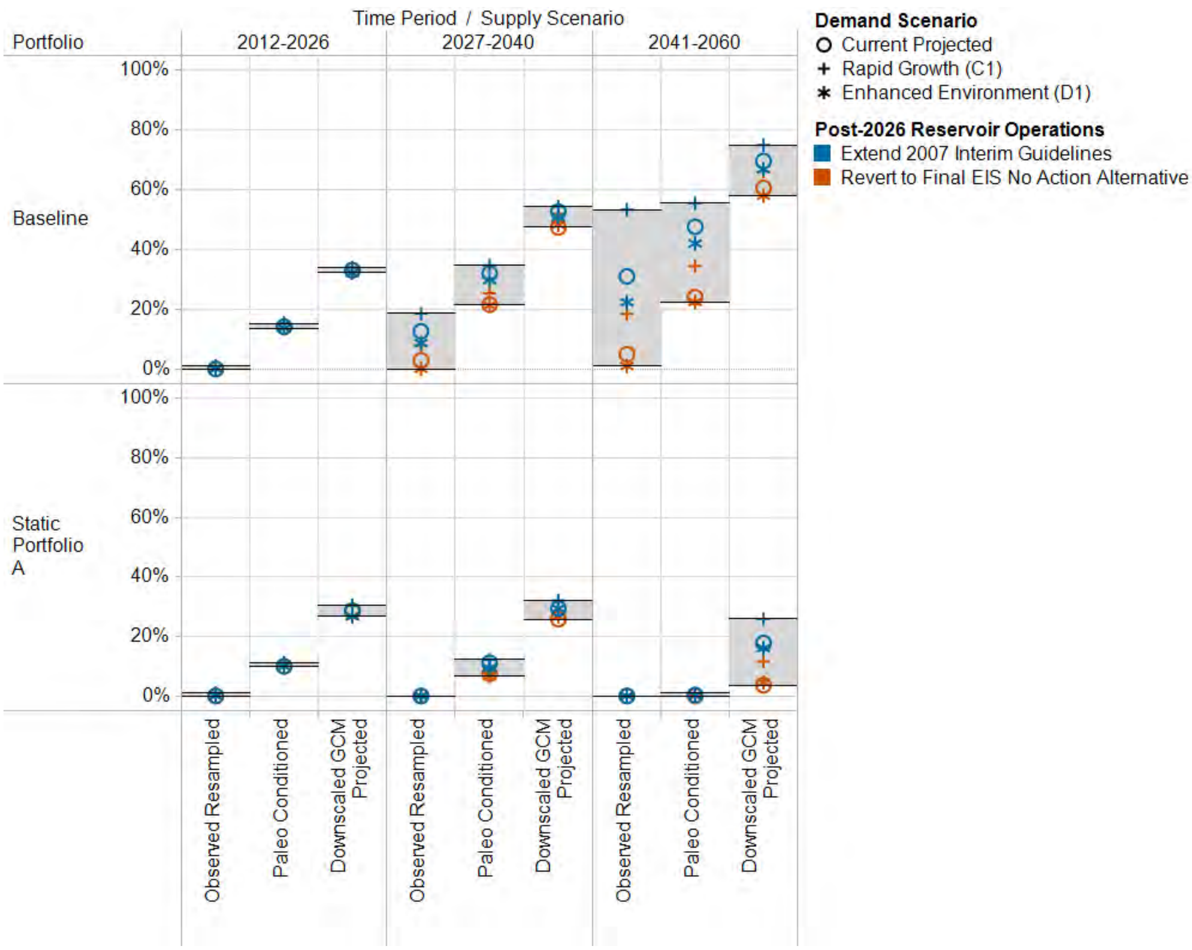
Static Portfolios

In addition to identifying a range of future demands, *Technical Report C – Water Demand Assessment* identified demands for Colorado River water beyond basic state apportionments in the Lower Division States. In the Baseline simulations, deliveries were limited to basic apportionments; as a result, these additional demands were only met during Surplus Conditions. Before attempting to address the added strain of demands growing beyond the Lower Division States’ basic apportionments, the effectiveness of options to remedy system performance within apportionment was explored. Due to the rather sizable supply and demand imbalances that are projected to occur, all representative options included in *Portfolio A*, described previously, were implemented as soon as available per their respective characterizations; such a strategy is referred to as *Static Portfolio A*. This ensures the full extent of the collective option capacity is considered in addressing vulnerabilities and imbalances. From this exercise, vulnerabilities were significantly reduced. In the case of some indicator metrics, the fraction of years vulnerable went from over 50 percent to as low as 5 percent. While this reduction was an encouraging indication of effectiveness, it is clear that in order to eliminate vulnerabilities entirely, additional investment would be required.

As established earlier, significant demands above basic apportionment exist and must be considered as part of a comprehensive study of the Basin and its resources. Several options generate potential yield that could be directed toward either these additional demands or toward broader Basin resources. Assumptions were developed that attempt to balance option benefits between these needs. In the implementation of *Static Portfolio A*, yield is directed to target demands above basic apportionments until system vulnerabilities increase measurably, upon which the benefit is directed away from meeting the demands and used to benefit Basin resources. This demonstrates the potential to strike a balanced approach with regard to yield benefit. Sensitivity results with different levels of balance between these needs show comparable improvements in resource vulnerability.

Using the *Static Portfolio A*, results for the Lake Mead pool elevation vulnerability, the impact of supply and demand scenarios on resource performance was explored by comparing against the Baseline results. Figure 18 shows two sets of model results – with and without options, delineated by time period, supply, demand, and assumption regarding Lakes Powell and Mead operations past 2026[22].

FIGURE 18
Percent of Vulnerable Traces for the Lake Mead Elevation Indicator Metric Across Three Time Periods for the Baseline and *Static Portfolio A*, by Supply and Demand Scenario



Graph reflects a subset of all scenarios evaluated for the portfolio analysis – Supply Scenarios: Observed Resampled, Paleo Conditioned, and Downscaled GCM Projected; Demand Scenarios: Current Projected (A), Rapid Growth (C1), Enhanced Environment (D1); Lakes Powell and Mead Post-2026 Operations: 2007 Interim Guidelines Extended, Revert to 2007 Interim Guidelines Final EIS No Action Alternative. Horizontal lines represent the minimum and maximum results across all demand scenarios.

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22 For modeling purposes, future system conditions were modeled under two assumptions with respect to the operation of Lakes Powell and Mead beyond 2026. In one assumption, "Extend 2007 Interim Guidelines," it was assumed that the 2007 Interim Guidelines would remain in place from 2027 through 2060. In the other assumption, "Revert to Final EIS No Action Alternative," it was assumed that operations would revert back to those in the 2007 Interim Guidelines Final EIS No Action Alternative.

In the early time period (2012-2026), vulnerabilities are driven solely by supply scenarios; demand trajectories are still quite similar, and reservoir operations are governed by the 2007 Interim Guidelines. Even the difference between with and without options is somewhat small, mostly due to the lack of early options to address Lake Mead falling below 1,000 feet msl. The middle time period (2027-2040) shows some separation along the demand and operation policy dimensions, particularly for the Observed Resampled supply. However, for the more taxing hydrology scenarios, the differences in the percentage of vulnerable traces across demand scenarios become more muted. The effect of the portfolio has a similar dampening effect on the differences in the percentage of vulnerable traces across demand scenarios. In the final time period (2041-2060), differences due to demand and assumptions regarding Lakes Powell and Mead operations are at their largest, especially in the Baseline. The “Revert to No Action Alternative” assumption shows lower risk of vulnerability in Lake Mead elevation by creating sizable shortages in the Lower Basin. With the implementation of all options by the end of the final period, all but the Downscaled GCM hydrology vulnerabilities are reduced, again largely trumping the other parameters. Therefore, demand and operational policy can impact vulnerability outcomes but tend to be overshadowed by hydrology differences or portfolio implementation.

Dynamic Portfolios

To assess the appropriate timing of simulated option implementation, a dynamic method for implementing representative options was developed. In this method, options triggered only when needed, based on signposts that precede conditions associated with vulnerable events. These signposts are listed in table 12 and the use of them allowed for implementation of options in the model simulation only when needed. The lead time listed in table 12 was the longest period between the triggering of a signpost and occurrence of a vulnerability that still retained sufficient predictive skill. Additionally, only options that addressed the anticipated vulnerability were implemented given a particular signpost. However, signposts did not signal when feasibility-level studies, permitting, construction, or other key implementation decisions would be required. This would require a consistent and concerted effort to conduct project activities well in advance of triggers included in the model.

System Response Variables

Dynamic implementation of options in the model simulations of the four portfolios resulted in substantial system and resource improvements over Baseline results in addition to reducing over-investment. Relative to the static portfolio described above, the dynamic implementation of options reduces the annual portfolio cost by over 25 percent in 2060. This result speaks to the significant benefit to a dynamic and adaptive approach over one that is static.

In figure 19 and in all subsequent figures displaying portfolio results, in order to facilitate a comparison between the portfolios and Baseline conditions, the results were computed based on all supply and demand conditions and in addition for both assumptions regarding Lakes Powell and Mead operations after 2026.

Figure 19 shows all portfolios reversing the declining median Lake Powell pool elevations from the Baseline. Further, the 10th percentile pool elevation improved by 80 to 120 feet. It is noteworthy that even with such an improvement, levels can be still significantly low, indicating that some scenarios still pose a challenge to the system, even with options in place.

TABLE 12
Vulnerability Signposts

Indicator Metric/ Vulnerability	Lead Time	Conditions				
		Lake Powell Elevation (feet msl)	Lake Mead Elevation (feet msl)	Lees Ferry 5-year Mean Flow	Upper Basin Shortage	Lower Basin Demand Above Apportionment
Lee Ferry Deficit[1]	5 Years	3,490	Not applicable	12.39 maf	Not applicable	Not applicable
Lower Basin Shortage (>1 maf over 2 years)	3 Years	Not applicable	1,060’	13.51 maf	Not applicable	Not applicable
Lower Basin Shortage (>1.5 maf over 5 years)	3 Years	Not applicable	1,075’	13.51 maf	Not applicable	Not applicable
Mead Pool Elevation (< 1,000’)	3 Years	Not applicable	1,040’	13.35 maf	Not applicable	Not applicable
Upper Basin Shortage (>25%)	0 Years	Not applicable	Not applicable	Not applicable	25%	Not applicable
Lower Basin Demand Above Apportionment	Varies	Not applicable	Not applicable	Not applicable	Not applicable	Demand above basic apportionment is within 100 kaf of permissible level

[1] A Lee Ferry deficit is assumed to occur in any year when the 10-year running total flow at Lees Ferry is less than 75 maf. The deficit is computed as the difference between 75 maf and the 10-year running flow in a particular year.

Following results for Lake Powell are the probability and magnitudes of Lee Ferry deficits in figure 20. A Lee Ferry deficit is assumed to occur in any year when the 10-year running total flow at Lees Ferry is less than 75 maf. Again, all portfolios showed improvements over the increasing probability of Lee Ferry deficit seen in the Baseline. In some cases, the probability even appeared to have stabilized at less than 2 percent. Although the risk of a Lee Ferry deficit was notably lowered, the median magnitude was affected less. In fact, at the 90th percentile, there appeared to be some slight increases in deficit magnitudes. This is likely an artifact of reducing the number of deficit events, particularly those of smaller magnitudes, thus shifting some of the more-extreme condition to the 90th percentile. Importantly, the portfolios that stabilize the probability of a Lee Ferry deficit contain an option for an Upper Basin water bank. This bank is used to provide additional water to reduce the risk of Lee Ferry deficit.

FIGURE 19
10th, 50th, 90th Percentiles for Lake Powell End-of-December Pool Elevation for the Baseline and Four Portfolios

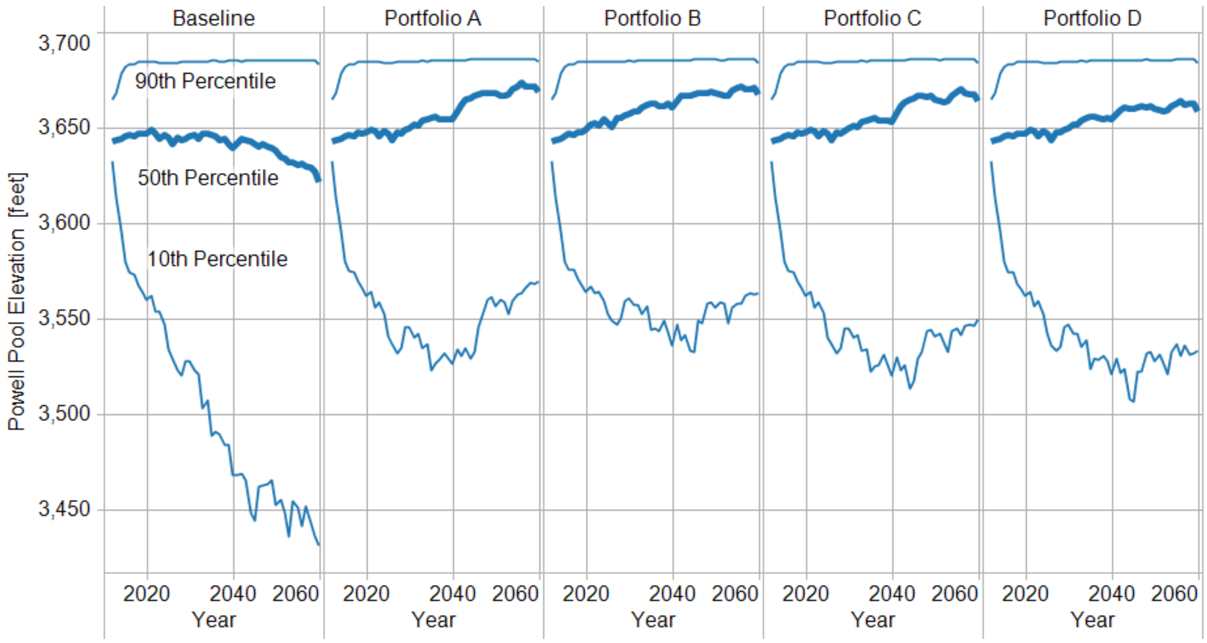
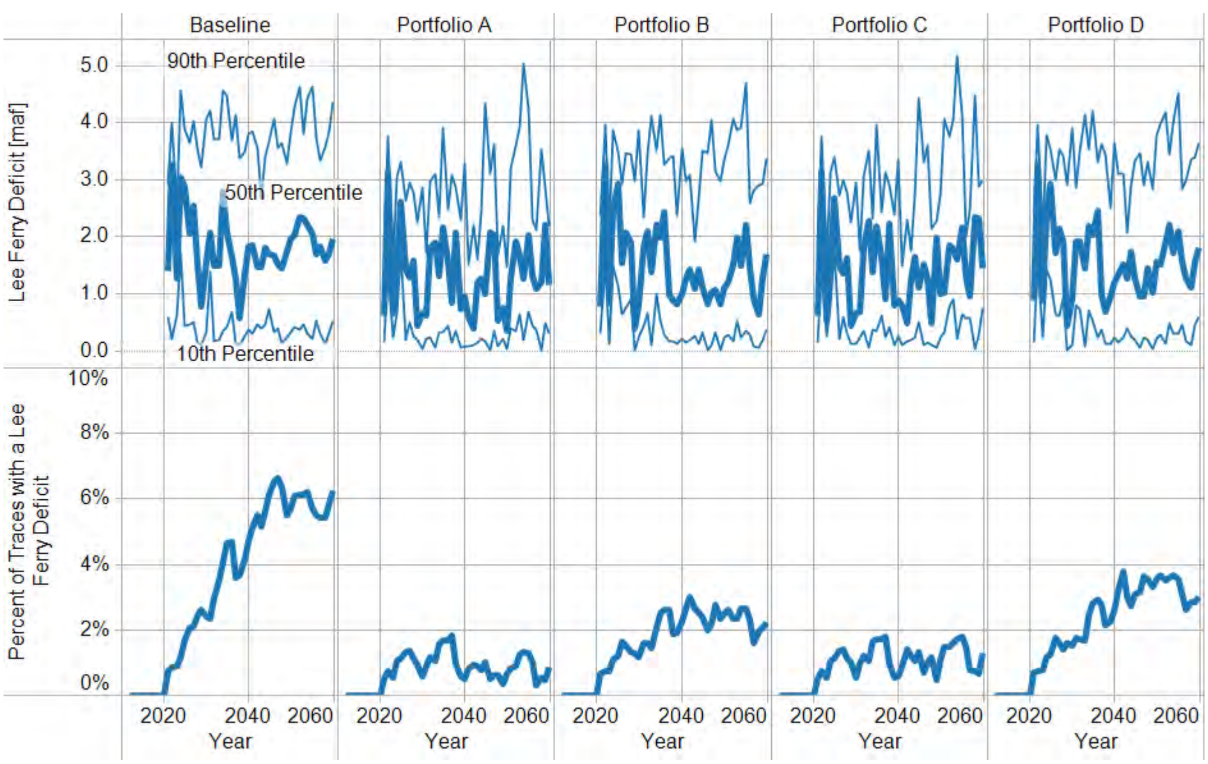
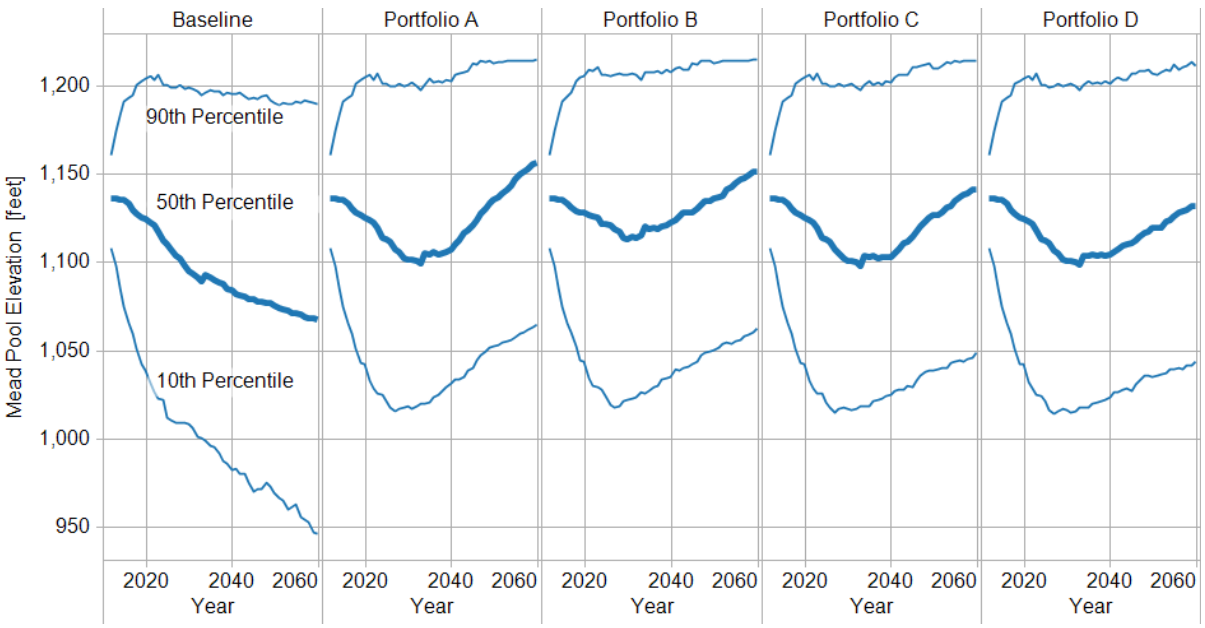


FIGURE 20
10th, 50th, 90th Percentiles for Lee Ferry Deficit in Years in Which a Deficit Occurs (top) and Percent of Traces (bottom) with a Lee Ferry Deficit for the Baseline and Four Portfolios



Lake Mead pool elevations also improved relative to the Baseline, albeit not as immediately and to a lesser magnitude, as shown in figure 21. The delayed recovery of the median pool elevation was due to a combination of option availability for implementation and the additional demands above basic apportionment that were not addressed in the Baseline run. These demands all originate in the Lower Basin, and therefore add extra demand strain on Lake Mead, calling for greater releases. In 2060, relative to the Baseline, median pool elevations rose 60 to 90 feet depending on the specific portfolio. Not surprisingly, *Portfolio A*, which had the largest maximum potential yield, saw the largest increase, whereas the *Portfolio D*, with smallest maximum potential yield, showed the smallest gains.

FIGURE 21
10th, 50th, 90th Percentiles for Lake Mead End-of-December Pool Elevation for the Baseline and Four Portfolios



Water Deliveries Indicator Metric Performance

Consistent with the improved system conditions, resource indicator metrics showed reductions in vulnerabilities. Figure 22 shows water delivery indicator metrics and percent of years vulnerable by three time periods. Additionally, in *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*, results are shown for the percent of years vulnerable and indicating the percent of traces or simulated futures vulnerable. This helps in understanding the persistence of vulnerable events both within and across traces. For example, a low percent of years vulnerable but high percent of traces vulnerable, indicates that, albeit infrequently, the indicator metric tends to be vulnerable at least once in most traces. Conversely, a high percent of years but lower percent of traces vulnerable suggests considerable persistence of additional vulnerabilities once one has occurred for a particular trace.

FIGURE 22
Percent of Vulnerable Years for Each Water Delivery Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

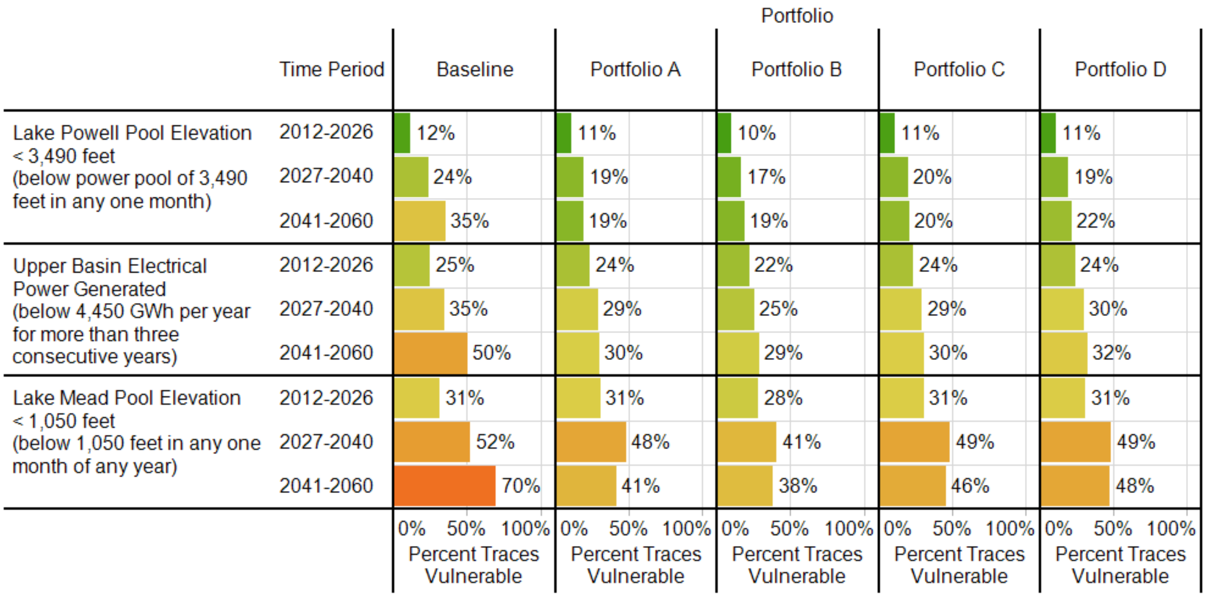
	Time Period	Baseline	Portfolio A	Portfolio B	Portfolio C	Portfolio D
Upper Basin Shortage (exceeds 25% of requested depletion in any one year)	2012-2026	4%	3%	3%	3%	3%
	2027-2040	5%	3%	3%	3%	3%
	2041-2060	7%	2%	2%	3%	3%
Lee Ferry Deficit (exceeds zero in any one year)	2012-2026	0%	0%	0%	0%	0%
	2027-2040	3%	1%	2%	1%	2%
	2041-2060	6%	1%	2%	1%	3%
Lake Mead Pool Elevation < 1000 feet (below 1000 feet in any one month)	2012-2026	4%	4%	4%	4%	4%
	2027-2040	13%	7%	7%	8%	8%
	2041-2060	19%	3%	3%	5%	6%
Lower Basin Shortage (exceeds 1 maf over any two year window)	2012-2026	7%	5%	5%	5%	5%
	2027-2040	37%	22%	19%	23%	23%
	2041-2060	51%	10%	10%	13%	14%
Lower Basin Shortage (exceeds 1.5 maf over any five year window)	2012-2026	10%	9%	9%	9%	9%
	2027-2040	43%	35%	30%	36%	36%
	2041-2060	59%	23%	23%	26%	28%
Remaining Demand Above Lower Division States' Basic Apportionment (exceeds moving threshold in any one year)	2012-2026	0%	0%	0%	0%	0%
	2027-2040	40%	2%	1%	1%	2%
	2041-2060	93%	5%	5%	7%	5%
		0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable

For all metrics shown, vulnerabilities in the first period tended to change little from the Baseline results. This was a result of the combination of often low vulnerability risk in the early period and few options available to address vulnerabilities when they occur. The middle time period was the first to significantly diverge from the Baseline for most indicator metrics. However, in some cases, it was also the most vulnerable window, owing to the fact that options may have only been available for a short time, and as a result, little benefit accrued to reduce vulnerability. Demands above basic apportionments were not included in the Baseline modeling and thus the results showed a marked improvement under simulations with portfolios. Also, one might expect *Portfolio A* to show the greatest reduction in vulnerabilities simply by having the greatest yield available to address imbalances; however, this was not always the case. Because this portfolio includes the Upper Basin banking option, water generated by conservation was not immediately available to address vulnerabilities, but was instead “banked” to help hedge against future Lee Ferry deficits. This is the same reason that *Portfolio A* was particularly effective at reducing the probability of Lee Ferry deficits.

Electrical Power Resources Indicator Metric Performance

As shown in figure 23, electric power resources exhibited performance improvements similar to those in the water delivery indicator metrics. As more options are implemented, increased flow helps to raise pool elevations and greater downstream demand requires larger releases. This combination is a two-fold benefit to hydropower.

FIGURE 23
Percent of Vulnerable Years for Each Electric Power Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

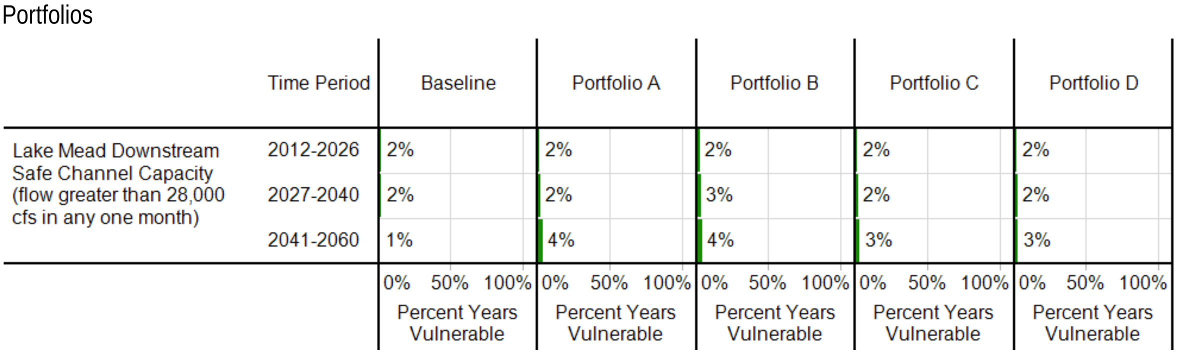


Gigawatt hour (GWh)

Flood Control Indicator Metric Performance

As shown in figure 24, under the Baseline conditions, flood control vulnerabilities were few and actually decreased over time due to the increase in available storage associated with increasing demand. Under the various portfolios, the occurrence of vulnerabilites remained low, but did increase slightly. This result stems from the implementation of options that increase pool elevations, which in turn, reduces capacity to absorb extreme flow events.

FIGURE 24
Percent of Vulnerable Years for Each Flood Control Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios



Cubic feet per second (cfs)

Recreational Resources Indicator Metric Performance

Figures 25 and 26 show recreational resource indicator metric vulnerabilities. Specifically, the metrics in figure 25 are river boating vulnerabilities, and those in figure 26 pertain to reservoir recreation. River boating indicator metrics are based on the shift in long-term average availability of flows deemed acceptable (total days) and optimal (optimal days) from simulations reflective of current conditions with variable hydrology (control run). In general, the optimal flow metrics were consistently more vulnerable than the total flow metrics. This is because the window for optimal flows is more stringent and therefore more sensitive to changes in streamflow. All portfolios demonstrate improvements for the boating indicator metrics. *Portfolio A* showed the most improvement. The improvement in *Portfolio A* and in *Portfolio C* is due to the Upper Basin banking option, found in both, which routes conserved water from across the major tributaries to a conceptual storage facility near Lake Powell. By routing the conserved water, resources that depend on in-stream flows tend to benefit, including river boating recreation.

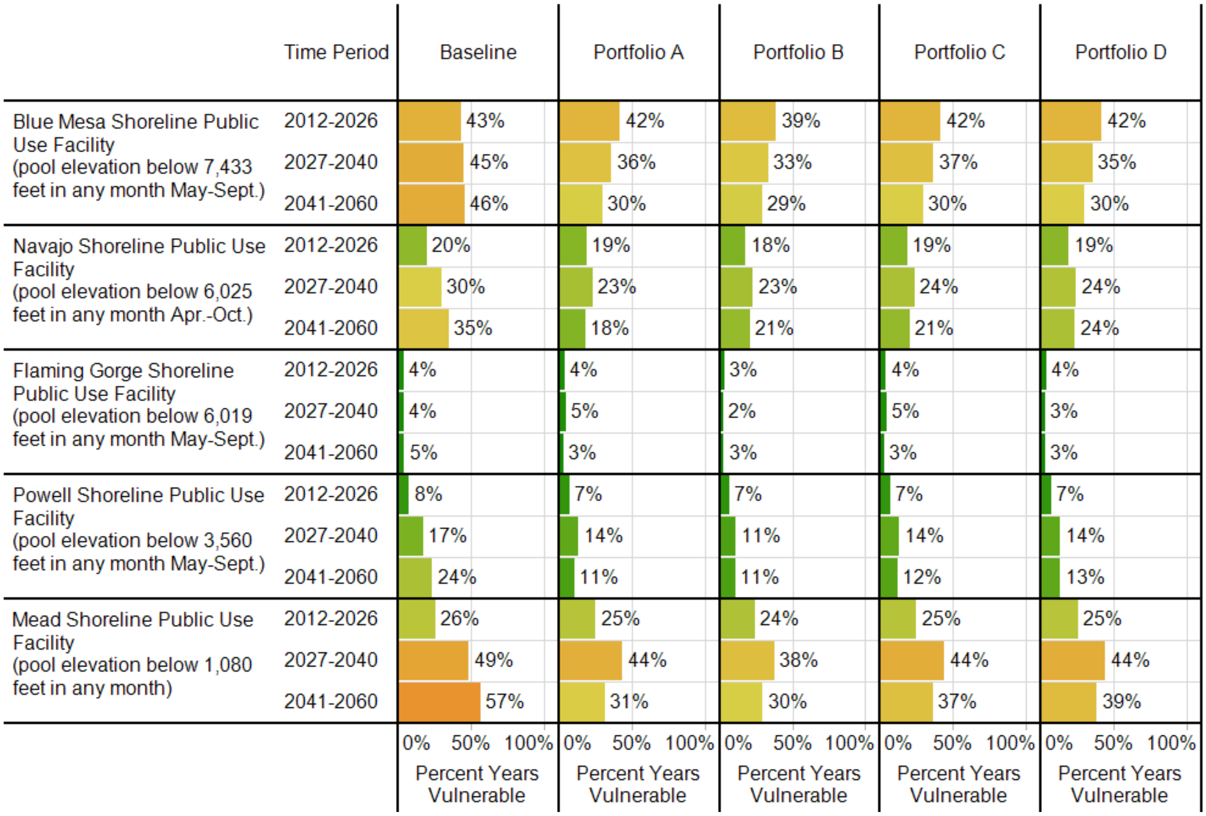
FIGURE 25

Percent of Vulnerable Years for Each Recreational (boating flow) Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

	Time Period	Baseline	Portfolio A	Portfolio B	Portfolio C	Portfolio D
Colorado River Optimal Boating Flow Days (below 10th percentile of control run)	2012-2026	10%	9%	9%	8%	9%
	2027-2040	31%	24%	26%	24%	28%
	2041-2060	38%	25%	28%	28%	32%
Green River Optimal Boating Flow Days (below 10th percentile of control run)	2012-2026	7%	6%	6%	6%	7%
	2027-2040	21%	15%	17%	16%	19%
	2041-2060	25%	16%	19%	16%	20%
San Juan River Optimal Boating Flow Days (below 10th percentile of control run)	2012-2026	5%	4%	5%	4%	5%
	2027-2040	19%	10%	16%	11%	18%
	2041-2060	27%	15%	22%	16%	23%
Colorado River Acceptable Boating Flow Days (below minimum of control run)	2012-2026	6%	5%	4%	5%	5%
	2027-2040	21%	14%	14%	14%	17%
	2041-2060	30%	14%	16%	17%	19%
Green River Acceptable Boating Flow Days (below minimum of control run)	2012-2026	1%	1%	1%	1%	1%
	2027-2040	5%	1%	4%	2%	4%
	2041-2060	8%	2%	4%	2%	5%
San Juan River Acceptable Boating Flow Days (below minimum of control run)	2012-2026	2%	2%	2%	2%	2%
	2027-2040	7%	2%	5%	2%	6%
	2041-2060	13%	3%	7%	4%	9%

"Control run" reflects conditions that might be expected under current demand and Observed Resampled water supply conditions, and was used as a reference for evaluating change in vulnerability associated with future changes.

FIGURE 26
Percent of Vulnerable Years for Each Recreational (shoreline facilities) Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios



For reservoir recreation, Flaming Gorge performed notably well, even under the Baseline simulations. This is attributable to a combination of more-optimistic streamflow projections in the Upper Green River due to projected climate change and slower growth relative to other regions. Reductions to vulnerabilities at other locations in the Upper Basin were largely from conservation and weather modification options that serve to either increase reservoir inflow or reduce the required release.

Ecological Resources Indicator Metric Performance

Ecological resource vulnerabilities were calculated based on reference flow conditions that were derived to reflect instream and riparian habitat conditions. In most cases, the indicator metrics were derived from biological opinion recommendations and coordinated through the Metrics Sub-Team. Ecological resource indicator metrics are shown in figure 27. Based on the discussion of river boating vulnerabilities, it would be logical to expect that the portfolios with the Upper Basin banking option and associated routing of flows would benefit ecological resources more than other portfolios. In the case of the Yampa and San Juan river metrics, the outcome was consistent with this expectation. However, for the Green and Colorado rivers, the improvements were largely commensurate with other portfolios because of the particular flow recommendations at those sites. The Green and Colorado river flow prescriptions are specific with regard to timing and volume. As such, increases in flow resulting from routing water to the bank may not help resolve vulnerabilities if the flow pattern is not consistent with the flow recommendations. Coordinated routing of flows would be required to achieve the maximum benefit to those more-detailed flow requirements.

FIGURE 27
Percent of Vulnerable Years for Each Ecological Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

	Time Period	Baseline	Portfolio A	Portfolio B	Portfolio C	Portfolio D
Colorado River (ecological vulnerability)	2012-2026	9%	9%	9%	9%	8%
	2027-2040	25%	20%	20%	22%	19%
	2041-2060	38%	30%	28%	30%	31%
Green River (ecological vulnerability)	2012-2026	4%	4%	4%	4%	4%
	2027-2040	12%	11%	11%	11%	11%
	2041-2060	32%	31%	28%	31%	32%
San Juan River (ecological vulnerability)	2012-2026	7%	6%	6%	6%	6%
	2027-2040	30%	16%	21%	17%	21%
	2041-2060	52%	23%	36%	26%	33%
Yampa River (ecological vulnerability)	2012-2026	1%	0%	1%	0%	1%
	2027-2040	8%	0%	6%	0%	7%
	2041-2060	31%	1%	25%	1%	25%
Hoover Dam to Davis Dam Flow Reductions (greater than 845 kaf in any one year)	2012-2026	1%	1%	1%	1%	1%
	2027-2040	10%	6%	5%	6%	7%
	2041-2060	12%	4%	4%	7%	8%

Portfolio columns: Percent Years Vulnerable (0% – 50% – 100%)

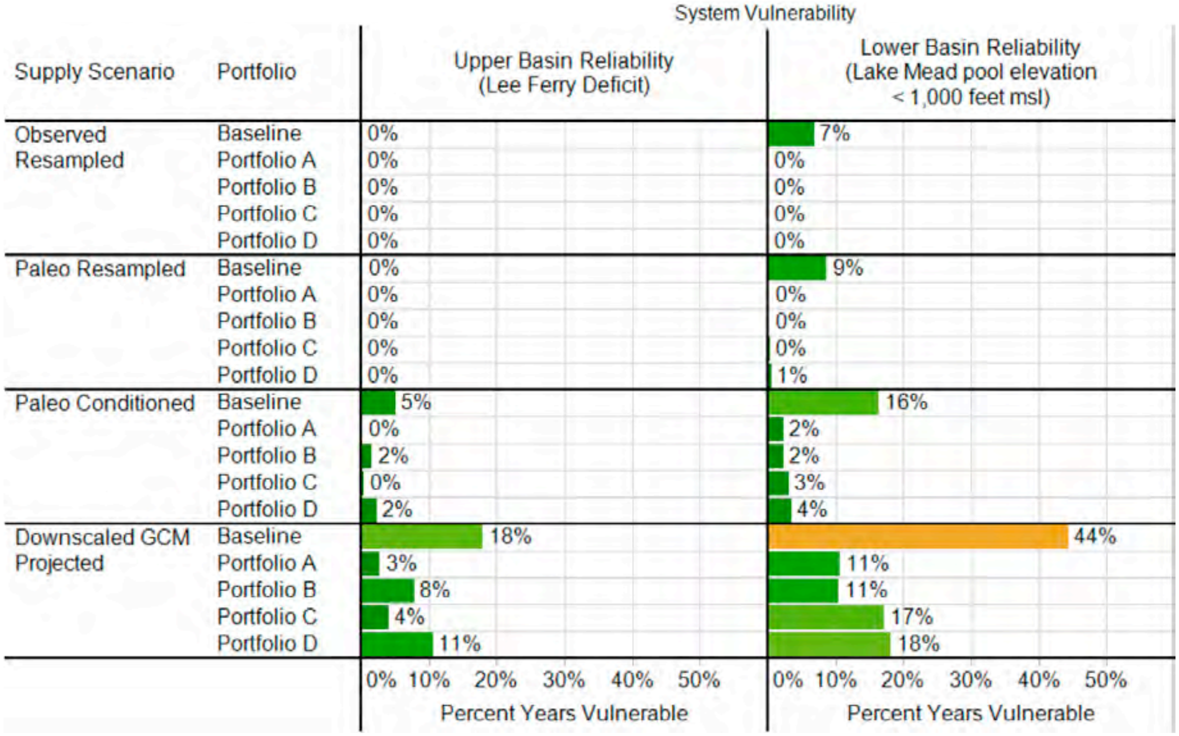
8.1.3 *Portfolio Comparison and Option Analysis*

Although the portfolio analysis successfully demonstrated that system reliability can be improved, it is not without significant cost and performance tradeoffs. Figure 28 illustrates the performance across portfolios by supply scenario in terms of addressing two key water delivery vulnerabilities—Lee Ferry deficit and Lake Mead pool elevation below 1,000 feet msl. For this discussion these are refered to as the Upper Basin vulnerability and Lower Basin vulnerability.

Portfolio B favors options believed to have higher certainty of available water supply once implemented. As shown in figure 28 (on the right), this portfolio performs as well or better than all the other portfolios for addressing the Lower Basin vulnerability across all supply scenarios. The portfolio performs less well than *Portfolios C* and *A* for the Upper Basin vulnerability (figure 28, left), particularly in the Downscaled GCM Projected supply scenario (bottom row).

Portfolio C, while focused on options that favor lower energy needs and less environmental impacts, is more dependent on shifting social values towards additional conservation and reuse. Choosing to implement options characterized as having low energy needs (as a surrogate for potential environmental impacts) might come at the expense of having a less certain long-term water supply. Despite this tradeoff, this portfolio performs well for addressing the Upper Basin vulnerability (figure 28, left) and is particularly effective under the Downscaled GCM Projected supply scenario (figure 3, bottom row). *Portfolio C* is less effective, however, at addressing the Lower Basin vulnerabilities (figure 28, right). Note that the effectiveness of *Portfolio C* and *Portfolio A* at reducing Upper Basin shortage vulnerability is largely due to the inclusion of a Upper Basin water bank concept in these portfolios.

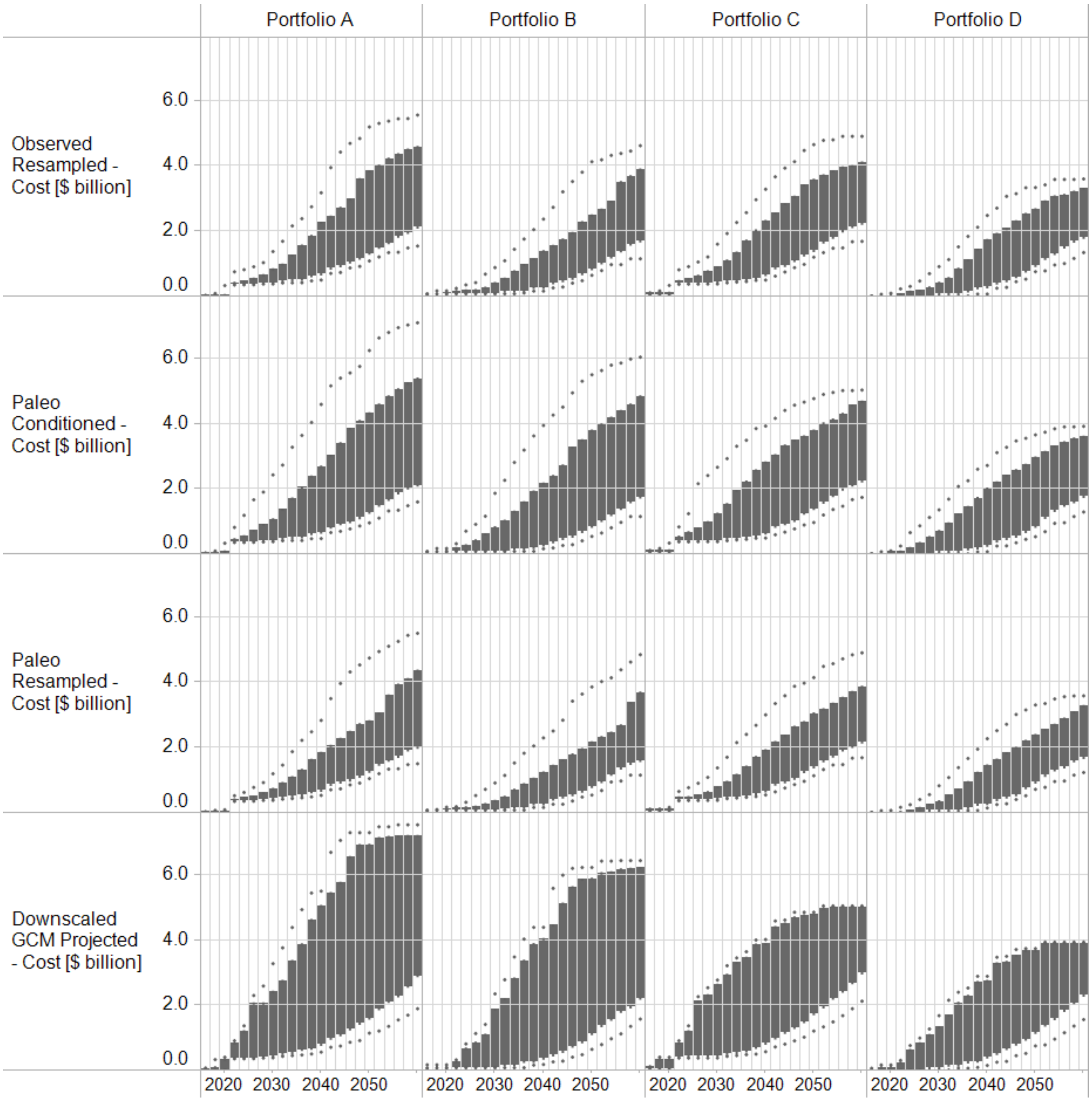
FIGURE 28
Percent of Years with Occurrence of Upper Basin (left) and Lower Basin (right) Vulnerability in 2041–2060 with Portfolios Implemented, by Supply Scenario



As discussed earlier, portfolios differ based on the representative options available to address supply and demand imbalances. As such, it is important to explore the portfolios beyond their ability to reduce vulnerabilities and improve system conditions. From analysis of the characterization criteria, the portfolios considered in the Study differ most notably on cost, energy needs, and long-term viability factors. Figure 29 shows the distribution of annual portfolio costs through time and for each water supply scenario. The box plots in the figure represent the inter-quartile range and the 10th and 90th percentiles. For all portfolios, costs increase substantially between the onset and end of the Study period. By 2060, the annual costs range from approximately $2 to $5 billion under the Observed Resampled, Paleo Conditioned, and Paleo Resampled supply scenarios, and increase to potentially $7 billion under the Downscaled GCM Projected scenario. *Portfolio A* is the most costly due to the inclusion of the greatest number of options, and *Portfolio D* is the least costly due to the inclusion of the least number of options. Although *Portfolio B are* costly, it brings a certainty of available supply and is risk averse in terms of the future security of providing water to users. By choosing to only consider options that were characterized as having moderate to high long-term viability, lower unit cost alternatives were excluded, which also had the effect of lowering total potential yield.

Portfolio C is similar in cost range to *Portfolio B,* except under the GCM Projected scenario, where it is less expensive largely due to the exclusion of some options that are only triggered under more-challenging water supply conditions within *Portfolios A* and *B.* Within *Portfolio C*, the emphasis on options characterized as having low energy needs might come at the expense of yield certainty. The purpose of exploring these differences is not to identify a "best" portfolio or strategy, but to acknowledge that there are various ways to address the supply and demand imbalance and that each has associated implications that must be considered in future planning and decision-making processes.

FIGURE 29
Total Annual Cost by Supply Scenario Resulting from Implementation of the Portfolios over Time



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

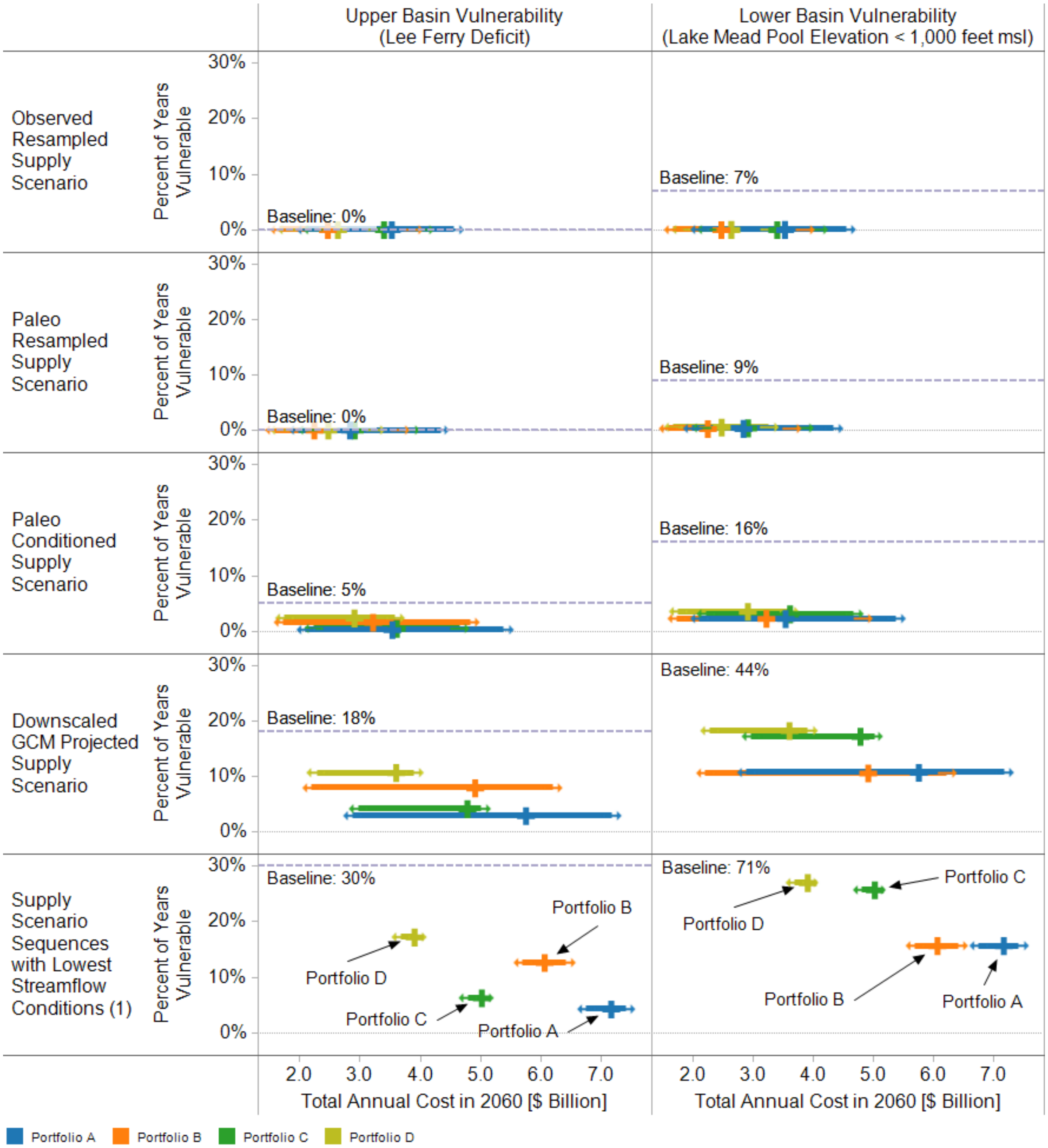
The intersections of cost, characteristics, and performance bound the discussion of portfolios and highlight the strategies used to craft each. Tradeoffs also exist with respect to portfolio costs, and these differ depending on the specific future conditions.As shown in figure 30, the annual cost, in 2012 dollars, for implementing the portfolios ranges from approximately $2.5 billion to $3.5 billion in the year 2060 when considering the median of the Observed Resampled supply sequences, and from $3.6 billion to $5.8 billion when considering the median of the Downscaled GCM Projected supply sequences. The inter-quartile ranges of cost are significantly larger. However, because of the appraisal-level option cost estimating used in the Study, the cost values contain additional uncertainty not directly reflected in these estimates.

When considering how the portfolios perform in stressing hydrologic conditions often associated with critical water delivery reliability vulnerabilities, the differences among the portfolios in terms of costs and ability to reduce vulnerability are more apparent. As conditions become less favorable, such as in the "Lowest Streamflow" subset of sequences (figure 30, bottom row), *Portfolios C* and *A* perform the best with respect to the Upper Basin Vulnerability and *Portfolios B* and *A* perform the best with respect to Lower Basin Vulnerabiltiy.

Portfolio C both performs better than *Portfolios B* and *D* in terms of reducing this vulnerability and has a lower range of costs than *Portfolios A* and *B*. For the Lower Basin Vulnerability, however, *Portfolio B* reduces vulnerability more than *Portfolios C* and *D* and also costs less than *Portfolio A*.

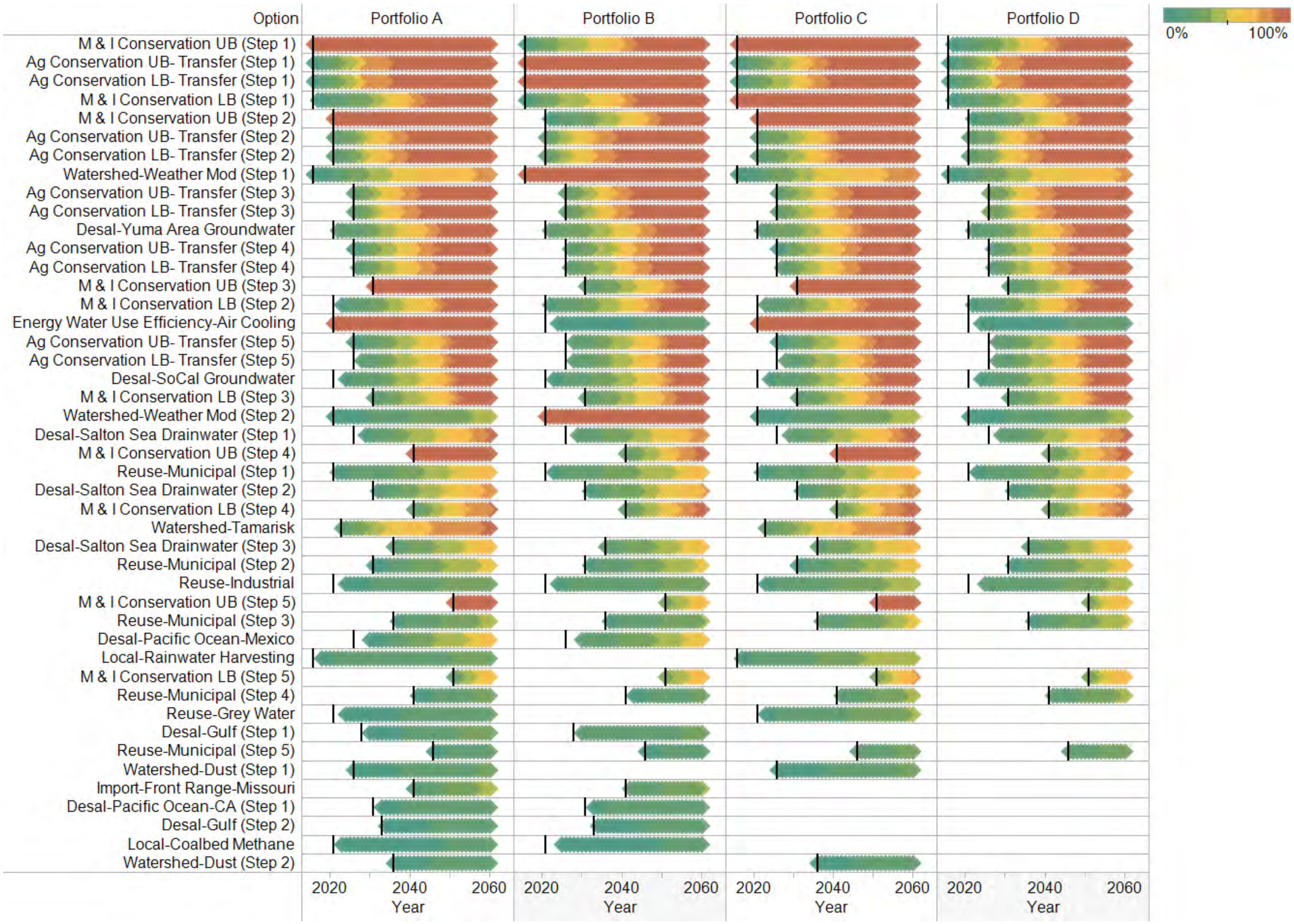
Portfolios were also evaluated for which options were implemented for each dynamic portfolio. Figure 31 shows the implementation frequency through time for options in each portfolio. Many options are common among all portfolios, but the frequency of use informs how each portfolio resolves the imbalance in a slightly different manner. The small vertical black line indicates the earliest possible date that the option could be available, assuming project feasibility is initiated today. Options that are implemented with high frequency shortly after becoming available suggest that investigation in the near future may be prudent due to the simulated short delay between availability and selection. In the case of *Portfolio A* and *Portfolio C*, conservation is implemented as soon as available in order to generate water for the Upper Basin bank. These are not triggered by signposts, but rather are assumed to be in place ahead of time to make this preventive strategy effective. In a broad sense, options such as agricultural conservation and transfers and M&I conservation are considerably relied upon in each portfolio because they are available early to address many vulnerabilities. However, as conditions become more challenging and the imbalance widens, there is also need for other options, such as desalination, reuse, and importation that may only be available in the longer term.

FIGURE 30
Portfolio Cost and Percent of Upper Basin (left) and Lower Basin (right) Vulnerability for 2041–2060, by Supply Scenarios and Lowest Sequences



(1) Conditions in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.
(2) Marker indicates the 50th percentile result and the bounds represent 25th and 75th percentile results.

FIGURE 31
Frequency of Option Implementation (percent of traces) for Each Portfolio



Through evaluation of the option implementation results across and within portfolios, the following findings can be summarized:

- Options that were frequently implemented and with a short delay from their first availability date: M&I Water Water Conservation (for all portfolios); Agricultural Water Conservation and Weather Modification (for *Portfolio B*); Energy Water Use Efficiency (for *Portfolios A* and *B*). Implementation of these options was common across portfolios and may require advanced planning as illustrated by the short delay in model implementation.
- Options that were frequently implemented and with a short delay under the Low Streamflow conditions (long-term flow less than 15 mafy and drought less than 13 mafy): Salton Sea Drainwater Desalination; Agricultural Water Conservation (all portfolios); Municipal Wastewater Reuse (*Portfolio C and D*). Implementation of these options was common across portfolios with short delay under low streamflow conditions. These options may also need advanced planning in order to hedge against these challenging conditions.
- Options that were frequently implemented and with short delay under the lowest streamflow conditions (long-term flow less than 14 mafy and drought less than 11 mafy): Desalination of Brackish Water in the Yuma Area; Missouri River Imports (*Portfolios A and B*). These options may only require advanced planning to hedge against the more severe conditions.
- Options that were frequently implemented, but with a longer delay under the Low Streamflow conditions (long-term flow less than 15 mafy and drought less than 13 mafy) include: Gulf of California Ocean Desalination, Pacific Ocean Desalination in California, Grey Water Reuse, and Dust Control, and Treatment of Local-Coal Bed Methane Produced Water. These options may allow for some delay in implementation.

8.2 Summary of the Evaluation of Options and Strategies

The system reliability analysis with options and strategies demonstrated that all portfolios have capacity to reduce vulnerabilities across resources and in doing so, making a sizeable reduction in the supply-demand imbalance. In the 2012 through 2026 period, reductions in vulnerabilities tend to be small, owing to generally low risks and lesser option availability in the near-term. In the latter two time windows, vulnerability reductions of 50 percent or more (relative to Baseline results) are seen in all resource categories. The one exception is the flood control indicator metric. A consequence of increased Basin yield and greater storage in reservoirs is a slight increase in flood control vulnerabilities.

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

Although the portfolios explored in the Study address water supply and demand imbalances differently, there are commonalities across the options implemented for each portfolio. All of the portfolios incorporate significant agricultural water conservation, M&I water conservation (1 maf each of both additional M&I and agricultural conservation was implemented in all portfolios), energy water use efficiency, and some levels of weather modification. However, some options were implemented more frequently in response to challenging water supply conditions. For example, ocean and brackish water desalination, wastewater reuse, and importation options were implemented for the most challenging water supply conditions in portfolios in which they were included. Future planning will require careful consideration of the timing, location, and magnitude of anticipated future Basin resource needs.

9.0 Study Limitations

As stated previously, the focal questions being addressed by the Study were:

- What is the future reliability of the Colorado River system to meet the needs of Basin resources through 2060?
- What are the options and strategies to mitigate future risks to these resources?

Although the technical approach of the Study was based on the best science and information available, as with all studies, there are limitations.

The detail at which results are reported or the depth to which analyses were performed in the Study was limited by the availability of data, methods, and the capability of existing models. Many of these limitations could not be overcome for purposes of the Study because of time and resource constraints. In some cases, these limitations presented opportunities for additional research and development and the improvement of available data. These opportunities will be pursued in efforts independent of the Study. Limitations exist in the areas noted below.

9.1 Treatment of Lower Basin Tributaries

For four of the inflow points below Lees Ferry (the Paria, Little Colorado, Virgin, and Bill Williams rivers), CRSS uses historical inflows (not natural flows) based on USGS streamflow records. In addition, the Gila River is not included in CRSS.

Many Colorado River planning studies have been completed over the past two decades where this treatment of the major Lower Basin tributaries was used; however, questions regarding the adequacy of the treatment of the Lower Basin tributaries in CRSS for the Study arose during the phases focused on assessing future water supply and demand. The current treatment of these tributaries limited the ability of the Study to fully assess the natural supply of the Basin, and the data and methodological inconsistencies present in the CU&L Reports limited the ability of the Study to gain a more-complete understanding of historical consumptive use in the Basin.

Despite these limitations, other approaches were taken in the Study to examine several important issues, including potential climate change impacts on the tributaries represented in CRSS, future demand scenarios on those tributaries, and future demand scenarios for the Colorado River from the Gila River Basin, factoring in other water supplies within that basin.

Reclamation will engage in efforts to: (1) resolve and correct, in collaboration with the Basin States, the methodological and data inconsistencies in the CU&L Reports pertaining to all of the Lower Basin tributaries; (2) develop natural flows for the Little Colorado, Virgin and Bill Williams rivers and modify CRSS to use natural flows for those tributaries; and (3) explore the feasibility and usefulness of computing natural flows for the Gila River Basin and the feasibility and usefulness of adding that basin to CRSS. Refer to *Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System* for a more-detailed discussion of these issues.

9.2 Treatment of Agricultural Land Use in Water Demand Scenarios

The water demand storylines were developed by the Water Demand Sub-Team which included participation from a broad range of stakeholders. The sub-team developed storylines based on key driving forces that represented a range of plausible futures regarding future demand. However, the assumptions in some storylines with regard to these driving forces resulted in the same directional changes in demand across the storylines. For example, the assumptions of continued conversion of agricultural land use to urban land use and lower-economic value crops being phased out in some areas led to overall agricultural land use (i.e., the number of irrigated acres) decreasing over time over all scenarios. Given recent projections of increased agricultural productivity necessary to meet future food needs, plausible futures should include increases in land use.

The application of a scenario planning approach to project future Basin-wide demand represents a new paradigm in the Basin and a significant advancement in Basin long-term planning. Reclamation and the Basin States are committed to continued refinement of scenario planning as part of a robust long-term planning framework for the Basin.

9.3 Ability to Assess Impacts to Basin Resources

The ability to assess impacts to Basin resources was limited by the spatial and temporal detail of CRSS. Described further in *Technical Report D – System Reliability Metrics*, some metrics have limitations in their ability to be assessed quantitatively and in some cases were assessed qualitatively. For example, CRSS tracks shortages in the Upper Basin when the flow is insufficient to meet the local demands as opposed to simulating the complex water rights system in each state that would be needed to appropriately model shortages to individual water rights holders and the lack of model representation of individual tributaries. This representation affected the ability of the Study to assess the impacts to deliveries in the Upper Basin. Another example is that several ecological resources metrics were evaluated through approximations at larger spatial scales and longer timesteps (e.g., monthly versus daily) than preferred or required for more-detailed assessments.

In some cases, particular modeling assumptions limited the detailed analysis of certain metrics. For example, when water is supplied to the system in the manner assumed to determine the Lee Ferry defecit, the uncertainty regarding metric results increases, particularly in the Upper Basin. However, due to the infrequent occurrence of a Lee Ferry deficit across all traces, these results are not disregarded. This uncertainty, however, should be considered carefully when viewing metric results, particularly in the Upper Basin, that have been impacted by this modeling assumption.

9.4 Options Characterization Process

The process undertaken to characterize options to help resolve potential water supply and demand imbalances strived to maintain an objective and consistent evaluation of the options. Several iterations of the option characterization were performed in an attempt to normalize ratings wherever possible. However, several limitations were inherently associated with the characterization of the over 150 options received. The limitations identified during the characterization process include the following:

- ***Limited Level of Analysis.*** The intent of the characterization was to perform a high-level analysis of a broad range of options potentially available to resolve Basin imbalances. This high-level analysis added the risk that not all of the potential costs and benefits of the options were considered. A detailed assessment by individual location for most of the distributed options (e.g., M&I water conservation, agricultural water conservation, and reuse) was beyond the scope of the Study.
- ***Potential for Subjectivity.*** The classification system used in the characterization process was relatively prescriptive; however, there was still some room for subjectivity when considering each option. Not all participants in the Study were in agreement with all ratings, but it was recognized that future efforts beyond the Study will result in a more in-depth assessment of the options.
- ***Uncertainty.*** The characterization was performed based on limited and high-level analyses. Therefore, knowledge of items such as costs, permit requirements, and long-term feasibility was highly uncertain. For example, cost estimates for infrastructure-type projects were based on past similar projects with adjustments for parameters such as scale and location. Similar statements can be made related to uncertainty with characterization of the other option criteria.

9.5 Consideration of Options

Due to the legal, regulatory, and sometime technical complexity of the options submitted, not all categories of options submitted underwent a quantitative assessment. As such, portfolios were largely limited to groups of options that lend themselves to modeling implementation within the Study’s timeframe, i.e. those that increase supply or reduce demand, with the exception of the Upper Basin water bank concept. The options modeled in CRSS do not necessarily reflect the entire range of innovative options and strategies that should continue to be explored in future efforts.

10.0 Future Considerations and Next Steps

Colorado River water managers and stakeholders have long understood that growing demands on the Colorado River system, coupled with the potential for reduced supplies due to climate change may put water users and resources relying on the river at risk of prolonged water shortages in the future. The magnitude and timing of these risks differ spatially across the Basin, particularly those areas where demand is at or exceeds available supply, are at a greater risk than others. The Study builds on earlier work and is the next significant step in developing a comprehensive knowledge base and suite of tools and options that will be used to address the risks posed by imbalances between Colorado River water supply and resource needs in the Basin.

The Study confirms that the Colorado River Basin faces a range of potential future imbalances between supply and demand. Addressing such imbalances will require diligent planning and cannot be resolved through any single approach or option. Instead, an approach that applies a wide variety of ideas at local, state, regional, and Basin-wide levels is needed. The Study's portfolio exploration demonstrated that implementation of a broad range of options can reduce Basin resource vulnerability and improve the system's resiliency to dry hydrologic conditions while meeting increasing demands in the Basin and adjacent areas receiving Colorado River water.

The Study is ultimately a call to action. The potential improvements in system performance and enhanced resiliency resulting from the portfolio analysis is encouraging, however a very long lead time is required to implement many of the portfolio options. When considering the potential onset of critical imbalances as early as 2025, it is imperative that the processes to further these concepts must begin in the near future. The next steps to begin these actions must be done collaboratively and continue to facilitate and build upon the broad, inclusive stakeholder process demonstrated in the Study.

The call to action must be answered by all stakeholders that rely on the Colorado River or its tributaries. Given the uncertainty associated with future conditions in the Basin, the ability to increase water supply reliability is even more important. There is no one option or one path that will provide certainty for the future water supply and rivers of the Basin. Responding to the uncertainty will require understanding all potential options and taking action must be the responsibility of all stakeholders. The political will to take necessary action must be directed towards a credible process to create solutions which examines the trade-offs of using various options while seeking to meet a range of Basin resource goals. As the next steps are taken, all stakeholders must be involved in considering future options and strategies and all evaluation and analysis of these options must be done with a high level of transparency with independent scientific review and opportunities for public comment.

The following sections describe those areas where additional steps should be taken following completion of the Study. These areas and recommended future actions are presented thematically and were developed cooperatively by Reclamation, the Basin States, tribes, and various conservation organizations.

Water Use Efficiency and Reuse

Further efforts to improve water use efficiency in the M&I, agricultural and energy sectors were a common element across all Study portfolios in providing a cost-effective solution for resolving imbalances in the near-term. This is an area that municipalities and entities in the agricultural sector have been and will continue to pursue. The approach taken by the Study to determine the potential for conservation in these sectors and their respective costs was at a Basin-wide level. Although appropriate for the Study, this approach does not reflect the important local differences in conservation potential nor does it reflect the legal issues associated with the various state water right policies. A key issue to be explored is the significant uncertainty related to the potential magnitude of conservation included in the Study.

A recommended next step is to establish workgroups associated with municipal conservation, agricultural conservation, energy conservation, and reuse. These workgroups would be convened by Reclamation. The purpose of the workgroups would be to identify existing programs, projects, and policies applied to municipal, agricultural, reuse, and energy sector conservation and the distribution of those programs across water users throughout the Study Area. The goal of these workgroups would be to consider new opportunities and programs, and potentially to develop a scope of work for feasibility-level studies to develop new approaches to encourage conservation that address key uncertainties and financial impacts. The groups' objectives will include focusing on water use efficiency at a local level, the application of approaches appropriate for different locations and regions, and exploring innovative and cost-effective ways to encourage increased water use efficiency and reuse opportunities with the goal of recommending the implementation of solutions resulting in cost-effective water savings and reuse.

Reclamation’s WaterSMART program provides several opportunities that could be used to further study and implement water conservation and reuse options. Through WaterSMART grants, funding could be made available for projects that save water or improve energy efficiency. The criteria for administering these grants could be modified to give preference to activities that build upon Basin Study outcomes. Through the WaterSMART Title XVI – Water Reclamation and Reuse Program funding could be made available for planning studies and the construction of water recycling projects.

Water Banks

Water banks are a flexible and innovative solution to avoiding imbalances. Both intrastate and interstate water banking occurs within the Lower Basin. In the Study, a conceptual Upper Basin water bank was explored where the benefit was twofold: 1) the bank provided increased flexibility in the Upper Basin to mitigate risk of potential future Lee Ferry deficits and 2) the water generated through conservation for the bank enhanced ecological and recreational resources as it was routed to a conceptual storage facility. Although there are significant legal, policy, and institutional challenges associated with potential banking options, the potential benefits associated with this option suggest that additional exploration and analysis of this concept may be warranted.

Presently, some of the Upper Division States are exploring the feasibility of water banking concepts within the Upper Basin. A recommended next step is to continue to work with stakeholders in the Upper Basin regarding water banking concepts. Reclamation is committed to exploring creative and flexible ways to use storage facilities and other Reclamation infrastructure, consistent with authorized purposes and the Law of the River, in an attempt to accommodate appropriate water banking options. Moreover, the Upper Division States will engage in a broader conversation with the Lower Division States and other stakeholders, at the appropriate time, to discuss how an Upper Basin water bank would operate.

Water Transfers

In terms of reducing demands and as conservation options, water transfers were also demonstrated through the Study portfolios as being an important tool for resolving imbalances in the near and long-term. Voluntary water transfers can have many potential benefits and in particular promote flexibility in adapting to uncertain future conditions. Many of the Basin States have been utilizing voluntary water transfers within their respective states to meet water management challenges and will continue to look to transfers as an important solution. Although negative impacts can be associated with certain types of water transfers, such as permanent dry-up of agricultural land, innovative strategies can be employed to avoid these impacts and are being explored by many states. The Western Governors' Association's (WGA) recent report on water transfers identifies innovative approaches and specific steps that states can consider in order to improve water transfer outcomes (WGA, 2012). Reclamation will engage with the Basin States as appropriate to improve opportunities for water transfers and develop third party impact reduction and mitigation techniques that can be applied throughout the Basin.

Water Supply Augmentation

Large-scale water supply augmentation projects could provide additional reliable water to meet future demands, although such projects face significant permitting challenges and currently are both expensive and energy intensive. The assessments of large-scale water supply augmentation projects conducted in the Study were strictly at an appraisal level; additional study is needed to better understand the appropriate timing of investments, effectiveness, and tradeoffs.

Recommended next steps include identifying and defining appropriate feasibility-level studies for large-scale augmentation projects most likely to overcome the challenges previously noted. Prior to conducting feasibility-level studies, key stakeholders would come together to review scopes of work and develop funding and cost-sharing for the studies.

Watershed Management

There were a number of watershed management activities that were explored in the Study. Two of these activities were weather modification and vegetation management. Weather modification is inexpensive and has the potential to increase the Basin's supply. Several of the Basin States have funded weather modification activities on an ongoing basis for many years. Nevertheless, significant uncertainty exists related to the effectiveness of snowpack augmentation activities to increase available water supply. In addition, there is also significant uncertainty related to the long-term reliability of the option due to its reliance on current weather patterns, which may not persist under climate change scenarios. Enhanced understanding of weather modification is needed including the certainty of measured efficacy within targeted watershed.

Recommended next steps include the application of existing operational experience and research to identify target watersheds for snowpack augmentation activities, and continuation of research to reduce water supply yield uncertainties.

Vegetation management activities are ongoing at the state and local level. Most of these activities occur with the help of local partners, such as the Tamarisk Coalition. These activities should continue and be encouraged into the future.

Mitigation of dust on snow as an opportunity to increase water supply is a relatively new concept, and bears further exploration with federal partners including the Bureau of Land

Management. A dialogue among the relevant federal agencies and the appropriate Landscape Conservation Cooperatives (LCC) should be initiated to better understand the origins and mitigation options for managing dust on snow.

Tribal Water

The Indian Reserved Water Rights of the tribes of the Colorado River Basin are unique and have attributes that must be recognized under federal law and distinguished from state law water rights. The Indian Reserved Water Rights of the tribes of the Colorado River Basin account for approximately 2.9 million acre-feet of annual diversion rights of the total apportionment of the Colorado River in the United States. The Study does not fully account for Tribal water demand nor reflect the potential use of tribal water by others nor show the potential impact on the Basin water supply if a substantial amount of the presently unused or unquantified tribal water is used by the tribal water rights holders prior to 2060.

Working together with the Tribes, and recognizing the unique attributes of Indian Reserved Water Rights, Reclamation acknowledges that the outcome of tribal water settlements must be accounted for in Reclamation's analysis of water supply and demand, in order to accurately project imbalances in the Colorado River Basin. Indian Reserved Water Rights are unique under federal law, they are held in trust by the United States for the benefit of Tribes, and thus a trust obligation exists to protect those rights.

In particular, CRSS was intended to evaluate water availability in the Upper Basin and Lower Basin and potential water supply and demand imbalances through 2060. Reclamation acknowledges that the Study results are limited in their ability to fully account for the effects of tribal reserved water rights on projected supply and demand imbalances, in light of the unique attributes of those rights. The Study does, however, summarize quantified tribal water rights in *Technical Report C – Water Demand Assessment, Appendix C9 – Tribal Water Demand Scenario Quantification*, but Reclamation does not intend that the current Study be used to assess the future impacts to tribal water use in the Basin.

In light of the foregoing, and in recognition of the Federal Government's continued trust obligation to work with members of the Ten Tribes Partnership to protect their Tribal Reserved Water Rights, Reclamation and the Ten Tribes Partnership are committed to joint future planning efforts that build on the scientific foundation of the current Study and advance critical information beyond the limited assessment of tribal water in the Study. Future Reclamation planning efforts should include a study capable of evaluating full tribal development, control, and protection of tribal water resources in the Basin. This study should be conducted jointly by Reclamation and the Ten Tribes Partnership with involvement by interested stakeholders including the Basin States. Considerations should include water banking, voluntary water transfers, improved efficiencies, re-use opportunities, underground storage, and other options. These options may aid tribal and non-tribal users with developing options not presently available to respond to supply and demand uncertainty in the decades to come.

Reclamation also recognizes the importance of continued dialogue with respect to tribal matters at a regional and local level. In particular, several issues were identified by the Inter Tribal Council of Arizona in their option submission to the Study and these issues warrant further discussion. These issues are described in *Technical Report F – Development of Options and Strategies, Appendix F13 – Options Submitted by the Ten Tribes Partnership and the Inter Tribal Council of Arizona.* Reclamation is committed to participating actively in discussions with tribal leaders, continuing to seek resolution on these issues, and exploring opportunities that will bring the tribal perspective to bear in enhancing the management of the Basin resources.

Environmental Flows

The Study recognized the importance of considering river flows to support flow and water dependent ecological systems, power generation, and recreation, through its adoption of metrics used to approximate the performance of these resources, the inclusion of an Enhanced Environment water demand scenario, and the inclusion of a conceptual Upper Basin water bank the objective of which specifically includes improving the performance of ecological and recreational resources. Although these activities resulted in a good first step towards incorporating the needs of flow and water dependent ecological systems and exploring concepts to better meet those needs under a range of future conditions, exploring ways to meet ecological and recreational needs should continue beyond the completion of the Study. Future efforts should strive to better understand and quantify the needs of these systems, better reflect those needs in a modeling framework, and further explore solutions considered in the Study as well as others that promote the protection and improvement of environmental and recreational flows. The solutions should be explored in conjunction with those that support other management goals and decisions as to achieve integrated water management solutions that benefit multiple uses.

Recommended next steps focus on identifying potential enhancements to CRSS to improve the modeling of ecological, recreational, and power generation flow needs. Through an LCC grant in which The Nature Conservancy is the principal investigator, a workshop will be held in late summer 2013 to explore and recommend modeling improvements to appropriately consider recreational and environmental flow needs. Reclamation and the Basin States are committed to considering the recommendations that come from this workshop and to continue the dialogue with interested stakeholders to explore opportunities to include recreational and environmental flow needs in future water management decisions. This dialogue will be continued through the formation of an exploratory work group of interested stakeholders to identify and assess options that provide multiple benefits to improve flow and water dependent ecological systems, power generation, and recreation. The intent of this work group is not to focus on new regulatory requirements, but rather to identify opportunities for infrastructure, operations, and transactions that could reduce projected vulnerabilities resulting from future supply and demand imbalances.

Data and Tool Development

CRSS was the primary modeling tool utilized in the Study. Originally developed to model Lake Powell and Lake Mead operations, the Study demonstrated the need to improve the spatial resolution of CRSS, particularly in the Upper Basin. Improvements to CRSS are needed to better support future endeavors identified in these next steps, such as analysis of Upper Basin water banking concepts, enhanced modeling of environmental flows, and exploring tribal water development and options to resolve imbalances related to tribal water. The scoping and design of these improvements will occur through Reclamation's Stakeholder Modeling Workgroup. This work will begin within a year of completion of the Study and may build on recommendations from the LCC workshop discussed above.

The Study has resulted in enhanced tools and datasets for water resource planning in the Basin. The Basin States will work with Reclamation to evaluate the ability to use the tools developed for the Study and update water demands and supply scenarios on a five-year timeframe. The

Basin States will work with Reclamation to support improvements in the Study's input information, modeling and analytical tools. The Basin States will also work with Reclamation in fulfilling the commitments regarding the Lower Basin tributaries specifically described in *Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System*.

Climate Science Research

The Study used the best available science at the time it was initiated. Nonetheless, climate science is rapidly evolving and a new set of GCM projections will soon be available. Next steps include prioritizing the research agenda of Reclamation's Hydrology Work Group to advance the technical foundation established by the Study regarding the use of climate projections in future studies.

Partnerships

The collaborative approach adopted by the Study was paramount to its success. Next steps should be taken in ways that build on its momentum and dialogue to increase the effectiveness of partnership responses when new challenges and opportunities arise. As in the past, the Federal Government can provide a leadership role in appropriate processes to facilitate this dialogue.

11.0 Summary of Next Steps

In recognition of their ongoing joint commitment to future action, Reclamation will convene the Basin States along with tribes, other Colorado River water entitlement holders, conservation organizations, and other interested stakeholders in early 2013 to conduct a workshop to review the recommended next steps and initiate actions to implement next steps to resolve the current and potentially significant future imbalances in the Colorado River system. In early 2013 Reclamation will also consult and work with tribes regarding tribal water issues reflected in this report.

In summary, there are several future actions that must take place to move closer towards implementing solutions to resolve imbalances in the Basin. First, significant uncertainties related to water conservation, reuse, water banking, and weather modification concepts must be resolved in order to adequately implement these approaches. Second, costs, permitting issues, and energy availability issues relating to large-capacity augmentation projects need to be identified and investigated through feasibility-level studies. Third, opportunities to advance and improve the resolution of future climate projections should be pursued and enhancements to the operational and planning tools used in the Colorado River system to better understand the vulnerabilities of the water-dependent uses, including environmental flows, should be explored. Fourth, as projects, policies, and programs are developed, consideration should be given to those that provide a wide-range of benefits to water users and healthy rivers for all users.

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Disclaimer

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

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

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