

RECLAMATION

Managing Water in the West

Colorado River Basin Water Supply and Demand Study

Executive Summary – Pre-Production Copy



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**U.S. Department of the Interior
Bureau of Reclamation**

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Executive Summary

Spanning parts of the seven states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming (Basin States), the Colorado River Basin (Basin) is one of the most critical sources of water in the West. The Colorado River and its tributaries provide water to nearly 40 million people for municipal use, supply water used to irrigate nearly 5.5 million acres of land, and is also the lifeblood for at least 22 federally recognized tribes (tribes), 7 National Wildlife Refuges, 4 National Recreation Areas, and 11 National Parks. Hydropower facilities along the Colorado River provide more than 4,200 megawatts of generating capacity, helping to meet the power needs of the West and offset the use of fossil fuels. The Colorado River is also vital to the United Mexican States (Mexico) to meet both agricultural and municipal water needs.

The Colorado River system is operated in accordance with the Law of the River¹. Apportioned water in the Basin exceeds the approximate 100-year record (1906 through 2011) Basin-wide average long-term historical natural flow² 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 use³ and losses in the Basin has averaged approximately 15.3⁴ maf over the last 10 years. 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 despite recently experiencing the worst 11-year drought in the last century. However, there have been periodic shortages throughout the Upper Basin and the adjacent areas of the Basin States that receive Colorado River water.

The challenges and complexities of ensuring a sustainable water supply and meeting future demand in an over-allocated and highly variable system such as the Colorado River have been recognized and documented in several studies conducted by the Bureau of Reclamation (Reclamation) and the Basin States over the past several decades. Looking ahead, concerns regarding the reliability of the Colorado River system to meet future Basin resource⁵ needs are even more apparent, given the likelihood of increasing demand for water throughout the Basin coupled with projections of reduced supply due to climate change.

It was against this backdrop that the Colorado River Basin Water Supply and Demand Study (Study) was conducted. Funded by the Reclamation through the Basin Study Program under

¹ 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.

² Natural flow represents the flow that would have occurred at the location had depletions and reservoir regulation not been present upstream of that location.

³ Consumptive use is defined as water used, diminishing the available supply.

⁴ 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.

⁵ Resources include water allocations and deliveries for municipal, industrial, and agricultural use; hydroelectric power generation; recreation; fish, wildlife, and their habitats (including candidate, threatened, and endangered species); water quality including salinity; flow- and water-dependent ecological systems; and flood control.

the Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program and the agencies⁶ representing the Basin States, the Study was conducted by Reclamation's Upper Colorado and Lower Colorado Regions and the representatives of the Basin States' agencies. The purpose of the Study was 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 did not result in a decision as to how future imbalances should or will 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.

The Study Area is shown in figure 1 and is defined as the hydrologic boundaries of the Basin within the United States, plus the adjacent areas of the Basin States that receive Colorado River water. In many adjacent areas, the Colorado River supply is in addition to other water supply sources used to meet water demands.

⁶ The non-Federal cost-share partners are: Arizona Department of Water Resources, the (California) Six Agency Committee, Colorado Water Conservation Board, the New Mexico Interstate Stream Commission, the Southern Nevada Water Authority, the Utah Division of Water Resources, and the Wyoming State Engineer's Office.

FIGURE 1
The Study Area



The Study was conducted in collaboration with stakeholders throughout the Basin. Interest in the Study was broad, and stakeholders included tribes, agricultural users, purveyors of municipal and industrial (M&I) water, power users, and conservation and recreation groups. Through outreach efforts, these interested parties were engaged and their input was considered. This broad participation and input was critical to the Study.

Because of the inherent complexities of the Study and the many diverse interests and perspectives, interim reports and technical updates were published to reflect technical developments and the ongoing input of stakeholders. Throughout the course of the Study, eight of these interim products were published. The final documentation for the Study is organized into three major parts: this *Executive Summary*, a *Study Report*, and seven Technical Reports.

Project participants and stakeholders are encouraged to comment on the information provided in the final *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 may inform future planning activities in the Basin. Instructions for submitting comments are also provided on the Study website at: <http://www.usbr.gov/lc/region/programs/crbstudy.html>

1.0 Projected Future Water 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 depend on a number of factors. The potential impacts of future climate change and variability further contribute to these uncertainties. Nevertheless, projections of future water supply and demand were needed to assess the reliability of the Colorado River system to meet Basin resource needs and to identify options and strategies to mitigate future risks to those resources. To be beneficial, these projections must be sufficiently broad to capture the plausible ranges of uncertainty in future water supply and demand. A scenario planning process was used to guide the development of scenarios that provided a broad range of projections, resulting in four scenarios related to future water supply and six scenarios related to future water demand.

1.1 Water Supply Scenarios

Since 2004, Reclamation has conducted a multi-faceted research and development programs to investigate and implement a variety of methods for projecting future streamflow for Colorado River planning studies. Based on this work and the information gathered in the scenario planning process, four water supply scenarios were quantified and analyzed. These scenarios are titled Observed Resampled, Paleo Resampled, Paleo Conditioned, and Downscaled General Circulation Model (GCM) Projected and are described as:

- **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 112 future downscaled GCM projections.

Under the Downscaled GCM Projected scenario, the mean natural flow at Lees Ferry over the next 50 years is projected to decrease by approximately 9 percent, along with a projected increase in both drought frequency and duration as compared to the observed historical and paleo-based scenarios. The range of this result varies amongst the individual GCM projections that comprise this scenario with some of the GCM projections showing a larger decrease in mean natural flow than 9 percent while others showing an increase over the observed historical mean. Droughts⁷ lasting 5 or more years are projected to occur 50 percent of the time over the next 50 years. Projected changes in climate and hydrologic processes include continued warming across the Basin, a trend towards drying (although precipitation patterns continue to be spatially and temporally complex) increased evapotranspiration and decreased snowpack as a higher percentage of precipitation falls as rain rather than snow and warmer temperatures cause earlier melt.

The process of using GCM projections and hydrologic modeling to generate projections of future streamflow presents a number of uncertainties and reflects methodological choices made in the Study. For example, choices of different downscaling techniques or the selection of a different hydrologic model to determine streamflow would yield different results. Notwithstanding minor methodological and reporting differences, the results presented in this report are consistent with Reclamation's report to Congress published in March 2011⁸ in fulfillment of the requirements within Section (§) 9503 of the SECURE Water Subtitle of the Omnibus Public Land Management Act of 2009 (Public Law 111-11).

1.2 Water Demand Scenarios

Historically, Reclamation has considered a single projection of future demands in long-term Basin planning studies. The Study considered a range of projections of demand, developed through a scenario planning process, which is a significant and important advancement in long-term water planning in the Basin. These demands were based on data and information provided by the Basin States, tribes, federal agencies, and other water entitlement holders. Through the scenario planning process, the most critical uncertainties affecting future demand were identified (for example, changes in population and water use efficiency) and were combined into six scenarios, as follows: Current Projected (A), Slow Growth (B), Rapid Growth (C1 and C2), and Enhanced Environment (D1 and D2).

Based on these scenarios, and factoring in both Mexico's allotment and water loss due to evaporation and operations, the Colorado River demand for consumptive uses is projected to range between about 18.1 maf under the Slow Growth (B) scenario and about 20.4 maf under

⁷ For the purpose of the Study, a drought period occurs whenever the running 2-year average flow at Lees Ferry falls below 15.0 maf, the observed historical long-term mean.

⁸ Bureau of Reclamation, 2011. SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011.

the Rapid Growth (C1) scenario by 2060. The largest increase in demand is projected to be in the M&I category, owing to population growth. Population within the Study Area is projected to grow from about 40 million in 2015 to between 49.3 million under the Slow Growth (B) scenario and 76.5 million under the Rapid Growth (C1) scenario by 2060. Additionally, the water demand assessment confirmed that the Lower Division States have demand for Colorado River water beyond their 7.5 maf basic apportionment across all scenarios.

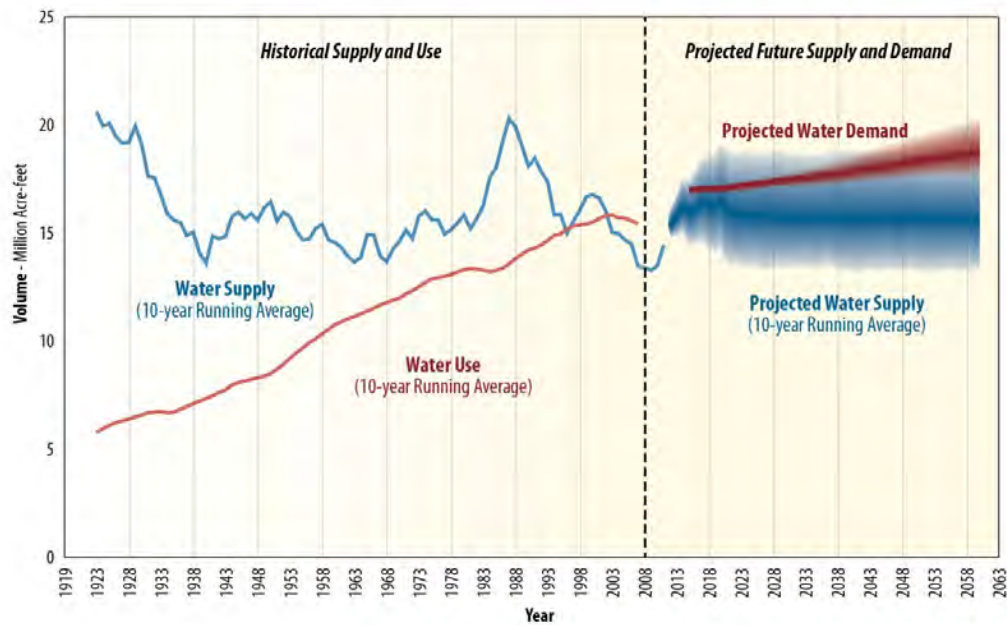
Non-consumptive⁹ demands, such as those associated with uses for hydropower and recreation and ecological resources, were included through the development of system reliability metrics and were not quantified in the same manner as demand for consumptive uses. For example, non-consumptive flow targets supporting the environment and recreational activities were developed for several locations throughout the Basin. The impact on these resources was assessed across all combinations of supply and demand scenarios in the Study's system reliability analysis.

2.0 Projected Future Water Supply and Demand Imbalances

The range of the projected future water supply and demand in the Basin, as determined through the scenario process, is shown conceptually in figure 2. Without additional future water management actions, a wide range of future imbalances is plausible, primarily due to the uncertainty in future water supply. Comparing the median of water supply projections against the median of the water demand projections (medians are indicated by the darker shading), the long-term projected imbalance in future supply and demand is about 3.2 maf by 2060. The imbalance, however, can be much greater (or less) under any one of the multiple plausible future supply and demand scenarios. The projected imbalance in figure 2 does not consider the effect of reservoir storage, which has and will continue to be used to meet Basin resource needs when demand exceeds supply. Through modeling and the use of system reliability metrics, which consider the effects of reservoir storage, the potential impacts associated with these imbalances to Basin resources were assessed.

⁹ Non-consumptive use is defined as water used without diminishing available supply.

FIGURE 2
Historical Supply and Use¹ and Projected Future Colorado River Basin Water Supply and Demand¹



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

3.0 Options and Strategies to Resolve Supply and Demand Imbalances

The Basin States 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.

To identify a broad range of additional potential options to resolve water supply and demand imbalances, input from Study participants, interested stakeholders, and the general public was solicited for consideration in the Study. The solicitation period was from November 2011 through February 2012, and those interested in submitting ideas were asked to complete and submit an option submittal form. During this period, over 150 options were received and were organized into 4 groups: 1) those that increase Basin water supply (Increase Supply), 2) those that reduce Basin water demand (Reduce Demand), 3) those that focus on modifying operations (Modify Operations), and 4) those that focus primarily on Basin governance and mechanisms to facilitate option implementation (Governance and Implementation). Despite the submission of several options that may ultimately be considered too costly or technically infeasible, the Study explored a wide range of options with the goal of ensuring that all viable options were considered.

From these broad groups, categories of options were developed, and each submitted option was assigned to one category based on its primary function. Recognizing that every option

submitted could not undergo further evaluation due to time and resource constraints, representative options that spanned the range of the option categories were developed. About 30 representative options were developed to ensure the concepts embodied in each submitted option were reflected and were further evaluated. Many of the representative options were evaluated quantitatively, which entailed an assessment of cost, yield, and timing in addition to assignment of a rating (“A” through “E”) to 14 other criteria, listed in table 1.

TABLE 1
Criteria Used to Evaluate Representative Options

Technical		Environmental	
Technical Feasibility		Permitting	
Implementation Risks		Energy Needs	
Long-Term Viability		Energy Source	
Operational Flexibility		Other Environmental Factors	
Social		Other	
Recreation		Quantity of Yield	Hydropower
Policy		Timing	Water Quality
Legal		Cost	
Socioeconomics			

Whereas many of the criteria were assigned a qualitative rating, the assessment of cost, quantity of yield, and timing entailed numeric estimates to facilitate the grouping of these options into portfolios and the modeling of those portfolios. Costs were computed as present day annualized capital, operating, and replacement cost per acre-foot of option yield. It should be noted that the assessment of these criteria was at an appraisal level and there are many associated uncertainties, especially with respect to estimates regarding costs and quantity of yield. For representative options for which the criteria listed in table 1 was not suitable, such as those options in the Governance and Implementation group, a qualitative description was provided. A summary of the representative options within the Increase Supply, Reduce Demand, and Modify Operations groups and the cost, yield, and timing, and inclusion in portfolios, where applicable, is provided in table 2.

The Governance and Implementation group consists of ideas and suggestions related to three major categories: Water Management and Allocation, Tribal Water, and Data and Information. Most concepts related to Water Management and Allocation and Tribal Water have significant legal and policy considerations and were included in the Study but were not assessed. Where appropriate, these concepts will require future discussions beyond the scope of the Study. Data and Information ideas recommended future data and tool development to support future planning activities in the Basin.

TABLE 2
Summary of Representative Options Including Cost, Timing, Potential Yield, and Inclusion in Portfolios

Option Type	Option Category	Representative Option	Estimated Cost (\$/afy)	Years before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)	Option Included in Portfolio
Increase Supply	Desalination	Gulf of California	2,100	20 – 30	200,000	1,200,000	Portfolios A, B (up to 400 kafy)
		Pacific Ocean in California	1,850–2,100 ¹	20–25	200,000	600,000	Portfolios A, B (up to 400 kafy)
		Pacific Ocean in Mexico	1,500	15	56,000	56,000	Portfolios A, B
		Salton Sea Drainwater	1,000	15–25	200,000	500,000	All Portfolios
		Groundwater in Southern California	750	10	20,000	20,000	All Portfolios
		Groundwater in the Area near Yuma, Arizona	600	10	100,000	100,000	All Portfolios
		Subtotal				776,000	2,476,000
	Reuse	Municipal Wastewater	1,500–1,800	10–35	200,000	932,000	All Portfolios
		Grey Water	4,200	10	178,000	178,000	Portfolio C
		Industrial Wastewater	2,000	10	40,000	40,000	All Portfolios
		Subtotal				418,000	1,150,000
	Local Supply	Treatment of Coal Bed Methane-Produced Water	2,000	10	100,000	100,000	Portfolios A, B
		Rainwater Harvesting	3,150	5	75,000	75,000	Portfolio C
		Subtotal				175,000	175,000
	Watershed Management	Brush Control	7,500	15	50,000	50,000	None
		Dust Control	220–520	15–25	280,000	400,000	Portfolios A, C
		Forest Management	500	20–30	200,000	300,000	None
		Tamarisk Control	400	15	30,000	30,000	Portfolios A, C
		Weather Modification	30–60	5–45	700,000	1,700,000	All Portfolios (up to 300 kafy)
		Subtotal				1,260,000	2,480,000

TABLE 2
Summary of Representative Options Including Cost, Timing, Potential Yield, and Inclusion in Portfolios

Option Type	Option Category	Representative Option	Estimated Cost (\$/afy)	Years before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)	Option Included in Portfolio
Increase Supply	Importation	Imports to the Colorado Front Range from the Missouri or Mississippi Rivers	1,700–2,300	30	0	600,000	Portfolios A, B
		Imports to the Green River from the Bear, Snake ¹ or Yellowstone Rivers	700–1,900	15	158,000	158,000	None
		Imports to Southern California via Icebergs, Waterbags, Tankers, or from the Columbia River ¹	2,700–3,400	15	600,000	600,000	None
		Subtotal			758,000	1,358,000	
Reduce Demand	M&I Water Conservation	M&I Water Conservation	500–900	5–40	600,000	1,000,000	All Portfolios
		Subtotal			600,000	1,000,000	
	Agricultural Water Conservation	Agricultural Water Conservation	150–750	10–15	1,000,000	1,000,000	All Portfolios
		Agricultural Water Conservation with Transfers	250–750	5–15	1,000,000	1,000,000	All Portfolios
		Subtotal			1,000,000²	1,000,000²	
	Energy Water Use Efficiency	Power Plant Conversion to Air Cooling	2,000	10	160,000	160,000	All Portfolios
Subtotal				160,000	160,000		
Modify Operations	System Operations	Evaporation Control via Canal Covers	15,000	10	18,000	18,000	None
		Evaporation Control via Reservoir Covers	15,000	20	200,000	200,000	None
		Evaporation Control via Chemical Covers on Canals or Reservoirs	100	15–25	200,000	850,000	None

TABLE 2
Summary of Representative Options Including Cost, Timing, Potential Yield, and Inclusion in Portfolios

Option Type	Option Category	Representative Option	Estimated Cost (\$/afy)	Years before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)	Option Included in Portfolio
		Modified Reservoir Operations	N/A	15	0–300,000	0–300,000	None
		Construction of New Storage	2,250	15	20,000	20,000	None
		Subtotal			588,000³	1,238,000³	
	Water Transfers, Exchanges, and Banking	Water Transfers and Exchanges (same as Agricultural Water Conservation with Transfers)	250–750	5–15	1,000,000	1,000,000	All Portfolios
		Upper Basin Water Banking ⁴	N/A	10	500,000	800,000	Portfolios A,C
		All Options			5,735,000⁵	11,037,000⁵	

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 The values related to Upper Basin Banking reflected assumptions developed for modeling purposes. It was assumed that bank water is generated through conservation; therefore, the potential yield of the bank is consistent with the Upper Basin portion of agricultural and M&I conservation and energy water use efficiency

⁵ Total does not account for several options that may be mutually exclusive due to regional integration limitations or are dependent on the same supply.

When considering all options and all categories, the potential yield is approximately 5.7 maf per year (maf) by 2035 and more than 11 maf by 2060. However, not all options are equally feasible or reliable in the long term. Some options, such as imports into southern California via submarine pipelines, water bags, icebergs, or those related to watershed management (e.g. weather modification or dust control), have either significant technical feasibility challenges or significant questions regarding their reliability. Excluding options that rate low for these factors, the potential yield is reduced to approximately 3.7 maf by 2035 and to approximately 7 maf by 2060.

Recognizing no single option will be sufficient to resolve future projected supply and demand imbalances, groups of options, or portfolios, were developed to reflect different adaptive strategies. Each portfolio consists of a unique combination of options that were considered to address Basin resource needs—for example, the water elevation in Lake Mead—that may exist under future combinations of supply and demand. Four portfolios were evaluated in the Study and represent a range of reasonable but different approaches for

resolving future supply and demand imbalances. The portfolios are not intended to represent all possible strategies for grouping options. Further, the Study does not result in the selection of a particular portfolio or any one option from any portfolio. The objective of the portfolio analyses is to demonstrate the effectiveness of different strategies in resolving future supply and demand imbalances.

Using the ratings associated with the criteria listed in table 1 to express certain preferences towards a future strategy, resulted in two portfolios, *Portfolio B* and *Portfolio C*. Two other portfolios were then developed, *Portfolio A* and *Portfolio D*, to represent a highly inclusive strategy (includes all options in either *Portfolio B* or *Portfolio C*) and a highly selective strategy (includes only options in both *Portfolio B* and *Portfolio C*). The four portfolios considered in the Study are summarized in table 3.

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 seeking options with proven technology that, once in place, will produce reliable long-term yield. The strategy represents a low-risk strategy in the long term, but allows greater risk with respect to permitting and implementation.

Portfolio C focuses on options that are technically feasible but also may have lower environmental impacts—low energy needs, lower carbon energy sources, low permitting risk, and low impacts to other environmental factors. The strategy can be defined as one that prioritizes options providing long-term solutions that are flexible and seek to enhance ecological and recreational flows while minimizing the effects on other Basin resources. The strategy represents a low-risk strategy in the near term but allows greater risk with respect to long-term performance of conservation measures.

TABLE 3
Study Portfolios

Portfolio Name	Portfolio Description
<i>Portfolio A</i>	Is the least restrictive and contains all options that are in both <i>Portfolio B</i> and <i>Portfolio C</i> .
<i>Portfolio B</i>	Includes options with high technical feasibility and high long-term reliability; excludes options with high permitting, legal, or policy risks.
<i>Portfolio C</i>	Includes only options with relatively low energy intensity; includes an option that results in increased instream flows; excludes options that have low feasibility or high permitting risk.
<i>Portfolio D</i>	Is the most selective and contains only those options that are included in both <i>Portfolio B</i> and <i>Portfolio C</i> .

4.0 Evaluation of Opportunities to Resolve Supply and Demand Imbalances

The evaluation of the effectiveness of the four portfolios at resolving future potential supply and demand imbalances consisted of the following: identifying the reliability of the system at meeting Basin resource needs under all future supply and demand scenarios without portfolios in place (termed “Baseline” system reliability); defining of vulnerable conditions—those stressing to Basin resources; and evaluating the effectiveness of portfolios as measured by their ability to improve system reliability and reduce vulnerabilities relative

to the Baseline. The estimation of cost and other tradeoffs associated with implementing the four portfolios was also explored.

The performance of Basin resources was measured through system reliability metrics (metrics). With broad stakeholder involvement, a comprehensive set of metrics that span six resource categories (Water Delivery, Electrical Power, Water Quality, Flood Control, Recreational, and Ecological Resources) was identified. From those metrics, levels reflecting vulnerability or resource risk were identified. The combination of a particular metric and the assumed level of risk are termed “vulnerability.” Two important vulnerabilities that provide an overall indication of system reliability are: 1) Lake Mead elevation dropping below 1,000 feet above mean sea level (msl) in any month and 2) Lee Ferry deficit¹⁰, when the 10-year running total flow at Lee Ferry, Arizona is less than 75 maf.

Baseline system reliability was modeled considering all combinations of the supply and demand scenarios. Additionally, two operational assumptions regarding Lake Powell and Lake Mead operations past the effective period of the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operation for Lake Powell and Lake Mead in 2026 were considered. Since each supply scenario has over 100 individual sequences, the Baseline system reliability is comprised of over 20,000 simulations. Despite the findings from the water demand assessment that the Lower Division States have demand for Colorado River water beyond their 7.5 maf basic apportionment, the Baseline system reliability assumes deliveries to the Lower Division States remain consistent with and within their basic apportionment.

In summary, the Baseline analysis indicates that without action, it will become increasingly difficult for the system to meet Basin resource needs over the next 50 years. Future projected development of water supplies and increased consumptive use in the Upper Basin combined with potential reductions in future supply results in reduced volumes of water stored in system reservoirs. With lower water elevations in reservoirs, the needs for resources such as hydropower and shoreline recreation were less frequently satisfied, while water delivery shortages increased. Decreases in flows in key river tributaries have negative implications for flow-dependent resources such as boating recreation and river ecology. These findings fully support the need to develop and evaluate options and strategies to help resolve the water supply and demand imbalance. Vulnerabilities for the latter period of the Study period (2041 through 2060) under Baseline conditions are summarized in table 4.

The Baseline system reliability also reveals that many combinations of future water supply and demand result in management challenges. In fact, most combinations stress some Basin resources through 2060. In the near-term (2012 through 2026), water demands are similar across scenarios, and the largest factor affecting the system reliability is water supply. In the mid-term (2027 through 2040), the demand for water is an increasingly important element in the reliability of the system, as are assumptions regarding the operations of Lakes Powell and Mead. In the long-term (2041 through 2060), the futures that consider the Downscaled GCM Projected water supply scenario, which incorporates projections of future climate, show a high inability to meet resource needs, regardless of the demand scenario and the operation of

¹⁰ 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.

Lakes Powell and Mead. The first stage in the portfolio analysis revealed that when all options in the most inclusive portfolio (*Portfolio A*) are implemented immediately upon availability, and without meeting demand of the Lower Division States above 7.5 maf, plausible futures still exist in which the system is vulnerable. While the implementation of these options results in a sizeable reduction in vulnerability (the percentage of futures resulting in Lake Mead elevations being less than 1,000 feet msl is reduced from about 19 percent to 3 percent), these results indicate that complete elimination of Basin vulnerability is not likely attainable.

Because the Lower Division States have demand for Colorado River water above their 7.5 maf basic apportionment, any Basin-wide strategy must take this into consideration. As such, the portfolio analysis was designed to not only implement options to reduce system vulnerability but also to satisfy the Lower Division States' demand above the 7.5 maf basic apportionment. Augmentation, reuse, and conservation (with and without transfers) were the only options included in the portfolio analysis that could be used to satisfy these demands.

A summary of the system reliability results with the four portfolios in place is also summarized in table 4. Each portfolio was modeled under all future conditions that comprised the Baseline reliability, resulting in over 20,000 simulations for each portfolio. The portfolios were modeled such that options were implemented only when needed to address specific vulnerabilities, thus minimizing the investment simulated in the analysis. As shown in the table, inclusion of the portfolios was projected to improve the ability to meet Basin resources needs (i.e. reduce vulnerabilities). The vulnerabilities related to critical Upper Basin and Lower Basin water delivery metrics were reduced by 50 percent or more. The results for metrics related to electrical power, water quality, recreation, and ecological resources demonstrate reductions of a similar percentage in vulnerabilities. Only the metric related to flood control below Hoover Dam shows a slight increase in vulnerability due to the potential for higher reservoir storage (and higher likelihood of high release) when portfolios were included.

Although these reductions in vulnerabilities are encouraging, vulnerabilities continue to be present under some conditions, even when every option was implemented as soon as it was assumed to be available. This result is primarily because of the hydrologic conditions driving those vulnerabilities. Statistical analysis was performed to determine the specific hydrologic conditions (e.g., droughts of a particular length) that tended to result in certain critical vulnerabilities (e.g., Lee Ferry deficit and Lake Mead elevation less than 1,000 feet msl). Under Baseline conditions, the potential for these critical vulnerabilities was found to be strongly correlated to long-term mean natural flows at Lees Ferry below the historical average of 15.0 maf and droughts of 8 years or greater in duration.

Although the implementation of the portfolios does not completely eliminate the occurrence of such critical vulnerabilities, the portfolios are successful in significantly improving the resiliency of Basin resources to these vulnerable hydrologic conditions. With portfolios in place, the system is able achieve similar levels of reliability under more adverse hydrologic conditions. Specifically, with portfolios in place, the long-term average flow to which the Basin is vulnerable is about 0.5 mafy less and the magnitude of the 8-year period of lowest flows is reduced about 1 mafy. This type of information provides insight into specific hydrologic conditions that the system should be able to successfully endure and can inform water managers when crafting strategies to effectively hedge against those events.

TABLE 4
Summary of System Reliability Outcomes (Percent of Years Vulnerable) for Baseline and Portfolios for All Scenarios, 2041–2060 Period

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

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

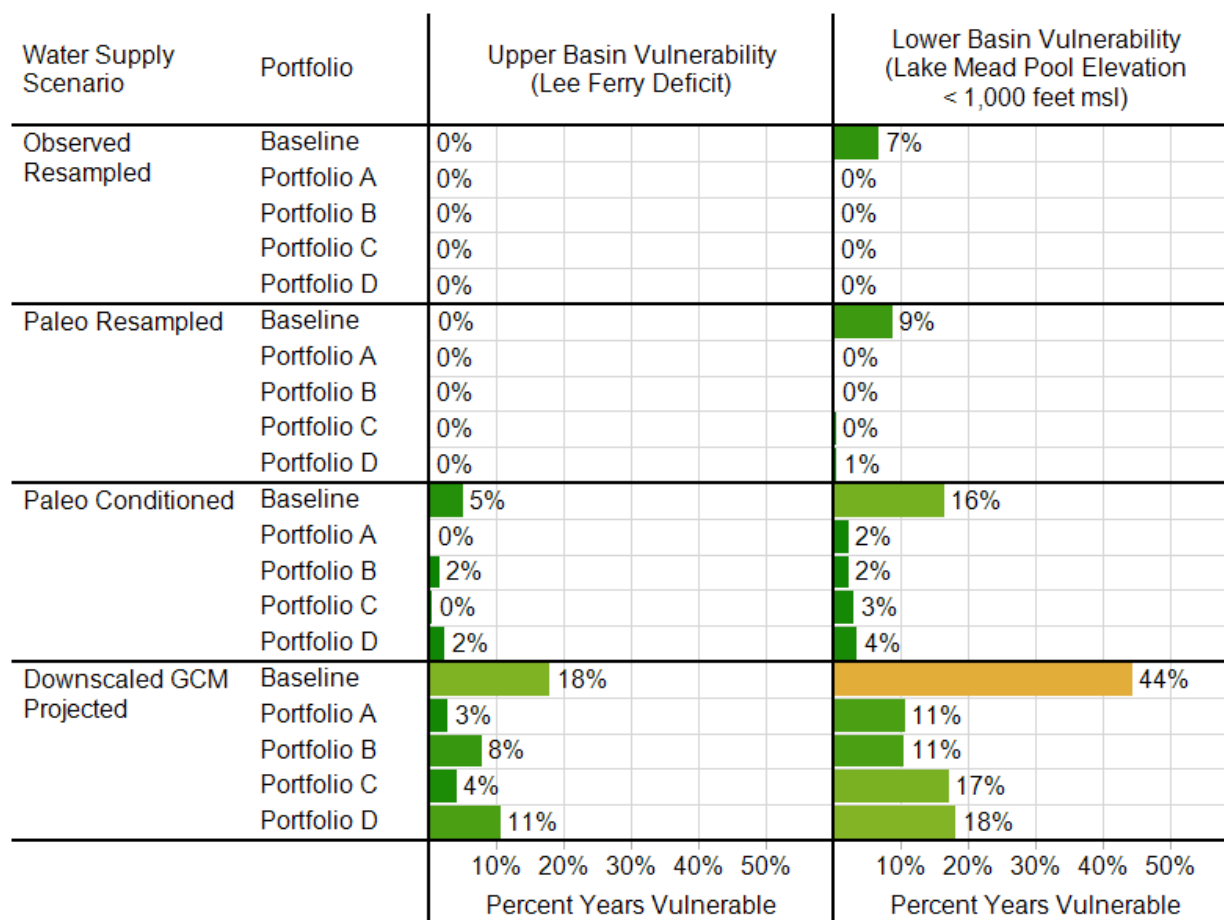
Although the portfolio analysis successfully demonstrated that system reliability can be improved, it is not without significant cost and performance tradeoffs. Figure 3 illustrates the performance across portfolios by water supply scenario in terms of addressing the critical Upper Basin and Lower Basin vulnerabilities.

Portfolio B favors options believed to have higher certainty of available water supply once implemented. As shown in figure 3 (on the right), this portfolio performs as well or better than all the other portfolios for addressing the Lower Basin vulnerability. The portfolio is less effective than *Portfolios A* and *C* for the Upper Basin vulnerability (figure 3, 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 water conservation and reuse. Choosing to implement options characterized as having low energy needs (as a surrogate for potential environmental impacts) might come at the expense of having a less certain long-term water supply. However, this portfolio performs well for addressing the Upper Basin vulnerability (figure 3, left) and is particularly effective under the Downscaled GCM Projected supply scenario (figure 3, bottom row). The effectiveness of this portfolio for addressing Upper Basin reliability vulnerabilities is largely attributable to the inclusion of an Upper Basin water bank that specifically targets this vulnerability. *Portfolio C* is less effective, however, at addressing the Lower Basin reliability vulnerabilities (figure 3, right).

FIGURE 3

Percent of Years Vulnerable for Upper Basin (left) and Lower Basin (right) Vulnerabilities in 2041–2060 with Portfolios, by Water Supply Scenario

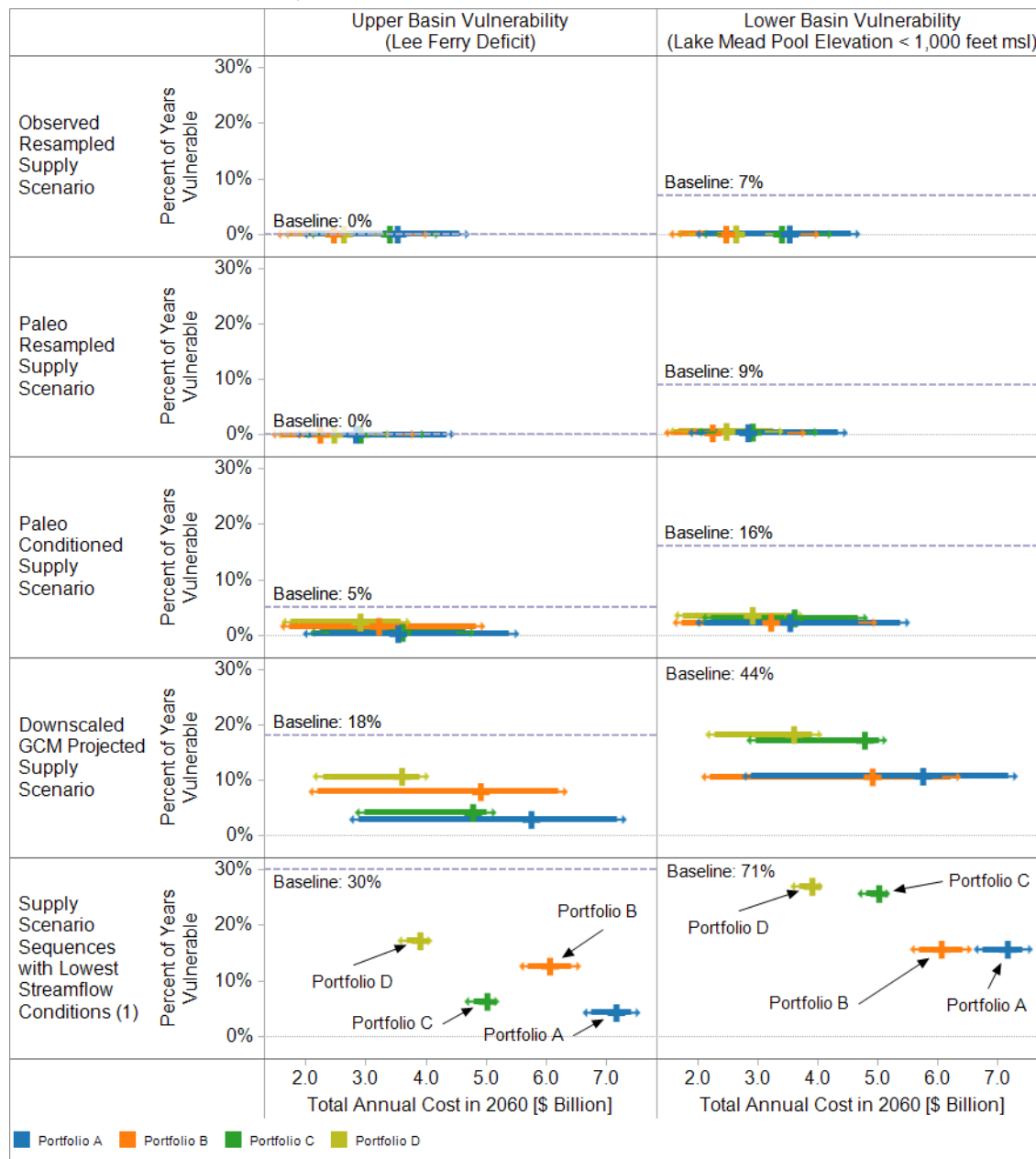


Tradeoffs also exist with respect to portfolio costs, and these differ depending on the specific future conditions. As shown in figure 4, the annual cost, in 2012 dollars, for implementing the portfolios ranges from approximately \$2.5 billion to \$3.5 billion in the year 2060 when considering the median 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 variability of the cost (reflected by the inter-quartile range or the length of the bars) reflects the varying size of the portfolios in different future conditions. Because of the appraisal-level option cost estimating used in the Study, the cost values contain additional uncertainty not directly reflected in these estimates. Across three supply scenarios (Observed Resampled, Paleo Resampled, and Paleo Conditioned), *Portfolios B* and *D* are generally shown to be less costly than *Portfolios A* and *C*. For the Downscaled GCM Projected water supply scenario tradeoffs between portfolios begin to become apparent. Specifically, *Portfolio C* leads to fewer vulnerable years with respect to Upper Basin vulnerability than *Portfolios A* and *B*, with an upper range of costs that is also lower than those for *Portfolios A* and *B*. Conversely, *Portfolio A* generally leads to the fewest vulnerable years with respect to Lower Basin reliability than other portfolios.

The differences among the portfolios become more apparent in terms of costs and ability to reduce vulnerability as one focuses on the future conditions that are particularly stressing to the

Basin. For water supply conditions that are less favorable, such as in the “Lowest Streamflow” subset of sequences (figure 4, bottom row), two distinct tradeoffs between reduction in vulnerability and cost across the portfolios are apparent. For the Upper Basin vulnerability, *Portfolio C* both performs better than *Portfolios B* and *D* in terms of reducing this vulnerability and has a lower range of costs than *Portfolios A* and *B*. For the Lower Basin vulnerability, however, *Portfolio B* reduces vulnerability more than *Portfolios C* and *D* and also results in lower costs than *Portfolio A*.

FIGURE 4
Portfolio Cost and Percent of Years Vulnerable for Upper Basin (left) and Lower Basin (right) Vulnerability for 2041–2060 across Water Supply Scenarios and Lowest Streamflow Conditions



(1) Lowest Streamflow Conditions are defined as those in which the average of the 2012–2060 natural flow at Lees Ferry is less than 14 mafy and the lowest 8-year natural flow at Lees Ferry from 2012–2060 averages less than 11 mafy.

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. The purpose of exploring these portfolios is not to identify a “best” portfolio or strategy, but to acknowledge that there are various ways to address the water supply and demand imbalance and to recognize that each approach has implications to be considered in future planning processes and decision-making.

5.0 Study Limitations

Although the technical approach of the Study was based on the best science and information available, as with all studies, there were 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, assessment methods, and the capability of existing models. These limitations provide opportunities for additional research and development and the improvement of available data, which will be pursued in efforts independent of the Study. Notable Study limitations include the following:

- **Ability to Assess Impacts to Basin Resources** – The ability to assess impacts to Basin resources, particularly in the Upper Basin, was limited by the spatial and temporal detail of the Colorado River Simulation System (CRSS), the primary model used in the Study. In particular, the Study’s assessment of water deliveries at local level, and ecological and recreational impacts were affected by these limitations. Future efforts will evaluate ways to improve the assessment of these resources in future studies which will include enhancements to CRSS, as appropriate.
- **Treatment of Lower Basin Tributaries** – CRSS uses historical inflows (not natural flows) based on USGS streamflow records for four tributaries below Lees Ferry (the Paria, Little Colorado, Virgin, and Bill Williams rivers). In addition, the Gila River is not included in CRSS. 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 Reclamation’s Consumptive Uses & Losses Reports limited the ability of the Study to gain a more complete understanding of historical consumptive use in the Basin. 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*.
- **Treatment of Agricultural Land Use in Water Demand Scenarios** – The development of the water demand storylines included participation from a broad range of stakeholders. The storylines were developed to represent a range of plausible futures regarding future demand. However, the assumptions in some storylines with regard to key 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. Although some scenarios do show increasing agricultural land use at a state and local level, given recent projections of increased agricultural productivity necessary to meet future food needs, plausible futures should include increases in land use.

- **Option Characterization Process** – The option characterization process strived for objectivity and consistency. The limitations identified during the characterization process included geographic limitations due to the extensive size of the basin and regional variety, the appraisal-level of the analysis, potential subjectivity during the characterization process, and significant uncertainty due to limited data. Specifically for those options associated with agricultural and M&I conservation and reuse, a detailed assessment by individual location for those options was not performed. Instead, these options were characterized at a Basin-wide level. The resulting assumptions were adopted for purposes of the Study and do not necessarily reflect achievable, or even desirable, local conservation goals for individual municipalities or agricultural locations. Further, not all stakeholders in the Study were in agreement with all characterization results, but it was recognized that future efforts beyond the Study should result in more in-depth assessments of the options and reduced uncertainty.
- **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.

6.0 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. In particular, 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 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 indicates that targeted investments in water conservation, reuse, and augmentation projects can improve the reliability and sustainability of the Colorado River system to meet current and future water needs. Ultimately, the Study is a call to action. To implement the water conservation, reuse, and augmentation projects identified in the Study, significant additional efforts are required immediately. These additional efforts, or next steps, include a commitment to further analysis and planning in many areas related to the Study.

In summary, there are several future actions that must take place to move implement 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 needs 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.

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.

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 will have to be constrained by funding, timing, and technological and other limitations, which may present 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 will develop and incorporate assumptions to further complete the Study. Where possible, a range of assumptions will typically be 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.